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HUMAN-CENTERED TECHNOLOGY FOR MAINTAINABILITY: WORKSHOP PROCEEDINGS

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This volume contains the proceedings of a workshop held on 12-13 September on human-centered design technology for maintainability assessment. It contains 23 original papers describing current technology in constituent fields such as computer-graphics, human modeling, anthropometric and related measurement problems, workstation concepts, and human factors evaluation. New research directions are highlighted, especially those proposed by the Armstrong Laboratory Human Resources Directorate.

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PREFACE

The Logistics and Human Factors Division of the Air Force Human Resources Laboratory[1] was pleased to sponsor a workshop on Human Centered Technology for maintainability design. The workshop was held in Dayton, Ohio on September 12 and 13, 1990 and was attended by more than 150 people. We are pleased again to present the proceedings of the workshop to the participants and to the human-centered design community.

We have had the goal of incorporating maintainability factors into design technology for many years. This goal is currently exemplified within the Logistics Systems Branch by our research thrust in Integrated Product Development, or IPD. We are developing and demonstrating a variety of design tools based on computer-aided design, computer-aided engineering, and computer-aided acquisition and logistics support technologies. A new subthrust within IPD called Human Centered Technology (HCT) has taken form recently. The overall objective of the workshop was to develop a common understanding of the state-of-the-art in this general field of HCT. The focus was on maintainability evaluation, but operability issues were also represented, and a broad range of relevant technologies, applications, and technical points of view were sampled. I attempt here to give an overview of the most important themes that emerged from the two-day interchange.

One of the core elements of HCT is human-modeling technology. An example of this is "Crew Chief", a joint program of the Armstrong Aerospace Medical Research Laboratory and the Air Force Human Resources Laboratory. Design tools like "Crew Chief" are beginning to take hold because they can help designers understand the physical limitations of maintenance people early and easily during system development Task visualization provided by modern computer graphics technology will empower a new medium for the human "ility" message in design evaluation.

In the future, we will be able to report a design problem and a design solution *visually*, not just *verbally*, and we will take advantage of related virtual experience technologies to simulate human performance in fuller aspect. With accurate graphical depictions of people using equipment and interacting with the proposed work environment, we will be able to influence design as it develops, not just react to it after it is complete. Video mock-ups of equipment and workplace designs will eventually replace physical mock-ups as platforms for human/machine evaluation. This visualizing future for human-centered design was a central theme of the workshop and it is featured in many of the papers in this volume.

But computer-graphics for task visualization and evaluation will lack credibility without accurate and realistic data describing human capabilities. Representation of human ergonomics in terms of anthropometry, biomechanics, and biodynamics was given special attention at the workshop. New techniques for anthropometric measurement and for representing different population groups using human-modeling technology were discussed. Some people believe that new data base development to increase ergonomic precision must be evaluated against the expected utility to be gained from greater precision in human-modeling applications in design evaluation. There may be a trade-off between the cost of greater precision and its practical utility for at least some classes of human/machine evaluation problems. At any rate, many feel that the ability of computer-graphics technology to *portray* the facts about human performance is outpacing our ability to *produce* these facts through basic research.

Design influence is only one part of the future role we envision for human-centered design technology. We also need to participate more effectively in planning system support for human

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[1] Now a part of the Human Resources Directorate of the Armstrong Laboratory.

resources. For equipment maintenance, especially, this means carrying forward the results of human-centered design evaluations to the acquisition logistics information and planning functions. The procedures already in place for this are called Logistics Support Analysis, or LSA. The data requirements for LSA are called Logistics Support Analysis Records, or LSAR. Making Logistics Support Analysis more complete and more efficient is one of the objectives of the Computer-Aided Acquisition and Logistics Support initiative, or CALS. Several papers and discussions brought out this CALS orientation as an important new direction for human-centered technology development.

The opportunity to advance the objectives of CALS using HCT is in doing a better job of verifying and documenting the human side of systems support. Improving the quality and accuracy of maintenance technical manuals, training development, and specification of personnel requirements are examples of CALS applications that HCT should support. In former times, these logistics support elements were referred to as the "personnel subsystem." Today they are more commonly called Manpower, Personnel, and Training, or MPT. However we call it, better planning for human resources hinges on the quality, accuracy, and timeliness of design documentation. This documentation, in the form of digital data bases organized around LSAR, will encode the results of HCT applications. As technology for graphical simulation of human performance matures, IPD technology for human-centered design will be able to capture many of these logistics support requirements. A CALS orientation to the management of human-centered design information will increase the value of LSA and LSAR in comprehensive product analysis and support system definition.

The development of HCT using CAD, CAE, and CALS engineering workstation technologies is a special theme of new research by AFHRL presented at the workshop. This research includes maintainability (DEPTH) and operability (AIRT) simulation technologies, as well as RAMCAD concepts for integrating maintenance manpower forecasts within design.[2] The maintainability technology will develop an animated human model capable of simulating dynamic human/machine interactions and create a versatile platform for capturing a wider set of human performance criteria. The operability technology will focus on human performance process model development for simulating complex cognitive task environments. The RAMCAD approach to manpower projection would link maintenance workload from reliability and maintainability parameters with a manpower costing tool to give designers a more complete evaluation of the costs and benefits of alternative ways of allocating or "packaging" equipment reliability and maintainability goals.[3]

Regarding technology applications and technology transition, the workshop naturally emphasized military requirements. The problems of pilots and cockpits (or operators and workstations) have been dominant concerns in this technology area. This will no doubt continue to be a primary focus of human-centered technology in the Air Force. But new applications are before us, and there is a new impetus to transition the products of our research investments to both military and commercial uses.

The realities of the declining defense budget and the changing military environment are bound to result in greater stress on upgrades and modifications for existing systems rather than major new systems in the future. Therefore, human-centered design evaluation techniques should be adaptable to this acquisition context. HCT should look for ways of retrofitting human/machine

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[2] DEPTH - Design Evaluation for Personnel, Training, and Human Factors; AIRT - Automation Impacts Research Testbed; RAMCAD - Reliability and Maintainability in Computer-aided Design

[3] An ideal distributed workstation environment for IPD would link "ility" domains horizontally and vertically in a seamless way. From an HCT perspective, this would mean passing human performance data from the "lower" physical level of human/machine integration to the "higher" level of system-wide human resource definition. It also means passing information between, for example, a RAM workstation and a human-modeling workstation.

design for systems we already have, for "reverse engineering" from the human factors point of view. Here is where much of the business will be, and where human-centered design might make its most important contribution to military capability. In addition, logistics information management will become more important as globalization of commercial - and military - product manufacturing and support processes continues.

In this regard, depot maintenance and repair of aerospace equipment need to be considered. The questions of technical data management, job design, and human factors in materials handling, manufacturing, and so on at the field level also apply to maintenance work at the depot level. There has been a natural tendency to look at maintainability problems only from the flight line perspective. But since Air Force design applications for the foreseeable future will stress retrofits, we are likely to find depot repair and manufacturing processes benefitting as much as deployed maintenance from technology for describing the human side of systems.

Finally, a word on the human side of the workshop itself. We are grateful to the workshop speakers for their excellent presentations and for the quality of their papers we present here. Colonel James Clark, Mr. Bert Cream, Ms. Wendy Campbell, and Mr. Mark Hoffman enthusiastically supported this project from beginning to end. The people of Systems Exploration, Incorporated also provided excellent support throughout. The organizational skills of Mr. Medhat Korna and the editorial skills of Ms. Susan Harper are vividly displayed here. Many colleagues also contributed to the workshop's success. These include Mr. Mike Young, Dr. Robert Patterson, Mr. Matt Tracy, Mr. John Ianni, Ms. Jill Easterly, Dr. R. Bruce Gould, Major Colleen Gorman, and Captain Rick Berry. To all, all thanks.

Edward Boyle

February 4, 1991

AFHRL/LRL
Wright-Patterson Air Force Base, Ohio

SUMMARY

This volume contains the proceedings of a workshop on Human Centered Technology (HCT) held in Dayon, Ohio on September 12 and 13, 1990. HCT uses computer technology, especially computer graphics, to create opportunities for human factors evaluation earlier in the design of systems. Important developments are discussed in the workshop papers. These include anthropometric man-modeling, computer-aided design graphics, and cognitive task analysis methods.

WELCOMING REMARKS

Colonel Irving J. LeBlanc

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Good Morning, I'm very happy to be here representing the Human Systems Division, AAMRL, and HRL. We've asked leaders in human-centered design from industry, academics, and the government to explore how the technology you represent can be used to improve system support and maintainability. I ask that you share your ideas and help us define high payoff technology that can be used to develop these tools.

I'm really impressed with the list of speakers, some top-notch expertise in a number of areas. A lot of familiar faces to the people in AAMRL.

The defense budget has been reduced and will be reduced further. We're looking at a smaller Air Force. At the same time, we have to keep our forces at a high level of readiness. It means doing more with less. It means doing things smarter. It means buying systems we know we can support.

It means doing things together -- the government, industry and academia. Truly joint efforts will be a key part of our future. We have a real success story in the Crew Chief program, a joint effort of AFHRL and AAMRL.

I want to briefly discuss the Crew Chief effort because I believe it's a model of a very successful joint effort and because so many of you have been involved in its development. Beginning in 1972, COMBIMAN was developed as a Computer-Aided Engineering (CAE) model of an aircraft pilot.[1] COMBIMAN has been in distribution since 1978, and has been used by industry, the U.S. Army, and the Air Force to evaluate design changes. In 1988, Dr. Bill Askren (then with HRL) and Dr. Joe McDaniel started a program to develop a variant of COMBIMAN to model the physical accommodation of a maintenance technician, and Crew Chief was born. In 1988, Crew Chief was completed and interfaced to several CAD systems used by aerospace designers, and can be used to evaluate the maintainability of aircraft and other complex systems.

The Crew Chief model allows the designer to simulate a maintenance activity on the computer-generated image of the design and to determine if the required maintenance activities are feasible. One of these efforts' greatest contributions to the state-of-the-art is the tremendous data base of human strength capabilities. The strength research which preceded the model, for example, involved over 100,000 strength measures; and more will be made in the future.

WHERE DO WE GO FROM HERE?

We must make improvements in the Air Force by addressing specific technology needs. There are many of them in the application domain of this workshop: system support and maintainability. They originate from a formal system of establishing requirements called logistics needs and manpower, personnel, and training needs. I'll provide some highlights to give you a picture of these current needs.

There is a need for maintenance speciality compression to reduce the support trail required by mobile combat forces. It's not hard to see how improvements in this area can save large amounts of money as exemplified in the costs of the Desert Shield deployment.

Another major effort is Computer-Aided Acquisition Logistics Support (CALS), which is a DOD/industry program to improve productivity through digitization and integration of technical information throughout weapon system acquisition. Included is the integration of reliability and maintainability into CAD/CAM processes to improve the flow of logistics information.

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[1] Computerized Biomechanical Man Model

Approximately 35 perecent of the lifetime cost of a military system is spent for maintenance. Excessive repair time is caused by failure of system design to adequately consider maintenance. The technician will spend hours making a repair which could have been completed in minutes if accessibility had been adequate. Ultimately, development costs and acquisition time, as well as life cycle costs and maintenance time, will be reduced if maintenance considerations are properly addressed in system design.

HOW CAN WE SOLVE THESE PROBLEMS?

In the near future, two advances in computer technology will influence the direction of CAE tools. The most obvious is the increased capability of low-cost engineering workstations. Second, there is a significant move toward standardizing on an operating system, so exchange of graphics data among different CAD vendors may soon be possible.

BEYOND THE IMMEDIATE FUTURE

We can predict that the virtual display technology being developed at HSD will be applied to CAD/CAM tools. The virtual display is a 3D stereo display which is mounted on the head, so that each eye sees a separate display, not just an alternating image. Resolution and picture quality will increase. Not only will the design appear in 3D, but the designer will appear to be inside the design. By planning the image with head movement, the perception of presence will be complete. In such an environment, the workstation controls should also be virtual. Instead of selecting a line to be changed or moved with a cursor, you can reach out and grab it with your hand, or rather a virtual image reproduction of your hand.

New technology is making inroads in body size measurement. Someday, we may be able to measure the human body in three dimensions. Already, new technology uses a laser scanner to gather data on head and face shapes. In the near term, such data are useful for head gear design, such as helmets and chemical protective masks.

I think I've said enough--it's time for the group to go to work. I'm extremely pleased that you have come here to share your expertise. Thank you very much for coming. I look forward to seeing your ideas on how to apply your technology toward improving weapon system supportability and maintainability.

Have a good workshop. Thank you.

HUMAN-CENTERED FOCUS IN SYSTEMS ENGINEERING

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ABSTRACT

The goal of Systems Engineering has always been a balanced, affordable design that meets all the customer's requirements. The development of Computer-Aided Design and Engineering technology, the resulting change to a simultaneous engineering process, progress toward data interchange standards at an enterprise level, and the rediscovery of Total Quality Management with its emphasis on the customer, all give new impetus and means to better attain that goal. Human-centered concerns are at the heart of satisfying the customer. The opportunity exists to effectively design for the end user at every stage of a computer-based, simultaneous Systems Engineering approach: during the development and refinement of design requirements; with Computer-Aided Engineering workstation tools to design for ease of operation and maintenance in knowledge-based design checking; and in the integrated development of effective training and support systems.

INTRODUCTION

As our keynote speaker pointed out, the manufacturing sector in the United States has been undergoing fundamental changes in the 1980s that will accelerate in the 1990s. The world will no longer buy whatever American firms produce. Foreign competitors have made significant inroads with enlightened management practices and responsive, integrated management systems that deliver quality to the customer. American manufacturers are now rethinking the way they do business and rapidly changing their own management approaches to improve quality and be more responsive to their customers. Under the impetus of Mr. Costello during his tenure in OSD, the revitalization underway in industry has been extended to the Department of Defense (DoD) and its military contractors.

THE NEW PHILOSOPHY

Among the new buzzwords are Total Quality Management (TQM), Simultaneous/Concurrent Engineering, Integrated Product Development (IPD), and Quality Function Deployment (QFD). TQM is a management philosophy in which everyone directs their effort to continuously improving the processes to deliver a better product to the customer. It emphasizes the proper role of management in strategic planning and in creating a productive environment that fosters commitment, initiative and innovation by the entire work force. It mandates that decisions be made with relevant data.

Simultaneous Engineering, Concurrent Engineering, and IPD are different names for a more responsive way to design and produce a product under the TQM philosophy. Engineering design has traditionally followed a functional organization flow: When one department has completed the design from its viewpoint, it "throws it over the wall" to the next department. The electronic engineers lay down a complete design that will function electronically, then a reliability engineer tries to make changes so it won't break as easily, then it goes to production engineering for modification so it can be built, and so on. The new method is to have all these people work together at the same time as one design team. The goal is a more balanced, economical, and effective design to meet all aspects of the customer's need, arrived at jointly rather than as a series of sequentially constrained compromises. QFD procedures provide a dynamic, hierarchical requirement structure to help the design teams do the critical translation of customer need into specific engineering criteria at each indenture level of a system design.

THE NEW ENABLING TECHNOLOGY

The goal of balanced design is not new. We have all attempted and given lip service to the concept of systems engineering. It is taking hold now in the form of these new buzzword techniques for two reasons: in today's competitive world economy it is now essential for survival, and advances in computer technology have now made systems engineering feasible and affordable.

The old Air Force 375 series regulations had the same goal but required laborious analyses of often inconsistent data that had to be documented on literally truckloads of paper. They added significantly to the time and cost of product development. Today, integrated shared data bases permit information configuration control, and Computer-Aided Engineering (CAE) software permits rapid analysis of alternatives and trade-offs. In this environment, an integrated systems engineering team produces better products that get to the customer faster at lower overall cost by getting all aspects of the design correct in the first release.

It is worth noting that the earlier attempt at systems engineering was directed at the defense industry by government regulation. The new systems engineering revolution has taken place in the private sector, accompanied by profound changes in corporate management and culture. The DoD and its contractors have been relative latecomers, but the aerospace industry is now fully committed. The major firms have been undertaking far-reaching reorganizations and large capital investments to get a responsive systems engineering capability.

One area where government and industry are cooperating is in the essential development of digital data and product definition data standards. The enabling technology will not be effective unless product design information can be easily communicated and shared among the computers in all departments of a firm, and between a firm and its suppliers and venture partners. The DoD, working with the National Institute of Science and Technology, is facilitating such standards development. Computer-Aided Acquisition and Logistics Support (CALS) is a comprehensive effort to establish electronic data interchange standards for product support information, and foster the development of CAE techniques to ensure more supportable products for the military.

ENGINEERING TO SATISFY THE USER

The new philosophy of systems engineering recognizes that customers buy products to meet a definite need and function. It is the customer's use that must drive design. This usually means designing things to be easy to operate and generally trouble free, and easy to get back in service if there is trouble. These concerns are the realm of specialists in reliability, maintainability, and human factors engineering. They must analyze how conveniently and safely customers can operate, service, and, if necessary, fix the product. But these specialists can only contribute effectively in systems engineering design teams if they have credible, responsive, computer-based models and analysis software that allow them to keep up with the design engineers from other disciplines as the design alternatives are generated and analyzed.

During the next two days, I hope to hear a lot about new developments that will provide computing environments for rapid analysis of people-machine interfaces. The importance of fast, user-friendly, flexible, and transportable tools for human-centered design analysis cannot be overemphasized. Of course, the most successful tools will be based on thorough understanding of the user's need, in this case the user being the human-centered design analyst on the product engineering team. How much detail is necessary in a model of human physical capabilities to be useful for design assessment? How closely must source data population demographics match target population and how can an engineer make that determination? What metrics can best represent the design dependent human performance and preferences in systems engineering trade-off analyses? How is the operational environment in which the product will be used or maintained accounted for? These are just a few of the issues that will have to be addressed in the development of practical and useful tools for human-centered design analysis.

PROVIDING DATA FOR PRODUCT SUPPORT

If you ever bought a toy for your kids and then discovered that the assembly instructions were in a foreign language, you appreciate the importance of product support. To be useful to the customer, a product must have adequate operating instructions and information on what to do if something goes wrong. In the case of complex military systems, this can mean a wall of manuals, elaborate test equipment, or automated job aids. It can also mean training courses and training equipment that may be as much of a design effort as the product itself. It may mean establishing service and repair centers stocked with appropriate tools, parts, and trained people. Under the system engineering philosophy, product support is an essential and inseparable consideration in product design.

The source data for developing and planning product support comes from human-centered design analysis. The manuals, the job aids, the training requirements, the manning requirements, and the service center layout all start from the product task analysis. A task analysis is the step-by-step identification of exactly what people must do to operate and maintain the product, how many and what kind of people it takes, how long it takes, and what tools, special equipment, or special environment they need. The job of developing the task analysis will be easier, faster, and more accurate if the analyst can use a three-dimensional dynamic display to quickly visualize the tasks, and a human performance model to test whether specific tasks are feasible. The immense advantage for multi-person coordination tasks is particularly evident. The human-centered design analyst may need some different workstation capabilities to do task analysis than to only do design assessment. There needs to be ready access to other data bases for referent data associated with comparable tasks on other products. Knowledge-based techniques which could assist in rapidly accessing such information, and in determining where more detailed feasibility analyses are warranted, would be helpful. The workstation environment should also facilitate documentation and control of the task analysis, and electronic communication to the other product support development activities.

The product support development process for military products is called Logistics Support Analysis (LSA). Under IPD, it is an inherent part of the systems engineering process. The CALS standards are being developed and implemented in defense contracts to ensure that this process is automated and integrated in a way that permits electronic data exchange. Clearly, a workstation to do human-centered design analysis and generate the essential task analysis must be CALS compliant to be used in the defense industry.

SUMMARY

Competitive pressure and advances in computer technology have brought about a fundamental change in the way products are being designed and developed. Design is becoming an integrated team activity rather than a compartmentalized sequential process. Emphasis is on a balanced, affordable design that provides what the customer wants. Human-centered design analysis now has increased importance, not only to ensure that the product can be easily used and maintained, but to provide the basic task analysis information for all the product support development activities. Human-centered design analysts need responsive computer-based models and analysis techniques to hold their own with the other engineering disciplines. I expect that this conference will show what significant progress has been made, and what still needs to be done, to reach this goal.

OVERCOMING BARRIERS TO COMPUTER HUMAN MODELING IN CONCURRENT ENGINEERING

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ABSTRACT

Computer-based mathematical models of humans can provide powerful tools for concurrent engineering analysis of human-machine interfaces. Long before mock-ups and models are constructed and simulators made operational, Computer-Aided Design (CAD) definitions of work space geometry and environmental constraints can be evaluated in many useful ways. However, such mathematical human models are relatively new, oversimplified, and incomplete. Many complex anthropometric and biomechanical relationships needed for their accurate formulation are yet to be discovered and reported. This paper describes some of the key barriers the author sees as preventing the immediate use of computer-based human models to concurrent engineering and offers current and potential methods to help overcome such barriers. The barriers discussed include (a) inconsistency in anthropometric dimensions measured across surveys, (b) inadequate reporting of anthropometric dimensions in biomechanical studies, (c) lack of data on civilian worker populations, (d) incomplete data on the locations of joints and lengths of internal links and of human joint ranges of motion, (e) lack of systems approach in academic studies, and (f) lack of well-defined processes for applying computer capabilities to development of human factors design requirements and evaluation of engineering designs early in the design process. Example solutions offered include (a) statistical estimation and empirical analysis methods, (b) forecasting and synthesis approaches, (c) new concepts for formally defining and extending link definitions and joint center locations, and (d) new concepts for obtaining future measurements and proposals to develop standards.

INTRODUCTION

Computer-based, interactive mathematical models of humans are versatile and powerful tools that can potentially facilitate concurrent engineering analysis of human-machine interfaces such as maintenance work sites. Long before mock-ups and scale models are constructed and simulators made operational, Computer-Aided Design (CAD) definitions of work space geometry and environmental constraints can be evaluated in a preliminary manner with regard to reach, access clearance, vision obstructions, capability of humans to exert force, and many other useful relationships. Experience has indicated these approaches are valuable for product design involving operability, maintainability, and manufacturing. As such models become more versatile, easy to use, and accurate, the advantages will increase.

However, such mathematical human models are still relatively limited in scope, and not as accurate as desired for realistic evaluation. One reason for this condition is that there are many complex anthropometric and biomechanical relationships, supporting data, and statistical interactions yet to be discovered and applied. These discoveries and applications are needed for accurate model formulation. Since such basic barriers have not been overcome, it is doubly difficult to go on to the less definite concepts such as time functions, workload, manpower requirements, physiological implications, and cognitive functions.

This paper identifies specific types of barriers related to anthropometry and biomechanics, and describes a number of approaches which may overcome them, thus helping industry to progress more quickly toward the goals of concurrent engineering. The discussion considers both long-range objectives and near-term options.

In addition to technical barriers, the basic concepts for effective organizational use of computer evaluation processes, including human modeling, that will support concurrent engineering goals have not been well defined and taught to many potential users. This paper suggests some general concerns about how such processes and policies should work and characteristics of the software interfaces with human models that are important to success applications.

OVERCOMING INADEQUATE INFORMATION AND CONFUSION

Through accidents of history and neglect of the proper study of man, many pervasively irritating, information-related barriers have been created in the path of progress. Some of these are legacies embedded in the literature and historical practice of anthropology. Like brick walls or boulders strewn on a path, they must be bypassed or broken down. However, most of the barriers discussed here are more appropriately visualized as various sizes of potholes, cracks, crevices, and canyons reflecting inadequacy of information, especially of the type and quantity needed for computer human modeling. The process of "overcoming" these is often to "fill in the crack" with new knowledge or to "build a bridge over the canyon" by a combination of clever analysis and new data.

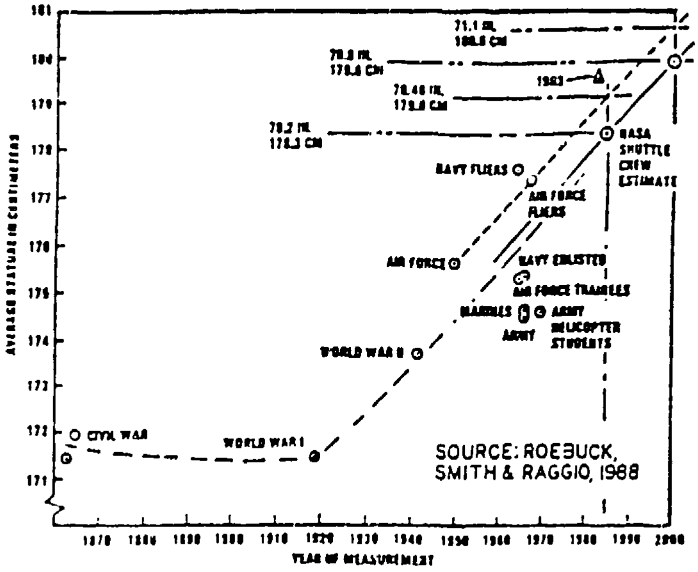
Seen from outside the field, it appears that the many reports and thick volumes written on these subjects should contain all the knowledge needed to formulate adequate models. However, many readers of this paper well understand how awesomely audacious is the concept of modeling the tremendous variety of human sizes, shapes, performance capabilities, and limitations. They know about the extremely uneven state of development in many critical areas and the utterly fantastic complexity of the human body. So, what can be done about it?

General Long-Range Approach

Briefly, the long-range view indicates a real need for a new and better, more comprehensive cycle of anthropometric and biomechanical surveys and detailed research. Past surveys actually need to be replicated on current populations using the recent knowledge gained from struggling with the problems. This time researchers must "do it right" for the new purposes of obtaining integrated, comprehensive and specific data needed for human modeling by graphic computer analysis. Most designs of surveys in the past have not even adequately considered the poor draftsman trying to draw a human form in a work site geometry. Current computer models are even more demanding, and not much good at fudging, or "winging it." Work space evaluation needs are increasingly different from the original anthropological goals of comparing racial groups or even later needs for design of clothing. Of course, before embarking on large-scale surveys one should perform small-scale measurement studies of selected samples from the expected populations (or, to be more correct, their antecedents that can be actually measured today). Such a preliminary "mapping of the territory" is both prudent and necessary, before exploring it in fine detail.

Barrier: Availability of CURRENT Population Data

One of the first questions to be asked is: "Are any of the currently available anthropometric data appropriate for today's or tomorrow's maintenance problems?" This question is raised because for the past 80 to 100 years there has been a remarkable secular (historical) growth in stature and related length dimensions of many of the world's populations (NASA, 1978a), and in some U.S. military populations as shown in Figure 1. The chart indicates that many years often pass between one anthropometric survey and the next. Experience in the recent past has shown that aircraft and aerospace projects have required a five- to ten-year development cycle from design to deployment (and some much longer). Thus, it is more likely that old data rather than current data will be used. By developing the practices of Concurrent Engineering (CE) it is hoped that American industry can shorten such development cycles significantly. Still, by the time an air vehicle is in operation for a few years the anthropometric data base which set requirements for aircraft projects may be two or more decades old.



SOURCE: ROEBUCK, SMITH & RAGGIO, 1988

Figure 1. Average Stature Versus Calendar Year of U.S. Military Men and NASA Crew, Showing Projected Growth Trends.

Long-Range Considerations: Forecasting Secular Trends. One method to offset the above-described problem is to prepare forecasts of anthropometric secular trends and use these estimations for design requirements. Examples of such processes performed for the space shuttle and the Freedom space station (and some of the resulting pitfalls) have been described in a paper by Roebuck, Smith, and Raggio (1988). For the long-range view, it is necessary to continue developing the art and science of forecasting, accounting for known trends in population immigration, aging, attrition, socioeconomic, and other factors (Roebuck, Kroemer, and Thomson, 1975; NASA, 1978; Kroemer et al., 1986). Such new approaches should be specified by the USAF as NASA has for the space station. Also, current specifications, such as MIL-STD-1472, ought to be revised to account for expected secular trends.

Near-Term Considerations: Available Forecasts. Fortunately, we now have available the anthropometric forecast which was performed during the early 1970 time frame to predict changes in anthropometry circa 1985 for male NASA pilots (NASA, 1978). Also, during 1986 a forecast was performed to extend the predictions to the year 2000 (NASA, 1987). These forecasts were performed with the goal of predicting anthropometry of flying personnel for aerospace vehicles. However, until forecasts are developed specifically for maintenance personnel, these available forecasts might be used with reasonable adjustments for differences in age, education, and other known factors. For example, non-pilots have in the past been generally shorter and of wider variability than flying personnel.

Unfortunately, the last decade has been one of some uncertainty in regard to the problem of forecasting. Some populations in the Free World have apparently begun to level out or stop their growth. Examples are those of Norway (NASA, 1978a), British civilians (Pheasant, 1968), and perhaps civilians in the U.S.A. Early returns from the 1988 survey of U.S. Army males (Gordon et al., 1989) seem to indicate that growth of Army males has slowed. However, this may reflect a difference in socioeconomic conditions for Army personnel. Caution is urged, and further near-term surveys and trend studies should be done to help understand and gauge the real trends more accurately.

Barriers: Missing and Unsatisfactory External Anthropometric Length Dimensions and Interrelations

"Potholes". Another typical barrier related to external anthropometry is the mismatch between model requirements and available data from anthropometric and biomechanics surveys. For example, the author recently compared available data from several major surveys to the needs for only 14 dimensions for a simple model, the Crewstation Assessment of Reach, Version IV (CAR IV) (Harris and Iavecchia, 1984). It was found that at least two dimensions were missing from each survey (Roebuck, 1989). Most of these "potholes" were lengths and heights. These do not necessarily cause traffic gridlock, but they do add the work of estimating dimensions that were not measured in a particular population of interest.

"Confusing Street Signs". Sometimes the question of dimension availability is confused by the many differences in titles for anthropometric measurements. This is an unsatisfactory condition which needs constant attention and upgrading of comparative documents to overcome. Also, it is one that could be minimized by periodic meetings of specialists in the field to set standards. Such a meeting, hosted by the Air Force, was reported by Hertzberg (1968). It is long past time to convene such a meeting again and expand its scope in light of modern human modeling needs.

"Wrong Turns". Problems can arise from inappropriate choices of measurements, as exemplified by the case of the Buttock-Leg Length. The ideal definition of the posture for obtaining this measurement is depicted in Figure 2a. All the link lengths (distances between

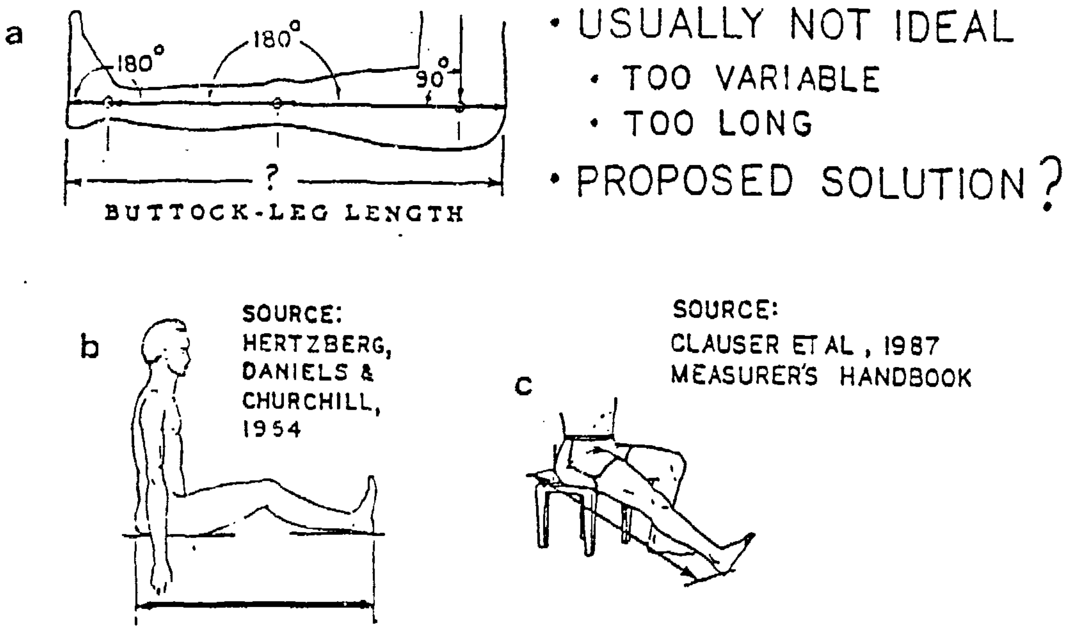


Figure 2. Ideal Posture for Buttock-Leg Length Measurement Versus Actual Postures for 1950 USAF Survey and 1988 Army Survey.

effective joint centers of rotation) are aligned perfectly, and oriented at 90 degrees to a theoretical trunk back plane. However, Figure 2b, from Hertzberg, Daniels, and Churchill (1954) reminds us that in actual practice many men cannot achieve the theoretical ideal posture. At best, such men can achieve a less satisfactory posture as shown in Figure 2c, where no links are perpendicular to the trunk. As a result, use of data based on either measurement 2b or 2c is subject to uncertainty about accuracy of the mean and the variance. In summary, all single-measurement attempts to define Buttock-Leg Length are unsatisfactory for all foreseeable purposes in design and in modeling. Following are some alternatives which make manageable many of these problems of missing lengths.

Long-Range Solutions: Alternative Measurements, Deriving Missing Dimensions. As a future simple fix for the Buttock-Leg Length problem, a more constructive recommendation is offered: Instead of one unsatisfactory measurement, make two easier and more accurate, related measurements and derive the needed result (Roebuck, 1989). One example of possible approaches is described in Figure 3, which suggests use of a measurement called Kneeling Height. By subtracting Kneeling Height from Stature, the difference obtained can be used to determine a length to be added to Buttock-Knee Length to derive Buttock-Leg Length.

Near-Term Solutions: Summing Two Statistical Distributions. An example problem is solved in Figure 4 to illustrate an approach for combining two known distributions which have normal or near normal distributions. The calculation process shown applies to summing Hand Length and Elbow-Wrist Length for 1967 male USAF Flying Personnel (NASA, 1978b). The result is called Forearm-Hand Length, and is one of the 14 dimensions mentioned above for the Crewstation Assessment of Reach (CAR) IV reach model (Harris and Iavecchia, 1984). A similar set of formulas (only a couple of signs are changed) is used for subtraction of two known dimensions. As an example, the Elbow-Wrist Length for USAF Flying Personnel in 1950

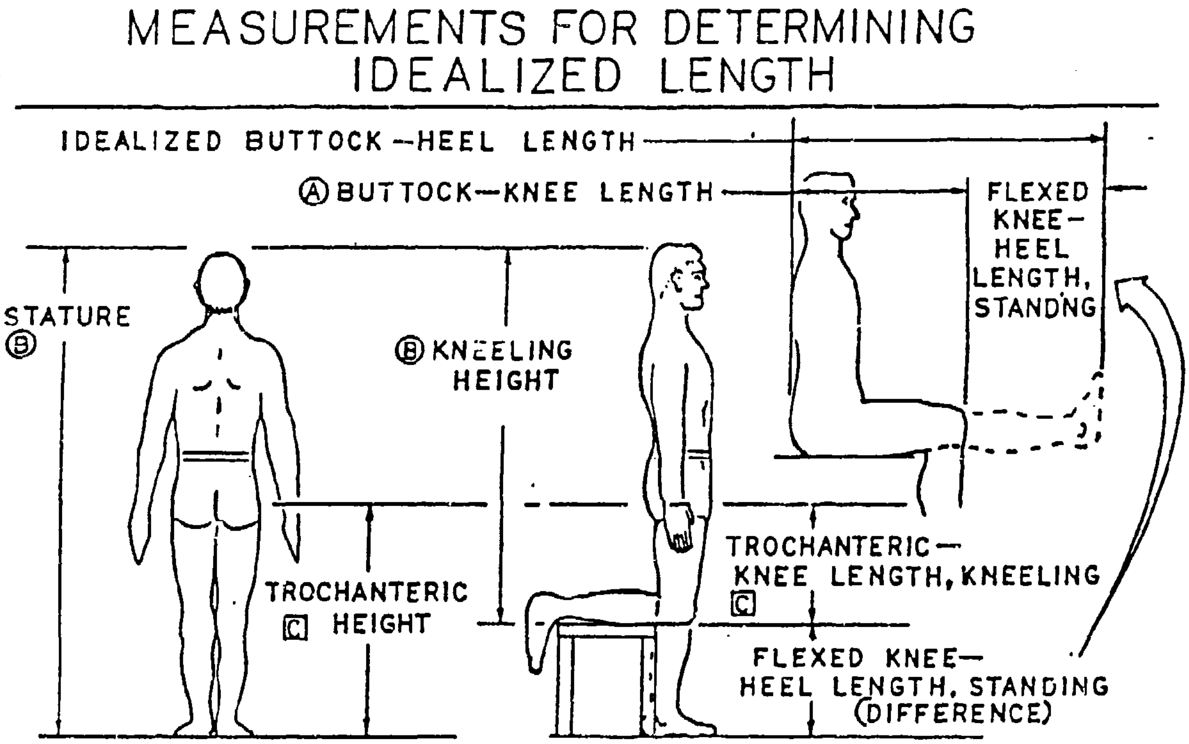


Figure 3. Kneeling Height Measurement to Derive Buttock-Leg Length.

SUM OF 2 KNOWN DIMENSIONS

PROBLEM: FIND MEAN AND STANDARD DEVIATION FOR USAF 1967 FLYING PERSONNEL (MALES) FOREARM HAND LENGTH.

GIVEN/APPROACH: FOLLOWING DATA AND CALCULATION TABLE FORMAT:

DIMENSION	MEAN	S.D.	CORRELATION COEFF. 1	2	3
1. HAND LENGTH	7.52	.32		.643	
2. ELBOW WRIST L.	11.81	.56	.643		
3. FOREARM-HAND L.	19.33	.80			

- ADD MEANS: $M_3 = M_1 + M_2$
- CALCULATE S.D.: $S_3 = \sqrt{S_1{}^2 + S_2{}^2 + R_{12} S_1 S_2}$

Figure 4. Summing Two-Dimension Statistical Distributions.

(Hertzberg et al., 1954) could be determined by subtracting Hand Length from Forearm-Hand Length. These examples are good reminders that useful anthropometric data for even one dimension in the context of human model constructions for populations typically must consider many numbers. Each dimension must be considered as (a) a statistical distribution and (b) a set of relationships to other dimensions. In fact, each dimension carries implications for an entire system of numbers which include data to yield the following essentials:

1. A measure of central tendency (e.g., the arithmetic mean)
2. A measure of variability (e.g., the standard deviation)
3. Measures of interrelations to other dimensions in the population (e.g., coefficients of correlation and/or regression equations)
4. Measures of deviation from a normal (Gaussian) distribution

Without all the above data in some form, it is difficult to create accurate mathematical models which describe the multiple combinations that can occur within the individuals of a population. (Parenthetically, it is only fair to note that the first two measures can be mathematically derived if two widely separated percentiles can be supplied, assuming that the statistical distribution is essentially normal.)

Many length dimensions meet the criterion of normality reasonably well. (Breadths and depths often are not so satisfactory, but are less likely to be summed or subtracted.) Unfortunately, not all survey reports include coefficients of correlation, or they are separately reported in less obvious places at a later time. However, alternate approaches are given later for estimating standard deviations when coefficients of correlation are missing.

Estimating Coefficient of Correlation for New Distributions. Another step in preparing data for use in the CAR IV model is inputting coefficients of correlation between all the 14 variable input dimensions used in the model. (Such correlations are needed for the Monte Carlo synthesizing process described later.) Therefore, if one of the necessary dimensions must be estimated, that new dimension must also have known or derived correlation coefficients between it and the remaining variable input dimensions used in the model. Solutions for this type of problem are not found in current anthropometry methods books. One sample problem solution is illustrated in Figure 5, which deals with the correlation between a newly derived dimension distribution and each of the addends used to derive it.

Barrier: Insufficient Multivariate Regressions

In addition to bivariate correlations, human modeling typically requires multivariate distributions which can help to accurately define dimensions of depth, breadth, and circumference of whole human forms. For most past large-scale studies, such data are not readily available or not available at all. In some cases the problem is mainly one of economics and priority of efforts. In other cases, the data were simply never analyzed.

Long-Range Solutions. Future anthropometric surveys should include many multiple regression relationships and provide the original data in computer files for reconstitution as needed to develop more of such relationships as needed. Such data could be valuable for many other populations in the data banks used for human modeling, particularly those which apply to the maintainer population in the military forces and to the pitifully few data applicable to the U.S. civilian work force that builds military equipment.

CORRELATION: SUM VS. ADDEND

PROBLEM: FIND CORRELATION COEFFICIENTS:

- FOREARM-HAND LENGTH VS. HAND LENGTH
- FOREARM-HAND L. VS. ELBOW-WRIST LENGTH

GIVEN/APPROACH: FOLLOWING DATA AND CALCULATION TABLE FORMAT:

DIMENSION	MEAN	S.D.	CORRELATION COEFF. 1	2	3
1. HAND LENGTH	7.52	.32		.643	.846
2. ELBOW WRIST L.	11.81	.56	.643		.952
3. FOREARM-HAND L.	19.33	.80	.846	.952	

•CORRELATION, 3 VS. 1: $R_{13} = \frac{S_1^2 + R_{12}S_1S_2}{S_1\sqrt{S_1^2+S_2^2+2R_{12}S_1S_2}}$

•CORRELATION, 3 VS 2: $R_{23} = \frac{S_2^2 + R_{12}S_1S_2}{S_2\sqrt{S_1^2+S_2^2+2R_{12}S_1S_2}}$

Figure 5. Calculating Coefficients of Correlation between Addends and Sum.

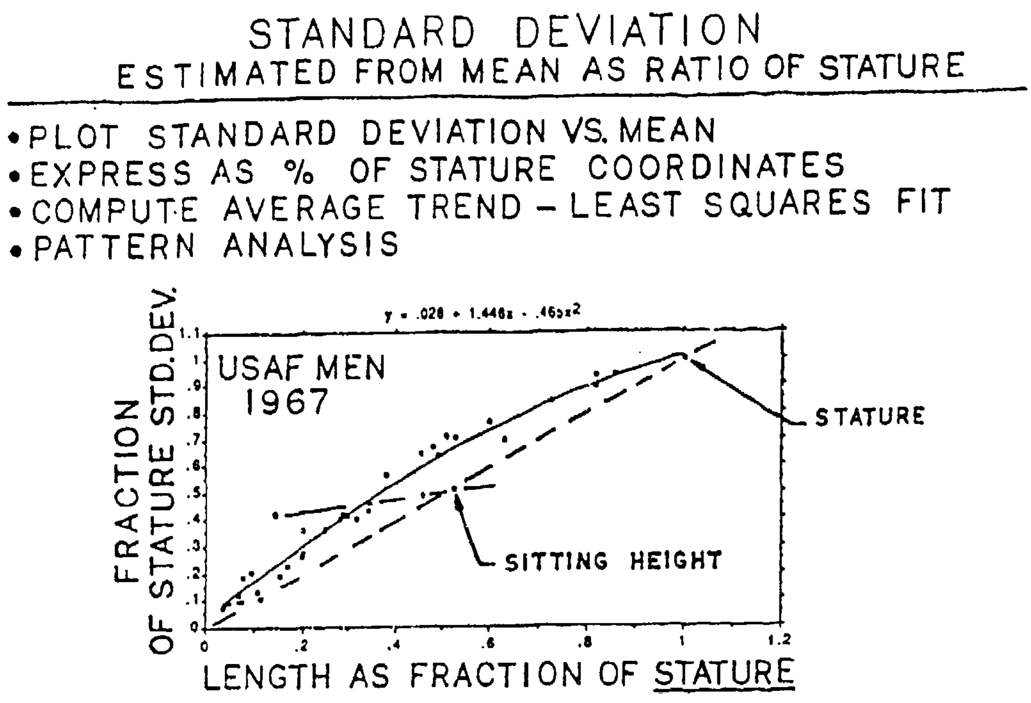
Near-Term Solutions. For a small number of military populations such multivariate regressions have been calculated and published for many combinations of useful dimensions. Examples are the 1968 Air Force Women (Clauser et al., 1968) and the 1967 USAF Flying Personnel (Churchill and McConville, 1976). The Air Force has made available certain types of access to its extensive computerized data banks. Working with these data, it is possible to develop additional multiple regression relationships.

Barrier: Missing Correlations Hinder Standard Deviation Estimation

In many cases adequate correlation data are not available in the literature, and the sources do not offer means by which they can be calculated. As a result, the foregoing simple formulas for combining dimensions, such as shown in Figure 4, cannot be applied.

Long-Range Solutions. Future large-scale anthropometric studies should include analysis charts that show the regressions of standard deviation as a function of the mean of the dimension distributions. These should be shown separately for lengths, breadths, depths, and circumferences. This approach is offered as a general, long-range solution goal because it has been shown helpful in the past and is a currently available method of estimation, as explained below. However, extensive research still needs to be done to more fully exploit and fine-tune this promising method, using data from past surveys.

Near-Term Solutions: Analyzing Relative Variability Trends. Lacking data on bivariate correlations or other information on variability, the estimation of variability of dimension distributions can be aided by analysis of trends of standard deviation as a function of mean of each distribution, using graphic presentations (Roebuck, Kroemer, & Thompson, 1975; Pheasant, 1968) The initial formats may use a direct plot of standard deviation versus mean. However, in Figure 6 a new, more generally useful approach is shown. The data have been normalized in terms



STANDARD DEVIATION
ESTIMATED FROM MEAN AS RATIO OF STATURE

- PLOT STANDARD DEVIATION VS. MEAN
- EXPRESS AS % OF STATURE COORDINATES
- COMPUTE AVERAGE TREND – LEAST SQUARES FIT
- PATTERN ANALYSIS

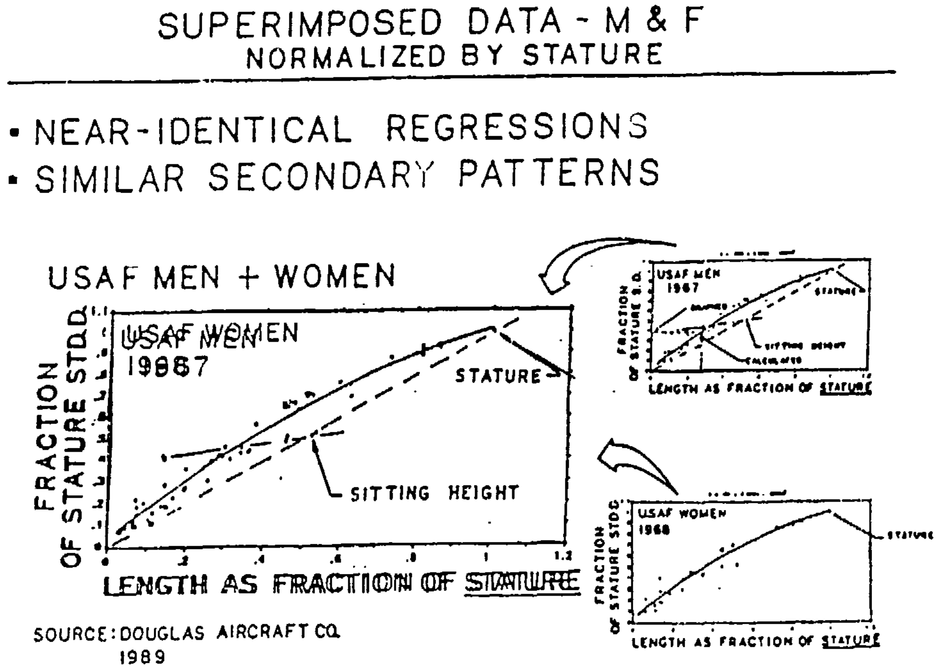
Figure 6. Stature-Normalized Graph of Relative Variability vs. Proportion of Stature.

of their relation to Stature. That is, all mean values have been divided by the mean of Stature and all standard deviations have been divided by the standard deviation of Stature. Such regression lines for lengths and heights display a convex upward trend, starting near the origin of the graph and passing very close to the coordinates for Stature (1,1).

Now, consider the same type of data for a quite different population, that of Air Force Women in 1968 (Clauser et al., 1968). We know that the absolute values of the means and standard deviations of such a population will be different from those of the males. However, if the data are shown in the normalized format, and the two graphs are superimposed as shown in Figure 7, the result displays clearly that the pattern of relative variability is almost identical. With this brief hint of underlying biological constraints on variability goes a recommendation and invitation to readers to participate in further exploration of these variability patterns with the goal of improving estimation accuracy.

Barrier: Lack of Data on Breadth, Depth and Contours of Limbs and Clothing

While missing data on lengths are annoying, even greater gaps arise when trying to develop a graphic model that mathematically describes "enfleshment," that is, external contours of the nude human body and of external surfaces of clothing and hair styles. Although the general consideration of contours is related to specific questions of breadths and depths, the latter are first considered as a separate topic in this paper. Graphic models require anthropometric data on depths and breadths of the limbs, especially the legs, to complete drawings of body outlines. Such needs are generally not met by large-scale surveys. Only circumferences are generally measured at specific stations along the legs. Sometimes a few breadths at the elbow and knee epicondyles and at the ankles are included. Among the few exceptions to this situation discovered by this researcher are the photometric data on some 250 young men reported by McConville, Alexander, and Velsey (1963). Other reports from which such data can be extracted are the small number of stereophotometric studies. Even the latter reported data need considerable analysis to pull out the needed information. Further, the number of sample subjects are relatively small compared to the USAF large-scale surveys that number in the thousands of subjects.



SUPERIMPOSED DATA - M & F
NORMALIZED BY STATURE

- NEAR-IDENTICAL REGRESSIONS
- SIMILAR SECONDARY PATTERNS

SOURCE: DOUGLAS AIRCRAFT CO. 1989

Figure 7. Superimposed Graphs of Stature-Normalized Relative Variability for Air Force Males and Females.

Long-Range Solutions: Measure More Breadths and Depths. The obvious solution for the long run is to plan for the needed dimensions in future large-scale anthropometric surveys. Again, this approach needs further detailed definition and agreement of international groups of interested professionals, followed by publicity and educational efforts for the community of anthropologists, biomechanics specialists, and others who have a stake in the new results. The conference on standardization reported by Hertzberg (1968) is an example of what could be done again with a modest level of support by the Air Force, possibly with help of other government agencies.

Near-Term Solutions: Estimating Depths and Breadths from Circumferences. In the meantime, there are some useful and simple approximation methods available for the specific problem of breadths and depths. Recent studies by the author have discovered some nearly linear relationships between measured circumferences and depths and breadths at the same stations of the limbs. The main source for such data has been the study of three-dimensional data for clothing manikins reported by McConville, et al. (1963). Figure 8 is one example of depth and breadth dimensions recently derived by the author from data for Air Force males. Lacking any other data, one could use such relationships to estimate depths and breadths for Air Force maintainers and even for civilian males and females. However, it clearly would be better to have actual confirming data on diverse populations. In the example graph there is also shown a line for the function of the knee circumference divided by pi. This curve can be considered the diameter of a circle with the same circumference as the measured body dimension. Not surprisingly, this reference curve nearly parallels those for depth and breadth.

As discussed later, such methods to estimate depths and breadths from circumferences can also be used to estimate the sagittal and lateral locations of centers of rotation for joints.

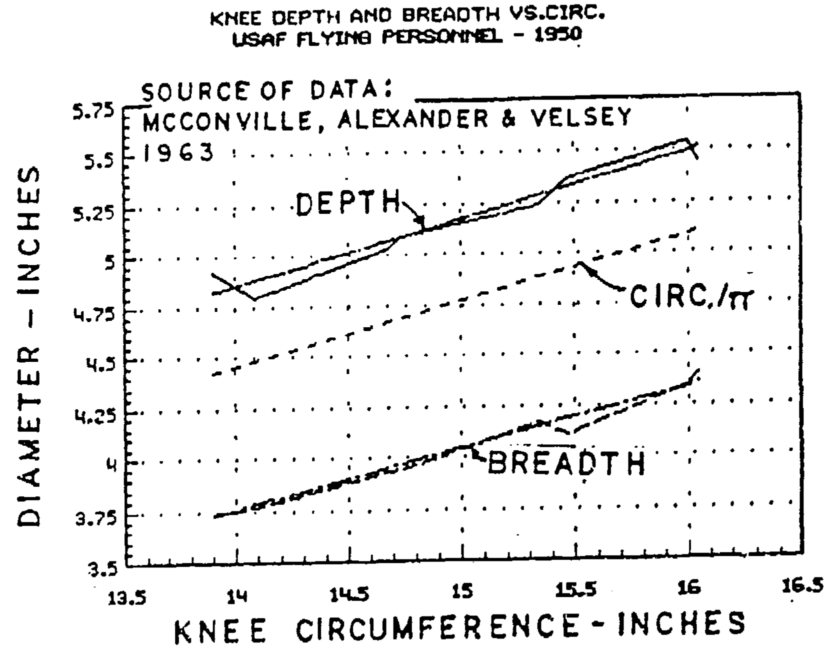


Figure 8. Example Graph of Breadths and Depths Estimated from Circumference Data.

Barrier: Insufficient Data on Contours and Limited Capability to Summarize the Data

Theoretically, many of the above problems could be solved by really complete and accurate "contour maps" of the human body, based on larger anthropometric surveys, using stereo video, stereo photography, or laser scan techniques. Then the needed lengths, breadths, depths, circumferences and even volumes, areas, and mass properties could be calculated as needed by later analysis. In fact, whole-body contour data on living persons are only available on modest sample sizes (one of the largest has n = 46). Even these small sample studies have been limited to a small number of populations. Further, most of these studies use only one body posture (standing), so that sitting dimensions are not derivable.

Admittedly, these approaches are expensive and complex. Even to describe a minimal number of useful breadths, depths, and offsets from internal link axes at key stations (where contours display local maxima and minima) requires between 100 and 200 dimensions. When one considers the amount of data and processing time associated with stereometric measurements of contours, the problem becomes even greater. The available detail stereometric data typically provide about 5000 data points. Future studies using the laser technology that is currently under development likely will have more comprehensive outputs and even larger data sets. The situation presents a difficult dilemma: Without the extensive data there is a barrier of insufficiency that may be considered a yawning chasm. On the other hand, when contour data do become plentiful there will be a glut of numbers which will require creative mathematics for analysis and major advances in data handling procedures for storage and retrieval. The long-range problems are already seen in the stereo data currently available.

Long-Range Solutions: Selection of Contours and Development of Analytical Formulations. The number of data points for extensive contour measurements can be somewhat mitigated by careful selection of key stations for measurement of contours. Key stations along the limbs include those at which maxima or minima occur, such as at ankle height, calf height, knee, gluteal furrow, etc. In the areas of the limbs between these key stations, where contours are changing slowly, fewer data are needed to provide needed engineering information. Rather than obtain a measurement every 2 cm, one could obtain measurements every 4 to 5 cm apart.

A more technically intriguing approach is to seek mathematical formulations that closely approximate the curves of the human body in areas important to work space design and clothing design. At least one mathematical technique to develop formulas of adequate accuracy seems to exist today (Carrier, 1989). However, the length of the formulas and the number of coefficients required may prove too extensive for practical applications. Further work in this area is still needed.

Near-Term Solutions: Use of Contour Data. The small number of available studies can be used to derive several useful types of information, considering them as generally applicable patterns of external shapes, and scaling the results to conform with other data, such as average body dimensions in principal planes. Analyses of depths and breadths versus circumference can be performed on the contour data to develop some generalized regression data.

Barrier: Contour Data on Clothing Exteriors

Consideration of the practical aspects of modeling in the electronic media raises questions of how to portray dimensions of clothing and the resultant impacts on workplace design. These questions are particularly important to design for maintainability, since the wearing of bulky cold-weather clothing can seriously degrade dexterity and impair access to restricted spaces. Currently limited data on clothing additions to the typical external anthropometric dimensions are insufficient when modeling in three dimensions and attempting to depict the entire outer surface of garments. In fact, data on outer contours of items such as shoes appear to be completely ignored in the human factors and biomechanics literature. If we cannot model such additional bulk adequately, the value of human models may be rather minimal for just the cases where they should be of most advantage.

Long-Range Solutions: External Clothing Dimensions. Clearly, attention must be directed toward a systematic and thorough, three-dimensional measurement study of typical maintainer clothing external contours and how they relate to the body parts they cover. Anthropometric and biomechanical specialists need to expand their horizons and apply their expertise to produce extensive measurements on clothed persons. These clothing data need to be correlated with the nude data and developed into predictive relationships for future use.

Beyond the static measurements and relatively constant-shaped safety glasses and hard hats, there is a need for software concepts to model the folds, shifts, and protrusions of pants, skirts, gloves, jackets, and safety harnesses as work is performed. There is a need to examine issues of safety in clothing, to predict possible snagging of clothing during ingress or egress of tight spaces, or to avoid safety hazards around rotating machinery or robots.

Further serious considerations apply to the restrictions of angular motion range and reduction of forces that can be applied when encumbered by clothing.

In the more general sense, hairstyles are also a consideration of bulk, snagging hazards, and clothing fit that may be of concern for maintenance personnel. While not classified as clothing, they are a part of the general problem of external contour modeling. These factors offer many opportunities and challenges for future research.

Near-Term Solutions. For the present this author can offer only the suggestion that careful study be made of the individual articles of clothing and the available data on bulk additions related to specific external dimensions. Creative and adaptive approaches are needed to model key clothing dimensions. This author knows of some currently proprietary concepts being developed as we speak. Probably others will be exhibited by interested researchers in the future.

Barrier: Lack of Data on Locations of Joint Centers of Rotation and Link Lengths Relative to External Skin Landmarks

Most mathematical geometry models of humans for work space design evaluations depend explicitly or implicitly on the concept of a stick figure, or a set of links connecting average centers of joint rotation. The usual assumption is that such links have fixed lengths. This popular fiction is a highly useful approximation for many types of models used for fit and function analysis. However, a basic problem is that data from standard, large-scale anthropometric surveys rarely report locations of such joint centers and link lengths.

Importance of Connectability, A Long-Range Concern. The foregoing example of summing two known distributions illustrates an important need to be considered in the planning of anthropometric surveys and of mathematical models: Many anthropometric length dimensions must be measured and selected so as to be connectable. For example, Hand Length and Elbow-Wrist Length both must be measured to the same landmark on the wrist to be accurately and simply summed by the procedure described. Coincidentally, these dimensions also closely define one aspect of the location of the wrist center of rotation, a valuable aid to modeling the lower arm/hand relationship. In contrast, some valuable data for work space design such as Buttock-Knee Length and Knee Height, Sitting cannot be so combined. Thus, the many surveys that do not provide needed locations of the approximate knee joint center effectively create barriers which make difficult the determination of many dimensions such as Buttock-Leg Length (also called Buttock Heel Length, or Functional Leg Length).

Long-Range Solutions: Changes in Attitudes and Goals. Future anthropometric surveys should focus on collecting functionally useful data on locations of effective, or average locations of joint centers of rotation as well as overall, external dimensions. In planning such measurements there needs to be a change in attitude from the academic scientist toward that of the design engineer. Rather than concentrate on the details of the joint motion at each angle, an overview concept needs to be derived in which the attempt is to minimize total error in predicting reaches and clearances. The following criteria are offered as a start:

1. The effective joint center locations within the body and the selected constant lengths of the interconnecting links should provide for accurately defining the major, standard external dimensions in standing, sitting, and reaching postures.

2. The extended limb links and Stature should be correct if they are derived using the link lengths.

3. End-to-end distances along body segments while they are being held with major joints at right angle postures should be correct. Thus, the use of the joint centers and link lengths should create no surprises and should be consistent with the standard anthropometric dimensions, such as Shoulder-Elbow Length, Sitting Height and Knee Height, Sitting.

4. Effective joint centers and link lengths should provide for minimal error over the full range of motion of the joints during reaching activity. Measurements at the mid-range of the joints are particularly valuable to model comfortable postures accurately. Otherwise, and possibly in addition, measurements at 45-degree angles are desirable for joints with a wide range of travel, such as the elbow, knee, hip, and shoulder complex.

With these guidelines, progress can be made toward a new set of simple, practical standard measurements which can utilize the methods of Reuleaux (1875). These methods are well known in the biomechanics literature, and need not be explained here again. Such modest changes in measurements can have a major benefit for modeling the human body for engineering purposes.

Near-Term Solutions: Flesh Links. While the above ideal measurements are not available, there are ways to derive new and useful approximations of the desired joint center locations. In the process of devising these techniques it has been found helpful to adopt a new general approach and define new concepts to organize the data and perform the estimation calculations. The basic concepts of internal link lengths described by Dempster (1955) has been extended to cover a new set of entities called "flesh links." These links are defined as distances or vectors between defined points on the internal link/joint set and specified points on the surface of the human body. Thus, they measure the depth of flesh (including bone) from the basic axes of angular position definition.

The points of origin within the body may be either joint centers or "stations" along the links between the joint centers. The distances to the skin surfaces (or clothing surfaces as the case may be) may be measured perpendicular to links or at some specified angle convenient for the purpose. For example, in deriving flesh lengths for a man standing in a natural, balanced posture, the internal links for the upper and lower limb typically lean forward 2 to 6 degrees. Horizontal distances from a vertical reference axis to posterior and anterior points on the skin are conveniently defined in the horizontal plane, rather than perpendicularly from the link axes. In contrast to internal links, flesh links may be considered as changing length as the flesh is compressed or displaced by sitting and standing, etc.

The power of this new concept is twofold: (a) it draws attention to the many missing data which define key points on contours of the external shape of the body and (b) it offers a formal method of defining and organizing the needed depths and breadths as they are derived. Data tables can be set up to define sets of links that functionally describe the important protrusions and valleys of the human form. Such links are generally directly related to standard segment length measurements rather than rough approximations based only on Stature, as defined by Dempster (1955) or by Dempster, Sherr, and Priest (1964).

The basic concepts for these links have appeared previously in various forms. Even in the CAR IV non-graphical model there are certain links and offset distances defined that exactly fit the above definition of flesh links. For example, the so-called "ankle link" can be considered a flesh link from the ankle joint to the surface of the foot at the heel. In the book by Roebuck, et. al. (1975) they are called terminal links. Having broken the conceptual barriers around internal links, it is also useful to define other types, such as the following:

1. Surface Links: Distances between two points on the surface of the body or clothing.
2. Pseudo Links: Distances between a part of the body (usually a joint) and another key, nonbody point such as the center of a tool handle or a control knob.

A need for brevity precludes further details about applying this concept. However, Figure 9 illustrates some examples of flesh links and their suggested titles for the leg and foot.

Buttock-Leg Length Revisited

Using the above concepts, another approach to estimating leg links and deriving Buttock-Leg Length is offered. Two pertinent flesh links were derived at the knee joint:

Upper Knee Flesh Link = .465 * (Knee Circumference, Standing) / pi

The factor .465 was derived from data on U. S. Army males and females (Gordon et al, 1989) using the difference between Knee Epicondyle Height and Knee Height, Sitting and its relation to Knee Circumference.

Foreknee Flesh Link = .333 * (Knee Circumference, Standing) / pi

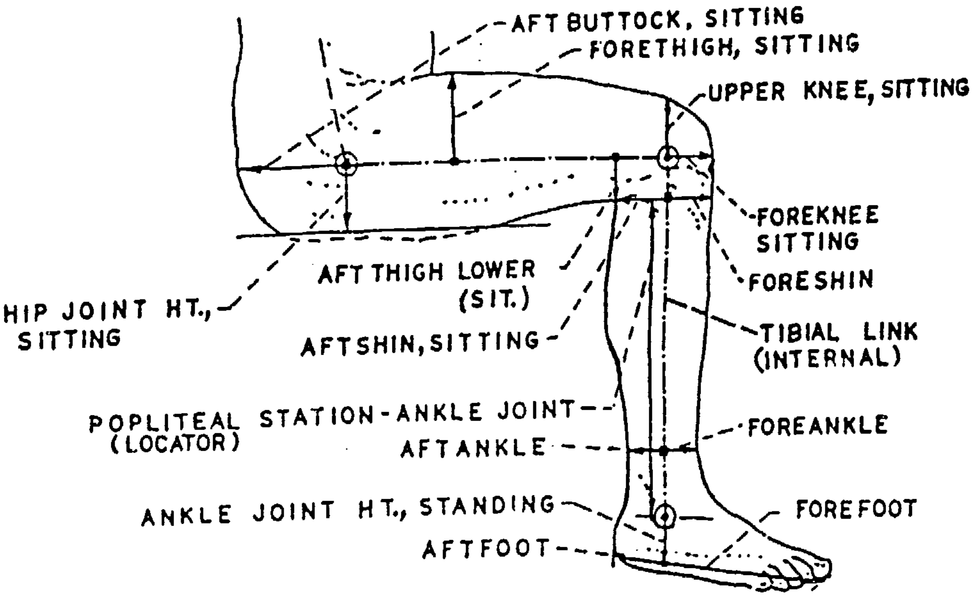


Figure 9. Examples of Several Flesh Links for the Leg.

This estimate was derived from graphics depicting the knee joint, based on published X-ray records and a variety of cut-and-try procedures whose description is beyond the scope of this paper. While the least well-supported by measured data, this formulation is a useful approximation until further measurements are obtained.

These key flesh links then are used to calculate two shorter, connec.LS 3 table leg segments that may be added to yield Buttock-Leg Length.

(Buttock-Knee L.) - (Foreknee Flesh Link L.) = Buttock-Knee Joint L.

(Knee Ht., Sit.) - (Upper Knee Flesh L. L.) = Knee Joint Ht., Sit.

Buttock-Leg Length = (Buttock-Knee Jt. L.) + (Knee Joint Ht., Sit.)

Note that the the terms involving the flesh links are functions only of Knee Circumference, Standing. Thus, it is possible to estimate the Buttock-Leg Length as a function of three commonly measured dimensions.

By dividing the Buttock-Knee Joint Length by Buttock-Knee Length, one obtains a fraction with which to estimate the standard deviation as a proportion of that for Buttock Knee Length. A similar number can be obtained for the Knee Joint Height. Combining the two standard deviations by the formula in Figure 4 (assuming the correlation between the two is the same as that for Buttock-Knee and Knee Height, Sitting) provides an estimate of the standard deviation for the idealized Buttock-Leg Length.

Barrier: Lack of Data on Combined Joint Motion Ranges and Globographics

After the link lengths and joint centers are established relative to the external dimension landmarks, there is a need to model their relative angular posture and ranges of motion. As a general rule it is assumed that the preferred comfort orientation of a joint is near the middle of its range of motion. However, we have little data on joint range of motion as regards the following aspects:

1. Limits of motion determined by adjacent and distal joint orientation (two-joint and three-joint limits).
2. Range of motion in other than principal planes of the body, particularly combinations of joint motions which include axial rotation of the limb.
3. Range of motion data relative to the specific population that is being modeled (data are usually from college students, not USAF maintainers, for example).
4. Restrictions caused by various types of clothing (e.g., gloves, parkas, chemical protection suits).
5. Starting orientation for the measurement is much too often missing in the definition of the measurement. In particular, this poses a serious problem for mathematical models that are based on the internal link postures as indicators of angular position. Many researchers use external surfaces (such as the lower or upper surface of the arm) as starting orientations.

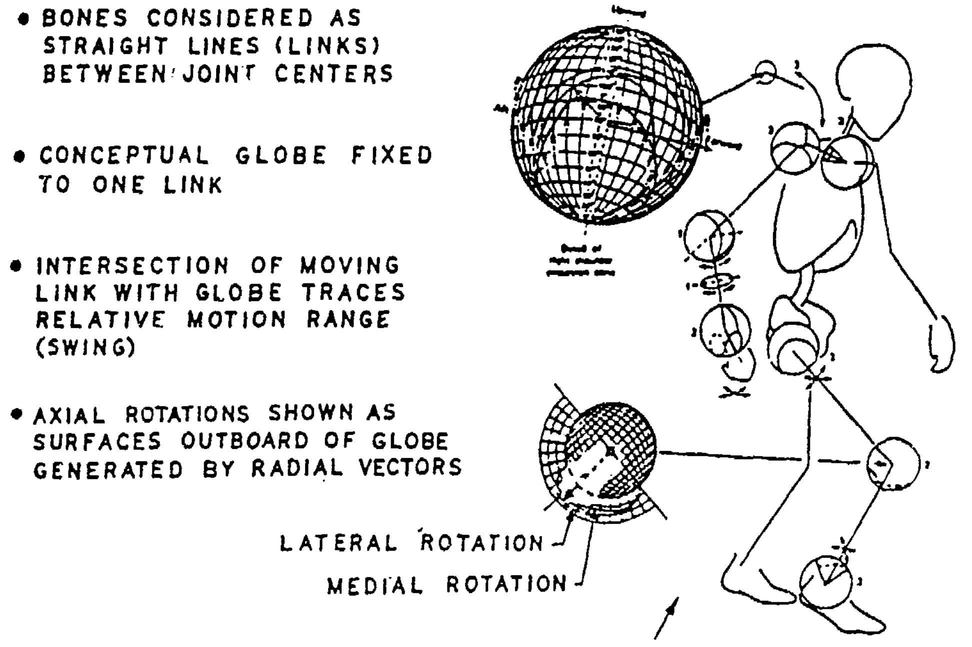
Some of the most glaring lacks of angular motion data involve the shoulder and hip joints. The common practice of measuring range of motion only in principal planes defines a very tiny percentage of the actual sinus cones of motion in these "ball and socket" types of joints. The only recourse of the designer is to consider motion range in each principal plane as acting independently. Joint motions surely are not independent at all the extremes of combined up-down, left-right and axial motion range. As a result, models will likely indicate more range of travel than can actually be achieved at orientations other than in principal planes.

Long-Range Solutions. There is need to perform research on much larger samples of humans which are representative of the maintainer populations and the conditions under which they work. To do so requires new, more easily used tools and procedures, and a new kind of thinking that accepts the need for such added measurements as part of anthropometry. Ideal data concepts are illustrated in Figure 10. Near the top of this figure is a "globographic" presentation of range of motion for shoulder flexion-extension and adduction-abduction, following the examples of Dempster (1955). Thus, the basic globographic concept widely expands the amount of coverage considered in most surveys. However, there is still something lacking. The globographic figures of Dempster (1955) and even the recent globographic depictions of shoulder joint motions of Engin and Peindl (1987) do not indicate concurrent effects of axial rotation of the humerus.

Lower on the figure is one special case example of a general method proposed by this author for depicting axial rotation capability by using two vectors oriented along the axis of the limb (the lower leg in this case). The length of these vectors extending radially from the surface of the globe defines surfaces outboard of the globe which indicate the amount of available inward and outward axial rotation for each posture combination of flexion-extension and adduction-abduction. (Note that for the knee there is practically no adduction-abduction, so the "surfaces" are reduced to lines on a plane.)

No Near-Term Solutions

Unfortunately, there are probably no comprehensive, immediate solutions for this type of complex problem. Although incomplete, the data of Engin and Dempster could be incorporated as general improvements for most current, near-term modeling efforts. For many models this would



SOURCE: DEMPSTER, 1955

Figure 10. Conceptual Globographic Representations of Joint Motion Range, Including Axial Rotation.

represent a major advance in thinking about joint range modeling. Some creative extrapolation is needed, since adequate data on large populations do not exist. Also, small-scale experiments may be performed to offer additional interim data until larger scale studies are performed.

ADVANCING THE STATE OF THE ART: PERCENTAGE ACCOMMODATION VS. PERCENTILES

Sometimes the barriers one faces in a project involve decisions on which is the better and more useful of two good approaches. For years anthropometry specialists and human factors generalists have tried to overcome the "average man syndrome" Daniels (1952). They tried to convert thinking of engineers toward specifying percentiles for dimensions. Out of this concept and background grew the practice of combining many high or low percentiles into sets of common-percentile, articulated drafting templates or manikin designs for convenience in early design layouts and for evaluating layout drawings. Used and interpreted properly, with replaceable parts of larger and smaller percentiles, such manikins have real value in avoiding the many errors that went with the average man concept.

Yet, many human factors and ergonomics specialists knew perfectly well that such manikins generally do not accurately characterize the chance of successful accommodation if two or more body dimensions, angles, etc., are critical to a design. Moroney and Smith (1972) and others have pointed out this concern clearly and forcefully. Several alternative and generally better approaches have been developed that recognize the importance of worst-case combinations of dimensions for different body segments. For example, a set of six specified combinations of body dimensions have been derived for Navy cockpit design, whereas eight sets of specified body dimensions have been defined for USAF cockpit design. Bittner (1987) has derived 17 sets of body dimensions, called CADRE. The design and evaluation process is somewhat more extended and complicated by this approach, in that more manikins must be defined and constructed, either as articulated templates or as electronic models. Yet, even these generally more comprehensive concepts may not be adequate as design criteria for maintainability.

Another more general approach is to seek a "goodness-of- fit" number, which may be called percent accommodation. This approach is currently in use in the automotive field for passenger car design evaluation. As embodied in a mathematical modeling technique, this approach attempts to generate several hundred statistically valid sets of body dimension combinations, possibly using a random selection process. Each of these combinations ("synthetic individuals") is then tested for fit, reach, etc., appropriate to the evaluation in question. This approach more closely approximates the process used in a large-scale evaluation of a mock-up or prototype by use of human subjects.

As a general concept, some form of this random generation approach appears preferable for the wide range of unusual body postures and access evaluations in complex work spaces that are characteristic of maintenance activity. The CAR IV reach accommodation model is one example of a model that has incorporated the concept with Monte Carlo generation of synthetic individuals. As it stands now, the CAR IV model is not an "off-the-shelf" candidate to solve many of the vision, clearance, strength, and other concerns of maintainability evaluations. However, such capabilities could provide the basis for useful routines for adaptation to generalized human modeling for maintainability evaluations. Future advancements in computer-based human modeling for maintainability evaluations could well follow a similar approach.

PROCESS AND POLICY NEEDS

If all the technical problems were solved, it would still be necessary to implement them through changes in organization, policies, and processes.

Barrier: Lack of Established Processes

While there is a bewildering and impressive array of electronic power now available to the planner, designer, analyst, evaluator, and administrator, the proper and effective use of these tools may yet lack something. Specifically, it seems to this writer that many companies probably have not yet understood and assimilated the new technology and developed the organizational formats, policies and procedures that take best advantage of them. This may be particularly true of a relatively new (to many) concept such as CE. Old habits and procedures tend to die hard.

Also, we must avoid "throwing out the baby with the bath water." We know that we must avoid interfering with brainstorming processes and early innovative activity during conceptual stages of design. However, the concepts of simultaneous engineering require that key requirements be introduced early and that designs be evaluated regarding maintainability and a wide range of other "ilities" early in the design and development cycle. What seems to be needed is a study of when and to whom various types of evaluations should be introduced. In the past ergonomics/human factors specialists often complained about being consulted too little, too late. It appears that approach was costly in terms of time, materials, and capital. Yet, if one responds to what the simultaneous engineering advocates seem to be saying, in the future we may actually need to avoid doing too much, too soon!

Long-Range Solutions. At some early times in the development cycle it seems appropriate to supply easy-to-use electronic checklists for designers and analysts. These should call up computer tools for graphical and numerical analysis procedures, such as human modeling simulations. This type of assistance should ensure that the tools are easy to gain access to and clearly indicative of what should be done with them. Among the many characteristics they must possess will be "fun to use," or they may well be ignored. The processes must be clearly defined, definitely scheduled, and considered an integral part of the engineering process before the geometry definitions and specifications are completed. They must be available for later use, when changes are introduced as a result of the initial evaluations and after subsequent iterations. This process must apply to air vehicle designs, GSE, supportability processes and tools, factory tools, and assembly processes planning. Still, there is a need to avoid overregulation and excessive, negative evaluation that kills off creativity and generates delays well beyond their long-term value to the product.

Near-Term Solutions The present gathering of experts and specialists communicating their concepts and current activities involving human-centered concurrent engineering for maintainability assurance is an immediate action designed to begin implementing the changes in policies and procedures needed. If better concepts and practices are put into place soon after disbanding the conference, some immediate gains in the policies and organization area can be expected. The problems being addressed are complex and there are many personal, political and economic issues to be addressed. However, we all can begin immediately to work toward solutions.

SUMMARY AND CONCLUSIONS

This paper has highlighted several technical difficulties and organizational/procedural needs related to anthropometry, and biomechanics, and their usage in computer-based human models. Emphasis was laid on support of simultaneous engineering related to maintainability requirements. Needs for fundamental changes are identified, including a new understanding of potential uses of data on anthropometry and biomechanics for the burgeoning era of computer-based graphic simulation. Three-dimensional definitions of landmarks and form are needed, and all measurements must relate to common axes, thus tying them together, end-to-end.

Methods to overcome specific difficulties have been offered, considering both long-range and immediate solutions. Pleas were made for forecasting of anthropometric trends and for more extensive and better surveys to better know our people as regards statistical changes brought about by immigrations, population shifts, aging, and other demographic concerns. New concepts described include the use of "flesh links," empirical approaches to estimating standard deviations, approaches for estimating missing breadths and depths of limbs by using circumferences, and methods to estimate locations of joint centers from external surfaces of the body. Also recommended are the convening of congresses and committees to standardize the new measurement methods, to define new terminology, and to update the data bases and collations in conformance with the new era in CAD methodology.

A preferred statistical randomization approach for manikin design and evaluation simulations was recommended. It is based on using many different combinations of possible body dimensions to determine a percentage accommodated instead of relying on a set of common percentiles in a few manikin models.

Also considered were procedures for providing designers and analysts with early and easy access to the electronic evaluation tools which use human models to simulate maintenance work. Such an infrastructure is essential to facilitate the human user's acceptance and smooth integration of concurrent engineering concepts.

A modestly revolutionary thought was also offered: Government encouragement of advancements in manufacturing and design technology through funding of automation and promoting simultaneous engineering for maintainability improvements, should also include funding and organizing large-scale measurement surveys of the civilian work force, the people whose hands and heads and muscles actually build the tools and assemble the aircraft used by the military services. Such an investment would provide to the U.S.A. a type of government support that is already benefiting some of our most competitive trading partners (e.g., Japan, Taiwan). It could have significant, widespread benefits to the U.S. economy, as well as aid to design of more readily maintainable airplanes.

If the lessons described in this paper are applied and the new programs advocated are funded and promoted, then we can deal with the barriers identified, and we shall overcome!

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CREW CHIEF: PRESENT AND FUTURE

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ABSTRACT

Crew Chief is an interactive human factors evaluation tool that interfaces to commercially available Computer-Aided Design (CAD) systems. The three-dimensional modeling system, developed by the Air Force, creates a computerized man-model representing a range of body sizes of both male and female maintainers. The user may place the Crew Chief model into a design drawing and run a series of analyses on the interaction between the man-model's physical capabilities and the design elements related to a specific task. Tools such as Crew Chief allow evaluation of proposed equipment and workplace designs before production. Since evaluation can now occur before equipment is actually built, there is real hope of influencing design to take ergonomics into better account. This paper describes the Crew Chief model in detail and discusses the results of an intensive user survey performed to initiate proposed enhancements to the model.

BACKGROUND

Thirty-five percent of a weapon system's life cycle cost is spent on maintenance and the equipment and personnel to support it (McDaniel and Askren, 1985). One third of all Air Force enlisted personnel perform maintenance-related activities. The high cost of maintenance is due, in part, to poor design. Much of this cost could be avoided if, during the system's preliminary design stage, the interaction between the maintenance technician and the system design could be analyzed.

To detect possible problems early in the design process, the Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL) and the Air Force Human Resources Laboratory (AFHRL), in conjunction with the University of Dayton Research Institute (UDRI), have developed a Computer-Aided Design (CAD) model of an aircraft maintenance technician, called Crew Chief. The model allows CAD users to detect design-induced maintainability problems by providing a realistic simulation of a maintenance activity. The use of this model allows the early identification of maintainability problems, thus reducing the need for a full-scale mock-up.

THE PROGRAM

Crew Chief is an interactive, three-dimensional (3D) model which is interfaced to existing commercially available CAD systems. This program provides ergonomic and anthropometric data in the form of a graphically displayed Air Force maintenance technician. The user may place the Crew Chief human-model into the drawing to analyze the interaction between the model's physical capabilities and the design elements related to a specific maintenance task.

The Data Base

Because Crew Chief is a simulation of the physical characteristics and limitations of the maintenance technician, an extensive data base has been developed to support it. The data base for the model was created from ergonomics studies specifically designed to simulate aircraft maintenance tasks. For example, strength data from test subjects were related to the aircraft technician population through a series of strength tests that had been previously administered to Air Force personnel. Since there are few restrictions on the assignment of Air Force personnel to their jobs categories, these subjects were determined to be representative of the Air Force maintenance technician population. In collecting data for the torque and materials handling data base, subjects performed one to seven of the same strength tests. Regressors are used to distribute the predictions across the maintenance population.

The data base also contains 222 different sizes and types of hand tools commonly used in aircraft maintenance. Evaluations using the tools include accessibility (reach, interference, work envelope, and visibility) and strength (torque).

The Man Model

Body size, gender, clothing encumbrance, and posture must be considered in ergonomics evaluations for maintenance. Crew Chief can accommodate one of ten body size/gender combinations (1st, 5th, 50th, 95th, and 99th percentile for both male and female maintenance technicians) based on military standards.

The encumbrance of clothing and personal protective equipment (PPE) is an important limitation for the maintenance technician. A designer has four types of standard clothing to choose from: (a) fatigues, (b) fatigues with jacket, (c) arctic gear, or (d) the chemical defense ensemble. This clothing interacts with the joint mobility limits and postures to model accessibility.

Because the Crew Chief model is three dimensional, it has a surface of facets (triangles) attached to the 35 links comprising the skeletal link system. A full 3D model is available for rotating and a hidden line model can be used for a clearer view on the screen or on paper plots.

To simulate the postures typical in maintenance, Crew Chief provides for 12 initial postures: (a) standing, (b) sitting, (c) kneeling on one knee, (d) kneeling on both knees, (e) bending, (f) squatting, (g) prone, (h) supine, (i) lying on one side, (j) walking, (k) crawling, and (l) climbing. Some of these postures reduce the mobility and strength available to perform a maintenance task. The posture changes when a task, such as reach, is performed.

ANALYSIS FACILITIES

Maintainability problems generally fall into three areas: (a) physical accessibility, (b) strength, and (c) visibility. Physical accessibility is affected by body size, posture, tool size, adjacent or interfering components, and the task performed (such as lift, push, pull, or reach). Strength involves the technician's physical ability (which is a function of gender, posture, and task performed) to apply a specified torque, and/or to lift, position, carry, or remove an object. Visibility or field of view is affected by the posture, location of the object relative to the model, and components which may obscure the work area. The functions within Crew Chief allow detection of these maintainability problems with the analyses described below.

Accessibility Analysis

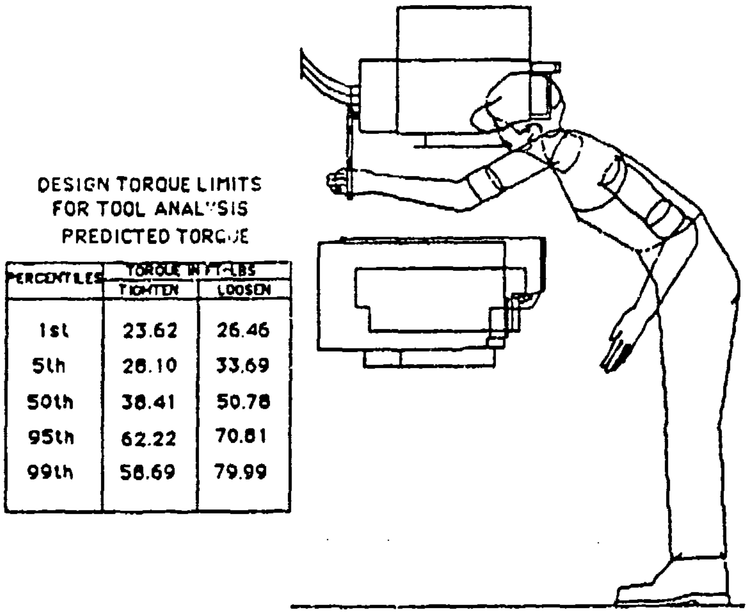
The Accessibility Analysis function is provided to perform analyses concerning obstructions between the human-model and elements of the CAD drawing around the location of work. The function is divided into two analyses: (a) Interference and (b) Work Envelope. Interference Analysis checks for contact between the human and CAD drawing elements. This interference checking is performed on the model's arm for every reach, but this function must be run to check the rest of the body. Since interference checking is a time-consuming task on typical computer systems, it was felt that this checking was best left as an option. Work Envelope Analysis, a quasi-dynamic interference check, presents a graphic display of the volume of space required to do work. This includes operating a tool or moving an object (such as a component to be removed or installed). The path of movement is depicted graphically with 3D lines.

Maintenance Task Analysis

The Maintenance Task Analysis function is designed to evaluate the interactions of the human-model and the user's design with respect to the model's physical characteristics. The function is separated into three segments: (a) Tool Analysis, (b) Materials Handling, and (c) Connector Analysis.

Tool Analysis. This function evaluates the ability to reach, with a tool and from a designated posture and position, a specified point (see Figure 1). This includes the ability to reach around obstacles between the model (holding the tool) and the task point. For specified wrenches, once it is determined that the point can be reached, the strength capability for the particular gender, posture, and tool relationship will be displayed. A limited visual analysis of tool clearance may be made when the tool has been positioned.

Materials Handling. This function evaluates the capabilities of the maintenance technician to lift, push, pull, turn, hold in position, carry, or reach an object (see Figure 2). In this function, there is also a table displaying the 1st, 5th, 50th, 95th, and 99th percentile strength capabilities for the starting and ending positions and the size and weight of the object, all of which are available to complete the task being simulated. Figure 1 shows a typical reach with a ratchet wrench.



DESIGN TORQUE LIMITS
FOR TOOL ANAL'SIS
PREDICTED TORQUE

PERCENTILES	TORQUE IN FT-LBS	
	TIGHTEN	LOOSEN
1st	23.62	26.46
5th	28.10	33.69
50th	38.41	50.78
95th	62.22	70.81
99th	58.69	79.99

Figure 1. Crew Chief Video Display.

Connector Analysis. The capability of the maintenance technician to attach a connector at a specified location is evaluated with this function. A user will find a table of the strength capability related to grip used and the size of the connector. This table displays the torque applied in inch-pounds across the five percentiles.

Visibility Analysis

A Visibility Analysis Function is available to the user that plots a map of visual azimuth and elevation line-of-sight angles to workstation components in the drawing. The plot is rectilinear, and depicts the visual field as seen by the Crew Chief model with its current eye position or from a user-chosen point in space. The vision limits are presented for the baseline condition, which is unrestricted, and for restrictions due to clothing or personal protective equipment.

A maintainability problem may involve combinations of these three analyses. For example, lack of visibility may aggravate a physical accessibility problem by making it more difficult to properly align and position a tool in a restricted working area.

SYSTEM INTERFACE

Crew Chief is broken into two software entities: (a) the interface and (b) the core program. The interface not only provides a link to the CAD system but also uses some of the graphics outputs to draw the model. Much of the user interface is dependent on the CAD software as well. The core program contains the code which remains in tact with all system interfaces. This includes data on strength, body dimensions, clothing, and tools, as well as algorithms for reach and other tasks.

Crew Chief Version 2 interfaces to CADAM Versions 21 with the Access module, MVS or VM operating systems, and FORTRAN-77. Version 1 of Crew Chief runs under CADAM Version 20 with the 3D Interactive and Manufacturing Module, the Geometry Interface Module, MVS, and FORTRAN H (Korna et al., 1988). Version 1 also works with Computervision CDS 4001 with an Analytical Processing Unit (APU). Version 1.1 (which is actually closer to Version 2 than Version 1) works with CADDS 4X software, Revision 4 or earlier. Crew Chief is also available in a system-independent version. A computer programmer can interface this version to other CAD systems by modifying the interface.

USER NEEDS

To look at future directions and needs, AFHRL mailed a questionnaire to Crew Chief users. Follow-up visits were made to 11 of the companies to clarify and provide additional details. The results consisted of an impressive list of possible model enhancements and additional capabilities. Some of these are discussed briefly below.

Automatic Task Composition

Current human-modeling software requires users to specify all basic movements rather than stating a task to be done. These models are good for detecting isolated maintenance problems, but they are too tedious for more complex tasks. Crew Chief, for example, is able to simulate the act of reaching for a single bolt with realistic body positioning, but if there are several bolts attached to a component, users must input all pertinent positioning data for each bolt.

Automatic task composition will require less input of higher level information. To remove a series of bolts, for instance, users won't need to enter data for each bolt. The model would be able to take data from CAD libraries to find the location of all bolts and remove them before the component can be lifted out. This removal operation requires advanced animation techniques to illustrate the simulated procedure.

Detailed Hand Model

Since most maintenance work is accomplished by hand, an effective human-model needs a detailed hand model. Data on human hand movements are available, and at least one computer-based hand-movement model has been developed.

Detailed Vision Model

Sophisticated vision models are now being developed by several research groups. Crew Chief includes a limited vision model, but it does not sufficiently display the effects of obstacles and lighting. Such factors must be included for vision simulations to be of maximum use in human-activity modeling.

Analysis of Multi-Person Tasks

A large number of maintenance tasks require more than one person to work together, especially when heavy objects are moved. It is critical in these situations to analyze the spatial and strength capabilities of multi-person tasks which Crew Chief does not currently permit. Crew Chief, however, does allow more than one model to be displayed but only one of them is "active." In other words, one model can do work while the others watch. Strength data for multiple maintainers still remain to be collected.

Expanded Task-Analysis Criteria

Task information presented through computer animation should allow for accurate definition of the perceptual and psychomotor abilities required to do the task. If enough detail about human/machine interactions can be collected, it should also become possible to describe the cognitive demands of maintenance tasks. With such data it is assumed an analyst can deduce accurate ability profiles for tasks, to group tasks into logical jobs, to develop job descriptions, and to establish valid criteria for selecting personnel to do certain jobs.

If simulations are extended to the entire system rather than just subsystems, the evaluation process can be extended into the realm of human-resource forecasting. Currently, the human-resource implications of proposed designs are far removed from human-modeling technology. Yet in the Air Force, for instance, human resources account for a great deal of spending. An organization that strives for more efficient use of personnel and training resources can reap considerable savings.

Interaction With Training Systems

Future human-modeling technology should support training in both information development and requirements analyses. On the information side, CAD drawings would be ported to automated technical manuals or used in the development of training literature. These, in turn, would be used to create accurate and up-to-date job guides or job-performance aids. More directly, the animated task performance might be videotaped for maintenance instruction.

These simulations provide a better basis for making decisions about the level of training needed for a task. Often, the human factors analyst must judge whether task performance should be supported by formal or on-the-job training -- a decision that is purely subjective without concrete information on task requirements. The objectivity and reliability of these judgments can only increase as graphics technology matures.

Workstation Version

CAD terminals are at a premium in industry. Design work monopolizes these terminals, thereby leaving no time for Crew Chief analyses. By hosting on a graphics workstation, several other advantages can also be seen. Not only are these workstations widely available in industry, but the improved processing speed and powerful graphics make them favorable for future models to be housed. The real-time movement of surfaced images was not feasible when Crew Chief was first conceptualized. Figure 2 gives an example of a solid figure working on a weapon system. Sticking with one platform will also eliminate the need to continuously update interfaces to new CAD software versions.

CONCLUSIONS

Crew Chief provides a method to evaluate the maintainability of designs and takes a big step toward reducing maintenance costs. The model cannot currently simulate all the aspects of maintenance activities but it can provide an integral piece of a larger human factors analysis tool. The Crew Chief data base and underlying technology can build a strong foundation for future related work. AFHRL has initiated research that proposes to integrate human-models with existing logistics data bases to foster a human-centered approach to weapon system design (Boyle et al., 1990). The ability to realistically simulate maintenance work with computer animation underlies this expanded role for task analysis in design evaluation. Visualizing complete maintenance tasks allows more accurate descriptions of human performance requirements. This capability will use a graphics workstation capable of importing CAD data and will build upon Crew Chief technology.

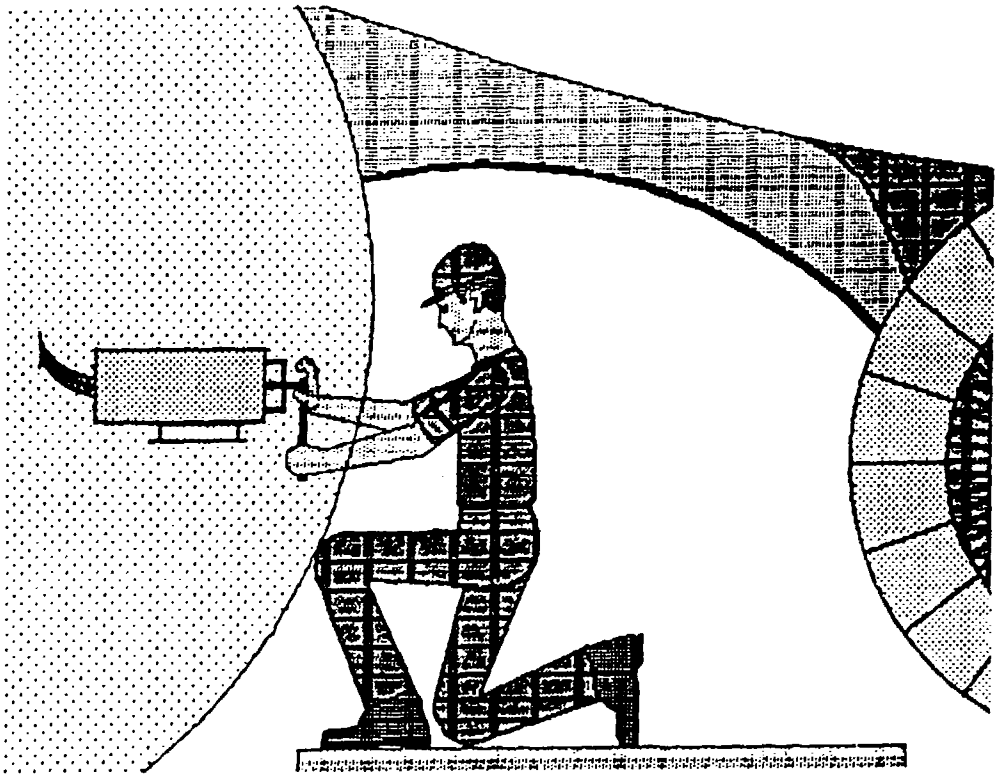


Figure 2. Solid Human-Model.

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HUMAN-CENTERED TECHNOLOGY: ENDS AND MEANS

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ABSTRACT

This paper outlines a desired approach for human-centered technology in Integrated Product Development (IPD). The key idea is to integrate Computer-Aided Design (CAD) with human-modeling technology to create a more unified approach to human factors analysis during design. The ability to realistically simulate maintenance work through computer-graphics animation underlies this human factors evaluation technology. The advanced human-modeling capability we seek will build upon research developments from Crew Chief and related technologies. We want to widen the scope of human factors evaluation during design to include personnel and training analysis. The use of Computer-Aided Acquisition and Logistics Support (CALS)-oriented data standards will allow task analysis results to be better documented and thereby improve work force planning for system support.

INTRODUCTION

People issues need to become a more visible part of Integrated Product Development (IPD). Maintenance human resources account for a large portion of the ownership costs of many military systems. According to the best-selling presentation slide still used - and accepted - by so many, the majority of these costs are determined very early in design. So it would seem natural to want to consider people issues more carefully, and earlier, in design engineering for new systems.[1]

But design technology for the human elements of systems has lagged other support "ilities" in the development of new technologies applicable to the IPD engineering world. That world is becoming organized around three computer automation technologies: Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), and, in the military, Computer-Aided Acquisition and Logistics Support (CALS). Human-centered technology must adapt itself to these CAD, CAE, and CALS technologies. Otherwise it will languish even while people continue to insist that about half of the life cycle costs incurred in system support are human costs. We have named this adaptation process Human Centered Technology (HCT). Since it is through CAD and CAE that new systems will be defined and evaluated, and through CALS that their support requirements will be captured, HCT must develop within these three domains. Within CAD and CAE, human-centered technology should provide a *design influencing* role for human performance. Within CALS, HCT should provide a *design documentation* role for better logistics management. This three-way integration at the level of enabling computer technology is a key objective of HCT.

RESEARCH OBJECTIVES

Accordingly, we have defined two basic research objectives for HCT.[2] First, we want to allow human performance limitations or capabilities which can degrade or enhance system performance for given design options to be evaluated during design so that they can be more readily accommodated. We think the most effective way to do this is to use computer-graphics human-modeling to present task analysis results through video simulation. Integration with CAD, itself a visual medium, will help to ensure that human performance problems identified by "virtual prototyping" of human/machine designs can be shown to equipment designers for resolution. In this context, task visualization is a new medium for an old message. Further, we want to use "prescriptive" human performance information and explicit design criteria to describe and illustrate how a given design might be improved.

Second, we want to integrate maintenance task analysis results with Logistics Support Analysis (LSA) through developing CALS data standards for digital data exchange. This will ensure that human-centered design information is accurately documented and preserved to aid in human resources and related logistics planning requirements for system support. To these ends, four research objectives for a new AFHRL program we call DEPTH[3] have been defined:

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[1] By "people issues," I mean the six MANPRINT domains: human factors, safety, biomedical, manpower, personnel, and training. The last three, taken together, mean human resources but are better known as Manpower, Personnel, and Training (MPT). The first three, taken together, equate to human engineering (HE). For present purposes, this is the only distinction that makes a difference. See Binkin (1986) for a readable overview of military MPT and HE problems. IPD means about the same thing as Concurrent or Simultaneous Engineering, although fastidious distinctions are sometimes made here as well.

[2] HCT at AFHRL/Logistics and Human Factors Division (LR) includes both equipment maintainability and operability technology, as well as computer support tools for collaborating design teams. This paper deals with the maintainability portion only.

[3] DEPTH - Design Evaluation for Personnel, Training, and Human Factors.

Create a Human-Modeling Workstation Environment

A computer graphics workstation will provide a versatile platform for the development, demonstration, and transition of computer-graphics human-modeling technology. An "open" workstation architecture will allow new or improved maintainability analysis methods to be readily incorporated in a modular fashion, and will also support an incremental, phased approach for technology transition to users. For many reasons, it is desirable for HCT to adopt common data architectures and "interoperable" software/hardware platforms.

The HCT workstation we envision will house a human-model, task simulation tools, human performance data bases, and CAD and Logistics Support Analysis Record (LSAR) interface software. Modular software design will provide a flexible and efficient means of updating and integrating new or modified applications programs, and aiding interim product transition to users. Human performance analysis procedures and data bases embedded within or federated with the computer graphics workstation will aid the task analysis process and provide a design diagnostic capability. The human factors analyses will be organized around a core human-model program resident within the workstation. This overall DEPTH concept is shown in Figure 1.

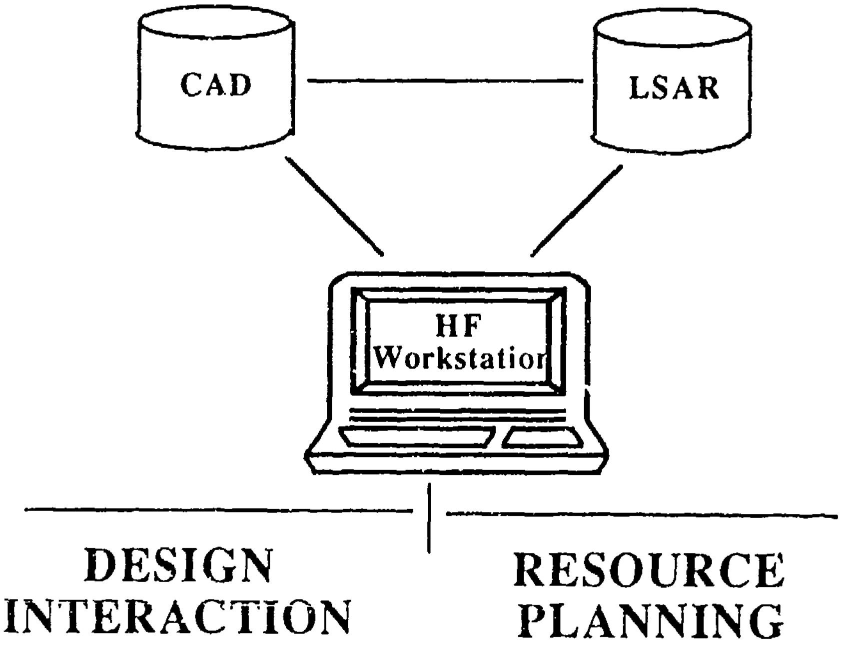

Figure 1. Integrating HCT With CAD and LSAR.

The HCT workstation should interface with commercially available CAD and LSAR systems. Software interfaces allowing the workstation to interrogate external data bases relevant to maintenance task specification and analysis will also be created. Potential data sources applicable to task specification, simulation, and performance evaluation include experimental literature, existing task analysis information, personnel and training data, field maintenance data, occupational safety and hazardous materials information, design guides and standards, and case history and "lessons learned" information.

Enhance Human-Modeling Capabilities

We need to develop and incorporate better capabilities to simulate and analyze human hand movement and visibility, multi-person tasks, and the effects of environmental stressors on physical workload and performance. Maintenance work, especially aircraft maintenance, requires manual skills. Many tasks require more than one person to perform safely. Different lighting and environmental conditions are often encountered in the real world. Hence, maintenance-oriented task analysis using human-modeling technology will benefit greatly from more realistic representation of these real-world working conditions. Technologies for some of these requirements are being developed, but they are not yet found within a single modeling environment.

Expand Human Factors Evaluation Criteria

These include, in addition to physical abilities, estimates of related perceptual and psychomotor abilities underlying task performance. Maintenance job design and training decisions would be much better supported if ways to accurately predict these nonphysical ability requirements through human-modeling methods were invented. In short, we think it is time - or soon will be time - for human-modeling to move up to the "higher human factors" involved in overall job design and work force planning. We need to estimate a fuller range of human performance criteria, not just physical criteria, to make this possible. Enabling technologies for expanding the range of human-centered design criteria include:

Enriched Task Simulation. Proposed human/machine interactions must be displayed in greater detail and with greater realism than they are now. This enrichment will come from the integration of CAD-based equipment design information, computer graphics and animation technology, and the automation of human performance and human resources data applicable to the proposed human/machine environment. The ability to combine visual and nonvisual task information underlies the advanced task analysis capabilities we seek. Technology developments in two key areas described below encourage us in this objective.

Human Figure Modeling (also variously called man-modeling or human-modeling or human-form modeling). Technology is advancing rapidly. We can create realistic, accurate depictions of maintainers interacting with prime equipment, support equipment, and the work environment. The ability to display a complete maintenance task, or sequences of tasks, through computer animation is a process here called automatic task composition. (see Korna's paper, this volume). This should enable broader estimation of both physical and nonphysical aspects of task and job requirements than current methods permit. Dynamic simulation of maintenance tasks using advanced human-modeling and animation technologies will provide a powerful visual medium for design evaluation and design influence.

Data Base Integration and Knowledge Representation Technologies are needed to better organize and synthesize human-centered information about task performance requirements and the task environment. The objective is to exploit existing knowledge and information about task performance requirements in human-centered analysis of new or modified systems. New media such as hypertext and compact-disk/read-only memory (CD-ROM) will support the varied uses of human performance and human resources information needed in the DEPTH workstation environment.

Create A "Prescriptive" Design Evaluation Capability

Human factors assessment should move from a merely descriptive level (i.e., "Something might be wrong") to a prescriptive level (i.e., "Something's wrong and here's how to correct it"). Easy access to relevant design goals and practical human performance criteria would allow a design check for human performance to be made. "Work around" measures which can overcome identified design deficiencies are also needed. It is not enough to merely display a simulated task performance. We also need to know whether the predicted performance meets preestablished design goals or exceeds known human performance limits before we can know whether we have a good design or a bad design. Such indicators are lacking in most current human factors simulation technologies. Potentially relevant human performance information is abundant, but it is scattered. We need to bring it together to make it useful.

CURRENT HUMAN FACTORS USES OF HUMAN-MODELING

Physical Models

A large number of human-modeling (or man-modeling) techniques have been developed. Kroemer et al. (1989), Hickey et al. (1985), Rothwell (1985), Hidson (1988), and Richards & Companion (1982) provide detailed descriptions and comparisons of System for Aiding Man-Machine Interaction Evaluation (SAMMIE), PLAID/TEMPUS, Crewstation Assessment of Reach (CAR), COMputerized BIomechanical MAN-Model (COMBIMAN), and Crew Chief, among others. Most human-models create whole-body representations using a basic link system, which is a simplified version of the human skeleton. Enfleshment algorithms can be used to create a more realistic illusion of the human form, and CAD rendering techniques can be used to make the display more visually compelling. In addition, many human-models use CAD graphics techniques to change the angle of view, to "zoom," to generate three-dimensional displays, and so on. In every case, an adequate anthropometric data base is required for the construction of human-models.

To date, the human-models have focused on the physical or ergonomic aspects of human/machine interaction. Kroemer et al. (1989) divide these models into anthropometric, biomechanical, and human/machine interface types. In short, the human-models are intended to help answer questions about the equipment or workplace such as:

1. Can the human-model fit into it? (anthropometry),
2. Can the human-model move or reach well enough? (kinematics),
3. How much force can be applied? (biomechanics),
4. How well can the human-model see? (visualization).

Evaluation of these and related physical aspects of human/machine design have been greatly facilitated by the use of computer graphics-based representations of the human figure within the proposed workplace.

Pilot-Operator Models

Another focus of human-modeling simulation has been the performance of the pilot-operator in the cockpit-workstation. For example, in the A^3I program (Army-NASA Aircrew/Aircraft Integration, this volume), and the Human Systems Division's (HSD) Cockpit

Automation Technology (CAT) program, attention falls on integrating visual and cognitive information processing requirements with human-modeling simulation for pilot-operator workload assessment. Elkind et al. (1989), and McMillan et al. (1989) provide detailed reviews of these and similar efforts. Baron et al. (1990) describe numerous human performance process models, again focused on pilot-operator cognitive workload assessment. These include the Human Operator Simulator (HOS). New work funded by the Army Research Institute is attempting to link HOS, a task networking tool called MicroSAINT, and an anththropometric model to create an integrated human-modeling technology. (See the papers by Kaplan and Laughery, this volume.)

Maintenance Models

Among the CAD-based human-models, only one, Crew Chief, deals specifically with Air Force equipment maintenance issues.[4] This software package presents a three-dimensional computer graphics model of a maintenance technician interacting with a CAD-defined work environment. A number of body sizes and postures, accurately scaled to reflect the Air Force maintenance work force, can be simulated. Available analyses include reach, visual and physical access, and strength characteristics of Air Force maintainers in various body postures. Use of common hand tools is also simulated. The model is supported by an extensive anthropometric data base describing both male and female populations. Crew Chief has been interfaced with CADAM and Computervision CAD systems so far. Details on Crew Chief technology and applications are found in Easterly (1989), McDaniel & Hofmann (1990), Korna et al. (1988), and Easterly & Ianni (this volume). From some points of view, the Crew Chief technology constitutes the baseline for the DEPTH human-modeling environment. Specifically, since we want to simulate Air Force populations accurately, we have no better anthropometric and ergonomic data to draw from. But from other points of view, the DEPTH human-modeling environment will move well beyond current Crew Chief applications in ergonomic assessment.

For example, Crew Chief users in industry have identified a number of enhancements that would improve its value in design evaluation. These include, in addition to task animation, an improved vision capability, simulation of multi-person maintenance tasks, assessment of environmental stressors, and detailed modeling of hand movements. Incorporation of these enhancements in the DEPTH research will serve the expressed needs of Crew Chief users. In addition, a solid baseline for the expanded task simulation and task analysis capabilities needed for DEPTH will be produced.

EXPANDING HUMAN-MODELING CAPABILITY

Current CAD/CAE approaches to human factors assessment, especially the human-models, use computer graphics technologies to specify and display human performance capabilities through video representation. The term "computational human factors" describes the general trend toward computers, and especially computer graphics, to represent human/machine performance. In these applications, human form (i.e., physical) and human process (i.e., cognitive) models replace or supplement the hardware mock-ups, simulators, and prototypes traditionally required to perform task analysis analyses during system design. In DEPTH, a CAD-based "virtual mock-up" of the work environment is to be created through computer graphics workstation technology to more fully define human performance requirements of maintenance work.

Three important benefits are gained by integrating human-centered design evaluation with modern design technology and logistics information processes in the manner we propose. The first is design interaction. The CAD link should permit earlier, more accurate, and more economical

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[4] Crew Chief is jointly developed by the H.G. Armstrong Aerospace Medical Research Laboratory (AAMRL) and the Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio.

evaluations of the human/machine interface. It is easier to change equipment designs when problems are detected early, before the design is fixed and hardware is fabricated. And it should be easier to persuade designers using the visual medium of computer graphics.[5]

The second benefit is in achieving design concurrency. Integration around CAD and CAE should allow human-centered maintainability issues to be evaluated simultaneously with other engineering and logistics support "ilities." The design engineering cycle should become less costly and time consuming, and more supportable products should result. This is a central objective of IPD. This research will create a human-centered design evaluation capability in consonance with this IPD objective.[6]

The third benefit is in linking with CALS-oriented design support information through the established LSA process. The idea of CALS integration with HCT is to create a design support data base in digital format - without paper - that contains more complete and more accurate documentation of the human-centered aspects of system maintenance.

The matching of physical characteristics of people with work requirements using CAD-based human-models is a technology nearing maturity. This is not to say that the technology is complete or perfect. Indeed, much remains to be done in the ergonomics domain to improve the representation of anthropometric, biomechanical, and other physical characteristics. But other aspects of the classical human factors agenda for system engineering also warrant attention and now appear to be reachable. The DEPTH research seeks to advance this agenda by exploiting emerging computer technology and building on the existing technology developed for the human-models. In addition to physical evaluation of human/machine design, we need to:

1. allocate functions between people and machines,
2. predict task performance times,
3. evaluate task manning/crew size,
4. minimize human error and its consequences,
5. maximize safety,
6. describe task steps and procedures,
7. design jobs and job performance aids,
8. develop training,
9. forecast manning, and
10. select and assign personnel.[7]

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[5] Is a picture worth a thousand words? Is seeing believing? When we understand, don't we say "I see"?

[6] In the mid-1980s, the Air Force advocated a very similar concept for design technology integration known as Unified Life Cycle Engineering (ULCE). See Kulp and Coppola (1987) for a description of ULCE and a rare mention of human-centered issues in an ULCE design environment. The integration of HCT with Reliability and Maintainability (R&M) through networked CAD workstations has been demonstrated.

[7] Read the seminal work of Robert Miller (e.g., Miller, 1953a, 1953b, and 1956), the landmark Human Engineering Guide to Equipment Design (Van Cott & Kincade, 1972), and the Price et al. (1986) study of human factors contributions to system design, and note the remarkable continuity in the human factors agenda through the decades.

Evaluation of these issues will surely benefit from accurate anthropometric and ergonomic models and data bases, but they are not wholly subordinate to them nor dependent upon their perfection. Hence, the key issue for DEPTH technology development is this: To what extent might CAD, computer-graphics human figure modeling, human performance information integration, and related technologies be exploited and combined to help us evaluate a wider range of human-centered maintenance criteria during equipment design?

Task Animation

The impetus for proposed expansion arises in part from new opportunities created by a rapidly developing array of computer technologies, particularly in the computer graphics field. These latter include the ability to create detailed, accurate, and realistic simulations of maintenance work through human figure animation. Advanced animation technology, if it can be economically added to current human-modeling capability, would greatly enlarge the task performance information available to the expert analyst during engineering design. Maintenance task analysis, aimed at the classical human factors criteria, could then be implemented using this technology. The limiting factors appear to be the degree of accuracy, detail, and realism that advanced computer technology can provide. For this purpose, the ability to animate the simulated worker and work environment - that is, to introduce realistic movement to the simulated display - is an important new requirement and opportunity for an effective computational approach to maintenance task analysis and human factors evaluation. Computer-graphics technology for task animation should allow visual assessment and confirmation of task performance. An ideal technology for this purpose would have the following characteristics:

Accuracy. An animated human-model should accurately replicate relevant human anthropometry, biomechanics, and movements. Interactions of the animated human-model(s) with the modeled work environment should appear to be natural. Equipment and/or workplace setups should be accurate representations of the relevant design features.

Detail. An animated human-model should be portrayed in sufficient detail to permit confident description of human abilities and task performance requirements. The work environment should be imaged in sufficient detail to ensure that the relevant human/machine interactions (i.e., equipment repair) can be portrayed. For example, the analyst should be able to call up special-purpose models for "close in" viewing of fine motor tasks or of tasks having high demands for visual discrimination. In addition, the analyst should have ready access to relevant information applicable to the task performance environment to assist in task specification, simulation, and evaluation.

Realism. An animated human-model should behave purposefully according to a logical plan of action. He or she should be capable of acting out task sequences in realistically timed motions. The human-model might appear to react, plan, detect obstacles, avoid uncomfortable or inefficient postures and movements, and so on. In short, the artificial person should appear to have a sort of artificial intelligence.

Knowledge Capture

The impetus of task analysis expansion also arises from the growing interest within many scientific disciplines relevant to human-centered design in discovering, systematizing, and "representing" their knowledge base. Examples of this phenomenon are found in the meta-analysis techniques used in the behavioral sciences (Hunter et al., 1982; Jones et al., 1985). Another example is Boff & Lincoln's (1988) compendium on human perception and performance for system designers. The challenge here has two parts: (a) to identify the state of scientific knowledge and other information applicable to a particular human-centered design issue, and (b) to find creative and effective ways of applying this knowledge and information to support the creation of improved human/machine simulation and design evaluation.

Automated Information Access. Human performance criteria contained in guides, handbooks, and military specifications and standards are being computerized in the hope of improving their usefulness in design and in other applications. The Army Human Engineering Laboratory, for example, has converted the MIL-STD-1472 "Human Engineering Design Criteria for Military Systems, Equipment, and Facilities" to hypertext format for use in a new microcomputer-based human factors analysis package (Carlow Associates, 1989). Another example is the proposed conversion of the AFHRL Occupational Research Data Bank (ORDB), a key source of Air Force maintenance MPT data, to CD/ROM format. The Boff & Lincoln engineering compendium will also be converted for use in hypertext format on a Macintosh computer under the Computer-Aided System Human Engineering (CASHE) program (Boff et al., draft).

Maintenance Data Base Integration. A complementary movement within the MPT domain has focused on integrating the task descriptive information contained in the numerous Air Force data bases documenting maintenance work and equipment R&M behavior. The most important and best known among these are the equipment maintenance records included in such systems as the Air Force Maintenance Data Collection System (MDC), and the occupational surveys conducted by the Air Force Occupational Measurement Squadron. Preliminary efforts to reconcile these data systems to support human resources analyses are documented in Driskill and Boyle (1986). The Defense Training and Performance Data Center (TPDC) is currently involved in similar work, called Crosswalk, to link equipment maintenance information with MPT information automatically. If these and similar efforts prove successful, the utility of the information in a DEPTH human-modeling environment will be greatly expanded. We should be able, for example, to easily "benchmark" comparable maintenance tasks with human performance data such as overall task time, crew size, performing specialist, task difficulty, aptitude, and safety considerations.

SPECIFIC EVALUATION CAPABILITIES

Estimating Maintenance Task Requirements

In addition to their demands for physical strength and size, maintenance tasks call upon a number of perceptual and psychomotor (or, simply, motor) abilities or skills. These include manual dexterity, multi-limb coordination, and color perception, to name a few. An important challenge for this research will be to create task representations rich enough to allow an analyst to make reliable and valid inferences about the requirements for these and other relevant human abilities in proposed human/machine designs. To do this, we must adopt, first of all, a standard language for describing these abilities; a taxonomy. Second, we must define how, and how well, these abilities can be represented and evaluated with available and near-term technologies.

Ability/Task Taxonomies. A number of scientific approaches to this problem have been described. The best recent summary of competing viewpoints is probably that of Fleishman and Quaintance (1984). To take one example, Fleishman describes 52 distinct human abilities that appear to underlie performance differences in a wide variety of laboratory studies and that seem to have adequate psychometric standing. His taxonomy includes, in addition to perceptual, motor, and cognitive abilities, several strength and flexibility abilities that seem highly compatible with current human-model uses and capabilities. These latter are named static strength, explosive strength, dynamic strength, trunk strength, extent flexibility, and dynamic flexibility. Fleishman bases his taxonomic framework on what he calls an "ability requirements" approach. That is, his 52 human abilities are considered to be relatively enduring characteristics of people rather than trained skills.

Another approach that may be applicable is the "task characteristics" method, also described in Fleishman and Quaintance (1984) and in Fleishman (1975). In this approach, attention falls on task-intrinsic properties. That is, they are independent of the human abilities they evoke. A task is conceived as having components: a goal, procedures, input stimuli, responses, and stimulus-response relationships. Each of these is decomposed into a number of task characteristics (e.g., precision and rate of response, number of procedural steps, and procedural complexity). A rigorous task descriptive language independent of the human operator is thus created. A third approach called "job requirements matrix" attempts to link the ability requirements and task characteristics approaches.

The relevance of this psychometric research on human ability taxonomies is in establishing a scientific basis and a common framework for describing task requirements. Note that some of these taxonomies include, but go well beyond physical and ergonomic criteria currently evaluated by the human-models. There is no apparent reason why such ability taxonomies and task analysis methods rooted in the behavioral sciences could not be adapted to a new task analysis context based on human figure simulation. Task visualization provided by computer-graphics video simulation would be used instead of real-world performance measurement or written task rating scales as the basis for design evaluation of task requirements and for the instrumentation of task simulation techniques. The right taxonomic framework can also provide a task-level basis for eventually uniting the physical human factors with the "higher human factors" involved in MPT evaluation.[8]

A TASK ANALYSIS VISION

The task analysis scenario using DEPTH technology could unfold as follows. Proposed equipment and work environment details are loaded into the workstation from CAD systems and data bases. A human-model, anthropometrically scaled to represent the target population accurately, is instantiated from resident software. A pre-defined task taxonomy provides the basis for describing human performance requirements for maintenance tasks. Ideally, the task would be displayed as an animated, 3D computer-graphic simulation.

The task would be simulated with sufficient detail, accuracy, and realism to permit reliable prediction and evaluation of task performance criteria. These criteria include body fit, reach, and static strength estimation like those found in Crew Chief and other current human-modeling technologies. But they also include information on overall task performance times, error sources, task constraints, perceptual and psychomotor ability requirements, task crew/team size, task steps and procedures, tool and support equipment use, and safety and hazard material handling considerations. If a task cannot be performed at all, or if the task demands a skill that exceeds some human performance or design constraint, such as task performance time, the analyst will have visual proof supporting a recommendation for a design change.

What design changes are needed and how these changes affect overall system performance goals are guided by a design evaluation aid, which contains human factors standards, "lessons learned" information, work force characteristic data, design requirements, contract specifications, and so on. When a preferred maintenance task activity is settled upon, the pertinent task information is documented and made available for work force planning and training uses through an LSAR interface. The idea is to pass off accurate, detailed information resulting from

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[8] Task analysis is fundamental to all MANPRINT domains, but the disconnects in task data requirements and uses preclude a fully unified and efficient approach to HCT for design. We have a separate research effort to develop a task descriptive language for this purpose. See Loose (draft).

maintenance task design to "downstream" human resources planning uses. The DEPTH workstation would not be used to perform these MPT-oriented functions but would support them primarily through the creation of an accurate, CALS-compliant, maintenance task data stream.[9]

As presently conceived, some of the task-relevant data may be supplied or represented using non-graphical means. The analyst should be prompted and aided in linking task conditions for the proposed design with information on task performance for the same or similar conditions on comparable existing equipments and task environments. The analyst may need to know, for example:

1. How do factors like temperature, vibration, and noise variation affect task performance?
2. What maintainability lessons learned apply to this task?
3. Are there safety and hazardous material handling criteria involved?
4. How long does it take to become proficient?
5. What is the task crew size and task performance time for comparable work?
6. What human factors design criteria apply, and are the criteria violated?

Information of these sorts abounds, but experience shows that it is not readily useful in actual design evaluation unless it is close at hand and well organized for the purpose (Boff, 1987). Innovative ways of "capturing" this information for use in a workstation task simulation environment are needed. In a similar fashion, task descriptive data underlying graphics-based simulation must be assembled from diverse sources and integrated within the workstation data base.

The ideal human-modeling environment, according to Kroemer et al. (1989), should use a standardized model structure (inputs, outputs, and language) so that the model is generally available and not limited to special cases or to expert users only. In addition, the model should simulate the real world; have three-dimensional form; be dynamic, predictive, validated, and time- and cost-effective; permit rapid analysis; permit on-line documentation; have sophisticated graphical display capability; and be user friendly. The DEPTH workstation environment should incorporate these features of the integrated "supermodel" concept Kroemer envisions.

It is difficult to specify in advance the exact arrangement and allocation of task descriptive information to visual vs. nonvisual modalities and to animated vs. static displays. These depend on the rate of advancements in enabling computer hardware and software technologies and on the success of efforts to automate and apply relevant task performance knowledge and information for workstation use. Promising research in the critical technology of human figure animation is ongoing. The work of Badler and his associates at the University of Pennsylvania on the JACK model is noteworthy. (See Badler, 1989; Badler, Lee, Phillips, & Otani, 1989, October; Phillips

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[9] I have written elsewhere about the eventual union of Human Factors and Manpower, Personnel, and Training (MPT) analysis that might be obtained through DEPTH-like technology. See "The POET Revealed" (Boyle, 1990). Needless to say, not everyone agrees that this is possible (see Pew's remarks in this volume). Everyone agrees that everything in human-centered design hangs on task analysis. Within the safe confines of this agreeableness, I see DEPTH as a way to do traditional task analysis using modern means.

& Badler, 1988; and Badler, Barsky, & Zelzer, 1990.) JACK is evolving into a general purpose task simulation and analysis tool with many of the features necessary for physical and psychomotor performance evaluation required by this research.

USES OF TASK ANALYSIS DATA

Video simulation should permit examination of complete tasks so that their underlying ability requirements can be reliably inferred. Both physical and nonphysical task requirements must be revealed to make better informed decisions about overall job design. Success in this would extend the uses of human-modeling technology beyond anthropometric or biomechanical aspects of design evaluation to include cognitive performance requirements as well. In short, we want a system for specifying, analyzing, and documenting tasks, as shown in Figure 2.

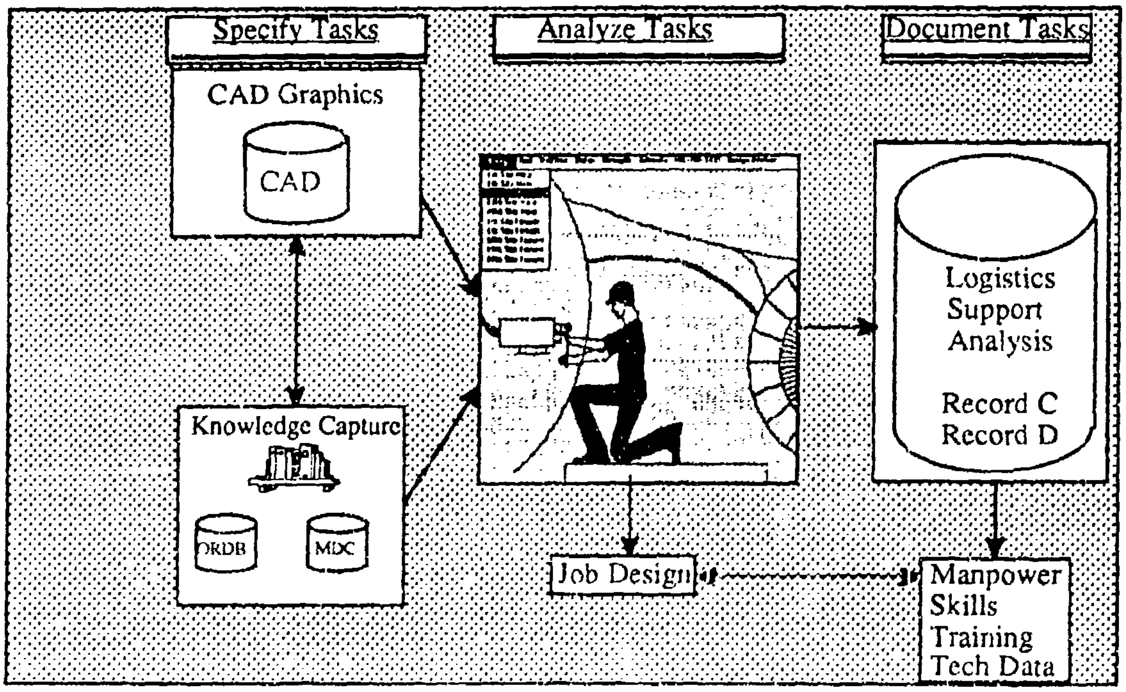

Figure 2. HCT Through DEPTH Task Analysis.

Maintenance Job Design

Once valid and practical methods to profile a wider set of human performance requirements at the task level are in hand, human-centered design issues at the job level may be reachable. For this purpose, a job can be thought of as simply a collection of tasks grouped for assignment to one worker. In the Air Force, this worker would be designated with an Air Force Specialty Code (AFSC) that identifies his or her job or occupation. Job design refers to the optimal allocation of tasks to job categories. It seeks the best allocation of tasks to an AFSC in terms of selection and training economy and individual utilization. This is an iterative - and somewhat artful - process involving many related factors (e.g., manning levels) and uncertain criteria (e.g., evolving design concepts). Even so, a number of guidelines for job design have been published.

Job Design Guidelines. Peterson & Purifoy (1960) discuss these in detail, and provide the following 30 year old but still apt comment:

"Job design is highly related to the equipment of the job, including prime equipment, tools, and test equipment. Usually the job design must be initiated well in advance of final equipment design so that the steps in the job design process which provide job-equipment feedback allow the analyst to influence equipment characteristics. Ideally, if the job design is begun during the preliminary design stage, it can and should be coordinated with equipment design. To a great extent, the engineer designing an item of equipment which is to be operated and maintained is at the same time designing the operation and maintenance tasks." (p. 166)[10]

Creating Maintenance Procedures and Job Aids. Given all this, maintenance procedures and job aids can be thought of as direct by-products of job design. Note in the idealized scheme above that the analyst/engineer is by turns a design influencing agent and a creative designer herself. The products of this iterative design optimization process become maintenance procedures and job aids. That is, the analyst who can define human/machine interactions accurately enough, early enough, and in sufficient detail can also define maintenance procedures. In some sense, job aids become ways to overcome equipment shortcomings that are not readily changed. They will lead the maintenance person to the correct (or most reasonable) diagnosis and repair action. The need for such job aids and the task information required for their creation can be established through the graphics-based task simulation technology this research seeks to develop.

Some Maintenance Training Issues

The CAD-based and CALS-compatible human-modeling technology developed by this research should produce a number of important practical benefits for maintenance training. These benefits can be divided into those supporting training information development, and training media.

Training Information. Accurate illustrations for technical manuals and other training publications could be provided in computer-graphic format from the workstation. CALS data exchange standards are important vehicles for the management and distribution of maintenance "tech data." Maintenance training in the military is governed by a systems approach to training called Instructional System Development (ISD). Task analysis information developed or confirmed through DEPTH workstation technology could aid ISD by providing earlier and more accurate maintenance information.[11] Adoption of CALS-compliant digital data exchange standards within the defense industry will permit rapid updating and distribution of maintenance training information in both text and graphic formats when equipment engineering changes require changes in training documentation. DEPTH technology should make important contributions to CALS by providing more accurate and more thorough documentation of the human-centered aspects of system maintenance and support.

Training Media. If visual/video simulation of a human-model is used to create and analyze a task or job as part of the design development, then the same technology might be used to train real people to do the task or job subsequently. All levels of maintenance training would be supported - technical school, contractor-site, and on-the-job. The correct (or incorrect) way of performing a task could be shown to trainees using human-model simulations recorded from the workstation display. Training media like these could become valuable by-products of the DEPTH design evaluation technology. They would be relatively inexpensive and easy to update if human-modeling visual simulation became a routine part of digital technical information flow under the CALS initiative.

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[10] Notice here the idea of engineering concurrency for human-centered design elements. This is precisely what Simultaneous Engineering tries to achieve.

[11] An ISD/LSAR interface for maintenance is being created under the CALS umbrella. The idea is to use maintenance task descriptive information from LSAR for training development.

INTERFACING WITH LSA AND LSAR

The human factors analysis workstation should help to integrate design technology with human-centered aspects of supportability analysis as we have them defined in MIL-STD-1388-1A and -2A. The computer-graphics human-modeling technology envisioned here should be in consonance with CALS requirements and IPD objectives. As shown in Figure 1, one way for this human-centered design integration to occur is to link CAD, the source of equipment information, with the LSA/LSAR process, the destination of maintenance task analysis information, through a human-modeling computer workstation. Some of the integration opportunities are highlighted below.

Description of LSA

Logistics support requirements for military systems, including the human-centered ones, are estimated during the acquisition process through a procedure called LSA. LSA is formally and explicitly established as an element of the system engineering process used by the Air Force to organize the design and acquisition of military systems. Results of the assorted LSA tasks and subtasks (MIL-STD-1388-1A) are recorded using data formats shown in detail in MIL-STD-1388-2A (LSAR). It has been estimated that about 80 percent of all LSAR data requirements involve measurements or judgments about human performance at some level. One objective of LSA/LSAR is to provide a structured way for supportability issues to influence equipment design. Another objective is to define requirements for the various elements of system support. These elements include maintenance manpower and personnel, training, training equipment, and technical data, among others. The DEPTH technology will advance these dual objectives for logistics supportability. Design influence and design documentation roles for human-centered aspects of equipment maintenance will be established.

Human Engineering Interface. The human-centered LSA/LSAR elements for equipment maintenance correspond to the standard human engineering requirements in military acquisition. Task analysis, workload analysis, and dynamic simulation are three important tools for evaluating the human/machine interface called out specifically in MIL-H-46855B "Human Engineering Requirements for Military Systems, Equipment, and Facilities." The LSA and human factors engineering (HFE) standards are, in fact, cross-referenced. HFE fits under the logistics element called Design Interface. From an LSA perspective, the DEPTH workstation produces a "virtual mock-up" for human/machine analysis. For typical maintenance tasks on military systems, there is little point in distinguishing HFE criteria from LSA data requirements. They are almost coextensive. For example, LSA Task 401, Task Analysis, specifies a number of maintenance HFE task criteria. These include procedural steps required to perform the task, task frequency, difficulty, crew size, personnel skill level and job specialty required, safety hazards, and repair times, among others. LSA criteria are the same criteria that HFE technology for maintenance work should seek to document. The traditional way of doing this, especially for critical maintenance tasks, is through task analysis using physical mock-ups or expert judgment based on verbal task descriptions. In this regard, see also LSA Report 006 "Critical Maintenance Task Summary" and the LSAR "B" Data Record "Criticality and Maintainability Analysis." A computational approach, using CAD and advanced human figure simulation technology to supplement (or even replace) physical mock-ups, should allow human/machine integration issues to be visualized, and allow task analysis to begin earlier and end more accurately than it does now.

LSAR Data Records. The "C" Data Record called "Operation and Maintenance Task Summary" consolidates the operations and maintenance tasks identified for each repairable equipment item. It is used to record support requirements such as tools, facilities, and training equipment. The "D" Data Record "Operation and Maintenance Task Analysis" requires detailed, step-by-step information on how tasks should be performed, the applicable task performance time, and the job specialist (or AFSC) required. These data become vital inputs for the development of maintenance technical data and the definition of personnel requirements for system support. Increasingly, they are inputs to "downstream" maintenance manpower and training planning requirements estimation. Other LSAR data requirements that might be satisfied by the advanced human-modeling simulation technology envisioned here are "Personnel and Support Requirements" (Data Record D1), "Support Equipment or Training Material Description and Justification" (Data Record E), and "Skill Evaluation and Justification" (Data Record G). Human-modeling should help LSA become more proactive in design by making early design data more reliable, and should help make LSA more efficient by moving task analysis information more rapidly to other human-centered disciplines.

DESIGN PRESCRIPTIVE LOGIC

Current human-models would be greatly improved from a user's perspective if they provided more specific information and guidance about the known or projected advantages or disadvantages of particular human/machine designs. At present, the user is often left to his or her own devices in making these assessments. Often, the significant investment required to generate a computer-graphic human-model results in an impressive display but little practical guidance about the goodness of a particular design from a human factors standpoint. Clearly, some way is needed to aid the design evaluation process once a display is created. The issue involves engineering both the user-interface and the user-utility of human-models. That is, it involves helping the user, and helping the user help the customer.

DEPTH WORKSTATIONEERING

User Interface

The software underlying this human-modeling technology, which is graphics-oriented, should present a graphics interface for design evaluation as well. The workstation user interface must be as modern as the human-modeling technology contained in the software. It is important for the success of human-centered design technology that people other than the computer programmers or software engineers who wrote the code be able to use the system to do useful task analysis work. There should be menus, windows, and other user-oriented software tools that would allow the human factors analyst to expend more effort on her own craft and less on someone else's. In short, the human factors workstation should be carefully human factored itself.

User Utility

The user should be able to quickly find out what scientific knowledge and other applicable information say about a particular task and task environment. A menu titled, for example, "HF Criteria For This Scenario" would lead the analyst to MIL-STD-1472 and other data applicable to the proposed task or job. This would help the analyst quickly determine whether relevant design or human performance criteria are violated, and by how much. A design check to confirm human performance capabilities is needed for practical task evaluation. The user must be able to find out what science, experience, or design requirements apply to a task design before she can say she has a good or a bad design. If she can't determine these things, she can't be of practical help to her customer, the design engineer. This implies a need for a workstation utility that can act as a design advisor to help in solving task specification, task analysis, and task evaluation problems.

TECHNOLOGY APPLICATIONS

Air Force acquisition strategy for the foreseeable future is likely to stress upgrades and modifications to existing systems rather than major new systems. To be most useful, the DEPTH technology program should be adaptable to the different design problems involved in modification and retrofit of existing systems, rather than solely to new system design. In addition, the technology should be adaptable to human-centered maintenance requirements analysis within the industrialized Air Logistics Centers (ALC) (depot maintenance), not just to flight line (or organizational) maintenance.

For these new applications, the question of anthropometry for different populations becomes especially relevant. The Crew Chief anthropometry, for example, is based on youth populations similar to Air Force maintenance workers. Applying these body data to other groups, such as Air Force depot workers, may not be valid if this work force is significantly different. We need new measurement techniques to help us accurately portray the physical characteristics of different populations of workers. We also need new workstation techniques that can allow us to rescale the anthropometry and related physical charactistics of the target population.

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HUMAN PERFORMANCE PROCESS MODEL RESEARCH

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ABSTRACT

Process models of human performance represent the human information processing system as an engineering system consisting of input/output devices, processors, and memory storage subsystems. The goal of Human Performance Process (HPP) models is to emulate human behavior through simulation of specific human information processes and attributes. HPP models are typically employed in engineering studies attempting to analyze task workload with the goal of predicting human performance.

HPP model research represents a unique focal point of cognitive science research. HPP model research blends together the information processing models developed by cognitive psychology and the computational techniques developed by artificial intelligence to create dynamic emulations of human performance. HPP model research provides cognitive scientists an opportunity to test both theories of human performance and implemented computational models.

To support HPP model research, the Air Force Human Resources Laboratory (AFHRL) had developed a first-generation testbed, the Automation Impacts Research Testbed (AIRT). AIRT consists of scenario generation and system prototyping tools, integrated with the HPP models. In this ongoing research, AFHRL is comparing the performance of process models to that of Air Force officers assigned to the air weapons controller career field. The equipment emulated in this study is the next generation air defense system, the Modular Control Equipment (MCE). AIRT supports research on process models by allowing removal of one operator model and replacing it with an actual air weapons controller. The human operator interacts with the team of operator models through voice recognition and generation systems as well as through the MCE interface. AIRT provides the capability to compare the performance of an actual operator with a modeled operator during identical interactive simulation trials. This paper will provide an overview of AFHRL's HPP model research and discuss the research issues associated with HPP model development.

INTRODUCTION

Process models of human performance (Card, Moran, & Newell, 1983, 1986) represent the human information processing system as an engineering system consisting of input/output devices, processors, and memory storage subsystems. Information flow and transformation are described in terms of key system parameters within each subsystem. The goal of human performance process (HPP) models is to emulate human behavior through simulation of specific human information processing attributes and processes. HPP models are being developed to permit psychological principles and data to influence system design. They are typically employed in engineering studies attempting to analyze task workload, with the goal of predicting human performance.

An HPP model representative of the state-of-the-art has been developed by the Air Force Human Resources Laboratory (AFHRL) through a contract to BBN (Corker, et al. 1989). This model consists of four subcomponent models: (a) visual, (b) auditory, (c) cognitive, and (d) psychomotor. The visual subcomponent models two types of visual processing: (a) active gaze and (b) monitoring. (Active gaze represents focused and directed movement to a target point; monitoring represents a scanning process.) The parameters modeled for both active gaze and monitoring are field of view, velocity of motion, saccades, and fixation pause. The auditory subcomponent models both the communication protocol employed by human operators and the bandwidth and memory limits of human auditory processing capabilities. The psychomotor subcomponent model incorporates Fitts' formulation relating movement time, distance, and accuracy to provide a probability of error. The cognitive subcomponent model depicts cognitive activity via a procedural representation consisting of "If some condition exists, Then execute some action" statements, and an inferencing engine which controls the application of the If/Then statements (which are normally called productions).

In addition to the subcomponent models, each operator model has an individually defined updatable world representation which is a description of the world as the operator knows it. It contains rules for decisions, an awareness of external events as seen through the operator's perceptual processes (i.e., audition and vision subcomponent models), and a declarative description of the world as the operator knows it. The declarative, or factual, information is represented in a frame-theoretic paradigm (Minsky, 1975). Declarative information includes "knowledge" concerning aircraft (types of aircraft and their capabilities), the operator's equipment (what components make up the equipment, and how to operate it), and rules of engagement (knowledge about the operator's expected behavior).

The AFHRL HPP model works in the following way. Information enters the world representation through the perceptual modalities. The cognitive subcomponent model is continually trying to match condition clauses against the data in the world representation. If a match is triggered the execution clause spawns, or generates, activities. These activities are then executed through the appropriate subcomponent model. The execution of activities can also change data in the world representation, which often results in the spawning of additional activities.

AFHRL's cognitive subcomponent model is the most elaborate attempt to incorporate knowledge-based modeling techniques into an HPP model. Knowledge-based models depict the problem-solving processes of experts. The expert's knowledge is represented in symbol structures, along with rules for manipulating the knowledge. Knowledge is often stored as heuristics: "rules-of-thumb" that individuals employ in making decisions. The knowledge-based model employed in AFHRL's HPP model is an expert system (Hayes-Roth, et al., 1983). It is unique in that the control strategy guiding the inferencing engine is based upon a psychological model of how human memory operates.

The AFHRL HPP model is very sophisticated compared to other HPP models; however, it is very simplistic compared to a human being. There are several aspects of the model that need continued research and development. First, the model has difficulty identifying human performance limitations due to high task demands. Second, the model does not readily depict different skill levels of personnel, from novice to expert. Third, the model has difficulty accurately depicting the processes involved with concurrent tasking, in which the operator is engaged in multiple tasks simultaneously. Fourth, the model isn't sufficiently sophisticated to model complex decision-making processes. (This is due to both a lack of understanding of human decision-making and a lack of efficient computational techniques to represent and inference large knowledge bases in real-time.) And finally, and perhaps most important, the model is unvalidated.

COGNITIVE SCIENCE AND HPP MODEL RESEARCH

Cognitive science is the interdisciplinary study of the acquisition and use of knowledge (Collins and Smith, 1988). Cognitive science views the human brain as a physical symbol system consisting of representation and processing systems. Two of the key disciplines involved in cognitive science research are cognitive psychology and artificial intelligence. Cognitive psychology research focuses on developing information processing models that depict human perception, memory, and thought. Artificial intelligence research focuses on developing computer-based models of human performance. HPP model research is the conjunction of these two endeavors. HPP model research blends together the information processing models developed by cognitive psychology and the computational techniques developed by artificial intelligence to create dynamic emulations of human performance. HPP model research is more constrained than cognitive psychology or artificial intelligence research. It constrains cognitive psychology by requiring the information processing models to be rigorous and complete in their specification of human capabilities. It constrains artificial intelligence research by requiring the computational models to emulate human performance and the underlying processes driving human performance.

HPP model developers often develop their models upon based cognitive psychology research, and then implement them with an AI-based knowledge representation strategy. When drawing on cognitive psychology, the model developer is concerned about the veridicality of the psychological theories; when drawing on artificial intelligence, the model developer is concerned about the computational efficacy of the data processing techniques.

Cognitive psychology's information processing perspective readily lends itself to the HPP model design process. Information processing models usually trace mental operations through a sequence of stages, from encoding of sensory information, through a series of mental operations, to the formation of either a mental product or a physical action. These stage models are easily transformed into engineering models. Additionally, cognitive psychology research often provides data distributions that can be used to define the ranges of information flowing through the system. However, there are serious problems for the model developer interested in using research results from cognitive science to develop HPP models. In drawing data from cognitive psychology the problems are interpreting (or reconciling) research results derived from different experimental paradigms, and then choosing a psychological theory to explain those results. There are usually a plethora of results, which can be explained in a multiplicity of ways.

Once the HPP modeler has developed a psychological model, the next step is to develop a computational implementation. A key computational implementation problem in designing an HPP model is how to represent knowledge. Artificial intelligence research has developed a profusion of formalisms to represent knowledge and emulate cognitive processing. In drawing on artificial intelligence research there is a problem selecting the most effective computational implementation that supports the cognitive processes being modeled. Choosing the appropriate computation technique is difficult, since there are little data comparing the relative advantages and disadvantages of different techniques.

Consider the the issue of how to model human performance limitations due to excessive task demands. Most psychologists would agree that performance limitations are due to the human's inability to attend to multiple tasks simultaneously. Psychologists invoke the theoretical construct, attention, to explain the process by which humans reduce the information bombarding them. The basic idea is that to perceive any stimuli one must first attend to it. Attention research attempts to explicate the limits of, and processes involved in, human attention. But psychologists' agreement on attention ends here: There are two dominant research paradigms generating research data, and two very different theoretical perspectives attempting to explain the data.

As discussed by Kahneman and Triesman (1983), the two dominant research paradigms in attention research are (a) the filtering paradigm and (b) the selective-set paradigm. The filtering paradigm is distinguished by three features: (a) the subject is exposed simultaneously to relevant and irrelevant stimuli, (b) the relevant stimuli control a relatively complex process of response selection and execution, and (c) the property that distinguishes relevant from irrelevant stimuli is normally a simple physical feature (e.g., color or shape). In the selective-set paradigm, the subject is prepared for a particular stimuli and is instructed to indicate as quickly as possible the detection, or recognition, of that target. Thus, in the selective-set paradigm the subject is searching for one of several stimuli, whereas in the the filtering paradigm, the subject is analyzing multiple stimuli.

The filtering and selective-set paradigms were each created to study a different aspect of attention. The filtering paradigm was developed to study the limits of performance and to measure the extent to which different tasks can be combined without loss. The selective-set paradigm was developed to study the brain's ability to resist distraction, and to establish the locus beyond which relevant and irrelevant stimuli are treated differentially. Research results derived from the filtering paradigm suggest (in general) that the brain is organized as a modular system by modalities and that interference between stimuli arises chiefly within rather than between the separate, semi-independent subsystems. Research results derived from the selective-set paradigm suggest that the brain has an impressive ability to parallel process multiple stimuli, even within the semi-independent subsystems. These results are obviously contradictory. The filtering paradigm results imply that a HPP model should have a processing bottleneck in each modality; the selective-set results suggest that a HPP model should have parallel processors in each modality. Perhaps these results can be understood by looking more closely at the theories which attempt to explain them.

There are two major classes of theories of attention: (a) filter theories and (b) resource theories. Filter theories promote an information flow model that comprises several processing mechanisms, one of which is more constrained than the others. The constrained processing mechanism can be conceptualized as either a channel through which only a limited amount of information can flow, or a processor which can only process a limited amount of data. Filter theories can have single or multiple stages of information processing. In contrast to filter theories are the resource theories. Resource theories promote an energy- or activation-based model. Resource models stress that the information processing system has a limited amount of resources with which to process information. Resource theories can have a single pool of resources, or multiple pools of resources. In the following discussion we will briefly consider a single and multiple filter model, and a single and multiple resource model.

The first and most influential single stage filter model was proposed by Broadbent (1958). The central construct in Broadbent's model is a limited-capacity channel, preceded by a selective filter and a short term sensory store. The limited capacity channel leads to a mechanism that selects and controls the system's response and a long term store. Broadbent's filter is influenced by the properties of the incoming information, as well as by information of the long-term store. Selection by the filter is based upon physical features, for example the speaker's voice characteristics, of the input. Research by Triesman (1960) demonstrated that the filter model proposed by Broadbent needed to be more complex. In experiments where subjects were asked to shadow (verbally repeat) a message presented in one ear while attempting not to attend to a second message presented in the other ear, subjects occasionally responded to meaningful stimuli, for example their name spoken by a different speaker, in the non-shadowed ear. These results demonstrate that information can be selected by the filter via properties other than the stimuli's physical properties.

An example of a multistage filter model was proposed by Triesman (1986). Triesman proposes a two-stage model. The first stage works in parallel over the entire visual field extracting features from incoming stimuli. This stage uses separate features like color, size, contrast, and curvature to create a stack of feature maps. The second stage works serially, employing focused attention to identify objects and their settings by combining features. Focused attention operates via a master map. The presence and nature of discontinuities are registered in the master map. Attention employs the map to simultaneously select all features in a selected location, creating an integrated temporary object representation. The temporary object representation is then compared to a recognition network which specifies critical attributes of perceptual objects. Prior knowledge and expectations play a major role in guiding attention in this system.

As summarized by Gopher and Donchin (1986), the most comprehensive resource model developed to explain human performance was developed by Kahneman (1973). Kahneman's model limits the amount of resources available at any time, but it allows the resource level to vary with the level of arousal. Arousal, and consequently performance, changes in the classical inverted U-shaped function. Increases in arousal increase the amount of resources and performance capacity to a point; beyond that point (the [illegible] the inverted U) performance falls off. Changes in the level of arousal are controlled by f[illegible] from the execution of ongoing activities. Additionally, there is a mechanism responsible f[illegible]ocating resources. This allocation mechanism is influenced by enduring dispositions and momentary intentions, in addition to the feedback from ongoing activities. Research results from experimental paradigms, where the subject had to engage in two tasks, simultaneously showed that the performance of certain tasks interfered more with some tasks than with other tasks. These results implied there must be more than one pool of resources, and that different tasks draw differentially upon these distinct resources.

Multiple resource theories model the information processing system as a number of processing mechanisms each having its own supply of resources. An example of a multiple resource model was developed by Wickens (1980, 1990). Wickens' model proposes three structural dimensions of the human information processing system: (a) processing stages, (b) codes, and (c) modalities. The processing stages dimension defines two separate resources: (a) perceptual-cognition (input processes) and (b) response processes (output processes). The second dimension contrasts spatial and analog codes involved in information processing. The third dimension contrasts perceptual modalities (visual versus auditory input). The first two dimensions are associated with different resources in Wickens' model. The third dimension is not associated with resources, but affects resource utilization through interactions with the other two dimensions (Wickens, 1990). To the degree that tasks are similar across dimensions, they will use the same resources and, hence, interfere with each other.

These theories conceptualize attention in very different ways. The two filter theories described above model human information processing from an information theory perspective. Information theory is concerned with the manipulation, transformation, and transmission of information, irrespective of the physical or biological properties of the system. Theories based upon information theory usually model the system structurally. In filter theories, limitations in human performance can be due to information failing to pass through filters (usually conceived as physical entities), or as the overloading of a central processor with too much data. The two resource theories described above model information processing from a more biological perspective. These theories posit that the entity has a limited amount of resources for processing information, with resources being conceived as energizing forces required for task performance.

Interestingly, resource models posit that the amount of resources available at any given time varies with arousal. The entity can perform more tasks when aroused. The concept of resources, however, is not related to any specific structural model.

The problem for the HPP model developer is how to integrate ideas from different theoretical perspectives into HPP models. A filter-based model would emphasize structural channels and processing units in each modality. There would be filters that would act as gatekeepers in the channels. (It is still an unanswered question as to whether the modalities would process information in parallel.) The filters would be parameterized to pass information based upon the physical properties of the stimuli. The HPP model would need to track stimulus properties. Additionally, there would be processing units having fixed amounts of processing capabilities. Human performance limitations would most often result from overloading the system with information. On the other hand, a resource model would emphasize the quantities of resources available to the organism. These resources would most likely be tied to specific sensory modalities and processing systems. The HPP model would track resource expenditures and allow processing only if resources were available. The model would also track the entity's level of arousal, or activation, and modify resource availability accordingly. Human performance limitations would most often result from the lack of available resources.

Integrating concepts from different theoretical perspectives into a HPP model is very challenging. The choices made strongly influence the subsequent research the model can be used for. For example, creating a HPP model based on resource theory should allow the modeling of the effects of stress; creating a model from a filter perspective may not.

Let's now consider some additional shortfalls of the AFHRL HPP model, specifically, its inability to model different skill levels, and complex decision-making. The focus of this discussion will be on knowledge representation techniques. Lack of effective knowledge representation techniques is currently the most serious problem limiting the sophistication of the cognitive component of AFHRL's HPP model.

Elaine Rich (1983) lists four properties required to effectively represent complex knowledge in a given domain: (a) representational adequacy, (b) inferential adequacy, (c) inferential efficiency, and (d) acquisitional efficiency. Representational adequacy is the ability to represent all the kinds of knowledge required in a given domain. Inferential adequacy is the ability to manipulate the representational structures in a way to derive new structures representing new knowledge inferred from old knowledge. Inferential efficiency is the ability of knowledge structures to use new information to focus the attention of the inference mechanism in the most promising direction. Acquisitional efficiency is the ability of the knowledge structure to acquire new information easily. Several knowledge representation techniques accomplishing these objectives have been developed by artificial intelligence researchers. These knowledge representation techniques fall into two categories: (a) procedural methods and (b) declarative methods. Procedural methods represent knowledge as procedures for employing the knowledge. Declarative methods represent knowledge as a static collection of facts with a limited set of procedures for employing them. The following discussion will focus on one procedural and three declarative knowledge representation techniques. All of these techniques can be employed to create knowledge-based models.

The most commonly employed procedural representation is the production system. (It is the knowledge representation technique employed in AFHRL's cognitive subcomponent model.) Once again, a production system consists of a set of rules, or productions, each comprising a left side that determines the applicability of the rule, and a right side that describes an action to be performed if the rule is applied. The rules are compared against a data base of the current world state to determine if the conditions for activating, or firing, the rule exist. The final component of a production system is the control strategy (inference engine) that specifies the order in which the productions will be compared to the world state and a way to resolve conflicts that arise when several productions become active simultaneously. Production systems have been employed in a variety of knowledge-based systems. Production systems underlie most of the expert systems that have been built. They are very useful at recognizing patterns and generating appropriate actions. Production systems are an excellent way to model data-driven behavior.

The limitations of production systems are several. First, because production systems are data-driven, they are not well suited for modeling intentional behavior. An analyst employing an HPP model built around a production system must manipulate the scenario to elicit the desired behavior. It would be preferable to just program the desired intentions into the cognitive model. Second, the computational efficiency of a production system decreases rapidly as the size of the rule base increases. Currently, production systems over a few hundred rules usually require tens of minutes to inference the data base. This limitation of the size of the rule base limits the complexity of the behavior that can be modeled to procedural behavior. Complex decision-making will probably require production systems with several thousand productions. Third, as the size of the production system increases, the difficulty of adding knowledge increases. Experience has shown that additional rules often have unusual and unforeseen effects on an existing production system. Adding rules significantly increases the time required to test and debug the system Finally, experience with production systems has shown them to be brittle. (Brittleness is the tendency of a system to fail badly when the boundary conditions of knowledge are exceeded.)

In contrast to the production system of knowledge representation are the declarative knowledge representation techniques. Declarative techniques have not been widely employed in operational (as opposed to demonstration) artificial intelligence systems. Because there are little data on which to compare the performance of declarative techniques, the discussion will provide an overview, defining and contrasting three different techniques.

Semantic nets (Quillian, 1968) were one of the first declarative techniques developed by artificial intelligence researchers. In a semantic net information is represented as a set of nodes connected to each other by a set of labeled arches, representing relationships among the nodes. Examples of relationships include ISA, INSTANCE-OF and COLOR. The power of semantic nets is in the ability of computer programs to solve problems using stored information. The relationships between two objects can be found by spreading activation from the two nodes and seeing where the nodes' arches intersect. Semantic nets are general enough to describe both events and objects. Interestingly, one of the problems with semantic nets is that they're too general. As Woods (1975) points out, some kind of formalism should be applied to defining arch classes to prevent a proliferation of relationship types.

A second declarative knowledge structure is the frame (Minsky, 1975). Frames are a general mechanism designed to represent prototypical objects, situations, or locations. Typically, frames are used to describe classes of objects. A frame consists of a collection of slots which provides a framework for describing the properties of the object, situation, or location. Normally, associated with each slot is a set of conditions that the values filling the slot must meet. Additionally, each slot may have a default value. The default values are employed when the frame becomes active and there isn't any information available for a particular slot. Related frames are often grouped together to form a frame system. Frame systems allow an object to be considered, or represented, from several views. Frames support inferential reasoning techniques. For example, frames contain information about prototypical objects. This allows unseen object attributes to be inferred as present. Additionally, because frames describe typical instances of the object or concept represented, it is easy to identify departures from the norm.

Scripts (Schank & Abelson, 1975) are structures that describe stereotypical sequences of events. Scripts, like frames, consist of a set of slots; information associated with the slots describes the values the slots may take on and provides default values when information is not available. Scripts differ from frames in that scripts employ specialized slots. Example specialized slots include entry conditions, results, props, and scenes. Entry slots specify conditions that (in general) must be satisfied before the events described in the script can occur. The results slot describes the conditions that will be true after the script's events have occurred. Prop slots describe the objects involved in the events of the script. Scene slots describe the actual sequence of events that will occur. Scripts are useful in creating coherent interpretations of events from a collection of observations.

An advantage of employing a declarative representation is that each fact in the data base need only be stored once, regardless of the number of different ways it may be used. Additionally, in declarative schemes it is easy to add new facts. These three declarative techniques differ at the level of detail at which the world is represented. The issue is whether one should employ a simple or complex scheme. Simple schemes, like semantic nets, only require a small number of primitives to inference the data; more complex schemes, like scripts, require more sophisticated inferencing mechanisms. Additionally, simple representation schemes support broader inferencing of the available data. However, breaking complex representations down into primitives requires a significant amount of computational overhead and data storage space.

A major question for the HPP model developer is, which knowledge representation techniques have the greatest potential to expand the capabilities of a cognitive model? The issue is twofold. First, does the computational technique have the capability to model the desired psychological functionality? Second, is the technique sufficiently computationally effective? As an example, consider the modeling of different individuals' skill levels. Skill levels can vary from the inexperienced novice who has been trained to perform the task, but actually hasn't performed the task outside of a classroom, to the highly skilled expert who has automatized task performance. The first computational issue presumes, of course, that a psychological theory exists which explains novice/expert differences. In this instance, most psychologists would say the expert is better at encoding and manipulating information. The expert's improved performance is due to his ability to "chunk" information into meaningful patterns. This chunking allows the expert to exceed normal working memory limitations. The first issue is then, which techniques are better at modeling this difference? For example, one possible way to model novice/expert differences using AFHRL's HPP model would be to incorporate a frame with a variable number of slots into the world representation. An expert's frame would have more slots, representing more working memory capacity. However, now consider the second issue: computational effectiveness. Even though the addition of a frame with a variable number of slots would allow us to model the psychological functionality, the computational effectiveness of the production system is still severely limited. We cannot create a system with enough productions to model the range of behavior required to show novice/expert differences. The unanswered question for model researchers is this: What is the range of behavior that can be modeled by other techniques?

AFHRL'S RESEARCH AGENDA

AFHRL has developed a first-generation testbed, the Automation Impacts Research Testbed (AIRT), to support further model research. AIRT is a research vehicle for the development and testing of real-time interactive modeling technologies, including HPP models. AIRT consists of scenario generation and system prototyping tools, integrated with the HPP models. In this ongoing research, AFHRL is comparing the performance of the HPP models to that of Air Force officers assigned to the air weapons controller career field. The equipment emulated in this study is the next generation air defense system, the Modular Control Equipment (MCE). MCE is normally operated by a team of air weapons controllers who perform different functions. With AIRT, AFHRL has emulated the MCE and a team of four operators. AIRT supports research on process models by allowing removal of one operator model and replacement of it with an actual air weapons controller. The human operator interacts with the team of operator models through voice recognition and generation systems, as well as through the MCE interface. AIRT provides the capability to compare the performance of an actual operator with a modeled operator during identical simulation trials.

AIRT was developed using an object-oriented programming approach (Bobrow & Stefik, 1986). Three concepts define an object-oriented approach: (a) objects are defined in terms of classes which determine their structure and behavior; (b) behavior is invoked by sending a message to an object; and, (c) descriptions and behavior of objects may be inherited from more general classes. The application of these programming constructs creates a powerful modeling development environment. For example, defining objects in terms of classes (a above) and allowing behavior to be inherited (c above) supports the creation of object libraries that can quickly be tailored to specific applications. A model developer first defines a class of objects, such as human operators, specifying the attributes and behavior of the class. Objects of this class can then be created by duplicating the basic structure; in our case we cloned four operators. These objects inherit their basic behavior from the class. This behavior can then be refined within the individual objects. For example, we have defined four different operators each with different behaviors. Additionally, objects have procedures specifying how to communicate and to whom. Objects communicate through message passing (b above). Message passing allows objects to implement their methods for responding to a message locally, within the object. An object's methods can be changed with no impact on the rest of the program.

Object-oriented programming supports the rapid development of highly modular software. Software development is rapid because the model developer can access and tailor pre-existing libraries of objects, thus reducing development time. Furthermore, the inherent modularity of objects allows changes to be made quickly to classes of objects (or individual objects), with minimal impact on the rest of the program. Software modularity supports HPP model research by allowing the testing of different psychological theories and computational implementations with minimal software recoding.

AIRT development was initiated as an exploratory development, or proof of concept, program. The goal was the demonstration of new interactive modeling techniques. Technological advances achieved by this effort include models of domain-specific operator behavior and knowledge, "soft" prototypes of an equipment interface, human-in-the-loop simulation, and real-time simulation of emulated operators interacting both with the human-in-the-loop and the "soft" equipment prototypes, all integrated on one mini-computer. Although AIRT was developed as a proof-of-concept program, it has the potential to enhance human performance model (HPM) research.[1]

A recent report from the National Research Council (1990) entitled "Quantitative Modeling of Human Performance in Complex, Dynamic Systems" identified eight research issues associated with extending the scope and applicability of HPMs to the analysis of human performance issues in complex systems. These issues are (a) complex/comprehensive models; (b) model parameterization; (c) model validation; (d) underutilization and inaccessibility of human performance models; (e) potential for misuse and misunderstanding in applying HPMs; (f) accounting for mental aspects of tasks; (g) developing and using knowledge-based models; and, (h) accounting for individual differences. Modeling testbeds like AIRT have the potential to help investigate most of these issues.

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[1] HPP models are a subset of HPMs. HPP models differ from HPMs in that they're more comprehensive models of human performance. HPP models attempt to model the process of human information processing, whereas HPMs attempt to model the results of human information processing.

The first issue is the development of complex/comprehensive models. Traditionally, HPMs were designed for specific, single-task, person-machine situations. However, in most real-world situations the operator is faced with complex tasks requiring multiple inputs and outputs.

Additionally, operators usually have multiple goals and are frequently interrupted in task performance. Modeling of real-world tasks demands the development of more sophisticated models. The report lists two recommendations. First, because attention will be a key component of any comprehensive model the report recommends pursuing research in this area. Second, the report recommends the investigation of models that integrate single task submodels into comprehensive models. AFHRL's HPP models research supports both goals.

Attention research requires a complete model of human performance and sophisticated, complex tasks for study. AIRT as a research tool provides both. The HPP models in AIRT attempt to completely model human information processing, from perception to cognition. Furthermore, AIRT supports research on very complex dynamic tasks. Air weapons controllers often control several aircraft through a system (the MCE) which has 240 operating modes. With AIRT, scientists can compare the performance of HPP models having attention-based sub-component models with the performance of actual operators under identical task demands. Additionally, modular code allows the substitution of submodels based on differing theoretical perspectives into the overall model. For example, attention models based upon the filter and resource theories described above could be developed, integrated into the HPP model and compared against the performance of actual operators.

An object-oriented approach like that employed in AIRT supports the creation of comprehensive models. In an object-oriented paradigm each single-task submodel is an individual object. These objects are easily integrated into a comprehensive model through the construct of message passing.

The second issue the report addresses is model parameterization. The report notes that as models become more complex (i.e., employ more parameters) the data necessary to specify the parameters become more difficult and costly to collect. Two of the report's recommendations are (a) that model developers identify and classify all model parameters, and (b) that a goal of research be the development of estimation techniques to uncover the distribution of parameter values. AIRT can support both of these recommendations. First, AIRT's implementation lends itself to parameter documentation. An object-oriented programming approach provides structural and organizational information lacking in traditional programming environments. The process of organizing information in terms of types and classes, and the specification of communication protocols enhances both the model developer's and other analysts' ability to understand model parameters and their interrelationships. Second, AIRT's ability to compare the performance of human operators to models under identical simulation trials has great potential to enhance our ability to collect data from which to derive estimation techniques. Employing AIRT, scientists can collect data on the performance of human operators engaged in complex tasks, and test estimation techniques designed to reproduce that behavior.

The third research issue discussed in the report is model validation. The report points out that as models become more complex they become more difficult and costly to validate. It should be fairly obvious that a testbed like AIRT that allows the models to be compared to actual operators is a significant advance in model validation technology. This is not to say that AIRT is a panacea for model validation. There are some very difficult methodological issues associated with the study of complex tasks. First, given the complexity of the tasks being studied, it is difficult (and possibly undesirable) to get experimental subjects to respond in identical ways. Consider as an example, an air weapons controller task in which several unidentified aircraft are approaching a restricted zone where high-value assets are being protected. The controller has two aircraft airborne flying a holding pattern. The controller has several options. He can query the radar transponders on the approaching aircraft; he can order the airborne aircraft to intercept the unidentified aircraft and perform a visual identification; or he can order aircraft on the ground to launch, intercept, and identify the incoming aircraft. These options are not mutually exclusive: the controller will probably execute at least two options. A key issue for the scientist is how constrained the task is made. That is, is the controller told to execute only certain tasks, in a given order? If the task is too constrained, you lose data on individual differences. Conversely, do you let the individual controllers decide on the actions they'll take, and the order? If the task is too unconstrained, you generate data with high variability and little experimental control, which will be very difficult to analyze.

A second difficult model validation issue is, given that the HPP model performance diverges from the performance of actual operators, how do you identify the HPP model subcomponent that is creating the difference? Did the scanning model not see the aircraft? Did information in the short-term memory model decay too quickly? Or is there some problem with the cognitive model? A constrained-task approach offers the best chance of isolating the problem; eventually, as we solve the analysis problems, we hope to accommodate a less constrained approach. Even constrained AIRT-style testbeds offer significant validation capabilities.

The fourth research issue identified by the report is the underutilization and inaccessibility of most HPMs. According to the report, most complex HPMs have not been widely used, nor subject to independent evaluation. The report recommends that government agencies support the development of easily used versions of models on the most inexpensive machines possible. This is exactly the course of action AFHRL is pursuing. AFHRL is planning to make AIRT and its HPP models available to interested researchers through the Crew System Ergonomics Information Analysis Center (CSERIAC). CSERIAC is the information analysis center responsible for acquiring, analyzing, and disseminating technical information on crew system ergonomics. One of the functions CSERIAC provides is a repository for computer-based models of human operators. Scientists interested in acquiring AIRT should be able to obtain it from CSERIAC starting in mid-1991. It must be noted that AIRT was not developed to be a production quality system. The AIRT effort was an exploratory development program to demonstrate the feasibility of this new modeling approach. Follow-on efforts by AFHRL will develop production quality models and testbeds that will be transitioned to CSERIAC. AFHRL appreciates the additional amount of work required to validate and extend HPP models and is actively seeking to create and support a larger HPP model research community within academia.

The fifth research issue identified is the potential for misuse and misunderstanding of models as they become more complex. One of the report's recommendations is for better documentation of the model assumptions, theoretical bases, embedded data, and software requirements. Unfortunately, because AIRT was a proof-of-concept program it does not have the level of documentation called for by the research council's report. This is one of the key goals, along with the creation of a modeling environment a non-programmer can use, in the follow-on effort to AIRT.

The sixth and seventh issues identified by the report are the creation of models that account for the mental aspects of tasks and the development of knowledge-based models. We discuss these together because AFHRL's approach to the creation of models that can account for the mental aspects of tasks is to develop knowledge-based models. We would like to stress that knowledge-based modeling is still in its infancy. As discussed above, the most sophisticated knowledge-based models are capable only of modeling procedural behavior. Additionally, these models use procedural knowledge representation techniques which themselves have limitations (e.g., they are not good at modeling intentional behavior). Even so, testbeds like AIRT and modular object-oriented HPP models provide significant tools for further research. The modularity of the model is particularly valuable for testing alternate knowledge representation and inferencing techniques.

The final modeling issue discussed in the report is accounting for individual differences with HPMs. To date, individual differences have largely been ignored in favor of normative or average indices. The report notes that, due to the increased complexity of new systems, individual differences will play an increasingly important role in man/system performance. Testbeds like AIRT are ideal for investigating how individual differences affect the performance of complex tasks. Recall that AIRT emulates the next generation air defense command and control system, the MCE. AFHRL is planning to conduct research employing a relatively large number of subjects who potentially differ greatly in their skill levels. The subjects in these studies will be air weapons controllers with experience ranging from 1 to 20 years. We believe this experience range, and the potential number of subjects, will be enough to identify key individual difference parameters and to get a start on defining parameter data distributions. Finally, the ability to compare models and the ability to compare model performance to that of actual operators will support the development of models that account for individual differences.

AFHRL is taking a two-sided approach in developing and refining modeling technology. On the one hand, AIRT is a testbed for further modeling research, as described above. On the other hand, AIRT is a set of tools a designer can use to investigate computer interface design issues, trade-offs between personnel or automation, and task loading on operators. AIRT is an interactive, real-time simulation environment. Employing the scenario definition tools, rapid prototyping environment, advanced HPP models, and human-in-loop simulations, a designer can rapidly emulate and test different systems designs under emulated combat scenarios. AFHRL envisions the product of the follow-on effort to AIRT being used to compare alternate design options, from an operability perspective, during the trade-studies phase of new system acquisition.

SUMMARY

HPP models emulate human behavior through simulation of specific human information processing attributes. HPP models are being developed to permit psychological principles and data to influence system design. For example, this class of models is often used in engineering studies attempting to analyze operator workload. HPP model development blends together the information processing models developed by cognitive psychology and the computational techniques developed by artificial intelligence to create dynamic emulations of human performance. The development of HPP models is still in its infancy. Current models have limited applicability, and for the most part are unvalidated. However, HPP models have great potential for the future. Potential applications of HPP models include using them to conduct engineering studies of new systems, with the models taking the roles of the human operators; incorporating them into Computer-Aided Engineering (CAE) workstations where they could animate anthropometric man-models; and, employing them in cognitive science research to test psychological theories and computation strategies.

To support HPP model research AFHRL has developed AIRT. AIRT is a research vehicle for the development and testing of real-time interactive modeling technologies. AIRT consists of scenario generation and system prototyping tools, integrated with HPP models. AFHRL has used AIRT to emulate the next generation air defense system, the MCE, and a team of air weapons controllers. AIRT supports research on process models by allowing removal of one operator model and replacement of it with an actual air weapons controller. The human operator interacts with the team of operator models through voice recognition and generation systems, as well as through the MCE interface.

AIRT supports the study of complex tasks executed by operators with a wide range of skill level differences. Research on complex tasks is critical to the development of models capable of emulating complex cognitive skills. Additionally, the modular aspects of AIRT support researchers in comparing alternate models, or subcomponents of models. Modeling testbeds like AIRT have tremendous potential to support investigations of the research issues identified by the National Research Council Report (1990).

Finally, AFHRL realizes the enormous additional amount of work required to validate and refine HPP models. To facilitate this effort AFHRL is planning to make the AIRT software available to interested parties. This software will be made available through CSERIAC, a government center responsible for disseminating specialized information and tools for the investigation of crew system ergonomics.

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IMPLEMENTING MPT DESIGN REQUIREMENTS THROUGH RAMCAD

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ABSTRACT

This paper gives a brief discussion of reliability and maintainability (R&M) and their direct relationship to manpower, personnel, and training (MPT) factors in design. The technologies and methodologies associated with the Air Force Human Resources Laboratory's (AFHRL's) Reliability, Availability, and Maintainability in Computer-Aided Design (RAMCAD) program are also discussed. Lastly, a methodology is recommended that expands on the RAMCAD methodologies to directly tie MPT factors and requirements into the design cycle through R&M and automated Computer-Aided Design/Computer-Aided Engineering (CAD/CAE) workstation tools.

INTRODUCTION

To achieve the goals of Department of Defense (DoD) programs such as Reliability and Maintainability (R&M) 2000 and Integrated Manpower, Personnel, and Comprehensive Training and Safety (IMPACTS), the Air Force must greatly improve weapon system designs. To help in improving weapon system designs, the Air Force Human Resources Laboratory (AFHRL) embarked on the Reliability, Availability, and Maintainability in Computer-Aided Design (RAMCAD) effort in 1986. The RAMCAD effort is aimed at creating a design environment that fully supports reliability, maintainability, and supportability (RM&S) analyses through the use of Computer-Aided Design/Computer-Aided Engineering (CAD/CAE) workstations.

This paper documents how one part of the RAMCAD research performed so far can help the Air Force achieve the goals of R&M 2000 and IMPACTS. The paper is divided into five sections. The first is this introduction. The second discusses briefly the concepts of R&M and some of the R&M measures of merit (MOMs) used during design synthesis and analysis. The third section comments on the effects of R&M on manpower, personnel, and training (MPT) factors. The fourth explains some of the results of one aspect of the AFHRL RAMCAD effort and discusses how the concepts created under the RAMCAD research effort can help improve the designer's focus on R&M at all levels in the design process. The final section details how the RAMCAD work could be expanded to include MPT issues and drive a design.

RELIABILITY AND MAINTAINABILITY

Reliability

To discuss reliability, o[illegible]st first decide to focus on either the theoretical reliability or operational reliability of a system. There are some basic differences between these two concepts. For instance, when performing analysis on the theoretical reliability of a system, one starts by making certain assumptions about the operational environment of the system (e.g., weather and maintenance concepts) as well as other factors which will affect the operation of the system. Second, the failure rate of each individual piece of the system as well as how these components are integrated during the manufacturing process must be determined. These data are analyzed to determine the expected averages of various reliability MOMs for the system. However, the actual operational reliability of a system when it is fielded can be vastly different from the theoretical reliability. Changes in when, where, and how often the system is used during actual operational events can differ drastically from those assumed for the theoretical reliability analyses. These changes directly affect the actual system failure rates and cause the operational reliability to deviate from the results of the theoretical reliability analyses. There will always be differences between the theoretical and operational reliability of any system. The problem is all designers are forced to work in the theoretical reliability area, but eventually the design is evaluated against the operational reliability of the system. To help designers solve this problem, two separate things must be done. First, reliability analysis techniques and MOMs must be altered to help compensate for the errors made in the initial assumptions about any system. Part of this can be done by creating better comparability analyses. Second, the appropriate reliability analysis techniques and MOMs must be made available to designers in an easily understood format and at an early enough point in the design cycle that the results can affect the design. The research and concepts presented in this paper are a direct result of trying to solve the second area.

For the purposes of this paper, I have combined a few definitions of reliability and created the following definition for theoretical reliability. Theoretical reliability is the probability a system will perform its intended mission for a specified time interval, assuming the item is used within the conditions for which it was designed. Please note that this definition makes two basic and distinct statements. First, the reliability is based on probability and thus is a statistical calculation of how and when failures will occur. Second, these predictions are based on a set of operational conditions for which an item was designed.

There are many different MOMs used to determine the reliability of a system. The basic MOM is failure rate. It is usually denoted by the Greek letter lambda (l) in mathematical equations and is defined as the number of failures per unit of time. The two MOMs most commonly used by designers to measure reliability are Mean Time Between Failure (MTBF) and mission reliability. MTBF equals the reciprocal of the failure rate of the system, subsystem, or component being measured and is used to predict the average number of hours before a failure occurs. The mission reliability MOM is generally used at the system level and is used to measure the probability of the system successfully completing its mission based on the duration of the mission and the failure rate of the system. To ensure various reliability MOMs are [illegible] designer must be able to predict and alter how and when a system will break. This directly affects how a system must be maintained which, in turn, affects the MPT requirements of a system.

Maintainability

For this paper I have also combined a few definitions of maintainability to create what I define as a complete defination that takes into account all the important aspects of maintainability. Maintainability is the probability a system will be retained in or restored to a specified condition within a given period of time when maintenance is performed by personnel with specified skill levels, using prescribed procedures and resources. Again, my definition has two distinct requirements. First, it is based on probability and thus is a prediction that the system will be capable of being in a specified condition within a time limit. Second, the predictions are based on the maintenance personnel having requisite skills and training and that other required resources (e.g., technical orders, spare parts, test equipment) are available. Included in this concept of maintainability are the concepts of testability, accessibility, and repairability, which are the main drivers of most MPT requirements.

The most widely used measure of maintainability for designers is Mean Time To Repair (MTTR). MTTR is defined as "the average time required to perform maintenance over a specified operating period of time" [illegible]. MTTR can be used to measure both subsystem and system maintainability and can be used early in the design cycle based on predicted averages for the maintenance time of individual components. As a design matures, better estimates or actual data can be used. However, the accuracy of the [illegible] remains dependent on the accuracy of the predictions made for each component, subsystem, and system involved.

EFFECTS OF R&M ON MPT

The effects of R&M on MPT are widely documented and well known (Akpinar, 1986; [illegible], 1988; Perkin, 1986). Studies have shown that increasing the overall reliability of a system has a direct effect on reducing the total manpower required to generate a constant number of [illegible] period. Also, increasing the maintainability of a system (e.g., reducing the MTTR) will also reduce the manpower requirements of an organization. To address the personnel [illegible] of MPT, maintainability concepts such as "design for testability" have arisen [illegible] parts which has become a very important issue in design. The increased [illegible] caused many of the problems of practical importance to MPT [illegible] testability [illegible] concept of design for testability [illegible] by the technician [illegible] system diagnose its own [illegible] the technician [illegible] in repair and less [illegible] actually lower the [illegible] By lowering [illegible] technician, good [illegible] training [illegible] technician.

Properly increasing the R&M of a design to also take into account the results on MPT combines to cause an overall decrease in the life-cycle costs of the system. One study (Boyle, Plassenthal, & Weaver, 1990) showed that as either reliability was increased or troubleshooting times were decreased (or both), the overall manpower requirements of a standard squadron of 24 aircraft operating over a 30-day period would decrease. Figure 1 shows part of the results of this study under high (3.0 per day) sortie conditions. Similar but less dramatic results were demonstrated under lower sortie conditions. The range of troubleshooting times goes from a current baseline average to a complete removal of troubleshooting requirements (-100%). The baseline reliability estimate is an average of the reliability of current weapon systems while the improved reliability is based on the findings of the "High Reliability" Fighter study performed by McDonnell Aircraft Company and sponsored by Aeronautical Systems Division (McDonnell Aircraft Company , 1987).

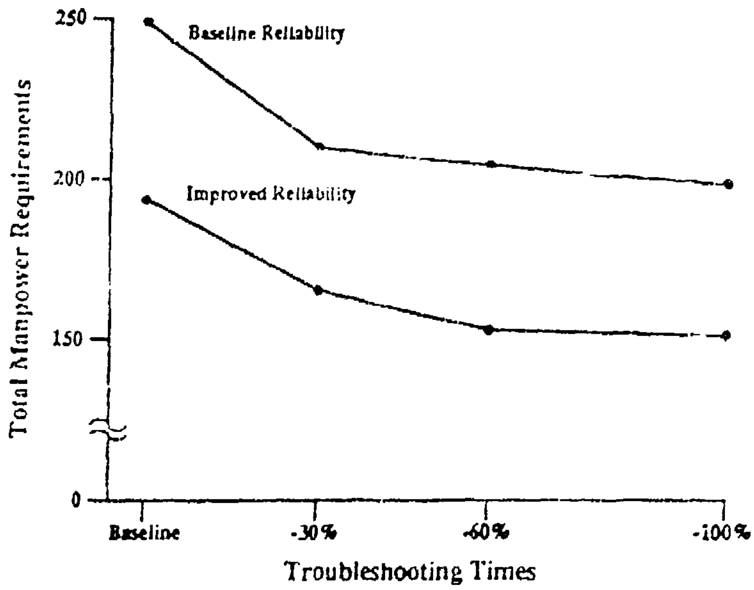

Figure 1 Effects of Reliability and Troubleshooting on Manpower Levels.

Unfortunately, increasing the reliability and maintainability of a system is not as easy as knowing what the results will be. Indeed, the increasing complexity required in today's weapon systems creates many problems that the advances attained thus far in R&M cannot offset. These circumstances make it impossible to sufficiently decrease MPT and other support requirements and still keep the systems operating at required levels.

One possible answer to this problem was mentioned in an Institute for Defense Analyses/Office of the Secretary of Defense (IDA/OSD) report (Watson and Hebenstreit, 1983).

> "...manpower technologies must be able to provide information useful in guiding system design. This capability is largely available today; it lacks only consistent and visible application in the system development and acquisition process.
>
> Developmental efforts over the last five years have added two important new dimensions to manpower technologies: (1) applicability at the 'front-end' of the system development process and (2) for rapid operation through automation."

Later in the same IDA/OSD report, the authors suggest the creation of tools that can generate a human "specification" for engineers working on new system designs. This specification would detail the number of personnel available as well as the specific skills and skill levels to which the system should be designed. It further states that this manpower component of the specification would have a direct effect on system reliability and maintainability goals.

I assert that currently there are no real MPT specifications that can be levied on a design at the detailed design level or at any other level deeper than system level through automated tools. This problem is caused by the lack of direct MOMs for MPT that can be allocated to lower levels of design. High-level MPT MOMs need to be converted into the various measures designers can understand and act upon. However, these MOMs are usually in the R&M arena. This is where programs such as RAMCAD can be helpful to the MPT world. If tools can be created that will allow the designer to build more reliable and testable systems without requiring a significant increase in the design time or cost, industry will use them and total system manpower requirements will decrease. In addition, tools that aid the designer in increasing the use of such concepts as built-in test (BIT) and built-in test equipment (BITE) will help lower the skill levels and training required for maintenance personnel.

RAMCAD RESEARCH EFFORT

History

In May 1986, AFHRL released a program research and development announcement (PRDA) requesting proposals to perform three specific tasks under the RAMCAD effort. The objective of the first task was to "develop application software and/or a translating device capable of integrating stand-alone commercially available RM&S software with CAD software" (AFHRL, 1986). The objective of the second task was to conduct long-term research in the following two areas: "(1) the improvement of the computer assisting techniques associated with RM&S analysis and (2) the development of methodologies to evaluate and validate the techniques developed under this task" (AFHRL, 1986). The objective of the third task was to "develop engineering curricula that address the use of RAMCAD in a CAD process" (AFHRL, 1986).

Twenty six companies responded to the PRDA with proposals covering one, two, or all three of the tasks. The main criterion used by the government to evaluate the proposals was the application of "new and creative solutions" (AFHRL, 1986) to the three tasks. Many interesting alternatives were in fact suggested for both the way the research should be performed under the proposed contracts and in the recommended techniques to be applied to CAD tools. Three contracts were awarded to perform research under the effort. The rest of this paper will focus on research performed by one contractor under the second task of the PRDA and how aspects of this research could help designers in estimating and controlling MPT requirements.

Describing the Design Process

With AFHRL funding, Boeing Computer Services (BCS) has been performing long-term research associated with the second task of the RAMCAD effort. The goal of this effort was to create a design methodology that would allow designers to better integrate RM&S issues and requirements into weapon system designs, implement the methodology through proof-of-concept software on a CAD workstation, and evaluate the impact on the design process caused by using the methodology.

BCS focused its attention on aiding avionic system designers of government weapon systems. Their first subtask entailed describing and analyzing the design process currently employed on avionic systems. The purpose of the subtask was to develop the information and understanding necessary to identify problems in the current design process, design methods, and associated analytical methods. This subtask was the key piece of the overall effort needed to develop the requirements that would eventually focus the methodology research through to its conclusion. To fully understand the design cycle and all of its implications, BCS began with a literature search on the subject. Much to their surprise, very little accurate information was published on the details of the design process. BCS undertook the job of creating their own description of the avionic design process from scratch using two primary sources: (a) interviews with over 30 senior engineers involved in avionics design within the Boeing corporation, and (b) reviews of DoD and Boeing design-related standards and documents. The engineers interviewed spanned all the functional specialties associated with an avionic design, including system engineering, circuit design, packaging, design assurance, manufacturing, and logistics support.

The work performed under this first subtask was a crucial step to ensuring that the methodology would be helpful to design engineers. BCS documented the results of this subtask in a report (Kitzmiller and Anderson, 1989) that not only described the design process at the proper level of detail, but allowed the researchers to determine many of the problems and inhibitors associated with the design process. The most important of these problems is that the design process and CAD/CAE tools have difficulties and impediments that inhibit the development of optimal designs. In reality most, if not all, of the designs created under the current design culture are not expected to be optimal designs but rather designs that "satisfice" (Simon, 1969) (i.e., meet the minimum requirements needed to ensure the design satisfies the design specifications). This is due in large part to the problems associated with the design process and CAD/CAE tools as they are described below as well as the profit motives associated with any development effort.

<u>Design Process</u>. The design process begins with high-level system specifications which are allocated down to lower levels. When the specifications are at a very low and detailed level, the designer creates a specific design which fulfills the allotted requirements. Unfortunately, this top-down approach is not implemented in a manner which generates direct relationships between the parameters and metrics used during each of the different design levels. This means that results of the models and analyses performed at one design level rarely can be accurately filtered down to the next level in a meaningful fashion (see Figure 2). This lack of information flow between design levels makes it almost impossible for a designer to know the relative importance of different design aspects. It is also almost impossible to ensure a design created at one level is the optimum design to fulfill the requirements of the next level up.

Due to the complexity of current designs, most design tasks are divided among many different groups and subgroups of design specialists that monitor the design with respect to their own specialty. Each group has its unique mode of design synthesis and analysis that works best for them. This forces design methodologies and tools to be very different from one group to another, and data cannot be easily transmitted between them. Much of the rationale and subtleties that cause a design to be created one way are lost in the exchange, leaving only an outline of the design data. This loss of data causes the overall rationale behind specific design decisions to disappear and allows any design changes at a later point to have hidden consequences. In addition, knowledge required to ensure a design meets all a customer's needs must come from individual experts whose time is in high demand. These experts are impossible to schedule on a single project for any length of time.

BCS broke down the knowledge required by designers and experts into four areas: (a) design principles, (b) design methodologies, (c) design knowledge, and (d) reference data (Kitzmiller & Anderson, 1989). The four areas are described below. BCS used the four-area notion to help explain some of the problems associated with the design process and to determine how their methodologies could help designers.

Design principles include concepts such as design for assembly and design for testability. These concepts can be further broken down into design rules to define the concepts. Unfortunately, to properly use the design principles requires extensive knowledge for each concept. Because designers need to keep abreast of many different design concepts, it is very difficult for them to obtain more than a cursory knowledge of any one. In reality, they often rely on peer review and technical experts to check their designs and fill in the blanks in their personal knowledge base.

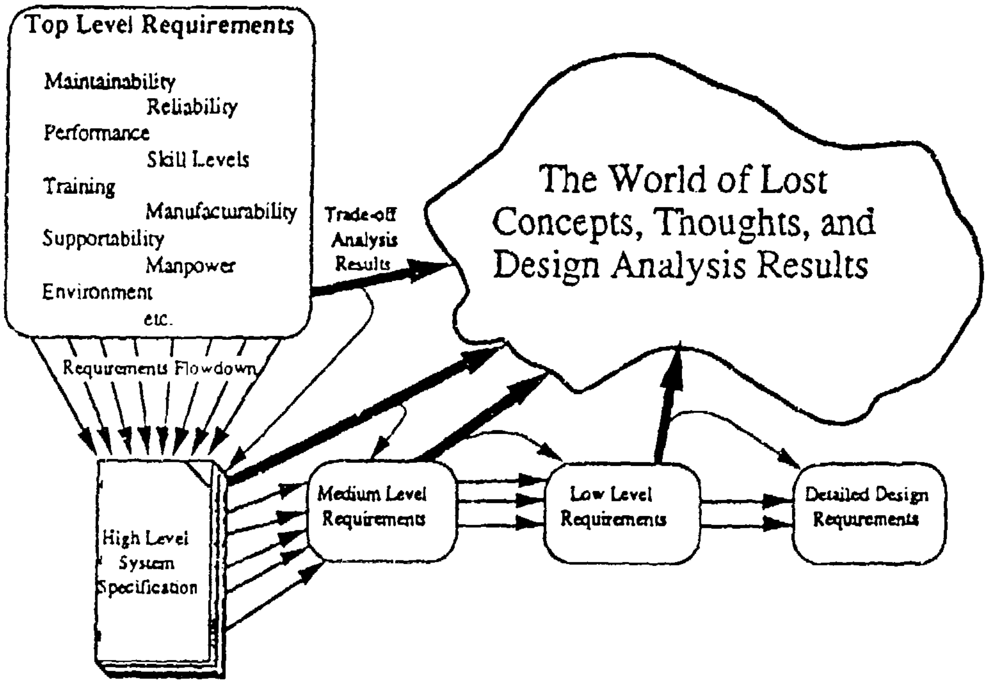

Figure 2. Current Design Requirement and Trade-off Analysis Flow.

Design methodologies can be broken down to three basic approaches: (a) synthesize; (b) simulate; and (c) test, analyze, and fix. All three approaches can produce excellent designs when implemented correctly. However, the first two methods require a great deal of upfront knowledge by the designer in many specialties for correct execution. On the other hand, the third method allows the designer to make a best guess and pass the design on to experts in different fields such as R&M, manufacturability, assembly, etc. These experts analyze the design and determine the problem areas. The designer then attempts to correct the problem areas and submits the revised design for analysis. Unfortunately, this requires many iterations and, due to time and cost considerations, is usually performed only until the design meets the most basic of the customer's requirements.

Design knowledge is that information obtained from previous design attempts and field data that allow a designer to improve a design for other than functionality considerations. Much of these data are buried in formal design notes and other program documentation as well as data bases that are not easily accessible or are incompatible with design systems.

The last area is reference data on components and design elements. These data are buried in numerous commercial and private data bases and manufacturers' reference manuals. Many of the individual sources are incomplete and a designer will often need to access many different sources to get complete data on a particular component. Usually, there is insufficient time for a designer to accomplish this for anything other than the most important components. In addition, on-line access to these data is expensive and often brings interfacing problems to the design environment.

CAD/CAE Tools. Due to the problems associated with relating different design levels to each other, there currently are no integrated CAD/CAE tools capable of addressing all phases of the design process. Indeed, there are very few tools out in today's market to aid system-level designers. Those available do not capture or analyze the relationships between the different levels of the design or help flow the design requirements to a lower level. Most of today's design tools are oriented toward helping in the final design stage and performing the analyses required by the different design experts. As a result, the tools are used more as drafting and documentation tools than as design aids, and the design process remains largely a pen- and paper-based task.

Many designers are aware CAD/CAE tools exist and can be used for design drafting and documentation. However, they are not aware of the possibilities presented by analysis tools that could be used instead of, or at least prior to, sending a design off to technical experts for assessment. This is basically the same problem identified at the beginning of the 1980s, which is that designers do not analyze their own designs. There are three main reasons why this problem exists. First, designers are not aware of the analysis tools. They do not realize what tools are available in their own companies to analyze the design before passing it on to technical experts. Second, if they do know about the tools, they usually are not trained on how to use the tools or what the results of the analyses mean. Thus, even if they ran an analysis, most designers would have to go to a technical expert to have the results interpreted into meaningful information. Last, even if designers understood the analysis outputs, they usually do not have the depth of knowledge required to find a technique to solve the problem. Again, they must go to the technical experts, or at least peers, for suggestions and implementation methods.

Methodology Research

After completing the design process research, BCS decided to create methodologies to help solve three specific design process problems. The first problem is the current inability to flow requirements and recommended design approaches down from system-level analysis to the detailed design level. The second problem is the lack of tools capable of analyzing a design both during and after design synthesis. The third problem is the requirement for designers to find and question experts about analysis results and possible solutions to the design problems found during the analyses.

To properly address these questions, BCS created a casebook of the design rules, heuristics, and guidelines required for designers to properly address the R&M aspects of a design. BCS determined and documented (Boeing Computer Services, 1989) many of the rules, heuristics, and guidelines conflicted, giving competing results. For example, adding BITE hardware to a design to improve the testability would cause a drop in the inherent reliability of the overall system. Thus, some form of expert knowledge is often required just to determine how much of a reliability or maintainability improving technique is appropriate and when the improvements start to become detrimental to the overall system.

The methodologies BCS finally created can best be described by describing the proof-of-concept software tools they created to implement the methodologies.

Statistical Testability Analyzer (STA). STA supports the flow of concept design to hardware mapping performed during preliminary system design. It supports this task through "a collection of testability related methods intended to aid a design engineer define, allocate, and evaluate the cost and effectiveness of a proposed design's test resources" (Boeing Computer Services, 1990). STA cannot recommend specific hardware or test changes to improve a design.

What it can do is provide the feedback necessary to determine the overall effectiveness of different testability techniques on different hardware types and highlight design areas which will not be adequately tested.

In addition to helping in the preliminary system design phase, STA can flow requirements down to the detailed design phase. This allows the detailed design engineer to get a clear picture of the design requirements. STA can also be used by the designer and system engineers after the design is analyzed for testability to report the differences between the predicted and the actual test coverages.

One of the strengths of the BCS tools is their integration. During the preliminary system design phase, design engineers will input data such as expected failure rates on specific hardware items (e.g., memory). During later analyses, the actual reliability analysis results are automatically fed to STA from the reliability program BCS created. This ensures that STA obtains the proper information and can highlight any missing information. It also eases the requirements on the designer to run different analysis packages and manually input the results of one analysis program into another analysis program.

Inherent Testability Analyzer (ITA). ITA is a design aid that quickly evaluates the inherent testability of a proposed design by measuring the design's controllability and observability. Controllability is the ability to set the inputs to an avionic component to known desired values. Observability is the ability to determine the output values of an avionic component and compare them to expected results. The testability of a component, subsystem, or system is directly related to these abilities. The strength of ITA over other commonly used testability tools is it is capable of and intended to be used to analyze either in-process or complete designs. The tool uses an algebra defined by BCS researchers (P-Algebra) to evaluate the overall testability of each component of a design and reports testability problem areas to the designer. This, in turn, allows the designer to correct testability problem areas during the first design iteration.

System for the Interactive Design and Analysis of Reliability (SIDECAR). SIDECAR is a design aid that evaluates the reliability of a design and recommends design enhancements. It provides an environment for the designer to perform the following analyses:

1. Estimate the failure rate, reliability, mean time to failure, and mission time of a component, subsystem, or system.
2. Estimate the resources (e.g., area, cost, power usage) required by a component, subsystem, or system.
3. Identify the components within a system or subsystem which are the main detractors from its reliability.
4. Conduct reliability enhancement studies that result in estimates of the reliability improvements and resource changes associated with a variety of reliability enhancement techniques.
5. Identify the design improvements that offer the largest payoffs in system or subsystem reliability based on designer specified resource criteria.

SIDECAR allows the designer to use a central interface to activate various reliability analysis programs. The designer uses the same interface to activate the SIDECAR advisor system, which takes the results of the reliability analyses and makes a reliability improvement recommendation. Possible recommendations include what components should be upgraded based on the component attributes available in a parts library, and what and where other reliability techniques (e.g., triple-modular redundancy) would provide the best results. Once the designer approves a recommended change, SIDECAR can perform the component upgrade or specify how and where to perform the reliability technique. SIDECAR then puts the results of the change onto the CAD/CAE screen along with any new recommendations.

CONCLUSIONS

The results obtained from the RAMCAD work are various methodologies that could, when fully implemented, help designers working at any level of the design process actually analyze a design at any point in the design process to determine how well it is meeting the design requirements. The BCS methodologies enable a designer to better address R&M while very possibly shortening the overall design time of a system. The current proof-of-concept tools demonstrate a partially integrated approach to design. Part of this integration is accomplished by allowing system-level engineers to pass some of the results obtained during system-level analyses to the detailed design engineer. They, in turn, use this information as a starting point and, through the improved design tools, attempt to create a design that meets or exceeds all the design requirements (see Figure 3). Any problems or requirements that cannot be met can be discussed with experts or passed back up the chain to the system-level engineers as shown in Figure 4. The system-level engineers determine the overall effect of the different subsystem end-factors on the total system and can tell the detailed design engineer of any possible detailed design requirement changes needed to meet the top-level requirements.

Future research in this area could focus on creating tools that more fully implement the RAMCAD methodologies. In addition, direct links could be created that reduce original MPT requirements to R&M requirements and top-level design end-factors to MPT end-factors as shown in Figures 3 and 4. Such a tool, properly constructed, could feed the results of R&M analyses from various levels in the design and from either partial or completed designs directly back through the R&M/MPT translation tool. This would form a way of analyzing a design at any time and determining how well it will meet MPT requirements. The end result of such a combination of tools is that MPT requirements would become a major driver of the design and could actually be measured by system-level engineers, not just MPT specialists.

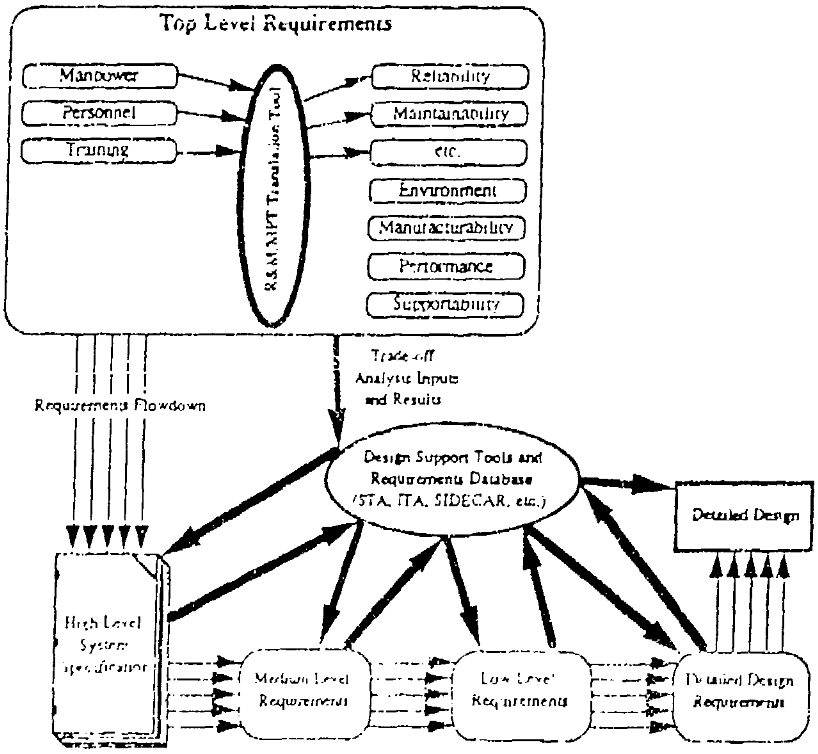

Figure 3. Future Design Requirements and Trade-off Analysis Flow.

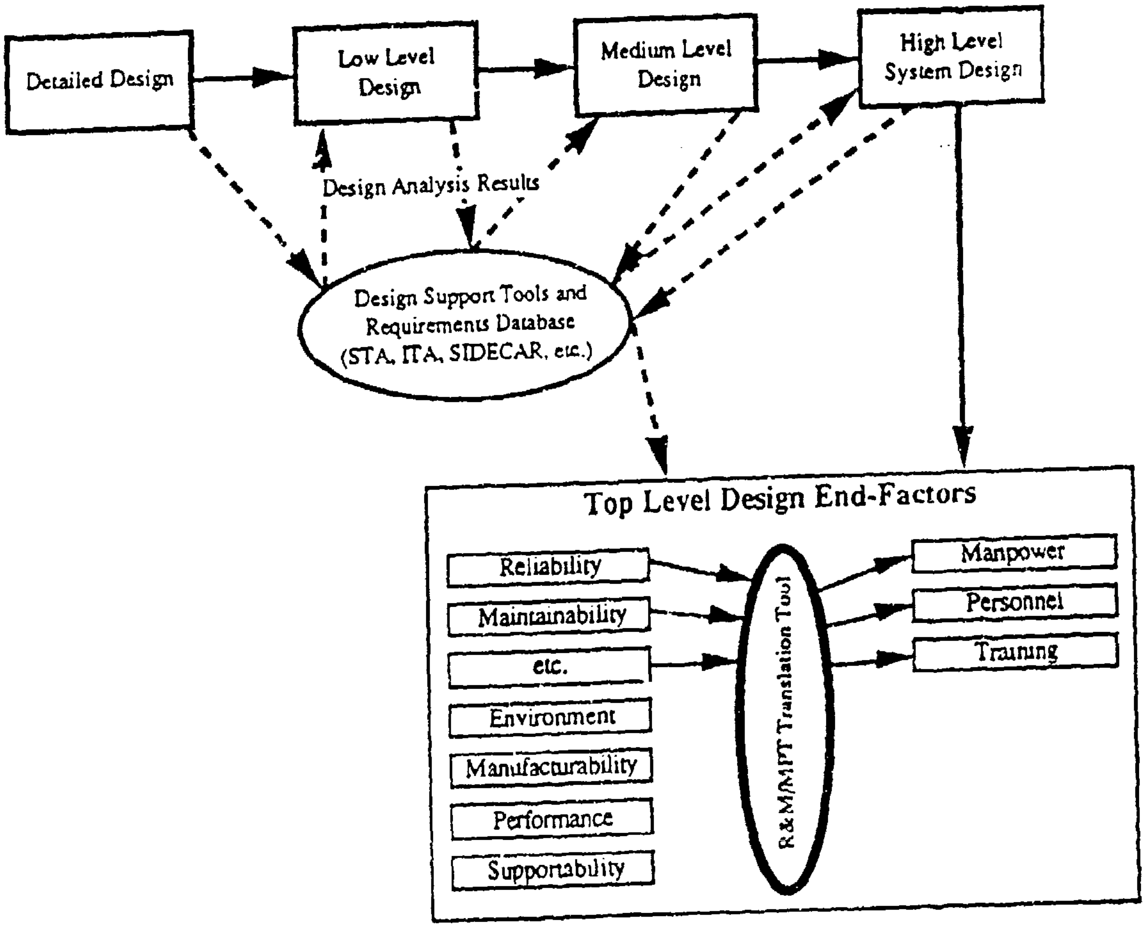

Figure 4. Future Integrated Design Flow.

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HUMAN FACTORS SIMULATION RESEARCH AT THE UNIVERSITY OF PENNSYLVANIA

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ABSTRACT

(The abstract of this paper is on the following page.)

Human Factors Simulation Research
At the University of Pennsylvania

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Abstract

Jack is a Silicon Graphics Iris 4D workstation-based system for the definition, manipulation, animation, and human factors performance analysis of simulated human figures. Built on a powerful representation for articulated figures, *Jack* offers the interactive user a simple, intuitive, and yet extremely capable interface into any 3-D articulated world. *Jack* incorporates sophisticated systems for anthropometric human figure generation, multiple limb positioning under constraints, view assessment, and strength model-based performance simulation of human figures. Geometric workplace models may be easily imported into *Jack*. Various body geometries may be used, from simple polyhedral volumes to contour-scanned real figures. Hign quality graphics of environments and clothed figures are easily obtained. Descriptions of some work in progress are also included.

1. Introduction

The Computer Graphics Research Lab at the University of Pennsylvania has been involved in the research, design, and implementation of computer graphics human figure manipulation software since the late 1970's. The history of this effort is too lengthy to detail here; rather, we wish to describe the current state of our system, called *Jack*, as of mid-1990.

The *Jack* sofware is built on Silicon Graphics Iris 4D workstations because those systems have the 3-D graphics features that greatly aid the process of interacting with highly articulated figures such as the human body. Of course, graphics capabilities themselves do not make a usable system. Our research has therefore focused on software to make the manipulation of a simulated human figure possible and even easy for a rather specific user population: human factors design engineers or ergonomics analysts involved in assessing human motor performance, fit, reach, view, and other physical tasks in a workplace environment. The software also happens to be quite usable by others, including graduate students and animators. The point, however, is that program design has tried to take into account a wide variety of physical problem oriented tasks, rather than just offer a computer graphics and animation tool for the already computer-sophisticated or skilled animator.

This orientation toward *tasks* gives *Jack* its particular flavor. As we are Computer Scientists, we seek computationally general yet efficient solutions to problems. Human factors engineers often analyze a succession of specific tasks or situations. The role we play is transforming the specific needs of the engineer or analyst into the general case so that

- at least some large percentage of situations may be successfully analyzed;
- there is sufficient research required to justify doing the software in the Computer Science environment; and
- conversely, the general problems are difficult enough to expect that a specific problem-oriented approach will be economically or technologically infeasible for a particular human factors engineer.

As we continue to interact with human factors specialists, and particularly our research sponsors, we have come to appreciate the broad range of problems they must address. The challenge to embed a reasonable set of capabilities in an integrated system has provided dramatic incentives to study issues and solutions in 3-D interaction methodologies, multiple goal positioning, visual field assessment, and strength guided motion, to name a few. Our Lab effort has involved full-time staff and dozens of students over the past few years. Many of them are mentioned in this paper. Their efforts will be noted here because such a large project must clearly involve a large number of contributors[1]. They have worked cooperatively and collaboratively on the common *Jack* framework. It must be noted, however, that the principal architect of the *Jack* system is Cary Phillips. To a great extent the "look and feel" of *Jack* (as well as the name) is due to him.

The remainder of this paper discusses the major *Jack* features, organized around the topics of body and other geometric object structures, anthropometry, user interface, positioning, animation, analyses, rendering, and external interfaces. The final section briefly outlines some of the relevant work in progress in our Lab.

2. Summary of *Jack* Features

Jack is a Silicon Graphics Iris 4D Workstation-based system for the definition, manipulation, animation, and human factors performance analysis of simulated human figures. Built on a powerful representation for articulated figures composed of joints and segments with boundary geometry, *Jack* offers the interactive user a simple, intuitive, and yet extremely powerful interface into any 3-D articulated world using only the three-button mouse, keyboard, and pop-up menus. All *Jack* software has been written in C at the University of Pennsylvania; it does not depend on any third-party software (or hardware) outside the usual Silicon Graphics Iris utilities. In this section we discuss the major features currently available in *Jack*.

2.1. Body and other geometric object structure

Bodies as well as all other geometric objects, called *figures*, are represented externally to *Jack* in a language (*Peabody*) which describes their attributes and topological connections [PHIL88]. Figures consist of segments connected by joints, each with various degrees of freedom and joint limits. Important points on each segment are termed *sites* and are used, for example, to describe the attachment locations of joints or the positions of notable landmarks. Geometric transformations called *constraints* are used to position figures in the world coordinate reference frame.

The surface geometry associated with a segment has its own local coordinate system and is typically described as a network of polygons called *psurfs*. Geometry and topology editing facilities written by Osman Niazi are supplied in *Jack* though it is not intended to be or substitute for a "real" Computer-Aided Design system. *Jack* is very comfortable obtaining its geometric data from other systems (Section 2.9).

2.1.1. Default body model

The default human figure in *Jack* consists of 34 segments and 52 degrees of freedom. The segments are:

TORSO PART(8): body root, lower torso, lumbar1, lumbar2, lumbar3, thorax1, thorax2, upper torso.

ARM PART(6 * 2): sternum, clavicle, upper arm, lower arm, hand, finger mass

LEG PART(5 * 2): hip, upper leg, lower leg, foot, toe mass

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[1] And, of course, sponsors. Please see the list in the Acknowledgments.

HEAD PART(4): neck, bottom head, eyeball(2)

There are 8 * 2 degrees of freedom from upper torso to fingers, 14 degrees of freedom from lower torso to upper torso, 10 * 2 degrees of freedom from hips to toes, and 2 degrees of freedom for the neck.

Normally the hands and feet are only minimally articulated (but see Section 2.1.6). There are five segments in the torso, yielding reasonable flexibility and appearance without sacrificing shaded drawing speed and interactive response. A full spine and torso model is available (Section 2.1.8).

2.1.2. User-specifiable topological structures

The body structure is not built into *Jack*; rather, the default body is there for user convenience. Any topological structure can be defined through *Peabody* and manipulated in *Jack*. In particular, this allows the use of figure models with greater or lesser articulation, as well as mechanisms, robots, insects, and so on. We frequently use a simpler human figure model or even a Puma robot model for testing purposes. More detailed spine, hand and finger models can be substituted for the simpler segments and used in any combination desired.

The joints that connect figure segments typically have up to three rotational degrees of freedom (translational degrees of freedom are allowed but are not used in the human models). Joint centers are described in terms of sites on the connected segments. While real human joints are not so simple, this model suffices for most ergonomic analyses. For a brief discussion of our efforts addressing more flexibility in joint action, see Section 3.6.

2.1.3. Independent surface geometry per segment

For interactive manipulation, detailed human figure surface geometry is usually unnecessary, however, the *psurfs* associated with each segment may be as simple or complex as desired. The default human model has a rather polyhedral appearance to keep the number of polygons low for graphical display update efficiency. The more accurate figures (the contour bodies, Section 2.1.7) may have hundreds of polygons per segment to give a smoother and more rounded appearance. The selections can be mixed from segment to segment: for example, a smoother head model with simple arms.

2.1.4. Other body models

Since the topology and geometry of figures are completely accessible, building any other existing body in *Peabody* and *psurfs* should be a rather simple matter. Transforming the segment topology is straightforward, and most geometry formats are readily converted into *psurfs*. Perhaps the most effort would be involved in establishing commensurate sites on each segment for the joint connections. For example, we are presently converting the Crew Chief model [EAST90] into a *Jack*-compatible figure.

2.1.5. Surface "clothing"

Clothing a figure is important for ergonomic analyses since clothing often affects mobility and joint limits. *Jack* presently contains three types of clothing:

1. A rather simple kind, implemented by Jiahe Lu, which is simply a color differentiation for various segments (e.g. brown legs and lower torso yield "pants," blue upper torso and arms, a long-sleeved "shirt," etc.);
2. A more realistic "thick" clothing, implemented by Eunyoung Koh, which is the actual expansion of the segment geometry (hence its diameter) relative to the segment axis while still preserving the overall shape;
3. Additional equipment (such as helmets, tool belts, pockets, air supplies, etc.) attached or worn by simply adding appropriate geometric models to segments.

All three improve graphics appearance. The second and third approach are the more serious since thick clothing and equipment should affect joint limits. This contextual modification of body capabilities is currently under development (Section 3.6). The attachment of loose fitting or draped clothing is another matter entirely and is not addressed here.

2.1.6. Hand model

Jack contains a simple geometric hand model, constructed by Wallace Ching, with fully articulated and joint limited fingers and thumb. The more interesting feature, however, is an automatic grip. Given a geometric object that is to be grasped, the user can specify one of three types of grips -- power, precision, or disk [IBER87] -- and *Jack* will move the hand to the object then move the fingers and hand into a reasonable grip position. The actual grip is completed by using real-time collision detection on the object's geometry to determine when finger motion should cease.

2.1.7. Biostereometric contour bodies

One of the most interesting body databases in *Jack* is derived from biostereometric (photographically) scanned body surface data of 76 subjects. Originally supplied by Kathleen Robinette of the U.S. Air Force Armstrong Aerospace Medical Research Laboratory, the data consists of approximately 6000 data points for each subject, organized by body segment and arranged in parallel slices. Marc Grosso, Jeff Weinberg, and Pei-Hwa Ho determined reasonable joint centers from the segment contours and surface landmark data, converted the segment topology into *Peabody* structures, and tiled the contours into polyhedral meshes [FUCHS77].

The major difficulty with the contour data is that it looks very realistic in the standard posture, but immediately developes annoying gaps when the joints are moved. Eunyoung Koh recently remedied this in a general fashion that extends as well to the clothing defined by the segment expansion method. Given two adjacent segment geometries, a procedure generates a curved surface to fill in a plausible solid connection between them depending on the joint angle and the respective tangets to the segments. This procedure fills the "gaps" between the scanned segment geometries and, by extension, the clothing defined over them.

The single torso segment in the original scanned body data was rigid. In Section 2.1.8 we describe how we dramatically improved that situation.

2.1.8. 17 segment flexible torso with vertebral limits

The lack of accurate flexibility in the torso is a notable weakness of most anthropometric models. Indeed, the default *Jack* figure and even the biostereometric bodies suffered from torso rigidity. Recently, Gary Monheit has constructed a 17 segment vertebral column (from lumbar to thoracic) whose movements are dictated by kinematic limits and some simple parameters [MONH90][2]. The torso, in turn, is broken into 17 corresponding "fat" slices, one for each vertebra. With this arrangement it is easy to have the contour body "breathe" and bend in a very realistic fashion. Movements of the torso are basically described by lateral, saggital, and axial rotations of the neck. The flexible spine shape is history-dependent, that is, the motion of each vertebra in space is not determined solely by these rotations: other parameters such as motion-resisting joints, and the motion-originating joint affect its actual path.

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[2] Previous modeling and simulation by Willmert [WILL82] apparently failed to adequately account for the joint relationships between vertebrae, especially in the neck. Numerical error also appeared to cause trouble. These problems do not plague the *Jack* torso model

2.1.9. Facial model

Humans have faces, and *Jack* provides two mechanisms for presenting a face on a human figure.

- A photograph of a [real] face may be texture mapped onto a contour body head. The figure bears a close resemblance to a real person and the resulting image looks reasonable even when rotated. The disadvantages are the rather delicate (for correct) positioning of the texture on the head and the requirement of ray-tracing to see the face[3]. Welton Becket and Dawn Vigliotti have provided this feature.
- A polyhedral model of a generic face may be used on a special head *psurf*. The advantages are that the polygons are displayed directly and, most importantly, the facial features are *animated* [PELA90]. While not important (perhaps) for human factors work, the expressions certainly enliven finished animations. The original facial data was supplied by Steve Platt [PLAT85] and extensively modified by Catherine Pelachaud, Soetjianto, and Khairol Yussof.

2.2. Anthropometry

Having a body model is one thing; being able to easily make it correspond to human size variation is another. Anthropometric scaling of body models is an important component of *Jack* [GROS89a].

2.2.1. Segment and joint attributes

The human figures used in *Jack* have various attributes associated with them that are used during manipulation and task analysis. The current set includes segment dimensions, joint limits, moment of inertia, mass, center of mass, and joint strength [GROS89b]. Segment dimensions are used to scale the segment geometry for proper sizing. Joint limits are used to restrict motion. Mass, center of mass and moments of inertia are used during dynamic simulations. The strength data is used for certain reach and lifting tasks. Raw anthropometric measurements (e.g. for specific landmarks or composite measurements such as "sitting height") can also be associated with an individual in the database.

The strength data may be based on tabular (empirical) data or strength prediction formulas [WEI90]. Strength parameters may be either scaling (e.g. gender, handedness) or non-scaling (e.g. depending on the population). In any case the user may alter the stored data or formulas to conform to whatever model is desired.

2.2.2. Population percentiles or individuals

Either population statistics may be used to provide percentile data, or else an actual database of [real] individuals may be used. The former, e.g., is common in U.S. Army analyses, while the latter is often used by NASA for the specific individuals in the astronaut trainee pool.

2.2.3. Spreadsheet interface for selection, changes, or database query

The interface to the anthropometry database is through *SASS*: the Spreadsheet Anthropometric Scaling System [GROS89b]. As part of *Jack* it offers flexible access to all the body attributes and a simple mechanism for changes. Specific body models may be selected or customized as needed. Queries about the contents of the anthropometric database are constructed entirely from pop-up menus without requiring user knowledge of a particular database query language. For example, the query

> "Find all females under the 25th percentile in stature who have left elbow strength greater than 15 ft-lbs."

is constructed by direct menu selection of each field, relation, and value. Individuals satisfying arbitrary requirements may be listed and selected for creation and display. *Peabody* model files are created by

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[3] Although more expensive display hardware can do the texture mapping in real-time.

SASS and made available to *Jack*. Alternatively, one can interactively manipulate the current body in *SASS* while displaying it in *Jack* to rapidly try out the effect of varying the individual, population percentile, gender, joint limits, etc.

2.2.4. Concurrent display of interactively selected dimensions

As noted above, a human figure may be modified by *SASS* while it is being displayed in *Jack*. In fact, the process is much more powerful than just updating a display. In Section 2.5.4 we will see that a figure may be subject to arbitrary goals for one or more of its joints. These goals are maintained (subject to joint limits and body integrity) during interactive manipulation. The process also applies to segment attribute changes done interactively in *SASS*: as the segment lengths change, e.g., the body will move to maintain the required position, orientation, or viewing constraints. It is therefore very easy to assess posture and viewing changes (as well as success or failure) across population percentiles or gender.

2.2.5. On-screen interactive strength data display

Besides the numeric listing of strength data, a graphical display feature is available. Interactive displays of joint torque or end-effector forces may be shown in *Jack* as the user manipulates the figure directly [WEI90]. Current as well as cumulative maximum forces or torques are displayed as moving bars in a *strength box* whose axes correspond to the joint's degrees of freedom. Individual, gender differentiated, and population percentile (95th, 50th, and 5th) strengths may be compactly and comparatively displayed.

Torques along a joint chain may be shown, too. Given a force on an end-effector, *Jack* can compute the reaction forces generated anywhere else in the body. Since the body is an active mechanism, forces may be resisted in differing amounts by activating different muscle groups. Phil Lee and Susanna Wei have implemented displays that show, given a weight held by an end-effector, the reaction forces (torques) at each joint degree of freedom along a given chain [WEI90]. In addition, a trace of the "safe" and "unsafe" regions (relative to the current strength model) is left in the display as the end-effector is moved about, producing a direct and real-time visualization of the accessible space.

2.3. Body somatotypes

Pei-Hwa Ho has examined the original biostereometric contour body dataset to select specimens covering the approximate midpoint and extremes of body somatotype for each of the 5th, 50th, and 95th percentile males and females: 18 body "styles" in all. This set is integrated into *SASS* with a new attribute for somatotype. The user can select a gender, somatotype, and percentile, causing one of the 18 prototype bodies to be scaled to the individual segment dimensions. The figures retain significant realism in form while providing infinite variability across all shape dimensions.

2.3.1. Multiple figures

Jack allows the manipulation and display of as many figures as desired up to the memory limits of the hardware. There are no restrictions whatsoever on the geometry, topology, or anthropometry used across the several figures.

2.4. User Interface

One of the the most attractive features of *Jack* is the natural user interface into the three-dimensional world [PHIL88]. A significant part of the interface is offered by the hardware capabilities of the Silicon Graphics Iris 4D workstation platform upon which *Jack* is built. The software, however, makes this hardware power controllable

2.4.1. Three button mouse and keyboard

Jack relies solely on the standard Iris 4D three button mouse and keyboard for interaction. The mouse is used to perform direct manipulation on the 3-D scene, e.g. selecting objects by picking their images, translating objects by holding down one or two mouse buttons corresponding to spatial coordinates, etc. The mouse is also actively used to negotiate through the pop-up command menus.

The keyboard is used for occasional command entry. The escape and control keys are used as meta-mouse buttons, e.g. to change the button interpretations from translation to rotation, or the affected coordinate frame from global to local.

2.4.2. Menu-driven commands

The command menus are built from the standard Iris menu library. There is a tradeoff in making all the commands accessed this way: simplicity and an uncluttered screen are advantages, while on the other hand frequently used commands are treated the same as infrequently used ones.

2.4.3. Command completion

To alleviate the menu bottleneck, any *Jack* command maybe entered via the keyboard. To save typing, and to act as a simple help system, command completion shows the choices for any partially-entered command.

2.4.4. Natural 3-D interactive interface

The naturalness of the interface arises from the coherence of hand motions with the mouse and the correspondence between mouse cursor motion on the 2-D screen, a 3-D cursor (looking like a "jack") in the world, and 3-D objects displayed there. In particular, translations and rotations are selected with the mouse buttons (and perhaps a key), and the mouse motion is transformed into an appropriate 3-D cursor movement. Rotations display a wheel perpendicular to the selected axis; motion of the mouse cursor about the wheel display invokes a 3-D rotation about the actual axis. Any joint limits are respected.

Object selection is done by simply placing the mouse cursor over the desired part. If more than one object lies under the cursor, a button push cycles among the possibilities which are highlighted in turn.

Other motions that are easy to perform in *Jack* include real-time end-effector dragging (Section 2.5.5). The position and orientation of the end-effector is controlled by the same mouse and button interpretation method.

2.4.5. Multiple windows

Jack supports multiple independent windows into the current environment. Thus, e.g. one could be a global view, one could be a view from a figure's eye, another could be a view from a certain light source (to see what is being illuminated), etc. The camera and lights are represented as *psurfs* so that they may be positioned and observed just as any other object in the scene. Of course, as the camera is moved in one view, the corresponding camera view window shows the changing image. The same result obtains if a window view is attached to a figure's eye (or hand, etc.).

2.4.6. Perspective or orthographic views

The view in a window may be either perspective or orthographic. The latter is most useful when dimensions are important. In perspective, the three orthographic projections may be optionally displayed within the same window as wireframe "shadow" images on the imaginary walls and floor. These greatly assist in object and goal positioning.

2.4.7. Feature on/off toggles

There are a number of display features which may be turned on or off at will. These include the orthographic projections, a ground plane, shaded or wireframe mode, background star field, motion traces, and so on.

2.4.8. Command language files

Any *Jack* scene can be written out as an environment file; when read in it restores the exact situation for continued manipulation. Even more useful is the *Jack command language* or *jcl* file. This is a record of the *Jack* commands issued during a selected portion of an interactive (or program-controlled) session. The *jcl* files may be recursive in the sense that they may contain commands to read and execute other *jcl* files. Such files also provide a command format for external (non-interactive) control of *Jack*, e.g. from an animation procedure.

2.5. Positioning

The manipulation power in *Jack* comes from novel real-time articulated figure positioning algorithms. These embue the jointed figure with "behavioral intelligence"; that is, the ability to respond to varied positioning *goals* as well as to direct joint rotation.

2.5.1. Joint degrees of freedom

Joint angles may be manipulated directly to position a figure. During rotation, a rotation wheel will appear only for allowed degrees of freedom.

2.5.2. Rotations subject to joint limits

During rotation, the displayed wheel will follow the cursor, but the joint will only be allowed to rotate to the joint limits. For two and three degree of freedom joints, the joint limits are tested in the individual rotation directions. This is not totally correct, especially for a complex joint such as the human shoulder, but it suffices for most purposes. Adding more accurate joint limits is possible in the future (Section 3.6).

2.5.3. End-effector position and orientation goals

One of the most powerful features of *Jack* is the positioning of a joint by specifying the other end of the kinematic chain (e.g. the shoulder or the waist for a hand movement), and giving the end-effector an arbitrary position or orientation goal (or both) in space. Using a real-time inverse kinematics procedure based on nonlinear optimization (with linear constraints) written by Jianmin Zhao, a joint space solution (subject to joint limits) is computed for the intermediate joints along the chain [PHIL90, ZHAO89]. The solution moves the selected joint (end-effector) to the goal if it is reachable, otherwise it moves as close as feasible given the figure posture, the joint chain, and the joint limits. Any failure distance is reported numerically as well. This movement does not represent how a person would actually move, nor does it attempt to find the "best" or most "natural" position. It merely achieves goals. For better postures, additional goals can be created and maintained (Section 2.5.4).

There are several goal types available:

- position (a point in space)
- orientation (e.g., a particular orientation of the proximal segment coordinate space)
- position and orientation (weighted to arbitrate conflicts: e.g. a position may be achievable only by violating the orientation goal or *vice versa*, so the weight determines which to favor)
- aim (a specified direction on the proximal segment should point at the desired point; this is frequently used for eye and camera positioning)

- view (a specified direction; like "aim" except that twist is not allowed so the camera or eye view will not rotate (roll) along its sighting axis)
- line (a position anywhere along the line is acceptable)
- plane (a position anywhere in the plane is acceptable)
- half-space (a position anywhere in the half-space volume is acceptable)

In order to distribute intermediate joint motions more realistically, a stiffness parameter can be set for each joint degree of freedom if desired, or for the chain as a whole. The stiffness forces motion to be favored or resisted more in a degree of freedom, e.g. to encourage torso bending rather than twisting. Over a chain, the stiffness may favor motion at the proximal or at the distal end.

Inverse kinematics executes in "real-time," meaning that most positioning actions are accomplished in time that is not much different than that required by a real person.

2.5.4. Multiple simultaneous position and orientation goals

The goal satisfaction procedure has the additional advantage of operating on multiple simultaneous goals of any of the above types. For example, a figure can be seated by supplying goals for the feet (to stay on the floor), the center hip (to be near and just above the chair seat), the knees (to stay in front of the hips) and the neck (to stay above the waist). Some of these goals may be plane goals (such as for the feet) or half-plane goals (to keep the waist above the seat and in front of the chair back). As usual, joint limits are respected and the best solution (though it may be a local rather than global minimum) satisfying the goals is displayed. If the goals are not entirely satisfiable, some minimum distance solution will be offered. If the results are not acceptable, more goals may be added. This algorithm still runs in real time for modest numbers of goals; it is superlinear convergent with each iteration of complexity of just $O(nm)$ where n is the number of degrees of freedom and m is the number of goals. A sample posture to move the figure's head over the end of a large upright tube, aim the view to see the bottom of the tube, and grasp the tube with two hands at opposite sides while keeping the elbows out in a plane parallel to the tube axis took only 23 seconds to solve on a Personal Iris workstation.

2.5.5. Real-time end-effector dragging

Since inverse kinematics is available, and since multiple goals may be active, *Jack* allows a joint to be moved interactively by attaching a position or orientation goal to the 3-D cursor controlled by the mouse [PHIL90]. The solution time is actually reduced because the current posture is likely to be close to the solution at the next input position, so the algorithm converges quickly. To avoid waiting for the solution, however, *Jack* updates the joint angles at every graphics window update by taking the solution obtained thus far. As the goal is moved or rotated, the posture changes as quickly as possible and "catches up" with the user whenever there is a significant pause in cursor motion.

2.5.6. Rotation propagation when joint limits are exceeded

A consequence of joint limits and inverse kinematics is an apparent "behavioral intellegence" in the manipulated figure. If the wrist is twisted, the rotations propagate along the arm toward the fixed end as joint limits are encountered. Thus the user can freely move the joints about and the remainder of the body will act in a reasonable fashion.

2.5.7. Constrain center of mass of entire figure

Cary Phillips developed an interesting application of the multiple goal solution algorithm by constraining the center of mass of a figure. The center of mass is not a specific joint or point of the body, rather it is a computed quantity. Nonetheless, *Jack* permits it to be a participant in a goal. By constraining the center of mass to lie along a line goal above the figure's support polygon, a *balanced* *reach* may be effected. The motion is most dramatic when only one foot is constrained to the floor; moving a hand causes the other leg to lift off the floor for counterbalance when it is needed![4]

2.6. Animation

The manipulations in *Jack* discussed so far are not really "animations" as we have already mentioned. For an animation we expect some coherence and smoothness to the figure's motion; it is not enough to merely animate a numerical search so matter how clever or effective it is. *Jack* incorporates a number of mechanisms to produce human-like motion.

2.6.1. Key parameter specification and rational spline interpolation

The simplest method of animation is based on the specification of a series of postures and the subsequent interpolation of the joint angles to create a smooth sequence of "in-between" postures. The important postures are called "keys"; the joint angles from key to key are parameterized by time (given for each key) and interpolated to compute values at any other time. A textual interface written by Jean Griffin helps in the creation and editing of the script keys and times. Jianmin Zhao implemented a method of interpolation and motion control using rational spline curves in a fashion similar to that described in [STEK85].

While capable of creating effective motion sequences, key parameter approaches put the burden of motion design on the user/animator, requiring skill and patience to define the key postures. There are alternatives, but each with advantages and disadvantages. *Jack* includes a useful selection, as we explain below.

2.6.2. Forward dynamics

One method of creating accurate and realistic motion is to use the physics of forces and torques to drive a figure (e.g. [ARMS87, WILH87]). The results are physically correct, but the problem is in determining the proper directions, magnitudes, and timings of the forces. Most people (or animators) cannot do that. Moreover, the motions tend to work best on passive figures (when they are under the control of external forces, e.g. falling, dangling, crashing) rather than on active ones (when the person is trying to perform some task, e.g. reaching, lifting, throwing).

For completeness, *Jack* offers motion control by force and torque specification using forward dynamics to compute joint positions and orientations. This procedure is being built by Mike Edwards.

2.6.3. Strength guided motion

A rather more useful, but more restricted, animation method developed by Phil Lee uses the inherent strength model stored for a human figure as the basis for computing certain types of motion. If the task involves moving a weight rather slowly to some goal position, then a *strength guided motion* algorithm computes a motion path based on the strength model and two additional parameters [LEE90]. The parameters are the comfort level at which the motion should be performed and the allowed deviation from a straight-line path to the goal. Using a number of strategies based on the available torque at each joint in an arm (plus upper torso) joint chain, the algorithm computes an acceptable posture at every instant (say, 15 times a second) of the action. Strategies include moment reduction, pull back, adding joints, and recoil to bring comfort to acceptable levels. Present limitations are two-dimensional paths, upper body chains, and inverse kinematics incremental positioning rather than a more realistic dynamical

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[4] I am personally very fond of the "worm on a fishhook" example: A linear chain of segments (the worm) is attached at one end to a point in space (the hook) and allowed to dangle below. As the free end of the worm is dragged about, the segments wiggle and contort to maintain the center or mass along a line goal below the hook. Very dramatic.

rate-control process (Sections 3.3 and 3.4). A useful range of lifting and reaching motions may be produced already, however, including weight lifting, rising from a chair, pulling the body upwards in a chin-up, and two-person coordinated lifting.

2.6.4. Hand grip

Using the real-time collision detection capabilities in *Jack* (Section 2.7.5) a hand may be made to grip any object. (Section 2.1.6 already mentioned this.) The motion is an animation in the sense that the fingers are moved until they contact the object. The grip is fake, though, as the object is merely attached via a constraint (in the *Peabody* sense) so that it moves in concert with the hand.

2.6.5. External control

Cary Phillips and Jeff Esakov coded the beginnings of a very powerful animation mechanism in *Jack*. By attaching a joint angle or some other parameter such as arm length or object size to a Unix *socket*, external processes can be used to control their values. The process can reside anywhere on the Ethernet attached to the host workstation, including the host itself. The process can be another user, an autonomous procedure, a physical sensor, or a simulation. Thus a gauge needle's rotation can be controlled by an external simulation, a joint angle could be read from a goniometer on an actual subject, or an object's location could be controlled by another user interacting in the same space[5].

2.7. Analyses

All the *Jack* features are available to compute certain aspects of some of the most commonly performed task analyses.

2.7.1. Reach space

Jack can display a trace of any site; in particular, it can show the path of an end-effector as it is manipulated. The resulting trace gives a good idea of the reachable space as the end-effector is dragged about. Any joint chain can be used due to the general inverse kinematics solution. Other algorithms being studied by Tarek Alameldin can compute the reachable space boundary or volume off-line [ALAM90].

2.7.2. Eye view

We have already seen that *Jack* can show the view from any object, in particular, a figure's eye. Besides the normal perspective view, a simplified retinal projection window may be drawn. Objects in front of the eye are mapped into a (radius, angle) polar plot. When features such as foveal or peripheral areas are drawn in the retinal window, the relative visibility of scene features may be assessed[6].

2.7.3. Translucent view cones

In addition to the retinal window, translucent view "cones" may be displayed from the eyes of a human figure. With the apex at the eye lens center, the shape of the cones follows any desired polygonal path, e.g. foveal area. By aiming the eyes with an interactive goal, the view cones follow the point of interest, converging or diverging as needed (subject to eye "joint" limits). Since the cones are translucent, workplace objects show though, giving the user a good impression of what can and cannot be seen by the subject.

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[5] Sometimes called *Virtual Environments* or *Virtual Reality*, e.g. [BLAN90].

[6] Much of the useful effort in this analysis mode was accomplished by a collaboration between Cary Phillips of our lab, Aries Arditi of The Lighthouse in New York, and Mike Prevost of the NASA Ames A^{3}I project.

2.7.4. Torque load and comfort during reach

Since the strength guided motion computes the instantaneous joint torques in the current (changing) body posture, this information is available for display. During such actions, moving bar charts can show the level of comfort, physical work, or fatigue.

2.7.5. Real-time object-object collision detection

In collaboration with the GRASP (General Robotics and Active Sensory Perception) Lab in our department, a real-time collision detection facility[7] was added to *Jack*. For efficiency, only a pair of selected objects are checked in real-time. The general problem is very costly (time-consuming) in complex, changing environments. Given that the user is normally in control of the simulated figure's motion, the limitation to checking, say, a lower arm against another object is useful but clearly sub-optimal. As we have mentioned, it is used to accomplish the hand grip in *Jack*.

2.7.6. Interactive body sizing under active constraints

We have already mentioned in Section 2.2.4 that changes to bodies made in *SASS* would maintain (as well as possible) any active constraints. Thus testing workplace reaches over any population range is nearly trivial: e.g. constrain the feet or lower body, set the reach goal for the desired end-effector, and alter the percentile field of the appropriate *SASS* spreadsheet display. In another situation, suppose the eye is constrained to the design eye point of a cockpit, the hands and feet are positioned to appropriate goals, and the shoulders and hips are restrained by point goals representing a suitable restraint system. Then running through the percentiles with reach goals for the hands, feet, and hips will show how well or how poorly the population can carry out that task.

2.7.7. Hooks to AI-based simulation system and Knowledge Base

The ultimate analysis tool is a simulation which executes some task and drives the human figure with a set of goals and timings. We are actively working in this area. Jeff Esakov is building a system, called *YAPS*, which is basically an object-oriented discrete event simulator running over a Knowledge Base [ESAK89, ESAK90]. Jugal Kalita has constructed verb semantics describing generic methods for achieving certain goals [KALI90]. Presently the lexicon of executable tasks includes computational definitions for *open, close, push, pull, put, place, slide, reach*, and *look-at*, as well as a few spatial prepositions and adverbial modifiers. A temporal planner organizes the goals in a reasonable order [BADL88, ESAK90]. A human performance rate predictor based on Fitts' Law (if appropriate) [FITT54] is used to postulate reasonable task durations for reach and viewing actions [ESAK89]. At the highest level, simple natural language task commands are accepted and animated [KALI90, BADL90]. The *YAPS* sysem supports some simple task planning and task interruption capabilities.

The *YAPS* simulation and Knowledge Base are written in CommonLisp. *YAPS* drives *Jack* figures through the UNIX socket interface. Our *YAPS* simulation is migrating from a Hewlett-Packard workstation implementation onto the Iris. At NASA Ames, the *MIDAS* simulator performs a similar function, communicating parameters over the network and driving the *Jack* figure as a helicopter pilot mannequin.

2.8. Rendering

Besides the hardware rendering available for polyhedral models on the Iris workstation, the *Jack* system includes a sophisticated ray-tracer written by Welton Becket. Its capabilities include anti-aliasing, textures, specularity, translucency, reflections, shadows, multiple light sources, material properties, and

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[7] Thanks to Janez Funda, who needed it for a telerobotic application.

chromatic aberrations. It successfully rendered hundreds of images for a movie containing over 45,000 polygons at an average rate of about 4 images per 45 minutes an Iris 4D/240.

2.9. External Interfaces

Jack can obtain geometric information from several commercial systems. This list grows as sponsors require *Jack* to handle data from diverse CAD systems.

- Wavefront Technologies (Preview and Model format; interface written by John Granieri)
- Pixar Rendennan (For image output)[8]
- SDRC I-DEAS (Universal file format; interface written by Cary Phillips)
- MultiGen (A polygon modeler; interface written by Cary Phillips)
- BRL-CAD (The Constructive Solid Geometry objects are polygonalized through code written by Osman Niazi; the Boolean operations are applied to these polygonalized objects in *Jack* based on an algorithm from Brown University [LAID86])
- Utah Raster toolkit RLE image files (Used for image manipulation)

There are some animation hardware and hardcopy capabilities supported in the *Jack* environment:

- Interface to Abekas A60 digital image store (written by Joe Procopio)
- Interface to Lyon-Lamb animation controller
- Hardcopy image output via Tektronix 4693 (RGB format) and Apple laserwriter (via Postscript)

3. Work in Progress

Jack is an evolving system with continual enhancements motivated by our desire to achieve certain graphic and animation goals as well as provide ever more powerful and usable human performance understanding and modeling. The following sections outline some of the enhancements in progress or scheduled for the near future.

3.1. Additional strength data

The present strength data for the arms must be augmented by similar data for the upper torso. Hand (grip) strength would also be a useful addition. The strength data we use is for isometric exertion and does not necessarily reflect proper values for strength during motion. There are many issues surrounding the validity of strength data. We prefer that the user supply an acceptable strength model simply because ours is probably not very good. *SASS*, however, makes changing the strength prediction functions or adding new tabular empirical data rather straightforward.

3.2. Fatigue model

During strength guided motion, *Jack* can compute a measure of the work or energy expenditure per unit time. This should be expressible as a muscle group load and hence generate some specific strength loss due to fatigue. Phil Lee is incorporating a reasonable fatigue model into *Jack* so that strength changes can dynamically affect movement (or the mere holding) of a weight.

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[8] In progress.

3.3. General force trajectory

The limits to strength guided motion must be relaxed. One is to extend the algorithm to 3-D motions. Fortunately, most movements are planar (at least over short distances [MORA86], so this does not appear to be a major difficulty. Somewhat more important is having a satisfactory strength model. The ability of *SASS* to interpolate strength values is critical to success here.

3.4. Dynamics rate-control during strength reach

Strength guided motion uses inverse kinematics to do the incremental positioning of the end-effector. A more accurate model is being developed by Phil Lee and Wallace Ching that uses a dynamics approach to insure that end-effector motion does not exceed realistic and consistent accelerations. There will be interesting interactions between the concurrent needs to reach the goal, sustain coherent muscle group [strength] activity, monitor comfort levels, and manage fatigue.

3.5. Walk procedure

The motions of the figure often appear stilted as it is unable to locomote other than by floating or sliding. Bill Kriebel is implementing a walk procedure based on Bruderlin and Calvert's model [BRUD89]. A reach task involving the entire body will then use locomotion to bring the end-effector within a suitable distance of the goal. (A definition of "suitable" must be determined.) Concomitant problems include path planning and collision avoidance if obstacles are present. A preliminary *Jack*-compatible spatial path planner written by Chris Yu based on the algorithm by Lozano-Perez [LOZA79] is available for experiments.

3.6. Dependent joints

The original *Peabody* and *psurf* structure, while robust, must be enhanced to permit groups of joints to work together as a unit. The idea is that these joint dependencies provide for more natural motion and easier control. The 17 segment spine and torso is a good example of the kind of dependency that is required. Other examples include clavicle motion as a function of shoulder position [OTAN89, BADL89] and head motion dictated by eye direction [SPAR89]. Jianmin Zhao and Cary Phillips are working out the changes in *Jack* needed to incorporate such structures.

Related problems include complex shoulder joint limits based on the shoulder position rather than just the geometrically required three [independent] degrees of freedom. This assumes even greater importance when dealing with the computation of joint limits based on clothing. It may not be possible to pre-compute the limits; rather, they may have to be detected as a certain tolerable level of intersection (collision) between adjacent segments and their attached geometry. In this case, joint motion is determined by segment compressability[9].

3.7. Anthropometry updates

Jiahe Lu is considering a significant set of changes to *SASS*. These include a corrected implementation of segment percentiles within a population, more appropriate segment scaling relative to the given population, stature adjustments when certain individual segment dimensions are changed, and global (cross-attribute) effects such as mass changes when sizes are changed.

Additional populations are also being examined for conversion into *SASS* format, especially the

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[9] The converse problem is somewhat easier; e.g. see [GOUR89, THAL90, CHAD89] for segment deformation given joint angles. The finite element approach may be viable for our version of the problem as well.

recent U. S. Army soldier data.

An attractive idea for training applications is to read the user's own anthropometry from a login file, and use his or her body description as the default scaling for the *Jack* figure. Tasks being performed would then be sympathetic to the user's own capabilities.

3.8. Clothing experiments

Joe Procopio is trying some simplified methods for defining clothing. One "trick" is to represent the garment as an articulated figure with "joints" at various seams. The garment is then brought to the proper shape by applying multiple simultaneous goals to bring the various parts into proper alignment or contact (e.g. [point] buttons to [point] button holes, zippers to line goals, etc.). Additional goals position the garment on the figure by identifying major points of contact (e.g. shoulders, front of chest, elbow, etc.). Some of this work is being done for the Army Natick Labs with Steve Paquette.

3.9. Three-dimensional input devices

In a previous system we experimented with direct 3-D input through a Polhemus 6-degree of freedom digitizer [BADL87]. We were limited by the rather slow speed of the inverse kinematics algorithm then available to us. Moreover, that algorithm suffered by providing a solution that was too local. With the new inverse kinematics procedure in *Jack* it should be easy to connect a spatial input device to drag the selected end-effector around in direct mimicry of the user's hand motion.

3.10. Passive position sensing

Since the early 1970's we have tried to understand how a computer could be programmed to observe human activity and describe or at least mimic the motions in a computer graphics model [BADL76, OROU80]. The ability to control a realistically shaped and behaved human figure with *Jack* opens the possibility of real-time monitoring activities. The inverse kinematics procedures may be robust enough to work from a few *two*-dimensional (e.g. image plane) joint positions and known anthropometric dimensions to establish 3-D locations for all the joints. Thus, given a [real] person performing some task in a remote location and passive monitoring from one or more video cameras, a simulated figure of the same size could be fit in *real-time* to the acquired positions. This real-time automated modeling will permit the indirect and low cost monitoring of EVA or other novel work activities where physical mock-ups are currently the only option. The computer models can be used for task planning, safety testing, task load predictions, and -- by making measurements on the simulated model -- indirect assessment of physiological states such as fatigue or comfort without direct sensing or verbal communication.

3.11. High level task control

Controlling human motion tasks specified by language commands or instructions is a long-term goal of our research. Analysis of the form and content of instructions has begun in collaboration with Computer and Information Science department faculty members Bonnie Webber and Mark Steedman [BADL90].

3.12. Task planner

One of the principal issues involved in understanding and executing instructions is the form of the action planner. Classical planning strategies do not seem to suffice for human motion because people are highly redundant mechanisms and use flexible, incremental, and interruptable plan execution. A reactive and incremental planning scheme for executing conditional and temporal instructions is being investigated by Moon Jung.

3.13. Task performance time database

The Fitts' Law formulation for task time performance is adequate for very simple reach and view tasks. For more generality the strength model can be referenced to obtain estimates of minimum trajectory times. This approach, however, is limited to knowing the strength model and, moreover, does not adequately compute timings for more complex task units (e.g. inserting a bolt into a hole). Libby Levison is examining several task time databases to see how they might be incorporated into the planner. These databases will be extremely useful for task analyses in the maintenance domain where nominal time-motion studies for common tasks have been extensively measured.

3.14. Language and speech interfaces

Once the natural language instructions can be used to generate a plan for execution by the simulated figure in *Jack*, a next step is to try speech input for the same set of understood commands. This work is presently underway in collaboration with Christoph Rumpf of Siemens Corporate Research in Munich using their speech understanding system.

4. Conclusion

Even though *Jack* is under continual development, it has nonetheless already proved to be a substantial computational tool in analyzing human abilities in physical workplaces. It is being applied to actual problems involving space vehicle inhabitants, helicopter pilots, maintenance technicians, foot soldiers, and tractor drivers. This broad range of applications is precisely the target we intended to reach. The general capabilities embedded in *Jack* attempt to mirror certain aspects of human performance, rather than the specific requirements of the corresponding workplace. There is only one "version" of *Jack*; though its features are sometimes motivated by a particular application, the solutions are shared by all who support the research effort. Of course, there are some general problems we wanted to solve that have contributed much to *Jack* from our own research perspective. We have enough on this queue to keep us busy for a long time.

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SIX YEARS INTO THE A^3I PROGRAM: PROGRESS & PROBLEMS

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ABSTRACT

The Army-NASA Aircrew/Aircraft Integration (A^3I) program is a joint exploratory development effort to advance the capabilities and use of computational representations of human performance and behavior in the design, synthesis, and analysis of manned systems. A major product of this goal is the development of a prototype Human Factors/Computer-Aided Engineering system called Man-Machine Integration Design and Analysis System (MIDAS). MIDAS contains tools to describe the operating environment, equipment, and mission of manned systems, with models of human performance behavior used in static and dynamic modes to evaluate aspects of the crew station design and operator task performance. This approach provides design engineers and analysts with interactive sysmolic, analytic, and graphic components that permit the early integration and visualization of human engineering principles.

This paper will briefly describe MIDAS's current architecture as well as the models and tools contained in them. The workstation capabilities which address specific steps in the crew station development process will be emphasized, together with the real world AH-64 Apache Longbow application chosen as a demonstration focus for our most recent phase of development. Also discussed will be a number of challenging problem areas which have arisen since the program's inception nearly six years ago. These discussion topics will include (a) identifying and addressing the needs of the workstation user; (b) methods for achieving the integration required by a comprehensive design and analysis tool such as MIDAS; (c) the level of detail differences between the conceptual design stage and the requirements of extant human performance models; (d) software distribution dilemmas and hurdles; and (e) validation requirements.

INTRODUCTION

The Army-NASA Aircrew/Aircraft Integration (A^3I) Program is a joint Army and NASA exploratory development effort to advance the capabilities and use of computational representations of human performance and behavior in the design, synthesis, and analysis of manned systems. A^3I is managed and executed by the Computational Human Engineering Research Office, an organization under the US Army Aeroflight Dynamics Directorate and the NASA Aerospace Human Factors Research Division, both at Ames Research Center. The program's goal is to conduct and integrate the applied research necessary to develop an engineering environment containing the tools and models needed to assist crew station developers in the conceptual design phase. A major product of this goal is the development of a prototype Human Factors/Computer-Aided Engineering (HF/CAE) system called Man-Machine Integration Design and Analysis System (MIDAS). This system provides design engineers/analysts with interactive symbolic, analytic, and graphic components which permit the early integration and visualization of human engineering principles. Currently hosted on a number of networked Symbolics and Silicon Graphics workstations, MIDAS serves as the framework in which research findings and models, developed by, or sponsored through the Computational Human Engineering Research Office, are incorporated.

Seventy to eighty percent of the life-cycle cost of an aircraft is determined in the conceptual design phase. After hardware is built, mistakes are hard to correct and concepts are difficult to modify. Engineers responsible for developing crew training simulators and instructional systems currently begin work after the cockpit is built and too late to impact its design. MIDAS gives designers an opportunity to "see it before they build it," to ask "what if" questions about all aspects of crew performance, including training, and to correct problems early. The system is currently focused on helicopters; however, its model and principal basis permits generalization to other vehicles.

MIDAS contains tools to describe the operating environment, equipment, and mission of manned systems, with models of human performance/behavior used in static and dynamic modes to evaluate aspects of the crew station design and operator task performance. The results are presented graphically and visually to the design engineers, often as a computer simulation of "manned flight." In this sense, MIDAS is similar in concept to computational tools such as finite element analysis and computational fluid dynamics which are used to improve designs and reduce costs.

The program began in the fall of 1984 and has completed four major phases of development toward a 1994 target date for a full prototype system. The most recent phase of development, demonstrated during June 1990, focused on the expansion of several elements of the system using the AH-64 Apache Longbow as an application. This paper will describe the MIDAS architecture, models, and tools in detail, as well as provide a summary of strengths and weaknesses found within this important effort in human performance modeling for system design.

DESCRIPTION OF MIDAS

The fundamental ideas behind the concept for MIDAS are embodied in Figure 1. The hope is to provide a prototyping methodology, rich in predictive human performance models and analysis capabilities, wherein designers could use computational representations of the crew station, operator(s), and world, not hardware simulators and man-in-the-loop studies, to discover problems and ask "what if" questions about the projected mission, equipment, and environment.

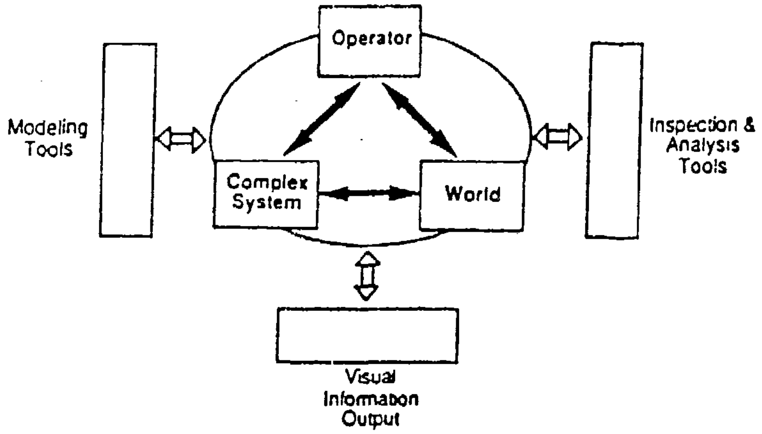

Figure 1. MIDAS Concept.

Because the crew station design process involves professionals from a wide range of disciplines, we have chosen to emphasize visualization as the primary form of information output. Graphic and iconic representations are predominantly used as a means to foster interdisciplinary communication. Furthermore, because the crew station design process includes extremely varied activities, the tools and models contained within the workstation have been developed to support multiple modes of operation. These modes currently include design specification and static analysis, as well as a dynamic analysis or simulation capability. The architecture and content of MIDAS have continuously evolved since the inception of the A^{3}I Program. It currently contains a number of tools and models hosted on a series of networked Symbolics and Silicon Graphics computers to meet the stated requirements. The current hardware architecture is shown in Figure 2.

A comprehensive set of models and tools is hosted on this suite of graphics and symbolic workstations. Each is described in detail below.

Mission Editor and Task Representation Tool

This component, written in Symbolics Common Lisp, contains the data structures and methods used to represent and decompose the required mission, environment, and human performance models of the crew. Also included are the causal relations existing between these elements required for analysis and simulation. Recent changes to this component have added the capability to use task objects and scenario agents in a library sense for building "custom" missions. This component expresses mission activities in terms of goals or states to be achieved, allowing the user to explicitly allocate such tasks to equipment or human operators, as well as providing for event-related operator responses which cannot cleanly be represented in a hierarchical fashion. Facilities also exist to review the mission/tasks at various levels of abstraction based on the specialization provided by the symbolic equipment and environment context.

The mission editor, task representation methods, and symbolic equipment models (discussed below) are valuable in themselves since they allow a user to explore the detailed task ramifications of various crew station designs. However, their real strength comes when used as part of the simulation. Mission, task, environment, or operator objects are instantiated when their conditions are met, executing their assigned procedures and spawning new activities. Contained

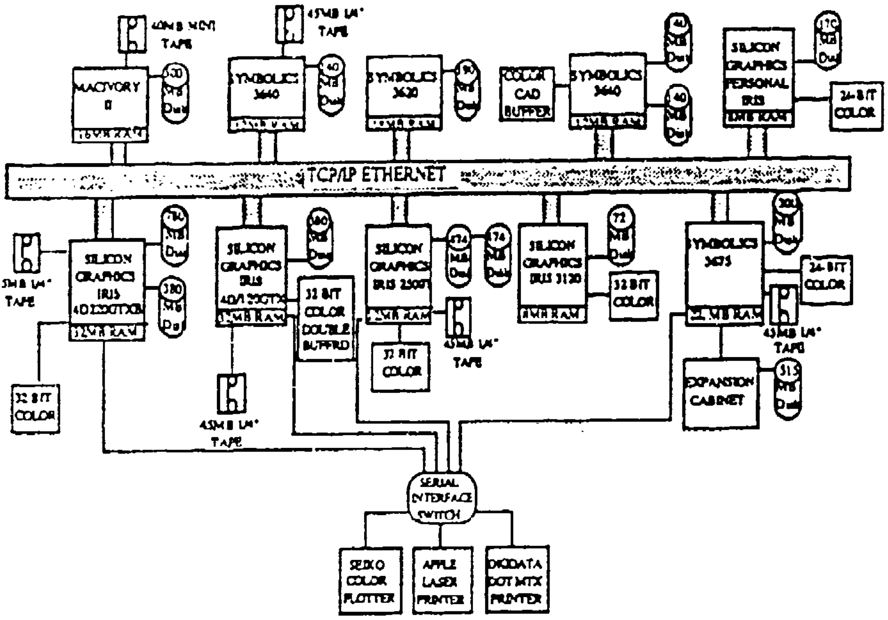

Figure 2. MIDAS Hardware Architecture.

within the various task objects is information on temporal relationships, preconditions, logical constraints, loading, subtasks, and relative priority. In this manner, the decomposed mission serves as a forcing function, "driving" the interaction of various models used during a simulation.

Symbolic Equipment Models

These generalizable structures, written in Symbolics Common Lisp, allow characteristics of the crew station equipment to be represented in terms of both physical and functional attributes which are used to specialize the mission tasks prior to a simulation. In this manner, MIDAS can support the generation of explicit operator actions which are sensitive to specific equipment designs. These structures also provide a model-based means to maintain and manipulate equipment state variables which drive the animation of graphical cockpit controls and displays.

Symbolic Operator Model

This model, also coded in Lisp, is understandably one of the most complex and continually evolving. It currently contains two major subcomponents, the scheduling and loading models described below. During a simulation, this model attempts to execute assigned mission activities subject to specified constraints, state variables, and other simulation object requirements. This model accomplishes this action by (a) updating the simulated operator's goal list to delete terminated or inappropriate goals; (b) examining equipment and world state variables to determine if event-response activities are required; (c) tracing the decomposition of mission goals to their lowest level, finding matching equipment operation patterns or activities which will satisfy them; (d) sorting these matched goal-activity patterns by priority; (e) interacting with the scheduling and loading operator model components as appropriate; and (f) executing these activities subject to physical resource (hand, eye, etc) requirements, Visual, Auditory, Cognitive, and Motor (VACM) load limits, and temporal/logical constraints.

Scheduler (Z)

This constraint-based, opportunistic model of operator scheduling behavior was developed using the blackboard architecture provided as part of the Generic Expert System Tool (GEST). Display portions of this component are written in Symbolics Common Lisp. Provided a task queue of indeterminate length, along with data about each task (such as logical constraints, estimated duration, resource requirements, etc.), Z solves for a near-optimal sequence and schedule based on a strategy of either time minimizing or load balancing, intended to represent possible operator behaviors. The scheduler contains modular components or knowledge sources that represent individual stages in the scheduling process, with an extended task-based decomposition (a "divide-and-conquer" technique) used to partition the overall scheduling problem. Z closely interacts with the MIDAS task loading model for reasoning about resource interactions between plausible concurrent tasks.

Task Loading Model

MIDAS contains an operator task loading model based on current research in multiple resource theory, scaling, workload, and perception. Based on attributes of the mission tasks, world state, operator, and crew station equipment, a resource classification taxonomy is used to classify individual tasks in terms of their demands on the Visual, Auditory, Cognitive, and Motor processing dimensions. In addition, conflict matrices are used to describe the interactions of these resource demands across different processing dimensions and tasks. An initial version of the task loading model has been coded in Symbolics Common Lisp.

Anthropometric Model (JACK)

A 3D, dynamic anthropometric model has been developed through a grant to Dr. Norman Badler at the University of Pennsylvania to address fundamental human anthropometry and motion considerations. This model, called JACK, is written in C and runs on the Silicon Graphics 4D series, providing realistic and physically quantifiable human figure motion within a 3D space environment. JACK allows the user to select different-sized human figures or graphic mannequins that include the 5th-through-95th-percentile male and female, based on NASA astronaut demographics. These mannequins can then be placed within a 3D object environment created and stored using a number of modeling packages. Articulation is achieved using a goal-solving technique based on specifying body joint orientations or end-effector (limb) goals. Joint limitations have been installed to eliminate unreasonable movements. Kinematic and inverse kinematic controls are applied so that goals and constraints may be used to position and orient the figure, with external/internal forces and torques applied to produce motion. A movement time calculation has been incorporated based on Fitts' Law, using reach site distance and target width.

Supporting graphic output in wire-frame, solid-filled, or smooth-shaded modes, key poses can be stored and interpolated for animation, allowing environmental limitations to be detected as a function of human size and movement characteristics. In addition, by attaching the "view" of the environment to the mannequin's eye, JACK displays a perspective corresponding to what the mannequin would "see" while moving in the environment, providing the first step toward further analysis and conclusions about object occlusion and visibility.

Volume Field-of-View Model

This model of binocular human visual representation in 3D space was developed by Dr. Aries Arditi at the Lighthouse of New York. It provides computer graphic methods for delineating and testing hypotheses about the relationship between two-dimensional visual field maps and the three-dimensional visual space they serve, under the conditions of (a) changing eye position; (b) occlusion by structures part of or are mounted on the observer such as facial structures, goggles, or headgear; (c) occlusion by environmental objects; (d) normal and abnormal defects of the visual field such as blind spots and areas of temporarily reduced visibility due to local adaptation and photopigment bleaching; and (e) variables that alter the focus of environmental objects on the retinas (accommodation and pupillary response). Instantaneous field-of-view volumes based on these factors are visualized by projecting their intersection with the object space in different colors. This model, written in C, is fully integrated with the JACK anthropometric model, which is used to determine the operator's head position and point of regard in the field-of-view.

Cockpit Display Visibility Model

This analytical model, developed by Drs. James Bergen and Jeffrey Lubin at the SRI/David Sarnoff Research Center, allows the designer to assess the visibility of cockpit objects imaged on the retina in terms of a visual system footprint. This footprint represents the projection onto the crew station of the sensory capabilities of the human visual system when considered as a detector/filter system. The existing MIDAS graphical, anthropometric, and vision modeling capabilities are used to describe the physical characteristics of potential designs and define the instantaneous volume field of view. Based on such information, this component provides methods to project the retinal photoreceptor apertures onto the cockpit model and support empirically-based predictions about the legibility of characters and symbols. Because the human retina is highly inhomogeneous, the retinal footprint produced is also highly inhomogeneous, depicting contours of visual performance data which describe the probability that certain imaged information will or will not be legible. Because factors such as ambient illumination in the cockpit, the adaptive state of the operator, and the reflective/emissive properties of displays are critical to consider in such contexts, this model will be enhanced incrementally to address each of these aspects. This component is written in C.

Cockpit Design Editor (CDE)

The CDE contains interactive 3D modeling utilities for graphically prototyping the crew station geometry, instruments, controls, and displays using a built-in library of primitive cockpit objects. Links can be made to other models or data files for animation of selected controls and displays. The CDE is written in C and is an extension to a commercial modeling package from Software Systems, Inc. called MultiGen®. Significant changes to this component have recently been made, allowing the creation and animation of multifunction displays containing graphical features, text strings, and dynamic fields. The CDE has been successfully used to build detailed 3D models of the complete AH-64 exterior, pilot and copilot/gunner cockpits and instrumentation, as well as a number of other vehicles. These applications provide both a feasible demonstration of its capabilities as well as graphical models for other MIDAS components.

Display Layout Assistant (DLA)

This tool is a prototypical component intended to provide designers with assistance in determining desirable spatial locations for cockpit displays. Displays are considered to be viewing windows for the operator through which he/she obtains information about machine and environment status. Just as the spatial location of objects in the physical world are completely determined by the forces acting upon them, the locations of the information sources being placed by the DLA user are determined in a similar manner. However, unlike the physical world, where the forces are entities like gravity and tabletops, the forces in this domain are engineering psychology principles suggested by Dr. Christopher Wickens in Elkind et al. (1989). The initial metrics include factors such as the functional and physical proximity of information sources, stimulus-response compatibility, and frequency of use. DLA can be provided in an analytic mode, using algorithmic solutions, or else in an evaluative mode, using rule-based heuristics. This component is written in C, with rules encoded using the CLIPS expert system shell.

Visual Editor and Simulation Tool (VEST)

VEST is an interactive 3D tool used to create, control, and observe from several visual perspectives, a 3D graphic representation of vehicles traversing through Defense Mapping Agency (DMA) terrain during a simulation. Users can select, by mouse, a viewing position from anywhere within the mission gaming area, zoom in on specific controls and displays for study, as well as include a representation of the JACK anthropometric model within the crew station for visualizing operator movement during a simulation. Like the CDE, this component is written in C as an extension to MultiGen®.

Aerodynamics & Guidance Model (AGM)

The MIDAS AGM is a two-part Fortran model, initially developed by Analytical Mechanics Associates Inc., which represents rather generic helicopter guidance and dynamics for uncoupled controls. Given the current position, orientation, and angular rates, the guidance portion of the model determines the control inputs required to fly to the next waypoint with its associated position, altitude, and airspeed. The aerodynamics portion of the model uses the computed controls to determine the helicopter's next position, attitude, etc., based on the simulation tick interval. The AGM's input and output are integrated with symbolic and anthropometric models of the pilot such that during a simulation, the computed flight control requirements are passed to the symbolic operator model as resource demands, with their actual start times and duration determined by the evaluation of such demands in the context of other pilot psychomotor activities. Flight control movements are graphically depicted by attaching the JACK anthropometric model's end effectors to the appropriate controls and using inverse kinematics to "pull" the model's appendages to the computed control positions.

Simulation Executive and Communications Module

This component, written in both C and Lisp, uses TCP/IP protocol as the basis for a simulation executive package to synchronize the execution of distributed components chosen for a simulation. This module also facilitates intermachine communication and message sharing between all MIDAS components by maintaining knowledge of all host and destination processes for each state variable or message sent during a simulation. A global cache or "data pool" concept is used to store and distribute in excess of 200 operator, world, and equipment state variables among the various MIDAS processes and objects.

Training Assessment Module

The training assessment module provides heuristic methods to estimate the media, instructional techniques, and time necessary to train various operators to "initial qualification" based on characteristics of the operator, task, and crew station equipment. This prototype knowledge-based system is implemented in the Automated Reasoning Tool (ART®) and Common Lisp on the Symbolics. This tool uses the Instructional Systems Design (ISD) methodology to assign each task a set of learning experiences (such as explanation, demonstration, part-task training, and full-task training) along with a medium for each learning experience (such as textbook/workbook, slide/tape, lecture, videodisc, and a wide range of simulation devices). For each learning experience and media assignment, a time to train is computed, based on the task, operator, and equipment attributes.

The software models and tools discussed above and currently hosted on the MIDAS hardware architecture are shown in the grey boxes of Figure 3. The unshaded boxes depict state

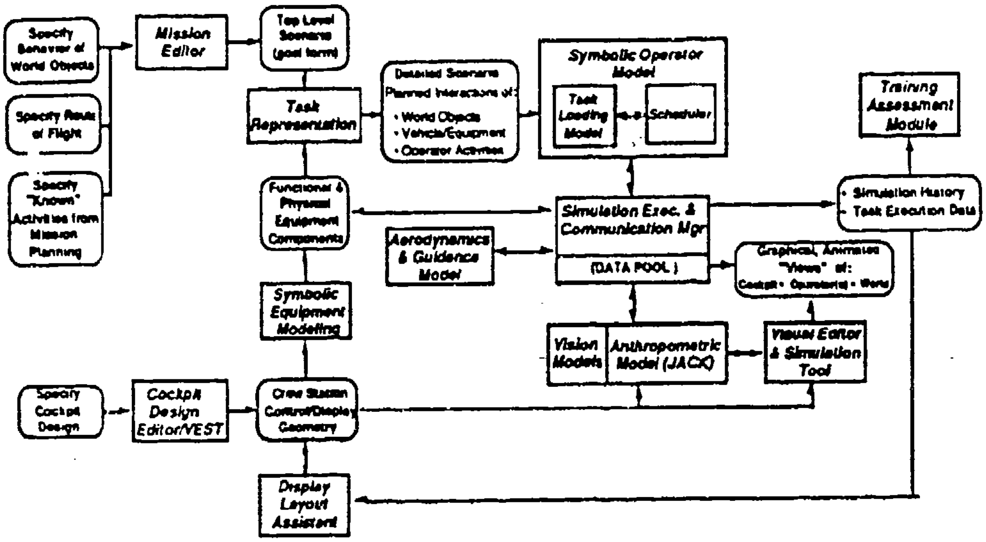

Figure 3. MIDAS Software Components.

variables or data structures which are either user-defined or computed by one component and used by another. The arrows shown indicate the general flow of information which is required for an integrated simulation.

The data flow actually employed within MIDAS during the last phase of development is shown in greater detail using an N^2 format in Figure 4. The components involved are portrayed in the shaded boxes on the diagonal of the figure. As shown in the legend, inputs are on the vertical axes of each box and outputs on the horizontal axes. For example, during each simulation "tick," the Vehicle Guidance Model computes the demands for control movement based on the current vehicle position, orientation, and speed (from the Dynamics Model) together with the next desired waypoint location, airspeed, and altitude (from the Mission Editor). These control requirements are then passed to the Symbolic Operator Model, which either accepts or rejects the controls based on other task demands. If accepted, the Guidance Model's computed controls are input to the Vehicles Dynamics Model and a new aircraft position and attitude are determined.

SUCCESSES

Machine Class Choices, Languages

Since the A^3I Program is a multiyear effort, it was understood early on that computer hardware would change radically over time. Thus, one of the first decisions was to standardize the operating systems and computer languages, rather than machines. These factors led to the selection of the following:

	Symbolic Models/Tools	Numeric & Graphic Models/Tools
Operating Systems	Genera	UNIX
Languages	Lisp	FORTRAN, C
Object-oriented methods	Flavors	C++
Machine Class	Symbolics	Silicon Graphics IRIS

MISSION EDITOR	Mission Reqmnts (Goal Form)		Operator Activites (Hierarchical & Evt. Resp.)			Waypoints with desired x, y, z ; Hdg, Alt, Airspeed			
Component Functions (State Achievers)	**SYMBOLIC EQUIP. MODELS**	Done							Control & Display States
	Tick	**SIM. EXEC**	Tick			Tick	Tick	Tick	Tick
		Done	**SYMBOLIC OPERATOR MODEL**	Task List, Constraints, VACP, Horizon	Attributes of Operator, World, Task, & Equip.	Accept/ Reject Controls		Reach-for & Look-at Site Cmds	
			New Task Sequence, & Loads	**SCHEDULR (Z)**	Tasks, Base VACM Loads				
				Scaled VACMs for Task Combos.	**TASK LOADING MODEL**				
		Done	Demands for Control Movement			**VEHICLE GUIDANCE MODEL**	Control Positions		
		Done				Position, orientation, speed	**VEHICLE DYNAMICS MODEL**		Hdg, Alt, Misc A/C Parameters
	Switch Movements	Done	Hand / Head Position, Reach Status					**ANTHRO. MODEL JACK**	Switch Movements Body Position
	Location/ Name of C&Ds	Done							**VEST**

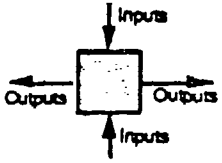

Figure 4. MIDAS Phase IV Integration N^2 Chart.

These choices for machines, languages, operating systems, and paradigms have been extremely fortuitous. The vendors have ably stood behind their equipment line, upgrading them as warranted, but maintaining a high degree of upward compatibility with source code written on older models. Unix and C, as almost everyone is aware, have become defacto standards among both research institutions and the graphics workstation market. Lisp still maintains a narrow edge as the language of choice for artificial intelligence applications, and Symbolics provides a powerful, but somewhat expensive, development environment.

Object-oriented programming methods have been adopted, where practical, in an effort to manage the complexity of the simulation software, and promote graceful incremental software development. This paradigm was adopted by the program long before it became "in vogue," and while not universally applied, it does help reduce the ultimate code bulk by making extensive use of software structures and promotes clean interfaces through its support for data abstraction. While Flavors has been used to date, a move will be made toward the Common Lisp Object System (CLOS) during the next phase.

Incremental Development

MIDAS is developed in phases, each eight to twelve-month period adding another increment of functionality to the existing configuration. Upon the completion of each phase's coding and integration, demonstrations are held, feedback solicited, compiled and assimilated, and technical planning meetings conducted to propose appropriate work for the next development period. A number of in-progress reviews are held to monitor the group's efforts and discover/correct problems. By this method, the program has been "bootstrapping" itself along very successfully since the first off-site planning meeting in the Fall of 1985.

This incremental prototyping approach has been helpful for several reasons. First, the program's objectives are so ambitious and associated with so much uncertainty that it simply would not have been possible on day one to have described the long-term functional requirements for what will likely turn out to be a 10-year effort. Small, concise periods of development allow the staff to focus on achieving the immediate requirements agreed upon, reviewing the recent research findings and progress of related developments prior to committing to long-range endeavors. This practice of phased development even allows periodic review of an adopted approach in its entirety. If, after a period of time, a selected path of modeling appears to be reaching a dead-end or is too restrictive, the approach can be abandoned and another one selected. With only a phase or two's effort invested, the temporary setback is not catastrophic and the entire downstream development does not have to be replanned with the change of course. Finally, incremental prototyping is ideally suited to changes in staff expertise and funding. As personnel experts in decision modeling or parallel processing, for example, are made available to the program, we can temporarily emphasize those aspects within MIDAS and rechart the development to other areas upon their departure. Similarly, the boom and bust cycle, so typical of government research and development funding, is quickly accommodated with this development style. Strong financial positions in one year can be used to purchase new equipment or initiate external efforts which begin their payoff during more lean funding periods.

In-House Development Emphasis

The key in our ability to use an incremental software development process has been an emphasis on conducting A^{3}I as an in-house program. The intimate involvement found with being the actual developer of a tool or model, combined with the lack of a long-term contract or specification, enables MIDAS to accommodate rapid changes in scope or direction. Maintaining internal configuration control of the MIDAS architecture and various models or tools also ensures we know exactly where the workstation stands and what will be required to incorporate a new component or model. An in-house approach was also adopted to make the methods and tools available to industry, other government agencies, and academia at no, or very little, cost. As an in-house effort funded by the government, the products of the program are in the so-called "public domain." Anyone should be able to have the software products for the asking. As is too often the case, achieving this objective is not as easy as it was intended to be (see "Problems" section below). However, we have undeniably made more progress with freely distributing software as an in-house program, than we would have if we had executed A^{3}I solely through contract means.

The in-house focus, however, does not mean that we do not take full advantage of external findings and expertise. In-house research or model development is conducted only if the required capabilities are not available, or if available, would fall outside the category of "public domain" entities. A considerable amount of research effort and money has been expended nationally, over more than three decades, to produce analytic methods, models, and structures representing the behavior and functions of human operators, with varying degrees of success. The A^{3}I Program is not explicitly charged with developing new models and methods, but instead will employ selectively those which have already been developed wherever possible. New research and development will be undertaken only when a critical void is encountered. Many institutions and industrial organizations have been quite willing to cooperate and make their work available for this purpose, and we attempt to provide full and frequent attribution to the cooperating contributors.

MIDAS also depends on formal extramural relationships with the university community and research institutions to provide models and research necessary to meet functional requirements. When establishing these relationships, every effort is made to ensure that the association is with the very best people and institutions available, and that the relationships are formed as joint efforts. The mechanism for this collaboration is usually a grant in the form of a cooperative agreement. The program staff contains many extremely talented computer scientists with skills not always available to university professors. Furthermore, the A^{3}I laboratory provides great symbolic and graphic computer power. With such cooperation, far more progress can be made than with each party acting independently as would be the case with a typical contract relationship. Additionally, the products of the research institute or university must be integrated into MIDAS; thus, the more cooperative the development, the easier the integration task.

The combination of an in-house focus and incremental development practices, together with selectively employing external experts for specific, well-defined portions of the project has been instrumental in the progress made to date. While this is a seemingly "obvious" approach to the objectives undertaken, a number of other projects with similar characteristics have chosen different execution methods with results not nearly as satisfying.

In-House Domain Expert

The A^{3}I Program has greatly profited from having a military helicopter instructor pilot on the in-house staff. In addition to offering readily available domain expertise, this individual was also a Lisp programmer and led the development of the mission editor and task representation components of the MIDAS workstation. His familiarity with actual helicopter operations, procedures, military doctrine, and task analysis was critical to understanding, reducing, and applying the wealth of existing data on pilot behavior, crew station controls and displays, and operational tactics. Many empirical and theoretical efforts in behavioral sciences are criticized because they cannot be generalized beyond controlled laboratory settings or simplistic notional scenarios. Having a domain expert close at hand serves as a reality check during the development of our various components, ensuring important attributes and factors were adequately represented.

A crew station design process study (Cody, 1988) was sponsored by the A^3I program and literally dozens of practicing cockpit designers/engineering psychologists have provided input to our development through workshops and demonstrations. However, in future phases we hope to have in-house design/analysis practitioners provide the focus and utility to MIDAS in a manner similar to that provided by the resident domain expert.

Real-World Demonstration Applications

Somewhat related to the above has been the program's success in tying each phase of development to an actual application. The most recent phase used the ongoing McDonnell Douglas AH-64 Apache Longbow Program as a source of data for controls, displays, mission profiles, and operator task descriptions. In fact, MIDAS-produced legibility predictions for the Longbow MFDs and volume field of view projections were used for that program's recent preliminary design review. Prior to that, the AH-1 Cobra Communications Switch Integration Program, which involved extensive flight test and data collection here at Ames Research Center, was used as a basis for comparison to our predicted simulation time lines and loading profiles. Finally, initial values for projected media requirements and instruction times from the Training Assessment Model were compared against the existing Apache Aircrew Qualification Course as a simple means of verification.

This practice of using operational equipment source data and test results has benefited the program in a number of ways. First, the use of existing data allowed us to concentrate on model development and integration—A^3I's true objective—rather than consume large amounts of time and effort generating specific task descriptions or time lines. Second, reasonably familiar applications allowed demonstration attendees to grasp readily the promise of the MIDAS capabilities by showing how specific, existing problems in the crew station design process could be addressed. Finally, real-world data and topical applications seemed to help with sustaining funding for our effort, something which should not be overlooked in today's budget environment.

PROBLEMS

Task Taxonomy

The lack of a formal, widely accepted operator task taxonomy in behavioral analysis and system development is an often reported shortcoming (Meister, 1985; Fleishman and Quaintance, 1984). This deficiency has been problematic for the A^3I program in a number of ways. First, we have yet to establish or adopt any one approach as our standard, somewhat hampering our overall progress due to the high degree of integration required among components. We initially started out with a rigid top-down hierarchy consisting of mission, phase, segment, function, task, subtask, etc., each containing characteristics and constraints about the activity required by some analysis process or model. This approach was initially favored because it allowed us to use a great deal of the task analysis/task description data published by other organizations examining helicopter crew behavior in the Army (Seigel, Madden, & Pfeiffer 1985) However, we quickly saw a number of limitations in putting this scheme to use. First, the various levels of abstraction and subtle distinctions between their associated characteristics made the actual practice of classification difficult and somewhat arbitrary. What might be a function in one segment of the mission was sometimes a subtask in another. The visual load arising from a task characterized as an "inspection" may be considerably higher than that associated with an "observe" classification, despite the fact that the actual activity is extremely similar. Additionally, a great deal of conditional behavior, such as responding to anomalous events, emergency procedures, etc., did not cleanly fall out of a typical top down hierarchy, yet needed to be represented during much of the overall mission. Finally, because of the inherent weaknesses with so many descriptive methods, it is hard to tell where the levied mission ends and the experience, doctrine, and procedures an operator brings to the job begins.

As previously mentioned, the fundamental idea behind MIDAS is to be able to vary attributes of the vehicle/equipment, operator, world, and mission, and then observe or assess their interactions. However, this lack of an unambiguous, descriptive task taxonomy has been a burden. It makes it difficult to build MIDAS incrementally, since during each phase the structure and content of our task representation seem to change radically. Additionally, the lack of a clear representation and content for the tasks impacts the development of, and interface with, other models. The mission and task representation contains the majority of the important variables needed by other components (temporal constraints, precondition, resource demands, etc.) and developing or integrating a planner, scheduler, or task loading model with the basic task representation in flux is like trying to shoot a moving target. Perhaps a new, formal taxonomy for task representation, such as that recently proposed as a military standard, will emerge and can be used in future phases to mitigate these problems (Myers et al., 1987). Until then we will continue to forge ahead with our relatively ad hoc approach.

Crew Station Equipment Representation

Closely related to the above is our handling of the crew station/vehicle equipment. In early phases, the actual equipment employed in the mission was not explicitly represented other than graphically. If a navigation task involved several keystrokes with an inertial navigation system and observing distance and bearing on a display, then these components were described or input by the analyst as part of the overall task decomposition. This implicit treatment of equipment dependencies is also a characteristic of several other modeling packages such as SAINT or Anacapa Sciences' Task Analysis and Work Load (TAWL) methodology.

In more recent phases, we have begun to model explicitly the equipment—both graphically and symbolically. The symbolic equipment models are very detailed representations and include individual switches or buttons modelled as finite state machines that accept as input the letter "A" for a keyboard buffer, turn on the power to a model of the VHF radio, or change the mode of a multifunction display. In this approach, the crew members' tasks are represented in goal form as states to be achieved. Similar to the planning approaches used by the artificial intelligence community, the detailed equipment models provide the primitive operations which allow the crew member to manipulate or achieve the desired state. In this way, the lower-level actions necessary in a task are actually derived from the specific physical and functional design of the equipment.

This matching process works quite nicely for discrete tasks, such as tuning a radio by rotating a selector, or arming the missiles by flipping a switch. More complex tasks can even be built-up in this manner by layering procedures or operating doctrine on top of these equipment models. However, this approach carries with it a number of drawbacks. First, it is not clear whether this method will generalize to continuous control actions since there often is not a direct mapping between the primitive control action and the state desired. Furthermore, the approach of inheriting or defining the lower-level tasks through the actual equipment models has to date only been used for actions where the crew member is trying to affect the state of the helicopter equipment. Many times, looking at displays, monitoring radio traffic, etc., are tasks which exist primarily to update the state of the pilot. Generating the tasks to look at certain displays (or combining several pieces of knowledge from multiple displays) from high-level goals to assess a situation or decide on further action does not appear to be something we can accommodate through the existing equipment modeling approach. In this context, what is required is the representation of the information content in cockpit displays as a means to determine the primitive operator tasks. Ideally, this approach should be able to capture the differences, for example, in a tape-scale versus digital readout of airspeed.

In addition, the simulated operator(s) within MIDAS naively have no internal understanding or "model" of the task or equipment represented. Thus, they possess perfect knowledge of all world/equipment states in the simulation. Research findings have shown that closed-loop operator/vehicle performance is influenced by both the "actual" task environment, as well as the operator's perception or internal model of this environment (Levison, 1989). Therefore, before we embark on an extension of our equipment modeling technique to address the information which displays or imagery can provide the operator, we must first include provisions for the characteristics of short-term memory, long-term memory, and their associated decay. As reported by the National Research Council, none of these endeavors is trivial (Elkind et al., 1989).

Finally, this type of equipment modeling is extremely labor intensive. Depending on the mission tasks under investigation, the modeling effort can easily approach an actual man-in-the-loop simulation in its requirements for equipment fidelity. Figure 5 provides a synopsis of the equipment modeling detail required for a very short, three-to-four minute scenario involving flight control, communications, and navigation tasks for our recent demonstration.

Level of Detail

As previously described, MIDAS is intended for the conceptual design phase of crew station development because of the high "payoff" for properly incorporating human engineering principles during this period. However, to date, most of the available human performance models and analytical methods of proven veracity have required as inputs, task, equipment, and environmental data which are generally not known until detailed design. Examples of this dilema clearly follow from the equipment modeling discussion above. Such requirements may include control friction or break-out forces which are helpful for workload classification, display characteristics such as contrast ratio, brightness, and font definitions for legibility analyses, as well as the detailed characteristics of cockpit equipment needed to produce specific operator activities and simulation models. All of these requirements and approaches involve an enormous amount of data. A direct scale-up from MIDAS's current three-to-four minute scenarios to a full-mission simulation, particularly one with stochastic execution times and events, would be prohibitive.

The apparent conflict between model/analysis needs and the intended use of MIDAS is still unresolved. There appears to be no consensus within the human performance modeling community about the appropriate level of input data needed to develop task descriptions or simulation models (Meister, 1985). As in most scientific endeavors, the answer to this query seems to depend on the questions being asked. However, it appears that if we wish to explore task implications for system design, particularly to assess alternative equipment configurations, then the maximum amount of detail is preferred. Until valid psychological principles are developed which can operate from more general data, the development team will continue to try to use abstraction, default values, and "libraries" of predefined task or equipment primitives in an attempt to ease the MIDAS user's burden of providing and managing an overwhelming amount of data.

Software Distribution

One of the first and foremost goals of the program is to be able to disseminate its products, not only in the form of results and conclusions described in reports and symposia, but as actual models and code for evaluation, commentary, and extension by interested parties. In fact, one of the major reasons for executing the program in-house was specifically to avoid proprietary aspects which might arise from external contracting. However, we did not want to try to build tools or models from scratch except when needed. Consequently, grants or cooperative agreements have been used for specific universities or research institutions having the extant knowledge and expertise in certain human performance areas. These relationships have allowed perfectly suitable components such as the JACK anthropometry model or the binocular, volume field-of-view model to find their way into the MIDAS workstation, either in whole, or in part. However, not all such

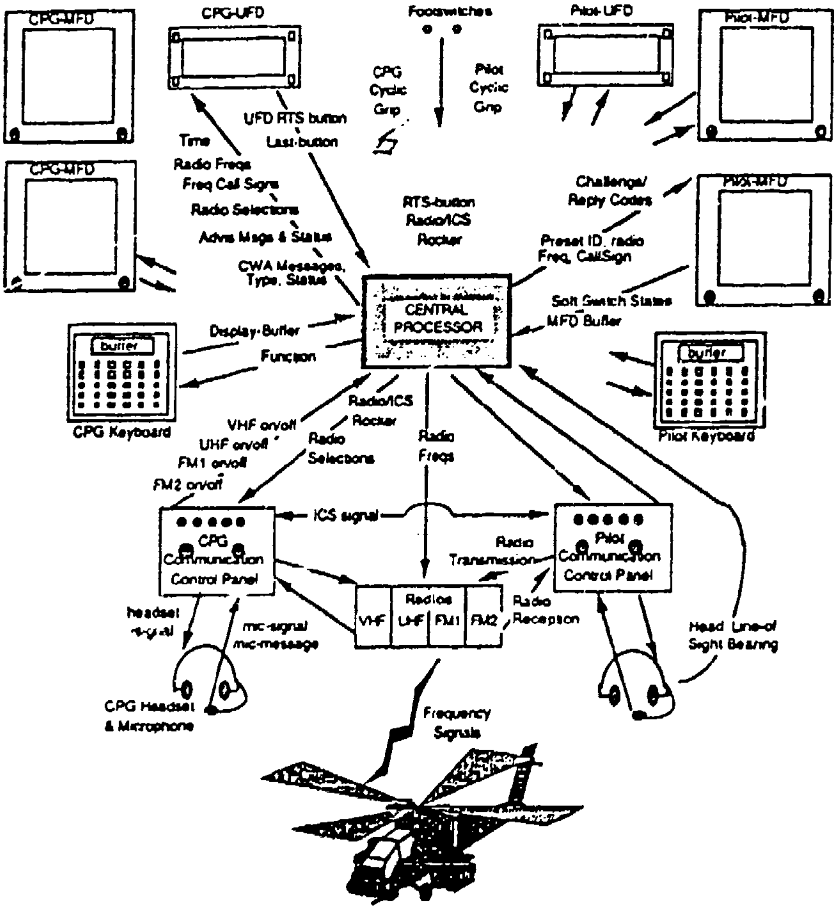

Figure 5. MIDAS Phase IV Symbolic Equipment Modeling Context: AH-64 Apache Longbow.

institutions share the same distribution goals that the A^{3}I program office may harbor. For some organizations, a specific tool or human performance model may be their major reason for existence and source of funding. Allowing a sponsoring organization to freely distribute it, particularly in source code form, will significantly erode their ability to garner additional funds for further development. Furthermore, a grant or cooperative agreement has rather weak teeth when it comes to enforcing rights in data. In fact, the only deliverable actually recognized under a grant is a technical report. So, although NASA and the Army may fund an institution, such as the University of Pennsylvania, to provide MIDAS with one of the most capable and promising anthropometric models available, the delivered software still remains their property and some of the distribution goals we had are lost.

While perhaps less than ideal, this situation is not out of the ordinary and even contains some encouraging aspects. Many organizations in addition to ours, including industrial concerns, have funded Dr. Badler. JACK was not brought to its present state solely through NASA money; hence, it would be inappropriate for us to claim unrestricted distribution rights. As a compromise, Dr. Badler has agreed to provide an executable version of JACK to the NASA Computer Software Management Information Center (COSMIC) for distribution to any party willing to pay some minor reproduction and dissemination costs. This allows potentially interested parties to gain access to a working copy of the software and explore its capabilities in their environment prior to committing to long-term support. In addition, each year, Dr. Badler's program of research also produces a number of outstanding graduate students adept at producing and using human performance models in computer-aided engineering. Curtailing the JACK software development support provided his organization through significantly less restrictive distribution may in fact be shortsighted. While a greater number of researchers and practitioners may be able to gain access to the existing JACK capabilities, the strength of his university research program and the production of new human engineering talent would be severely diminished by the reduced funding. Finally, each new contributor to JACK's development is allowed to start its relationship with the University of Pennsylvania by immediately benefiting from model features amassed through several man-years and millions of dollars of effort, rather than starting from a significantly less capable model for its application. Consequently, when all factors are examined, the short-term encumbrances with looking "outside" for MIDAS components, appear to be offset by long-term benefits of maintaining active research in human performance model development.

Another area where the A^{3}I Program's software distribution goals have suffered setbacks involves the use of commercially available general purpose tools and applications as the core of domain-specific components. Many of our development objectives can most efficiently and effectively be performed through using commercially available code as a foundation. Large amounts of related information are best stored and accessed through the use of a data base program. Expert or knowledge-based systems are easiest if started with one of the many powerful and flexible shells on the market. Graphical and visualization tools can most easily be built on top of libraries provided by the vendor, special purpose boards, or commercial CAD packages. Because our focus is on the human performance and crew station design domain aspects of MIDAS, the use of a common, relatively inexpensive tool or shell to aid us in the task is extremely attractive. After all, if we had to start with a higher-order language for everything we did, MIDAS would be significantly less mature. The use of a commercial tool/shell here or there does not seem like that much of a hindrance to distribution. However, these little packages add up, and they seem to creep insidiously into consideration each time a new, ambitious component is under development. Our Training Assessment Module (TAM) was developed using the ART®, a high-end, relatively expensive expert system shell. While well-received during our demonstrations, the approximately $30,000 licensing fee for ART® has inhibited several parties from using TAM. As another example, MIDAS has an extremely capable 3D graphical crew station prototyping tool called VEST. Because of the need early in the program for a convincing, powerful demonstration of such capabilities, a commercial modeling package called MultiGen® was used as this component's underpinnings. Despite the fact that the A^{3}I group has added approximately 30,000 lines of C code to the base product's 70,000, (including a number of significant features such as an animation capability, instrument primitives, and support for designing multifunction displays), the approximately $45,000 required for a MultiGen® license has precluded at least three industrial concerns from using this tool.

Recently, the program has been much more selective about using these types of tools. For our new scheduling model, a powerful, but inexpensive (less than $3000 for a license to government organizations) product from the Georgia Tech Research Institute called Generic Expert System Tool (GEST) was used for its blackboard architecture. Consideration is also being given to using GEST for the Training Assessment Module and either developing in-house a new 3D graphics editor or else using an inexpensive Computer-Aided Design (CAD) tool such as BRL-CAD to reduce our reliance on these expensive products.

Validation

The glamour and excitement with human performance modeling in system design tends to rest in development. The tedious, time- and data-intensive efforts of validation, even serious application, are rarely given the attention they deserve. Literature in the area of human performance modeling almost continually cites this deficiency (Baron et al., 1990; Elkind et al., 1989; McMillan et al., 1989; Meister, 1985). Two major factors seem to contribute to this situation. The first is that with highly complex, comprehensive models, it becomes very difficult to tease out the specific assumptions, parameters, and attributes which may or may not correlate with empirical data. Second, it is often more difficult to secure funding for extensive model validation effort than for initial model development.

In these regards, the models and methodology contained within MIDAS fare no better than the norm. Most are still in prototypical form, with serious validation-oriented work pushed off until later. While some, such as those in the volume field of view and legibility assessment area have very strong roots in proven theory and empirical work, it is extremely easy to stretch their bounds of applicability in the larger MIDAS context. With our attempts to represent the physical, perceptual, cognitive, and psychomotor aspects of human performance in the helicopter aviation domain, the wide gaps in model coverage make it tempting to misuse or misapply a model in an attempt to complete a comprehensive simulation. A model which may provide reasonable results in a limited domain or context is frequently called upon to supply parameters necessary for a downstream model's processing—something frequently not intended by the original model's developers. Determining to what extent models of limited scope, that have been validated independently in a research environment, can be assumed to be valid when incorporated as submodels into an integrated model is still an unanswered and worthwhile query.

Some empirical experiments are planned next year for our task loading model and Dr. Chris Wickens at the University of Illinois is actively developing and testing several theories of display formatting and organization under an A^3I grant. These theories, many of which have found their way into evaluation metrics included in our prototype DLA, are examples of the solid psychological basis which should be found across all human performance models.

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MAINTAINABILITY EVALUATION AND INTEGRATED PRODUCT DEVELOPMENT

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ABSTRACT

In this paper, a vision and approach of what needs to be accomplished to accelerate and effect expanded maintainability participation and influence during the design process will be addressed. The need for a vastly expanded maintainability role in an Integrated Product Development process has been recognized by United States industry and Department of Defense (DoD) through initiatives like R&M2000, Computer-Aided Acquisition Logistic Support (CALS), and Concurrent Engineering. Though the paper focuses on maintainability (as applied primarily to mechanical subsystems), it should be recognized that the concepts presented are also applicable to other supporting disciplines, such as reliability and safety, and their interconnection.

The concept that effective integration of disciplines requires near parity of the participant's technologies will be examined. It will be argued that the maintainability discipline must increase its rate of automation acceptance and knowledge development to eventually catch up with, and keep pace with, the advanced level of the design and analysis functions. Specific maintainability tool and technology development will be discussed as well as integration concerns relating to integrated product and process design. The paper will include a description of a method to imbed qualitative and quantitative maintainability requirements and goals into design trade analyses starting from the initial concept stage.

INTRODUCTION

The design of complex systems such as aerospace propulsion systems is an interactive process which requires integrating input for many specialist disciplines. Currently, in many companies, the mechanical design engineer performs the role of systems engineer in incorporating the diverse requirements of these specialists into the design process. The design process is basically performed in a sequential order which is a time-consuming process with each design, review, and planning activity taking its turn after the preceding activity is essentially complete.

Many companies in the United States are experiencing severe global competitive pressures. To compete and survive in a global market economy, U.S. firms must make fundamental changes in the methodologies used for designing and producing products. This is not a simple process, because development of complex military systems is lengthy and costly. Major weapon systems typically require 10 to 15 years to develop and deploy. Seventy percent of a product's life-cycle attributes (including quality and cost) are defined by decisions made during the concept exploration phase (Figure 1).

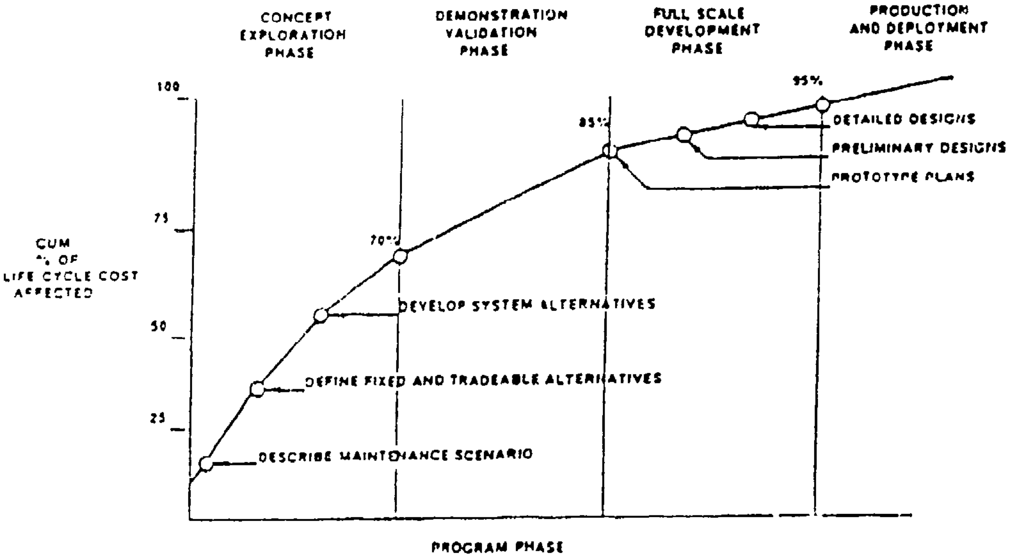


Figure 1. Cost Benefits are Related to Early Maintainability Involvement.

This is the phase in which many significant maintainability decisions, such as flange placement and modularity, are locked into the design. If a change in maintainability concept is desired later, it is generally too costly and/or too difficult to make (Figure 2).

It would be easier to update the design, and it would be more time and labor efficient, if the sequential design, review, and planning steps were accomplished concurrently, with participants having the ability to adequately cross communicate their ideas. Initiatives to reduce the length of the design/development cycle and, consequently, the cost of new product development have been recently introduced. The DoD's Concurrent Engineering initiative deals with the product development cycle while the U.S. Air Force's Integrated Product Development (IPD) initiative addresses the entire program cycle.

This paper speaks to the differences between how the maintainability discipline currently interfaces with the design, manufacturing, and support organizations, and how it will eventually

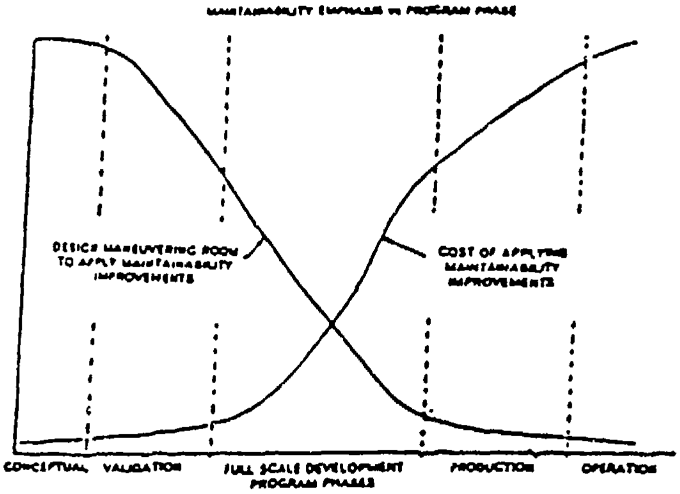


Figure 2. Effect of Maintainability Action vs. Program Phase.

interface under the IPD process. The paper will also show, by example, how a maintainability discipline is envisioned to operate within the IPD process, taking advantage of emerging technologies and tools which are now being raised to the level of being practical and available.

Mechanical design technologies have moved strongly into the computer age with Computer-Aided Design (CAD) systems in place at many contractor facilities. By comparison, computerization of maintainability discipline tasks lags as much as 10 years behind that of mechanical design systems. Therefore, automation of the maintainability, and other "ility" disciplines must be strongly accelerated to attain parity with the progress of the design system, as shown in Figure 3.

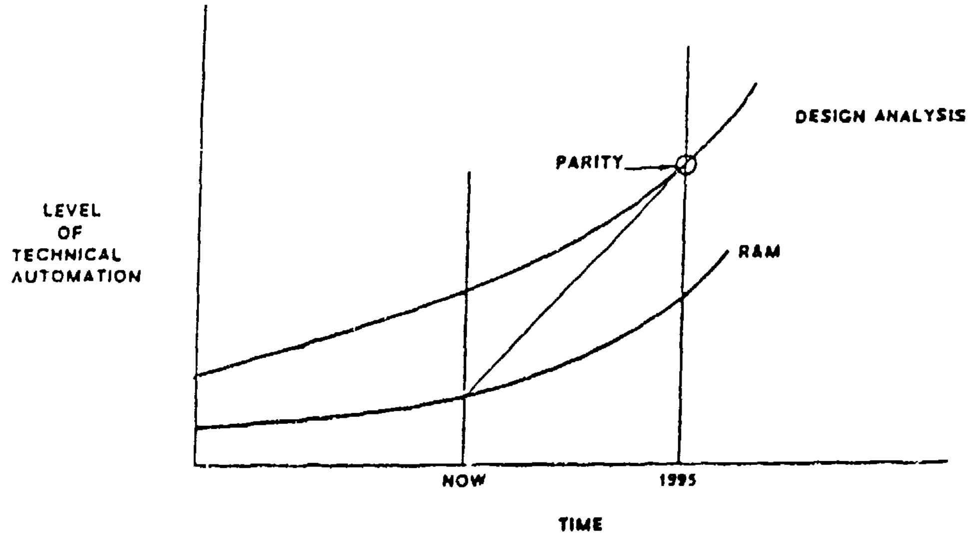


Figure 3. Time Phase for R&M to Reach Parity with Design Analysis.

The concept of Concurrent Engineering (CE) has been embraced by many U.S. firms and the DoD in an attempt to reduce product development time and improve product quality. Much of the understanding of CE has been gained from studying the successes of the Japanese product development process. Practices generally attributed to the Japanese product development process are:

1. Less time from concept to market
2. Higher quality
3. Structured approach to requirements definition
4. Multifunctional design team
5. Emphasis on manufacturing
6. Product and process simplification

In 1988, two DoD studies on CE were initiated. One, by the Institute for Defense Analyses, defined CE. The second, by the Defense Advanced Research Projects Agency (DARPA), initiated a five-year program called DICE (DARPA Initiative in Concurrent Engineering) to develop an open, computer-assisted CE environment.

More recently (1990) the U.S. Air Force instituted the new approach to systems acquisition called IPD which seeks to place quality products into the hands of the customer more quickly and at lower cost. The approach is built on (a) simultaneous unified integration of all related disciplines associated with fielding a product, (b) eliminating non-value-added tasks, and (c) continuously improving the remaining tasks to optimize development, manufacturing, and support processes.

CE and IPD may seem to be different names for the same process. CE's emphasis is on the product development cycle from initial requirement through prototyping. IPD, on the other hand, emphasizes the customer's requirements. IPD teams seek to unite the customer and the producer to define requirements, manage change throughout the development process, and provide support during deployment. Key features of both CE and IPD are to shorten development, reduce cost, increase quality, and increase availability. Figure 4 illustrates the sequential nature of the typical five-year cycle from design and development to field a jet engine. Also illustrated is how this time phase can be reduced 50 percent by using the principles of CE. These goals will be achieved by applying multifunctional teams, product and process automation, a manufacturing emphasis, and structured requirements definitions.

CUSTOMER REQUIREMENTS

The customer provides to the contractor, via request for proposal (RFP) or other communications, the support objectives for maintainability. They are given as quantitative and qualitative requirements and goals. During early design phases, the maintainability engineer takes the customer requirements/goals, and prepares projections and allocations down to the subordinate levels, which are then transmitted to the design engineers.

Some examples of quantitative parameters are:

1. Maintenance Manhours per Engine Flight Hour (MMH/EFH) or some similar parameter.
2. Fault Detection and Isolation Time
3. Mean Time to Repair (MTTR)

Examples of qualitative criteria are:

1. Maximize commonality
2. Minimize skill level
3. Maximize accessibility
4. Reduce support equipment requirements

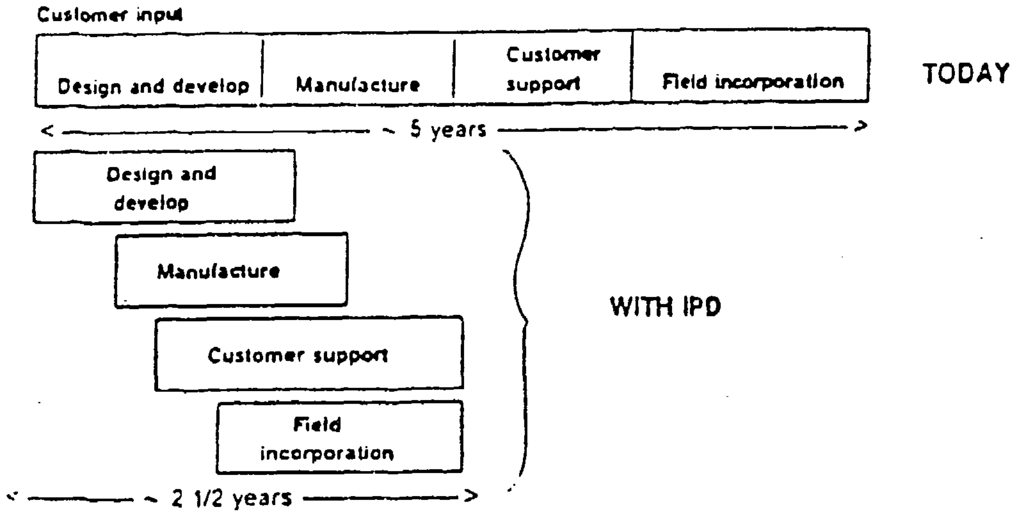


Figure 4. IPD Reduces Time to Product Introduction.

A more comprehensive list of qualitative design criteria can be found in MIL-STD-470B, "Maintainability Program for Systems and Equipment." Descriptions of some of the more important criteria follow.

1. Maintenance Concept (flight line, base shop, and depot). What type maintenance concept will the customer support? Depot plus flight line maintenance is referred to as "2 level" maintenance, while performing some tasks on the flight line, some at the base shop, and others at depot is "3 level" maintenance. The three levels of maintenance are today's traditional concept for mechanical systems such as trucks and aircraft power plants (non-avionics and electronics), but we also give consideration to how a two-level system for power plants might operate.

2. Maintainability Allocations/Predictions. The customer normally specifies an MMH/EFH and MTTR requirement. The maintainability engineer allocates these requirements down to the systems, subsystem, and component indenture level. As the design progresses, the maintainability engineer must review where the design stands in terms of the qualitative and quantitative requirements. At the end of the design phase, he or she must verify that the maintainability design requirements have been achieved by validation demonstrations conducted on hard mock-ups or actual hardware. In fact, the maintainability demonstrations will normally take place at several points in the design process with improved detail mock-ups. Although this is a costly process, the maintainability engineer of today has no better way to determine if the customer requirements are being met.

3. Maintenance Task Analysis. The maintainability engineer starts the detailed maintenance analysis at the earliest part of the design as is practical. He or she must update this analysis as the design progresses to feed the results of the analysis into the system maintenance plan and Logistic Support Analysis (LSA) record.

4. Human Engineering Evaluation. While the maintainability engineer is analyzing the design, he or she must also keep in mind the appropriate requirements related to human engineering. Human factors engineering is a key element in the Maintainability engineering process. Effective human engineering in the design provides the potential to obtain the best execution of manufacturing and maintenance tasks. This contributes to a more effective overall program and maximizes the positive aspects of human engineering in the design process. Optimum technician-to-engine interfaces increase the probability of successful task completion and result in improved system reliability.

In terms of the technician-to-engine interfaces, important points to keep in mind are:

1. External configurations must provide excellent accessibility.
2. The engine Line Replaceable Units (LRU) must be easily removed and replaced using single technicians of the 5% female to the 95% male category.
3. Special LRU handling fixtures should not be necessary.
4. Engine external designs must be foolproofed to prevent improper connections.
5. Parallel plumbing should have different disconnect points/interfaces.

5. Maintainability Design Evaluation. The maintainability analysis is the core of the maintainability engineer's effort during the design. During this evaluation, the design is reviewed for such things as:

1. General accessibility, work space, and work clearance
2. Interchangeability
3. Use of standard parts
4. Design techniques for fault detection and isolation
5. Limitations of numbers and varieties of necessary tools, accessories, and support equipment
6. Number of personnel required and skill levels of personnel
7. Inherent maintenance and maintainability characteristics of components to be used
8. Foolproofing
9. Weapon system integration

CURRENT MAINTAINABILITY INVOLVEMENT

Ten years ago, when the maintainability engineer was called by the mechanical designer to review the design, the "telling the mother she has an ugly child" analogy was quite appropriate. Any comments that might enhance the maintainability of the design were often treated confrontationally. The designer would often be so pressed by schedule, weight, cost, and performance that he or she would simply ignore the comments. Needless to say, a less than maintainable design resulted (Figure 5).

In addition, the background and experience level of the maintainability engineer has changed over the past 10 years. Few professional maintainability engineers existed 10 years ago and those that did usually had little or no practical field experience. To make up for this lack of experience, Pratt & Whitney hired retired military maintenance personnel, each individual having 20 or more years of practical experience in jet engine maintenance. This experience is now being passed on to the product during the design/development phase resulting in the elimination of many past maintainability problems and aggravations.

In today's environment, the maintainability engineer provides lessons learned to the mechanical designer upfront in the design process. These lessons learned are derived from previous test and field experience, and represent the corporate state of maintainability "what not to

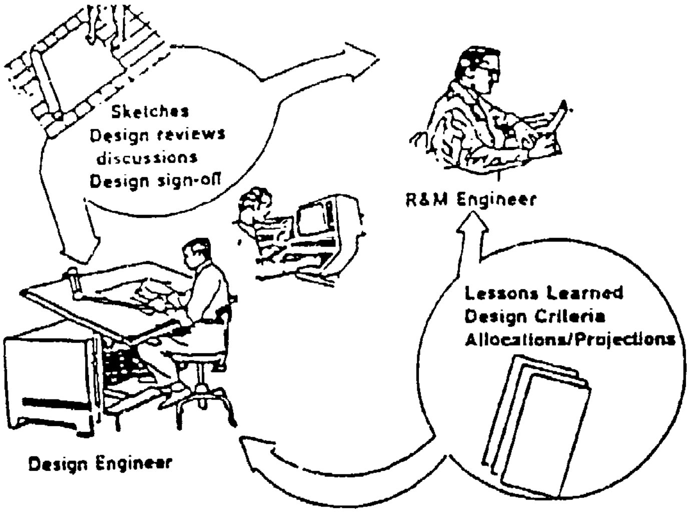
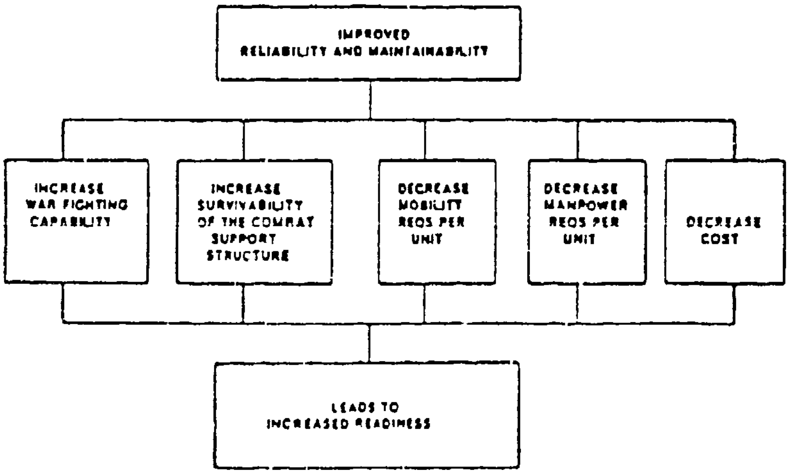


Figure 5. Current R&M Interface with Design Engineer.

do" examples for that assembly or component. In the case of a completely new design, a general checklist of good maintainability design practice is provided. Then, after the designer has completed the design, the maintainability engineer can review it for inclusion of the lessons learned as well as overall good maintainability features. While the maintainability engineer's review is less confrontational and experts greater design influence, concurrency with the design process is still lacking.

MAINTAINABILITY VISION FOR THE FUTURE

Today's military demands a new approach to weapon system supportability. Under the U.S. Air Force R&M2000 initiative, the customer is demanding weapon systems with increased combat capability at reduced cost. The five Air Force goals for R&M are:



Manpower availability is decreasing and, hence, the military is demanding reduced maintenance manpower requirements with lower and fewer skill levels. To some degree, this has been driven by budget constraints and the demand for lower operational and support costs, fewer spares, less test equipment and tools. To help meet these goals and needs, the maintainability engineering effort is now progressing toward total integration with the design effort. The IPD process using Integrated Process Teams is the vehicle to accomplish this integration. The mechanics and tools (knowledge and software) needed by the maintainability engineer to accomplish this within the IPD process are described below in two phases: Near Term (one to three years) and Far Term (three to ten years).

Near Term

The ability to create and/or modify a design several times in the time previously required for a single iteration has caused phenomenal growth in the use of CAD/CAM workstations. In 1985, it was estimated that some 10 percent of American designs were accomplished using CAD/CAM equipment. By the year 2000, this figure is expected to exceed 80 percent. The "ility" specialists will not be able to keep pace with the designers if they continue to use their traditional pencil and paper methods in this environment. Computer tools which automate the "ility" analysis functions must be developed. Tools that can be developed using current technology include a Lessons Learned data base readily accessible by the designer, a computerized design manual, and an "ility" rule-based expert system (Figures 6, 7, and 8). All three tools would be available to the designer using windows on the workstation. The Lessons Learned and Expert System could be accessed by keyword/phrase.

Use of solid 3D modeling from CAD/CAM files will enable the "ility" engineers to perform their task immediately after the design is far enough along to allow 3D modeling. Clearance checks (including engine/airframe interface) can be viewed immediately, reducing the need for costly mock-ups during the design phase.

First, training maintainability engineers in the use of CAD/CAM workstations must be accomplished. This will allow the design to immediately be reviewed by the maintainability engineer using the CAD/CAM workstation. This single step will give the maintainability engineer "concurrency." Second, Maintainability Lessons Learned should be in a computerized data base that can be sorted and provided to the designer automatically. In fact, this data base should be accessed directly by the mechanical designer on the workstation. This can be accomplished by constructing a Maintainability Expert System to place the Maintainability checklists and Lessons Learned in a rule-based data file that can be computer accessed by keyword/phrase.

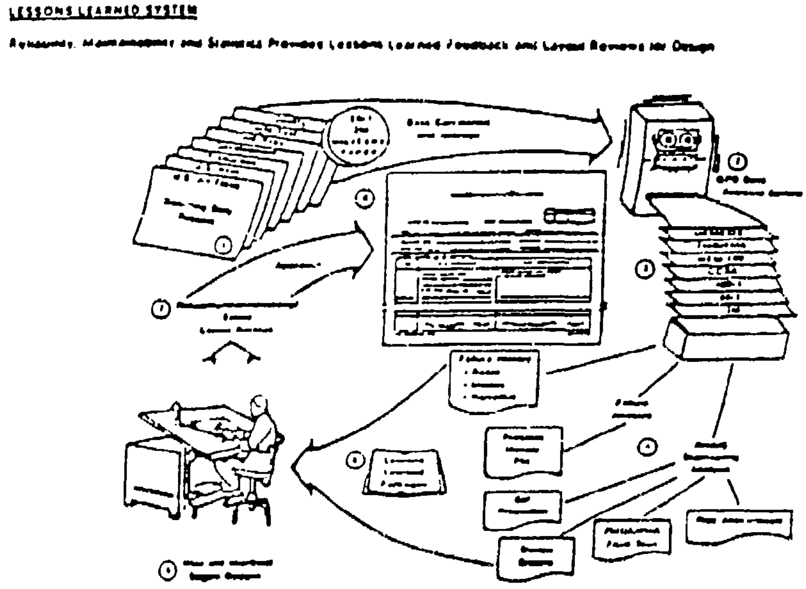


Figure 6. PHF Flowchart.

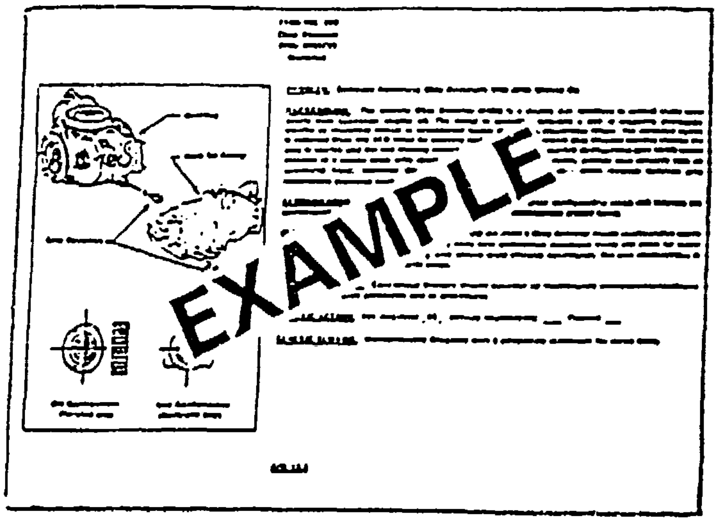
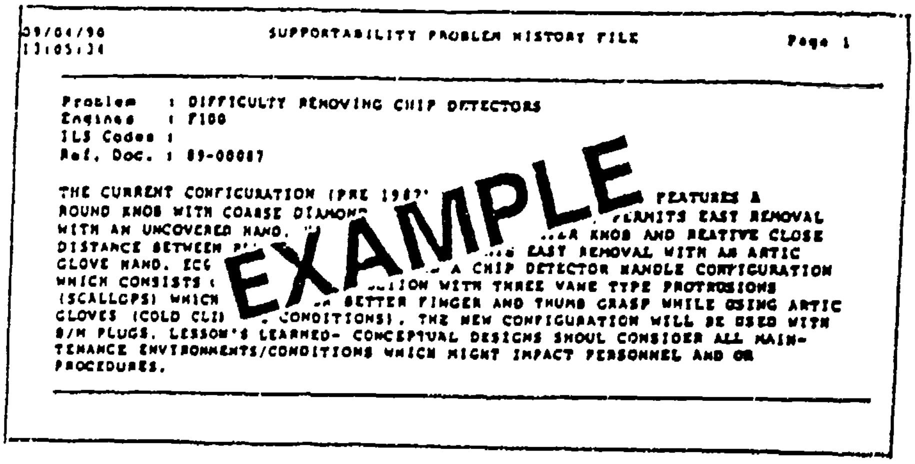


Figure 7. Example of PHF Problem Closeout Sheet.



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09/04/90                SUPPORTABILITY PROBLEM HISTORY FILE                Page 1
13:05:34

    Problem    : DIFFICULTY REMOVING CHIP DETECTORS
    Engines    : F100
    ILS Codes  :
    Ref. Doc.  : 89-00087

    THE CURRENT CONFIGURATION (PRE 1987' [illegible] FEATURES A
    ROUND KNOB WITH COARSE DIAMOND [illegible] PERMITS EASY REMOVAL
    WITH AN UNCOVERED HAND. [illegible] ..AR KNOB AND RELATIVE CLOSE
    DISTANCE BETWEEN [illegible] EASY REMOVAL WITH AN ARTIC
    GLOVE HAND. ECC [illegible] A CHIP DETECTOR HANDLE CONFIGURATION
    WHICH CONSISTS [illegible] ..TION WITH THREE VANE TYPE PROTRUSIONS
    (SCALLOPS) WHICH [illegible] BETTER FINGER AND THUMB GRASP WHILE USING ARTIC
    GLOVES (COLD CLI[illegible] CONDITIONS). THE NEW CONFIGURATION WILL BE USED WITH
    B/M PLUGS. LESSON'S LEARNED- CONCEPTUAL DESIGNS SHOUL CONSIDER ALL MAIN-
    TENANCE ENVIRONMENTS/CONDITIONS WHICH MIGHT IMPACT PERSONNEL AND OR
    PROCEDURES.
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Figure 8. Example of PHF Computer Screen Narrative.

Far Term

If the "ility" specialists are to truly influence the weapon system design, an integrated system where several characteristics are analyzed simultaneously on the workstation must be developed. Routine "ility" analyses (Lessons Learned, Design Manual and Expert Systems) could be done in background mode while the designer is on the workstation (Figure 9). The results of the analyses would then be available to the designer on request, improving the end design and freeing the "ility" specialist for other tasks. Thus, freeing the specialists from the "policeman" role allows them to help in the development of new computer tools and perform the task of resident troubleshooter.

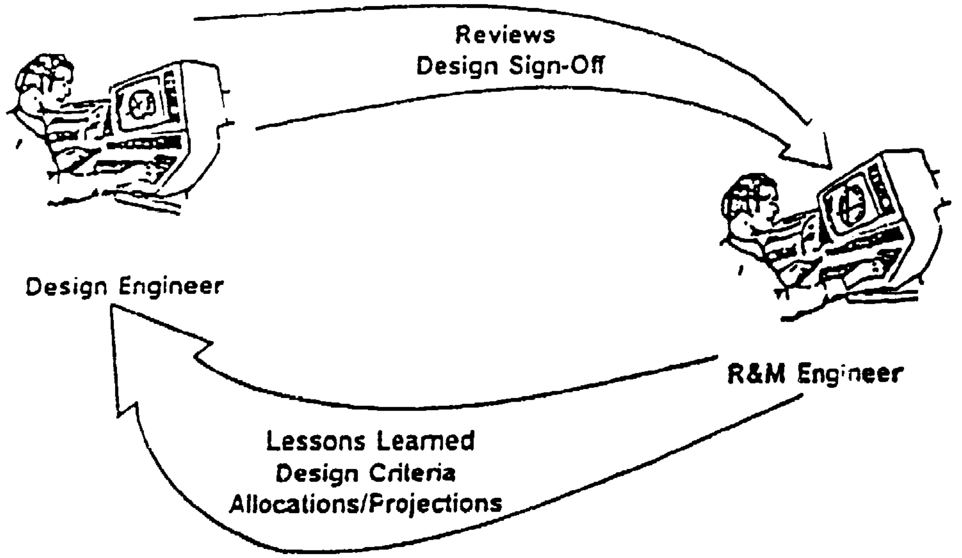
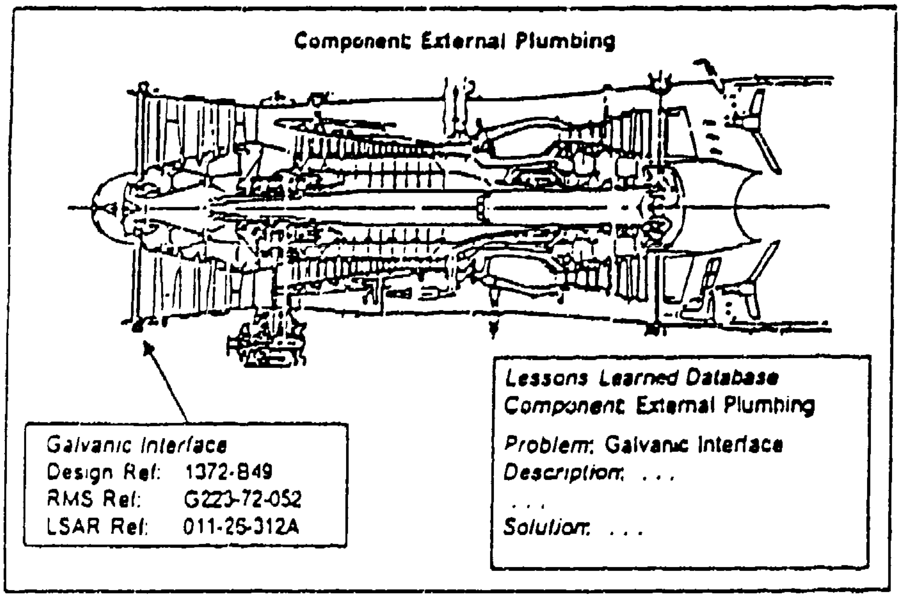


Figure 9. Automated Integrated System.

During the long term, the mechanical designer should have capability to call up on his or her workstation the Maintainability (and other functional areas as well) Lessons Learned Expert System and have it evaluate design for maintainability. If any part of the design possesses a "violation" of a Maintainability Lessons Learned from the Expert System, it is highlighted and the designer can then call up the specific experience being cited. The designer is, in effect, doing his or her own maintainability design evaluation (Figures 10 and 11).



Galvanic Interface
Design Ref: 1372-B49
RMS Ref: G223-72-052
LSAR Ref: 011-25-312A

Lessons Learned Database
Component: External Plumbing
Problem: Galvanic Interface
Description: . . .
. . .
Solution: . . .

Figure 10. Example of Future Reliability Call-Outs on Design Workstation.

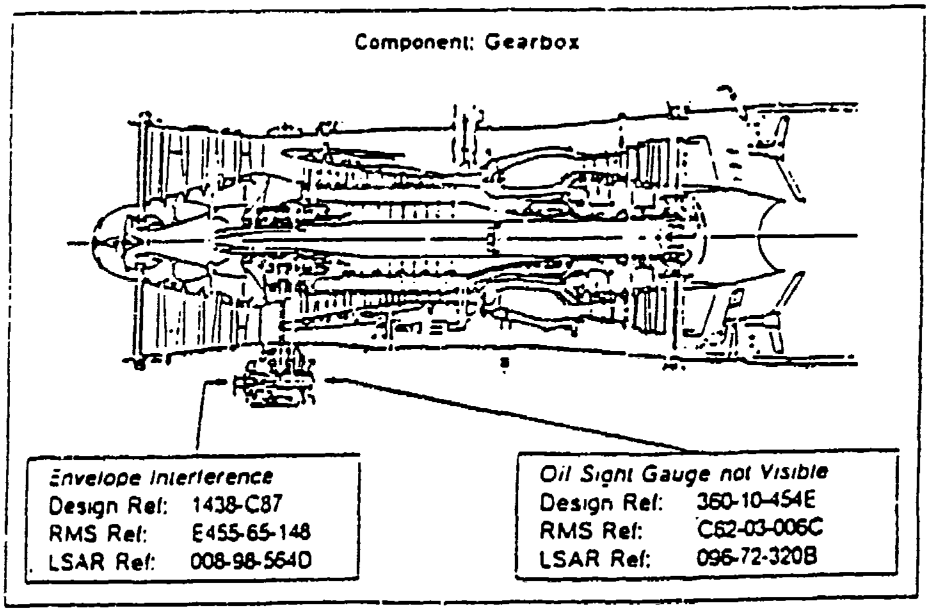


Figure 11. Example of Future Maintainability Call-Outs on Design Workstation.

The maintainability engineer now has the design on his or her CAD/CAM workstation and can use an advanced anthropometric evaluation tool (an enhanced CREW CHIEF) to evaluate accessibility, work space, and tools needed. He or she can call in a program option to simulate the removal and replacement of the part/subsystem/system with its associated task times being calculated automatically. The feature-based task times can be stored in a data base and accessed as needed, all automatically. The feature-based removal task data base can be accessed and any modifications can be made on-line by the maintainability engineer. After he or she is satisfied that the removal task is correct, it can be automatically stored in the LSAR data base. Thus, the labor intensive LSAR Maintenance Task analysis has been accomplished automatically. In addition, the CAD/CAM workstation can be used by the maintainability engineer to assess the LRU, subassembly, and module removal, as well as integration of the power plant with the airframe.

In addition to the integration aspects of CAD/CAM 3D modeling, the maintainability engineer can also call up the external plumbing and accessories drawings and check for interference, wrench swing, and other maintainability features.

The maintainability allocations can be done automatically based on previous history, and the maintainability predictions can be a natural fallout from the automated task analysis. Since this process is computer based, the maintainability engineer need only run an update when needed. This update will automatically access all of the designs needed and update the maintainability predictions if the design has changed. All of this will be done automatically in the envisioned far-term maintainability process.

WHAT WILL BE ACCOMPLISHED BY THE VISION

First, and foremost, the maintainability engineer's input and analysis can be concurrent with design. He or she can be assured that his or her "knowledge" has been used in the design. The prediction/allocations are done automatically along with the updates. The maintenance task analysis is now automated. All of these workstation automations free the maintainability engineer to look at the design concepts and work with the designer to fundamentally go beyond the current state of knowledge and improve the design even further with maintainability in mind.

TIMING/SCHEDULE

All the features mentioned in the near- and far-term visions can be accomplished by using technology available today. The hardware platforms required to perform the tasks are available but the software to perform the tasks needs to be developed. Pratt & Whitney's approach to automating maintainability is to implement the vision in incremental steps as shown in Figure 12. Each major milestone achieves a level of automation that can be used as it becomes available.

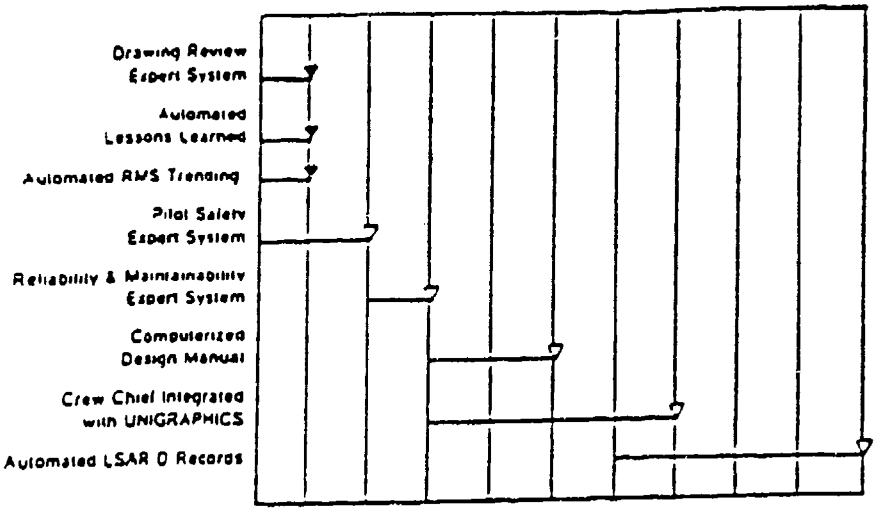


Figure 12. Pratt & Whitney's Maintainability Fully Automated by 1999.

SUMMARY

Maintainability engineering must become concurrent with the design process. To accomplish this, Pratt & Whitney has hired and developed highly-skilled maintainability engineers, initiated a maintainability Problem History File/Lessons Learned data base, and begun development of a rule-based maintainability design review system. This initiative will result in automated maintainability design reviews and automated maintainability tasks. This will free the maintainability engineer to concentrate on advancing the maintainability state-of-art.

EDGE: A CAD TOOL FOR SYSTEM DESIGN*

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ABSTRACT

EDGE (Ergonomic Design using Graphic Evaluation) is an ergonomic workspace design system which integrates several models of operator performance with a common graphic interface. In addition to serving as a practical design system, it also serves as a research tool for understanding the human system design task. EDGE users include both trained ergonomists as well as engineers responsible for the design of human-centered systems. A common input format, modeled after the traditional "work methods table" addresses the various input requirements of an expandable set of human performance models. Output from the performance models is displayed on multiple windows in varying levels of detail. Among the measures of physical stress currently integrated in the system are models of strength and three-dimensional torso biomechanics, NIOSH lifting limits, metabolic energy expenditure, and elemental time prediction. A primary EDGE objective is to provide ergonomic information to ergonomists and work space designers in formats conducive to their design activity.

* The work described here was performed at the University of Michigan Center for Ergonomics, with the author serving as co-principal investigator. The author is currently under contract to work with Center staff and industrial sponsors to ensure that the EDGE technology and related ergonomic models are integrated throughout the work space design process at major corporate sponsors.

INTRODUCTION

Concern for the human in design of larger systems such as automobiles or aircraft historically has focused on the driver or pilot. The worker involved in assembling or maintaining the system has traditionally received little attention. "Design for assembly" and "design for maintainability" are efforts to recognize the human cost factor of producing and maintaining these systems, assess the impact of design decisions on these costs, and improve the final design through early analyses of human system mismatches.

While automation, robotics, and automated test and diagnostic equipment have reduced the difficulty of some portions of production and maintenance tasks, many stressful aspects remain. This is particularly true of the physical aspects of these jobs where repetitiveness, awkward work postures, accessibility, or time constraints combine to increase the physical burden on the operator at the expense of product quality, reliability, or mission success.

Consciously designing production and maintenance work spaces for human operation is a complex process requiring the integration of information about processes, tools, work environments, parts, tasks, and human operators. In addition, design process and organizational hurdles, and ergonomic information availability and presentation are major limitations to improving the designs of manual work spaces.

A survey of ergonomic design practices among 40 workspace designers (Evans, 1985) identified specific design process limitations, as well as clearly stated needs for enhanced information presentation. Design process limitations include lack of specific information, e.g, clear design objectives, or sufficiently detailed information to perform the design; restrictive specifications, including insufficient clearances and floor space; lack of timely information for design decisions; and conflicting design information (e.g., frequent design changes). Ergonomic information requirements mentioned by the designers include (a) specific design guidelines or graphs for comparing preliminary design parameters against design criteria (e.g., load vs. location graphs), and (b) means for comparing the effects of single task parameters while fine-tuning designs.

To help engineers improve workplace ergonomics, several computer-based models have been developed to predict potential worker-job mismatches in the physical stress areas of strength, reach, endurance or time estimations (see Garg & Chaffin, 1975; Garg, 1976; and Karger & Hancock, 1982). While these models rely on similar descriptions of the work space, task, and operator to perform their own predictions, their focus has been on singular stress factors, and their unique input and output formats have made it cumbersome to consider interactions among stresses.

Several years ago, The University of Michigan's Center for Ergonomics initiated the development of an integrated ergonomic design system to overcome the limitations of poor or inadequate model integration, and to aid engineers untrained in ergonomics to understand and apply the complex computer models of human performance while designing manual workstations. The current Ergonomic Design using Graphic Evaluation (EDGE) system, being developed on a Micro VAXstationII workstation, is a product of this research.

This paper describes the EDGE system, its rationale, and applications. General issues for selecting such human performance models are also presented.

THE WORK SPACE DESIGN TASK

The development of EDGE has focused on three user interface objectives (ease of use, ease of learning, and consistency with the analyst's natural pattern of workplace design). These objectives have directed the design methodology for the EDGE interface toward the GOMS model of human-computer interaction (Card, Moran, & Newell, 1983). This model describes the user's procedural knowledge of the computer interface in terms of Goals (what the user must accomplish), Operators (the individual actions, such as pressing a key or moving a mouse), Methods (step-by-step procedures for accomplishing goals), and Selection rules (for specifying which method to use). This model is gaining acceptance as a method for determining what the user must know to operate a computer system.

At the very top level, the GOMS model was used to formulate what is involved in design tasks and ergonomic analysis. With this information an interface was structured for the conceptual needs of the user so that ergonomic analyses can be performed in a natural and efficient manner.

Based on previous research at the Center (see Evans, 1985; Evans et al., 1988), ergonomic design has been decomposed into a set of high-level activities, performed in an iterative fashion until the design is complete and an acceptable solution has been reached. The activities are presented in Figure 1 and include (a) identify work space design specification; (b) specify the manual tasks; (c) analyze the task; and (d) compare results with other designs or standards. Steps two through four, enclosed in the shaded area of Figure 1, are the portions of the design process supported by EDGE. Each of these has been further decomposed into lower-level design goals and addressed specifically through the user interface.

Specifying the manual tasks involves describing the task in a way that can be entered into the EDGE system for analysis. Because the design process does not necessarily follow a rigid format, the designer is not always prepared to enter all task information in a standard way. In addition, specification of all design parameters may not be necessary due to input requirements of the various ergonomic models. In general, the designer may need to specify the following types of information:

1. the task, as a series of elements involving actions, objects, and locations;
2. the operator characteristics, such as height, weight, and gender;
3. the criterion for task performance;
4. the task parameters, such as object weight, hand location coordinates, and frequencies; and
5. the initial values for the task parameters.

After the task has been described in sufficient detail, analysis of the work space may proceed. The analysis activities determine which task elements will be evaluated, and which analysis approach should be used, and specify any previously undefined task element parameters. The specific analysis approach may be determined by the expertise of the analyst. An expert may select specific models known to best apply to the problem domain, or the novice may prefer to allow the system to follow established routines which invoke all applicable or appropriate models.

Once the analyses have been performed, the designer evaluates the effectiveness of the results, either against previous design results or against design objectives and standards. The comparison is performed with respect to stated performance criteria or design objectives (e.g., 95 percent strength accommodation or back compression force below the NIOSH Action Limit). EDGE aids the designer at this stage by packaging the performance measures, parameters of significance, and criteria to highlight these relationships. The outcome of this comparison is either a completed design or a successive design iteration.

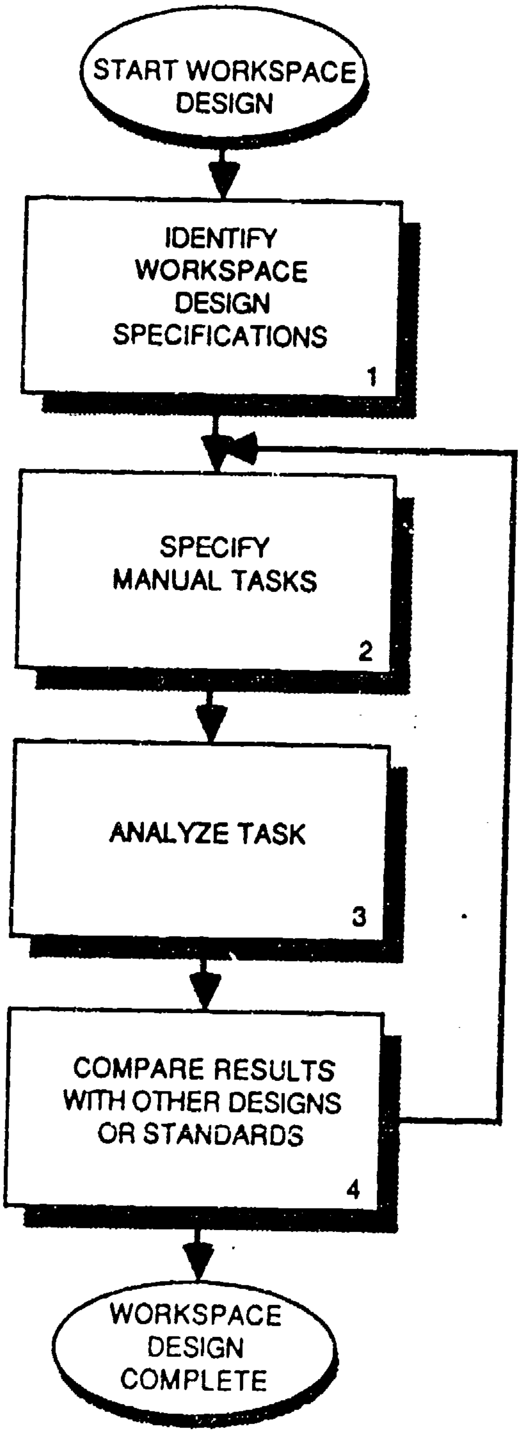


Figure 1. Top-Level Goals for Work Space Design.

The needs of the diverse user population will necessarily drive the development of the interface. Two user groups have been accommodated within system. One is the group of engineers responsible for manual work space design in industry, a group which, in general, has a fairly naive view of ergonomics. A secondary user of the system would be an ergonomics consultant, either within or outside the company; this group is well trained in ergonomics principles and can often find and solve many problems based solely on their own knowledge. The consultant's role differs from the role of the designer in that they will generally be alleviating known ergonomic problems and using the system to quantify the magnitude of the problem area and verify the improved solution. Thus, the EDGE system has been designed so that this user group will have the ability to do very specific analyses based on their knowledge of ergonomics.

Careful consideration of the user interface has been a major goal of this research. The ergonomic design task is complex and needs an interface which will support and guide the designer. Major emphasis is placed on development of graphical aids which support the interface, either through enhanced input, output or aiding techniques. The interface is intended to apply to a wide range of manual work space design and ergonomic evaluation activities. The current set of operator performance models interact with the interface, but are not bound to it. Models can be replaced or added without visibly changing the interface.

The EDGE System: Ergonomic Design Using Graphic Evaluation

The EDGE system employs this modular approach and uses existing models of strength, reach, metabolic energy expenditure, and elemental time prediction to aid in the design and analysis of manual tasks. Muscle strength requirements and low back compression force estimates are obtained from a variation of the 3D Static Strength Prediction Program (3DSSPP) described in Garg and Chaffin (1975). The variation includes a posture prediction feature which simplifies task input considerably. The posture prediction feature also serves as a mechanism for performing reach analyses. Biomechanical stresses acting at the lumbar region of the torso are modeled with an enhanced three-dimensional torso model (Chaffin et al., 1989). Strength and energy expenditure are combined for sagittal plane lifting tasks in a prediction of lifting limits provided by the NIOSH Work Practices Guide (NIOSH, 1981). Predictions of metabolic energy expenditure are based on research by Garg (1976). Elemental time predictions, used as input for other models, and as an overall measure of performance, are obtained from task heuristics and MTM-2 tables.

The basic EDGE system framework is shown in Figure 2. A designer interface serves as the bridge between the operator performance models and the designer. The interface is also the means for providing ergonomic information in formats of use to designers, and providing design guidance to aid engineers who are not trained in ergonomics. The framework is sufficiently flexible to allow the addition, deletion, or modification of performance models with only minor modifications to the EDGE system itself. Special-purpose subroutines handle the input and output to the individual models, and to related operator and work space graphic routines, human performance data bases, and design criteria. Operator performance models within EDGE share information pertaining to the operator, work space or environment, and task. The information categories, and their overlap among the current set of performance models, are shown in Table 1.

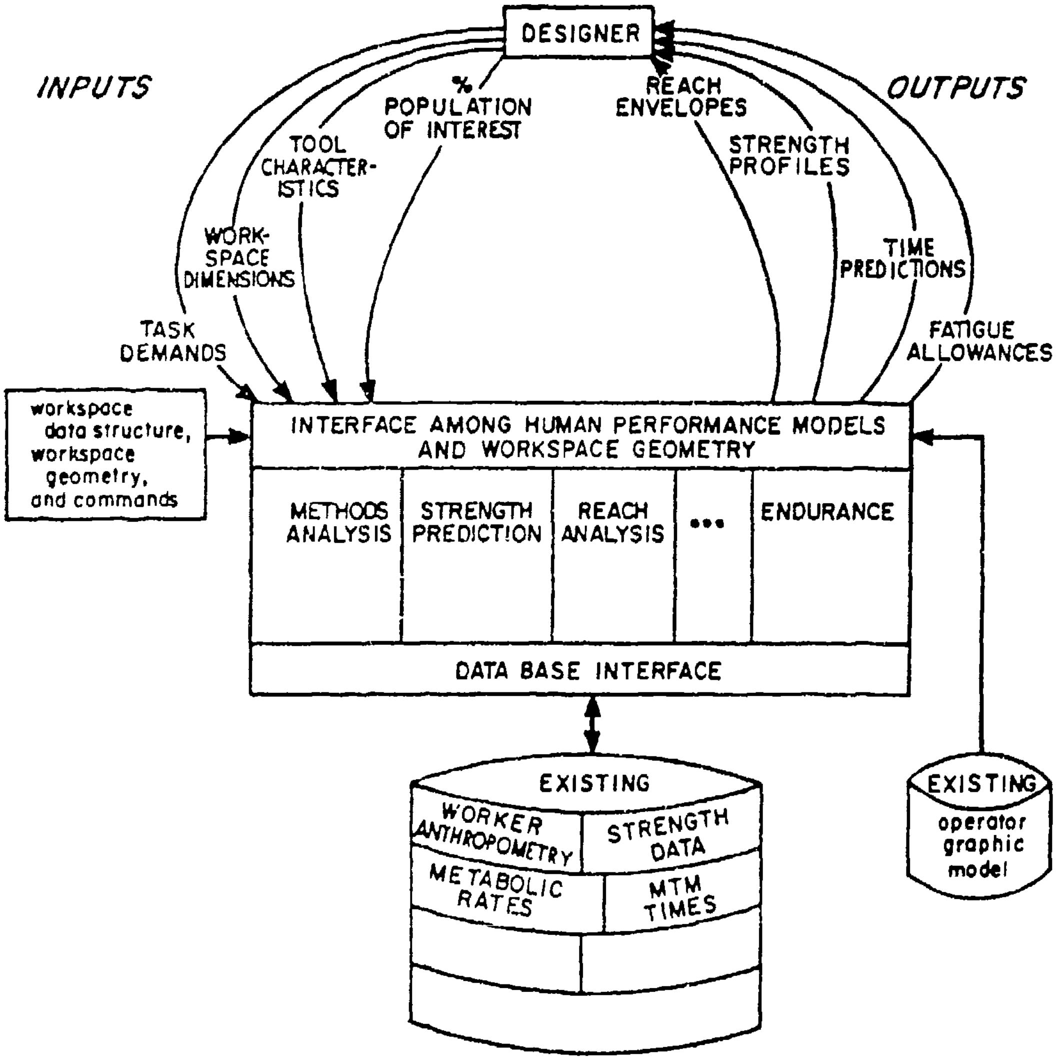


Figure 2. EDGE System Framework to Support Multiple Models of Human Performance in Ergonomic Design.

Table 1. Information Categories Shared by Selected Operator Performance Models in the EDGE Design System (Adapted From Evans, 1985, 1989)

Information	3DSSPP (Garg and Chaffin, 1975)	3D Torso Model (Chaffin et al., 1989)	NIOSH Lifting Model (1981)	Energy Expenditure (Garg, 1976)	MTM-2 (Karger and Hancock, 1982)
Operator:					
Age	I[1]	-	-	-	-
Size (stature, weight)	I	I	-	I	-
Strength	I	-	E	-	-
Reach, range of motion	E[2]	-	E	-	E
Endurance	-	-	E	O	-
Posture	I/O[3]	I	E	I	-
Task element					
Action	I(Direction of Exertion)[4]	I[5]	I(Lift)	I	I(Get/Put)
Frequency	-	-	I	I	I
Workspace					
Layout/locations	I	-	I	I	I
Clearances	-	-	-	-	I
Object					
Size	I	-	I	I	-
Weight	I	I[5]	O(Predicted)	I	I
Number of hands	I	I[5]	2 assumed	I	I
Handling characteristics	-	-	-	-	I
Performance Measures					
Muscle strength requirements	O	-	-	-	-
Balance feasibility	O	-	-	-	-
Torso muscle and back compression force	O	O	-	-	-
Reach feasibility	O	-	-	-	-
Lifting limits	-	-	O	-	-
Energy Expenditure	-	-	-	O	-
Time	-	-	-	-	O

NOTE:

I = Input parameter; O = Output value; E = parameter embedded within model.

[1] age embedded within strength profiles of 3000 industrial workers.

[2] in iterative mode, model will perform reach feasibility analysis prior to calculating biomechanical loading and strength of posture.

[3] iterative model allows input of general posture orientation, but produces detailed posture as output. Predefined postures include stand, sit, squat, deep-squat, stoop, lean, and split-leg.

[4] predefined exertions include lift, lower, push, pull, pull right, pull left, pull down, hold, torque-right, and torque-left. Users can also define their own exertion vector.

[5] implied through the hand force vectors.

System Components

The EDGE system contains a number of components which support the work space design process and facilitate the interface between models and designer. Among these components are 3D representations for the human operator, work space locations, and objects; a methods table for defining sequences of task elements; and operator performance criteria. EDGE uses the latter component, performance criteria, in evaluating model output and assessing design acceptability.

Operator and Posture. Operator profiles define the internal capabilities and structure of the operator model: its mobility, strength and linkages. Profiles can be modified by an experienced user if the design population differs from the default operator description. Kinematic data are currently embedded within the strength/reach prediction model (see Garg & Chaffin, 1975) preventing user modification. The operator consists of a 13-link model, with its origin on the floor at the midpoint between the ankles. Body segment lengths are expressed as a ratio of body height (stature) based on "average" ratios developed by Drillis and Contini (1966). Link enfleshment parameters, used to define the three-dimensional contours of the operator model during graphic display, are based on anthropometric breadth, depth, and circumference measurements, adjusted by stature.

A posture descriptor specifies the general body orientation for each task element. Posture descriptions completely define the body orientation, i.e., all 17 angles required to position the legs, trunk and arm segments in three dimensions. Angles may be explicitly defined by the designer to accommodate the restrictions or obstructions of the work space, or selected from menus of predefined postures. Inverse kinematics algorithms are being developed to automate and simplify the posture definition process.

Work Space Locations. At this time, work space geometries exist primarily as lists of locations. In addition to the 3D location reference point defined relative to the work space origin, locations also contain a location case, which specifies the expected object "fit" at the location and is used in determining the MTM-2 put movement code. The code distinguishes between Loose and Close fit, with the latter requiring some correcting motion to engage, as with assembling non-symmetric parts.

Objects. Objects apply to any number of locations or tasks, in any combination. Additional properties include object dimension, weight, handling code, handhold locations, and handhold case. Handling code identifies the ease of handling for use in predicting movement time. Codes differentiate between balanced, unbalanced or awkward to handle, or requiring extra care. Handholds are point-locations, defined in the object coordinate system. Handhold class defines the get movement class during movement time prediction, and identifies the type of handhold provided. Classes include (a) an adequate handhold exists for a power grasp, as with a tote box or cart handle; (b) location prevents power grip, but secure hold is possible, as with an ammunition cartridge; or (c) no obvious handholds: multiple regrasps needed to gain control, as with large awkward subassembly components.

Tasks. Task elements identify the action (as a direction of exertion), the specific object, work space locations and operator postures for origin and destination of exertion, and element frequency. Employing direction of exertion as the primary action verb is in contrast to the traditional MTM elements of reach-grasp-position. These whole body activities are more meaningful for the design applications and operator biomechanical and posture analyses considered by the system user.

Workload and Performance Criteria. Workload stress is the objective descriptor of operator physical performance under the specific combination of task actions, object weight, hand locations, frequency, and posture data supplied by the designer. Workload stress relevant to material handling and maintenance tasks include biomechanical (whole body and muscle strength, body balance, and low back stress), kinematic (whole body reach with body balance), metabolic (energy expenditure), and temporal or time and motion.

Ergonomic performance criteria define specific critical values or regions of acceptable stress levels. They are compared against the predicted task-related stresses in evaluating work space/task designs. Example criteria include the minimum population strength or reach percentile accommodated, the maximum allowable back compression force, the maximum allowable lifting limit, as a function of the NIOSH action limit, the maximum energy expenditure rate, or the maximum percent allowed for nonproductive or body-assist time per task element or cycle.

System Input

Task elements, consisting of action, object, location, posture, and frequency tuples, are entered onto a spreadsheet-like work methods table, such as shown in Figure 3. Separate windows appear for defining object dimensions or locations in the work space. Graphical templates are provided for predefined postures or actions/exertions to guide the user during the input process. A menu-based window environment manages the various input screens and forms. The user specifies the inputs once, and the system interface processes and reformats them for each individual model.

A common input format was established for addressing the input requirements of the varied human performance models. A "work methods table" was a common means already in existence for structuring industrial tasks and specifying task element sequences. The table metaphor has strong precedence in manual job analysis methods, and was adopted for the EDGE system as well. The table provides a verbal description of discrete tasks in a free formed manner. Table rows correspond to task elements. Cells within the rows expand to allow for detailed specification of object dimensions and weight, location coordinates, and hand location data used to describe the location-object interface. Additional cells are also available for user-defined annotation or comments.

Input screens are also provided for operator descriptions and design criteria specification. In the current system, operator anthropometry is restricted to values for height and weight. Given the expertise of the users, the design orientation of the system, and the fidelity of the models, this level of detail is appropriate. As the base of performance models supported by EDGE expands to include reach contours or visibility checks, more sophisticated methods will be required to more accurately depict operator anthropometry. The system accommodates design criteria and uses the criterion for evaluating model predictions and comparing designs. The user supplies or uses default values for male and female strength accommodation levels, maximum back compression force, energy expenditure, or target elemental time.

System Design Tasks

EDGE provides the designer with several specific functions for evaluating work space and task configurations. The functions or design tasks are selected based on the nature of the operator's tasks and the types of physical stresses affecting performance. Specifically, the design tasks:

1. evaluate operator physical stress during a single task;
2. evaluate the cumulative stress during repetitive tasks;
3. perform "what-if" analyses by varying task parameters; and
4. compare operator performance over two or more task designs.

While several performance models are provided in the system, all models do not uniformly apply to all task elements, (e.g., the NIOSH lifting model applies only to lifting elements). The system indicates which models are available, appropriate, and are ready to run based on completely defined data (e.g., the elemental time prediction requires location-object pair data corresponding to fit and grasp, information not required of any of the other performance models). Default data are available and can be used in running the models as well. Elements can be analyzed as discrete elements, (e.g., for the biomechanical strength prediction model) or as a contiguous sequence (e.g., for the metabolic or elemental time prediction models). The designer selects the operator tasks to analyze, and then selects the performance model using the cells in the left columns adjacent to each task element (as shown in Figure 3), or lets EDGE execute all applicable performance models.

EDGE provides for "what if" analyses by allowing the designer to vary task or work space parameters along specific dimensions. Output formats aid in identifying the trends in design outcome, interactions among parameters, and overall design result in light of workload and performance criteria. As the design progresses, and parameter changes affect performance, the designer can periodically stop and review the results and compare the cause-effect relationships of the design iterations. The outcome helps to delineate further areas for investigation.

System Output

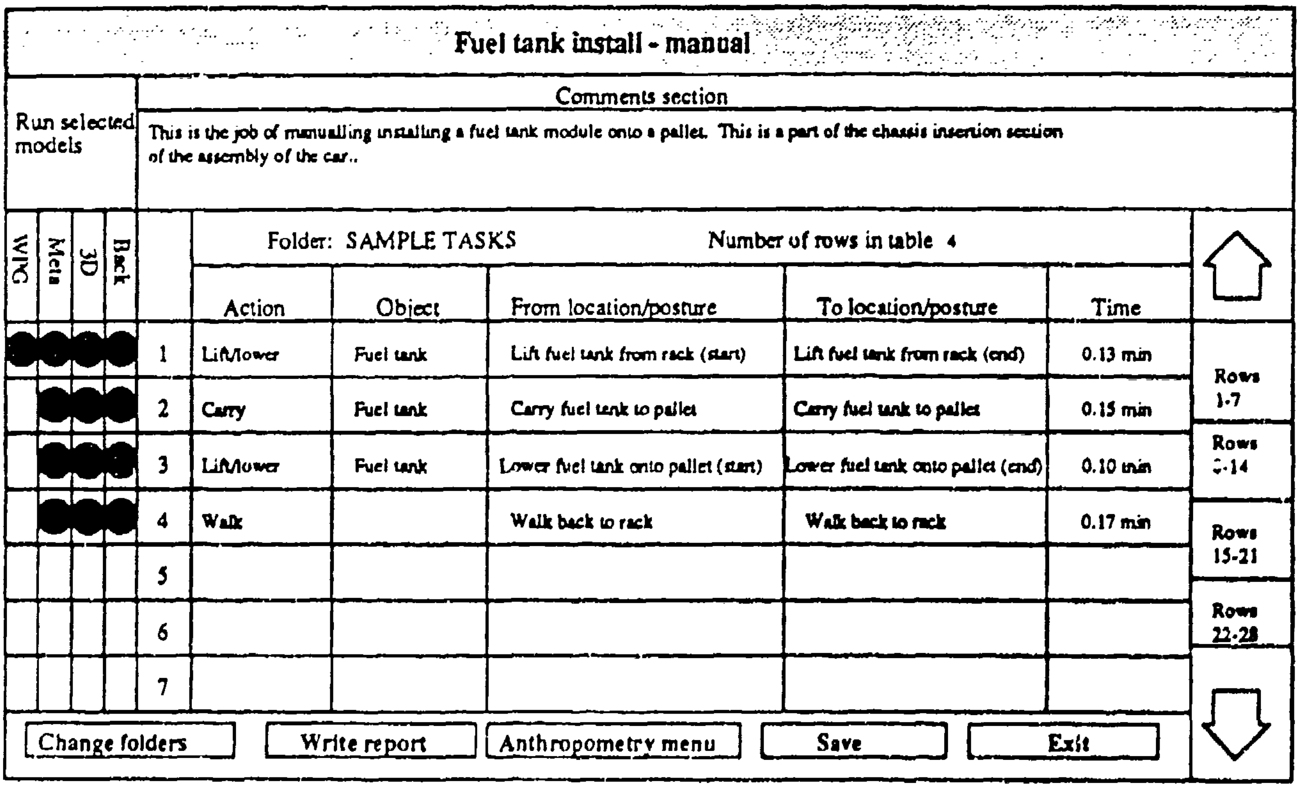
Primary ergonomic output displays employ two-dimensional graphs to show trends and three-dimensional layouts to project the enfleshed operator within the work space. The objective is to avoid overwhelming the designer with too much detail. Formats for system output correspond to the design tasks just discussed. They have been constructed to aid in detecting design deficiencies, diagnosing the possible cause, and correcting the problem.

Preliminary output screens provide performance and workload results at a very general level, across tasks if appropriate. They indicate exceptions or unacceptable cases which deserve further attention. EDGE identifies "exception" tasks by comparing performance model outcomes against stated performance criteria. Figure 4 shows a sample primary output screen. The "AL" notation in the 3D Strength columns indicates that the predicted strength accommodation level failed to meet the NIOSH Action Limit guideline to avoid the risk of musculoskeletal injury. Data would be separated for males and females.

Subsequent displays focus on specific parameters within stressful tasks. As individual tasks are selected, a three-dimensional operator graphic depicts the posture with the object and hand location information. Muscle strength percentiles are coded based on stressfulness and superimposed over each joint, providing a direct mapping between stress and body location. The combination of display formats and user control over what is presented leads to quick identification of task element high drivers, and directs the designer's attention to the critical parameters to change.

ISSUES FOR DESIGN MODEL SELECTION

The relative recency of these integrated design models and the interest in their development should drive system designers to ask questions of model developers and of themselves to identify their model needs. They need to identify the people who will be using the human performance models, what their skills are, and where they fit in the overall system design process. The amount of time available to study design issues, the quality and quantity of information available, the expertise of the designers, and the corporate Computer-Aided Design (CAD) culture all influence how the model will be used, if not which one applies. These issues are discussed in more detail above.



Fuel tank install - manual

Comments section

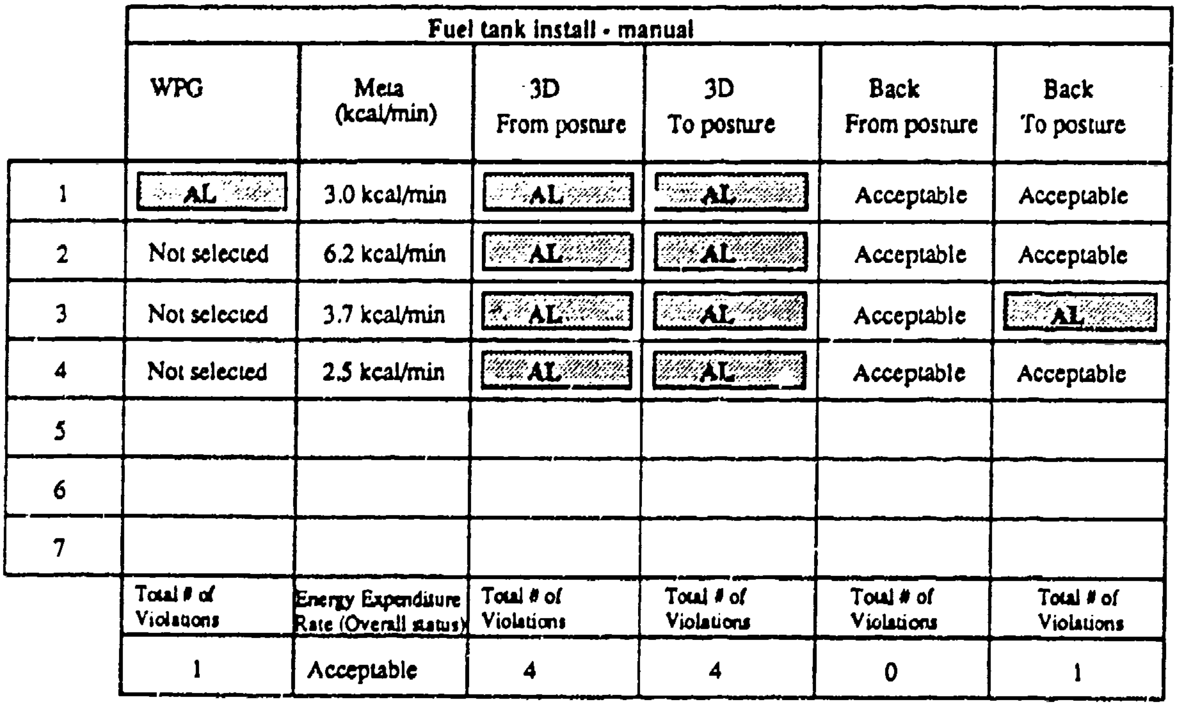
This is the job of manualling installing a fuel tank module onto a pallet. This is a part of the chassis insertion section of the assembly of the car..

Folder: SAMPLE TASKS

Number of rows in table 4

WIPG	Meta	3D	Back		Action	Object	From location/posture	To location/posture	Time
●	●	●	●	1	Lift/lower	Fuel tank	Lift fuel tank from rack (start)	Lift fuel tank from rack (end)	0.13 min
	●	●	●	2	Carry	Fuel tank	Carry fuel tank to pallet	Carry fuel tank to pallet	0.15 min
	●	●	●	3	Lift/lower	Fuel tank	Lower fuel tank onto pallet (start)	Lower fuel tank onto pallet (end)	0.10 min
	●	●	●	4	Walk		Walk back to rack	Walk back to rack	0.17 min
				5					
				6					
				7					

Figure 3. Work Methods Table Input Window for EDGE Task Entry.



Fuel tank install - manual

	WPG	Meta (kcal/min)	3D From posture	3D To posture	Back From posture	Back To posture
1	AL	3.0 kcal/min	AL	AL	Acceptable	Acceptable
2	Not selected	6.2 kcal/min	AL	AL	Acceptable	Acceptable
3	Not selected	3.7 kcal/min	AL	AL	Acceptable	AL
4	Not selected	2.5 kcal/min	AL	AL	Acceptable	Acceptable
5						
6						
7						
	Total # of Violations	Energy Expenditure Rate (Overall status)	Total # of Violations	Total # of Violations	Total # of Violations	Total # of Violations
	1	Acceptable	4	4	0	1

Figure 4. High-Level EDGE Analysis Output Window for Sample Task.

Who Will Use the Model?

Decisions impacting the human-systems interface are generally made by several diverse groups located throughout the organization and the design process. The impact of these decisions may go undetected until the pieces are assembled at system mock-up, or later. Clearly, the need exists for design decision aids which answer the questions of physical stress within the current design structure, whether it is the traditional serial process or follows the concurrent engineering model. Often, in the interest of tight time frames and reduced human factors manpower, this means that the models and tools will be used by persons trained in industrial or mechanical engineering rather than ergonomics or human factors. The choice of system user has implications for the type of interface and the types of analyses. The human performance expertise should be provided to the designer (via expert systems or enhanced decision support systems), whenever possible, rather than expecting users to come to the system already endowed with it.

The EDGE framework assumes that the system would be available to and used by all designers, as well as any in-house ergonomic experts. The interface has been designed to address both groups, providing structure and assistance to the untrained, and permitting free-form input and analysis selection for the expert.

How Easy/Difficult Is It To Use?

Ease of use is influenced by the complexity of the model inputs and the design assistance provided by the output. Cumbersome or complicated input requirements, coupled with the time constraints of the design process, and the impatience and inexperience of the designer will preclude a model's use in all but the most severe cases. For example, automatic posture prediction, although often limited in fidelity, is adequate for rough posture estimations in the first iterations. This is especially true when the alternative requires inputting 20 angles in a range of local coordinate systems. Similarly, the availability of well-documented system defaults and design templates will aid the user in the initial stages of design.

Model output should also support the design process. At a minimum the output should provide for detection of design problems. At the least, this involves comparing model output against available criteria and displaying exception cases or outliers. An example would be highlighting a task which yielded a muscle strength prediction of only 10 percent capable. A further step requires that the output aid in diagnosing the problem. With the above example, the system would locate the body region which is limiting the strength capability, in this case the shoulder. A final aid would provide remediation Here the system suggests a course of action to alleviate the problem. In this example, based on the exertion at the hands (30 pounds) and the posture (standing with arms extended), the system suggested that the load location be brought closer to the body, reducing the horizontal distance. In many current systems, the first two interventions are possible. The third is considerably more difficult, particularly when multiple factors are involved, yet is worth working toward.

Is It Compatible With Other Systems?

Human performance issues cover many dimensions which often interact. The EDGE system is an attempt at combining several measures of performance within the related domain of physical stress models. Problems arising in such integration efforts include consistent model structures (e.g., compatible link systems or angle notations), level of information detail (tasks described at the THERBLIG level (e.g., reach, grasp, position) versus aggregated actions (e.g., assemble)). Other models are appropriate within a given man-machine interface design as well. A challenge for model developers will be to investigate means by which these diverse models can be integrated together to assess overall operator performance in complex systems.

Independent of other areas of performance, the models should be developed to work within the intended CAD environment. The advantages for the models are immediate access to design data, such as work space geometries, part dimensions, process or methods standards, or previous designs. The advantage for the designer is immediate access to the answers within current design activities.

CONCLUSIONS

The EDGE system provides a valuable tool for the design of workstations where operator physical performance is an issue. There is, however, considerable room for enhancements to better represent the human operator, and to address the needs of a range of system designers.

Future research is needed to develop enhanced performance models which reflect a wider range of task conditions. The biomechanical strength prediction models presented here reflect static, or slow, controlled exertions. Predicting performance under dynamic exertions is the next step. Research is needed to develop models which reflect both dynamic responses and dynamic strength capabilities. Both static and dynamic models are in need of improved posture prediction algorithms which accurately reflect the body kinematics under loaded conditions. While "snapshot" images of operator postures may be acceptable for static exertions, dynamic activities require techniques for operator animation which depict the operator's task-oriented postures over time.

The focus of these models should be on both preliminary and detailed design. The burden of supplying input information for existing models hinders their use in preliminary design, when the quantity of operator, task, and environment information is often too limited to meet the model's requirements. Catalogues of previous designs, used as templates for preliminary design may be one solution. Design integration with existing company CAD data bases is also essential to make the models available throughout the design process, and to eliminate the need for redundant input of previously defined layouts, object geometries, or corporate standards.

Finally, the technical expertise of the model user should be considered in developing interfaces for a wider range of system designers. Expert design aids which assist in detection, diagnosis, and remediation should enhance the process for all designers, as well as for the operator, the ultimate recipient of the improved design.

The EDGE system represents a significant effort aimed at providing ergonomic information to ergonomists and work space designers in formats conducive to their design activity. It has integrated several relevant measures of operator performance within a consistent graphical interface and sought to realistically reflect the domain of design problems encountered in industry today. Coordination with industrial sponsors and intended users serves to reaffirm its relevance as a design tool and ensure its integration with the overall design process. Future efforts will link the EDGE system with existing corporate design systems, providing immediate access to part and facility layouts, production standards, and methods tables, and produce ergonomic analyses as part of existing work space design activities.

ACKNOWLEDGMENTS

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HUMAN PERFORMANCE MODELING: AN INTEGRATED APPROACH

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ABSTRACT

The life-cycle cost of military equipment (or for that matter, civilian equipment) is determined during the design phase. Computer-Aided Design (CAD) packages facilitate the layout or mechanical design of equipment, also providing the ability to make quick changes without the inconvenience of redrawing the entire design. Mathematical models evaluate the dynamics of the potential design or its components before actually building a prototype or testing it. Lately, there has been a move to provide anthropometrically and biomechanically correct models of the human beings that will use the equipment. In fact, some of the more sophisticated human figure models include strength, vision, reach, and animation modules. In addition, there are physical and cognitive models of a human's ability to perform tasks (task analysis and workload models).

However, a problem exists for the user of these models. In general, the models are separate entities, available on a variety of incompatible hardware platforms, frequently written in incompatible languages (making translations impractical). Little or no thought is given to the fact that each model contributes to the overall design process. Thus, the need exists for integration of the total operation. This paper proposes a practical approach for consolidating the modeling, hardware, and software issues into a manageable entity, keeping in mind the needs of potential users, that is, the engineer-designer, the human factors specialist, and those developing requirements for new pieces of equipment.

HUMAN PERFORMANCE MODELING: AN INTEGRATED APPROACH

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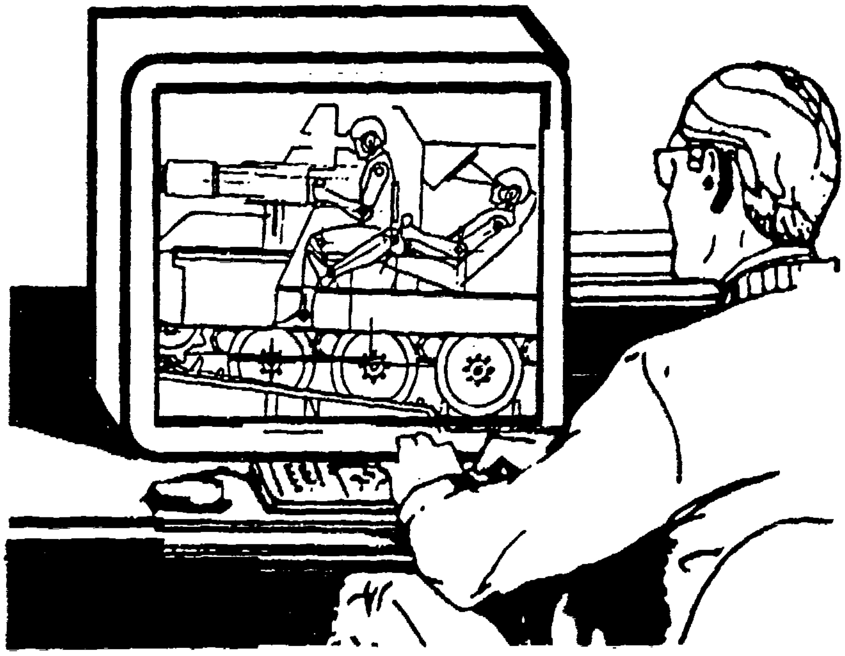

Over the next several years, the Department of Defense (DoD) will spend millions of dollars developing physical mock-ups of a wide variety of new hardware, ranging from infantry weapon systems with varying degrees of complexity to all types of ground, air, or sea vehicles. The DoD's current and future challenge in materiel development (and in training) is how to influence and manage the development of new technologies with less people, time, and money. To meet this challenge, the DoD has a need for methods and procedures that provide front-end consideration and analysis of human performance requirements. A promising technology is human performance modeling that simulates and animates the interactions among operators, tasks, materiel, and environment. Significant hardware (and training) development costs can be avoided if new human performance modeling tools are applied at the beginning of a system's development rather than in the middle or at the end.

Current hardware and software technologies have made people the limiting factor in the effective operation and support of materiel. Studies show that, in many situations where equipment and system failures were believed to have been caused by human error, the error was in fact a result of the equipment or system being developed with little or no consideration of the capabilities of the people who were to operate and maintain it in a field environment.

The reasons for this are many and include time constraints, limited budgets, lack of knowledge, information gaps, and especially a lack of analytical tools. DoD has a need for methods and procedures that aid and inform designers, trainers, developers, managers, and decision makers. There currently exists the capability to simulate mechanical parts and whole materiel systems, sometimes within accurately represented environments. This is done by taking system descriptions--often computer-aided design (CAD) drawings--and performing such procedures as finite element analysis and, for example, in the case of ground vehicles, simulation of vehicle travel at varied speeds over varied terrain. These simulations can yield keyframe or animation imagery that aid the designer in identifying potential weaknesses in mechanical design. If a man-machine system is being designed or evaluated, however, it is clear that the total system is not being accurately simulated since a crucial factor, the human, is omitted. The first solution to this shortcoming is the development of a dynamic ergonomic model that accurately represents the human figure both anthropometrically and biomechanically.

The ability to simulate a dynamic human figure by simply using a computer can be a powerful tool in predicting and understanding how people will interact within a given environment. It is important in the DoD to perceive how well a "soldier" would accomplish a mission in a given environment using the materiel provided and to design new equipment to enhance the soldier's effectiveness. Knowledge of the design constraints imposed by human body size, including the encumbrances caused by various clothing ensembles, and physical limitations is important to materiel developers in understanding the interaction between human performance levels and equipment design.

A second element of the man-machine design or evaluation problem is the need for a dynamic strength model that accurately represents both the physical strength and the dexterity requirements to perform various jobs. For maximum utility this strength model should undoubtedly be a submodel of the ergonomic model.

A third element of the man-machine design or evaluation problem is the need for a vision model. The vision model must be capable of addressing both vision and lighting issues ranging from the use of relatively simple sighting systems on combat rifles, to the field of view requirements for instrument displays, and to the use of indirect vision devices. This vision model should also undoubtedly be a submodel of the ergonomic model.

Another element of the man-machine design or evaluation problem is the need for a model that properly represents the cognitive attributes required by the operators of the equipment. The most sophisticated system in the world is useless if the "soldier" can't operate it. The Army Research Institute's HARDMAN model should play a significant role in human performance modeling

Equally important, for the combat developer who proposes a requirement, and the engineer-designer who develops the hardware, as well as the human factors specialists, is the ability to understand task and workload implications, either overload conditions or workload transition issues, for the human operators The engineer-designer and the combat developer must understand the implications of adding automation to the system. Automation does not necessarily reduce the task load of the operator. Designers and those developing requirements must also understand the effects that automation may have on space claims in a vehicle.

A predominant problem in applying many of the models that are in use today is that the models and submodels exist as separate entities. Almost everyone who develops them looks at their own little piece of the picture but no one looks at the whole picture and no one considers the user who must address a wide variety of issues. Integration of the different human-related models and submodels will allow everyone involved in the design process to look at the human's influence in a particular design.

An additional challenge is the integration of human-related models is their integration with computer-aided design/engineering models. One major advantage of integrating computer models of the human with computer models of hardware design is that "what if" analyses can be performed. Changes in the system design can be made on the computer and the engineer-designer can look at the impact of the changes on both the system and the human using it, all without the time and material expenses associated with building prototypes.

Another significant integration problem that exists for including human performance modeling in hardware design is the lack of agreement on which hardware platforms and programming languages should be used. While CALS (Computer Aided Logistics System) is attempting to develop standards for general software development, geometric based software which is the foundation for CAD programs and human figure/performance models is not currently a part of CALS "grand design." By the time CALS gets around to this type of software expensive decisions on software and hardware will already been made. Design is a visual process and it would be in the best interest of the human performance modeling community to select a hardware and software platform that provide extensive support to the visual process.

Members of the human factors community are currently using an assortment of evaluation techniques ranging from the placement of crude two-dimensional mannequins on blueprints to employing a variety of hardware and software systems to perform their evaluations. Those hardware engineers-designers that have actually moved out of the "dark ages" of pencil and paper designs manually placed on blueprints to the enlightened age of computer-aided design have already selected hardware and software systems for developing their designs. Getting the various CAD systems to "talk to one another" should be a top priority so that data files can be exchanged. Very few users have either the money to buy all the different systems or the time to learn them.

One of the best attempts at integration of human-related models is the MIDAS concept being developed by the Aeroflight Dynamics Directorate at NASA-AMES. But even MIDAS employs a wide variety of hardware and software and programming languages. Admittedly all MIDAS's hardware and software "talk" to each other. But, few can afford the inherent costs of such a system.

The Human Engineering Laboratory (HEL) at Aberdeen Proving Ground, Md.,as the Army's Lead Agency in human performance modeling, is moving forward in this area. HEL has selected a hardware and software platform and initiated a program to develop a technique for simulating the interactions among operators, tasks, materiel and their operating environment. HEL's Human Performance Model (HPM) program is based heavily on the use of *Jack*, a three-dimensional Computer Aided Design (CAD) ergonomic model developed by the Computer and Information Science Department at the University of Pennsylvania under the direction of Dr. Norman Badler. *Jack*, which runs on a Silicon Graphics Iris 4D computer workstation, is being developed for a number of civilian and Government agencies.

Jack is a program which displays and manipulates articulated geometric figures. *Jack* has many different aspects such as facilities for constructing geometric objects, positioning figures in a scene, performing various types of analyses with the figures, and describing motion of the figures. Within *Jack* there are also facilities for specifying lighting and surface property information, and for rendering high quality images.

Jack is primarily an interactive system. It is predicated on the belief that geometric operations are best performed interactively and graphically. Most operations in *Jack* use the mouse, both to pick commands from menus and to specify geometric transformations. Parameters and values may also be entered directly from the keyboard.

Jack provides an anthropometrically and biomechanically reasonable representation of the human body. The *Jack* figure has progressed from a simple "skinny body" representation composed of 112 polygons based on NASA data to the current "contour body" representation composed of nearly 5300 polygons based on data from the Air Force's Armstrong Aerospace Medical Research Laboratory (see Figure 1). Body dimensions are accessed and manipulated by means of Spreadsheet Anthropometric Scaling System (SASS) (see Figure 2). SASS can accept data from any population. For example, the results of the latest (1988) Army Anthropometric Survey (ANSUR) can be entered into SASS for use by those designing systems for the Army population.

Jack enables the analyst or designer to perform several types of human factors analyses in three dimensions. These analyses include tests of whether the soldier will fit in the system, whether the soldier will be able to reach controls and mechanisms, the soldier's field of view (see Figure 3), and whether the soldier has enough strength to operate or maintain the system and perform his tasks. Each analysis is important in evaluating a soldier's ability to use the materiel being developed.

Traditionally, analyses such as these had to be performed using paper and pencil or by placing crude two dimensional mannequins on blueprint drawings of the system being tested. In either case, blueprints had to be tediously redrawn each time a new design option or solution needed to be evaluated. Many problems were missed because the analyst or designer never really got the whole picture until an expensive (in terms of time and materials) mock-up of the system was built. By the time a mock-up was built, design options and solutions were limited because of the difficulty and expense of rebuilding the mock-up.

Jack also has an animation feature which is useful in depicting the postures and movements that each soldier would go through in performing a set of tasks in his or her operating environment (see Figures 4, 5, 6). Animation of the system design can aid the designer in visualizing the operator dynamics and interactions with the system. Interactions among soldiers can be inspected frame by frame if desired and at any scale or from any viewpoint. The animation sequences can be replayed and reanalyzed as required. Images in *Jack* can be viewed as wireframe drawings or fully rendered, solid objects.

By using a system like *Jack*, the designer can take easy-to-alter computer design drawings of the system and perform human factors analyses in three dimensions allowing him to better identify problem areas early in the design process. He can then change the drawings of the system and investigate a myriad of design options and solutions in a relatively short period of time, with time to make the changes on the computer being the only cost.

By building computer models early in the design cycle, the DoD can avoid having to build physical mock-ups of the actual situation or environment. This does not mean that mock-ups are useless, but early on, the designer may not know where people and items will be placed inside the environment, and it's much more flexible to have a computer graphics model that can be changed, instead of going to a machine shop and having them retool a portion of the mock-up.

While *Jack* is a very complex model, the interface has been designed to make it user friendly and easy to operate. An average user should be able to operate *Jack* with about 2 days of training

The basic premise of *Jack* and of human performance modeling is that better system designs will result from enabling designers to explore more design alternatives and to evaluate these designs before constructing costly and time consuming prototype hardware. The goal of the human performance model is to produce computerized figures which can be manipulated and animated easily, so that they perform tasks in a working or operating environment.

Finally, there are questions that management should be asking in regard to human performance modeling. There are suggested answers to some general questions and some questions that each organization must answer for themselves.

(1) What are the rewards of human performance modeling?
   - avoid costly design mistakes before building prototypes
   - faster and less costly development by reducing demand for early fabrication
   - substitutes faster, less expensive front-end evaluation
   - more thorough and frequent testing without additional labor or disruption of organizations

(2) What are the costs and risks?

- the major cost is the investment in hardware, but the hardware will probably be bought anyway for other purposes; the risks are low - the current way of doing business is slow, expensive and inaccurate - things can only get better

(3) What does DoD invest in?
- the hardware - which is probably going to be purchased anyway, and software development - which can be a shared investment among Government agencies and industry (Industry is already out there making use of these new techniques.)

(4) How much fidelity is needed?
- if the current design and manufacturing process placement of controls, instruments. etc.deals with the resolution of inches as "good enough", does the human performance modeling need to be accurate to the half millimeter?

(5) How is human performance modeling to be integrated with other modeling?
- as mentioned previously, a high priority should be getting the various CAD systems "talking" to [illegible] another to ease data file exchange.

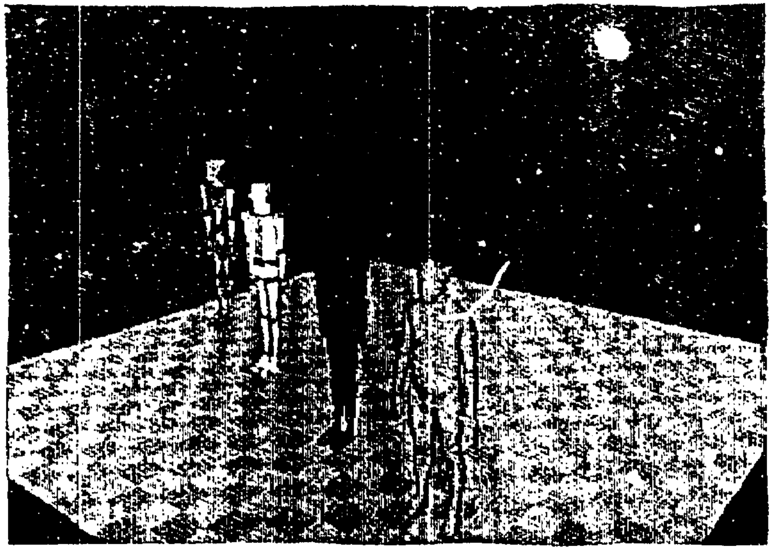

Figure 1. Evolution of the JACK Human Figure Model.

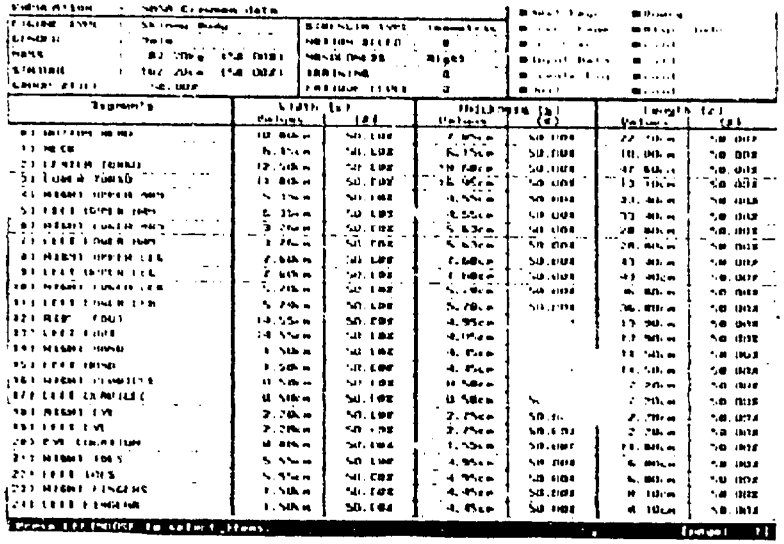

Figure 2. Example of SASS Data.

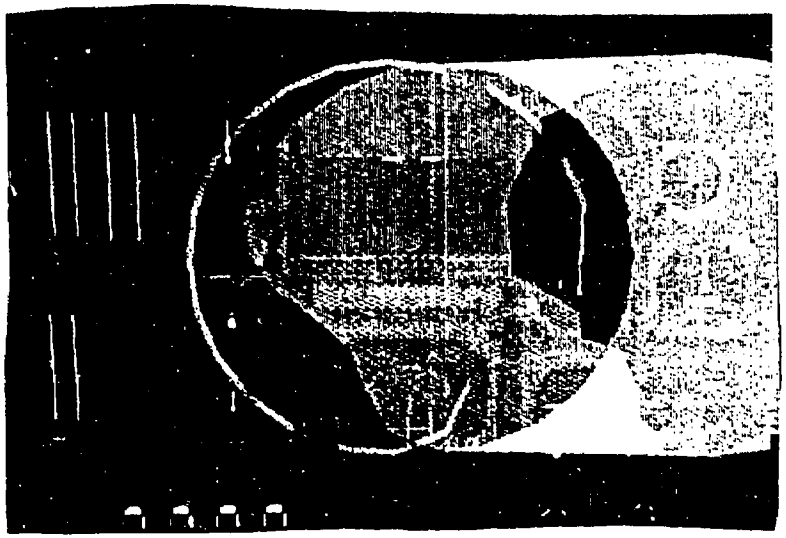

Figure 3. Example of Field-of-View Capability.

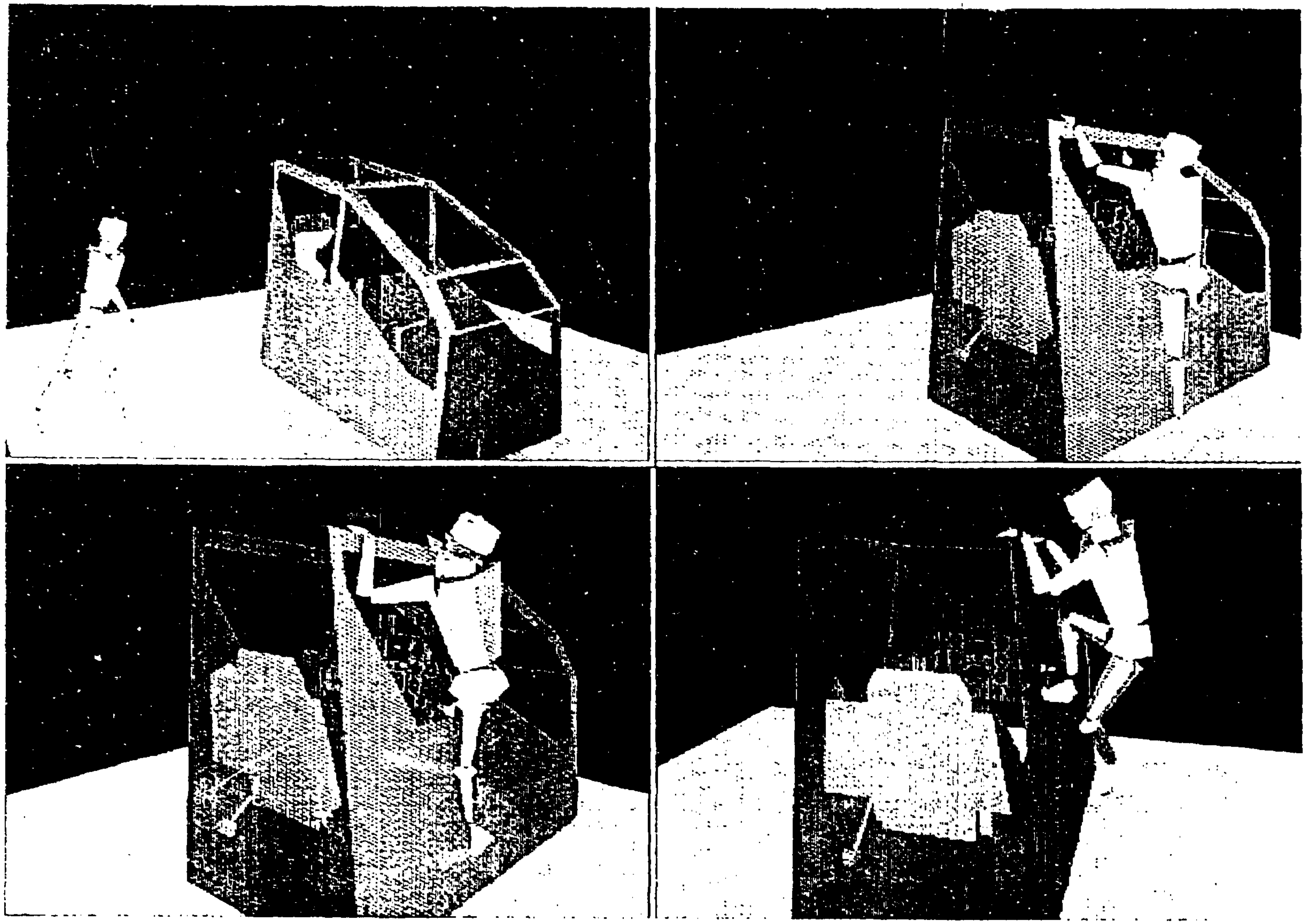

Figure 4. JACK Figure Integrated into CAD Files of Apache Helicopter (CAD files courtesy of NASA/AMES Aeroflight Dynamics Directorate).

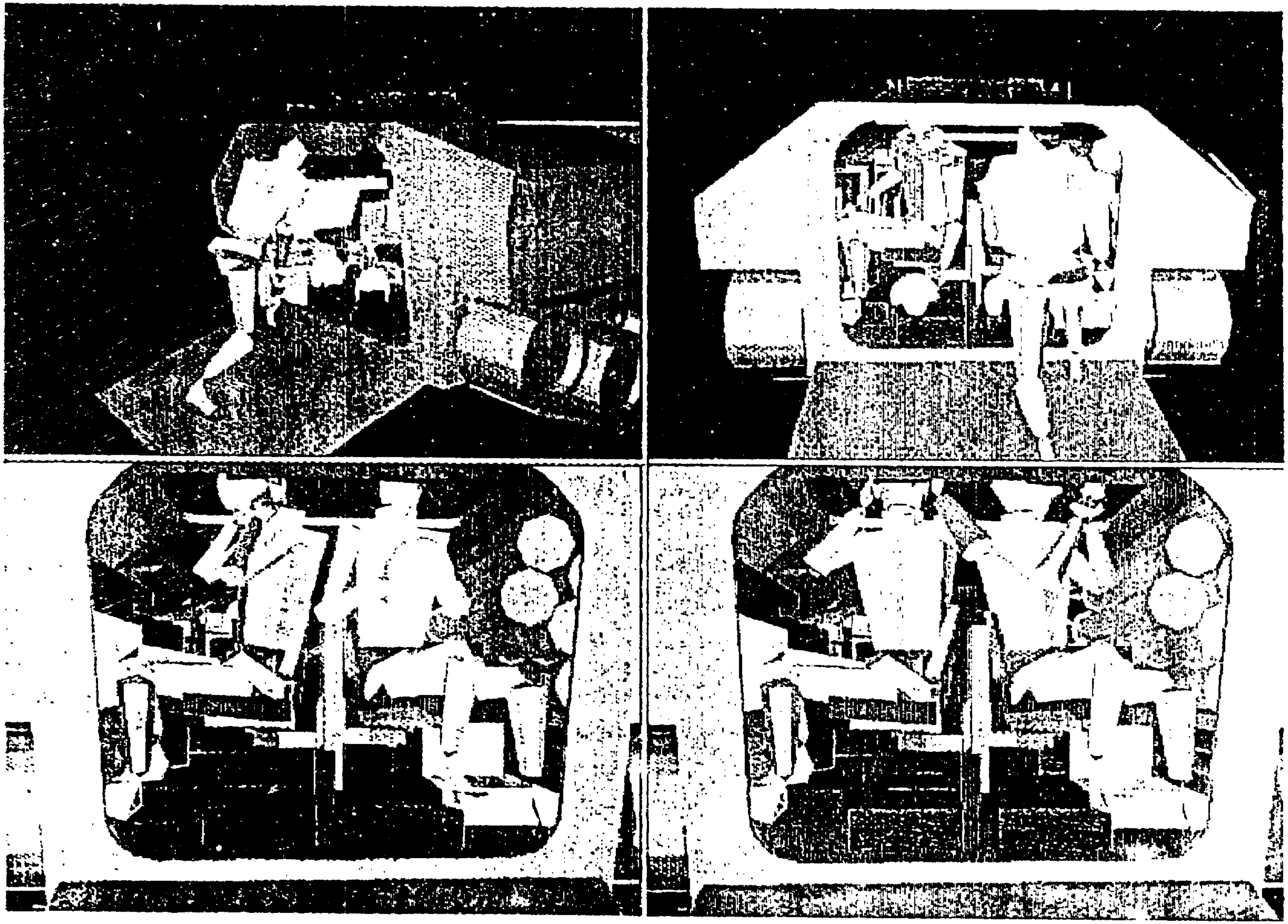

Figure 5. JACK Figure Integrated into CAD Files of Bradley [illegible] Fighting Vehicle
(CAD files courtesy of FMC Corporation).

TASK INSTRUCTIONS AND ACTION DESCRIPTIONS

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ABSTRACT

In this paper, I discuss natural-language task instructions and their relationship to human task behavior. While natural-language instructions, as action descriptions, are underspecified in many ways, they are unsurpassed in specifying the reason for behavior, if not its actual physical instantiation. Thus, natural-language instructions can serve as a resource for both human behavior and high-level control of animation.

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INTRODUCTION

In order to maintain equipment, people have to know *how*. One way of telling them this is through *instructions*. Or is it? Do instructions lead to the behavior that their designers intend, or are they merely a last resort – consulted only when all else fails? What is it that instructions can do for agents, and what is the consequence of this for designing equipment for maintainability. To address at least some of these questions, in this paper I will describe some work which tells upon

- the relationship of instructions, plans and behavior
- instructions and the beliefs they lead to
- the consequences for how instructions are designed and presented.

PLANS AS PROGRAMS

In early work in Artificial Intelligence, plans were viewed much like standard computer programs. Such plans were the output of *planning systems*, which used algorithmic and heuristic methods to build them from parameterized primitives (actions and tests) using composition operators indicating either serial execution, conditional execution, or repeated execution. Given such a plan, an agent (such as a robot or a person) was taken to execute it much like a computer would execute a program. That is, like a program, a plan was taken to both describe and control behavior.

David Chapman, in a 1987 paper (Chapman, 1987), has pointed out a number of problems with this *plan as program* view.

1. For planning systems, building such plans poses computationally intractible problems.
2. The plans that are produced are inadequate in a world which is characterized by unpredictable events and situations (that is, the real world). Actions don't always work as intended, and the world can change independently of an agent's actions.
3. The plans that are produced must be worked out in too much detail, if plan executability is to be "guaranteed". Such plans must be elaborated down to absolutely basic actions. This further exacerbates the computational problem.

4. It fails to address the problem of relating the plan 'text' to the actual situation. That is, plan texts refer to objects and actions through either labels or descriptions. In the world though, objects are rarely labelled and actions cannot be, so plan texts must be related to the world by some kind of matching process.

In a later paper, Agre and Chapman (1989) contrast a *plan as program* view with informal evidence they gathered on how people follow instructions. The evidence they used came from three occasions on which they gave visitors the same directions to the Washington Street subway station in Boston:

> Left out the door, down to the end of the street, cross straight over Essex then left up the hill, take the first right and it'll be on your left.

While in all cases, their visitors found the subway station, Agre and Chapman noted the following about their behavior in getting there. First, as is often the case in Boston, there are no street signs indicating Essex Street. Visitors had to make assumptions about how this part of the plan text related to the world in front of them. Secondly, because of a fence on the other side of Essex Street, they actually had to take a right and walk to the end of the fence before they could follow the next instruction "take a left up the hill". Thirdly, there is no feature of the landscape that is *a priori* identifiable as "the hill". Visitors nevertheless took the correct turn onto a street that they saw as sloping slightly upward. Finally, the visitors noted a parking lot on the corner they perceived to be the one associated with "the first right". Given this, they didn't bother to wait until they got to the corner before making a right: They simply cut across the parking lot.

Agre and Chapman characterize these features of human instruction-following as demonstrating:

- an ability to act on evidence known to be incomplete;
- an ability to interpolate additional actions not explicitly called for in the instructions but apparently demanded by the circumstances;
- an ability to optimize actions, taking advantage of features of the actual circumstances of action.

So instead of programmatically *following* instructions, people seem more to be *using* instructions, along with the situation they find themselves in, to accomplish their intended goals. Given this, it is worthwhile to turn our attention to instructions and see what resources they provide for people to make use of.

UNDERSTANDING INSTRUCTIONS

As a type of text, instructions have not been studied as much as narratives. Nevertheless, there are clear differences between the two, as well as similarities. The most obvious difference is that, while both can be used to describe tasks, what narratives usually describe is just *what happened* in one particular circumstance. (In thrillers and suspense novels, the circumstances are generally rather exciting, which is why many of us read them.) In contrast, instructions commonly specify *how to perform* a task in a wide range of circumstances that may change during the course of performance in quite different ways.

On the other hand, there is also an interesting similarity. If one looks carefully at both natural-language instructions and narratives, one quickly finds that they specify less what one is supposed to *do* than what one is supposed to *achieve* by doing it. For example, "apply paste to wall" and "install new spout" essentially specify that state the world should be in *after* some unspecified action is complete - that is, in a state in which the wall has paste on it or in which a new spout is installed. In a narrative, such specifications are generally sufficient: one does not need to know *how* some character in a novel installed the new spout in his bathtub. It is sufficient to know that that is how he spent his afternoon. But if one is supposed to carry out an instruction, one needs more.

To convey features of what the agent is actually supposed to *do*, instructions contain modifiers which add to the basic specification. For example, one can specify the instrument to use in accomplishing the goal

> *Using a paint roller or brush*, apply paste to the wall.

the direction in which to carry out whatever action is used to accomplish the goal

> Apply paste to the wall, *starting at the ceiling line and pasting down a few feet.*

the extent of coverage demanded by the goal

> Apply paste to the wall, *covering an area a few inches wider than the width of the fabric.*

concurrent effects to be avoided while performing one's chosen action

Apply paste to the wall, *being careful not to overpaste.*

as well as constraints on how an otherwise unspecified action is carried out

Install new spout. *Do not use lift knob or hose connection for leverage.* Damage may result. *Tighten by hand only.*

The point I want to make here is that the *underspecificity* often noted of natural-language in general, really hits home when it comes to instructions. While there appears to be no limit on the number of modifiers one can add to an instruction, the intended action will still be underspecified and hence a source of potential confusion to those who don't already know what action is needed.

The underspecificity of instructions is not confined to single action specifications: also underspecified are the intended *relationships* between actions. Consider the following instruction, which contains what is called a *free adjunct*:

Pour mixture over cheese, *speading evenly.*

First note that this can be understood as specifying a single action or as specifying two related actions. In the former case, spreading is not a separate action but rather a constraint on pouring – one should pour in such a way that the mixture spreads evenly over the cheese. When understood as two separate but related actions however, it becomes apparent that their temporal relationship is underspecified. One can spread *while* pouring, assuming one has a hand free, or one can spread *after* pouring. (Further discussion of free adjuncts in instructions can be found in (Webber, 1990).)

This type of temporal underspecificity is not limited to free adjunct constructions. It is also apparent in sentences with *when*-clauses, another construct often used in instructions. For example,

When you pour the mixture over the cheese, spread it evenly.

As above, this can be understood either as requiring the mixture be spread evenly during pouring or as requiring it be done afterwards.

The temporal underspecificity of *when*-clauses has been addressed by Moens and Steedman (1988). Appealing to the oddity of a sentence like (b) below, in contrast to its totally unremarkable counterpart (a)

a. When the sun set, my car broke down.
b. ?? When my car broke down, the sun set.

they argue that *when* is not temporally ambiguous. Rather, they claim that the apparent temporal ambiguity of the relationship between a *when*-clause and its main clause follows from the fact that *when* only indicates a *contingent* relationship holding between the two events rather than a *temporal* relationship. They ground their claim in the fact that people conceptualize events as part of arrangements (e.g. sequences) that are planned, predicted or otherwise seen as governed by agencies. People see the events involved in these arrangements as being contingently related. Different contingent relations between events imply a different temporal order between them. When an arrangement of events is therefore described in a text, the temporal order that someone will take to hold among them will follow from what contingent relationships s/he takes to hold.

There are many different types of contingent relationships. For example, (1) the action or event specified in a when-clause may be understood as a sufficient precondition for performing the action specified in its main clause

> When the two handle sections are in line with one another, tighten the wing nuts on both sides of the handle.

(2) The action specified in a when-clause may be understood as *causing* the event described in the main clause

> When the engine/blade cross bar control is released, the engine/blade will stop.

(3) The action specified in the main clause may be understood simply as being the next thing the agent should do after the event specified in the when-clause, in order to accomplish some higher goal

> When the engine starts, release the ignition switch.

(4) The action specified in the when-clause may be understood as being a high-level description of more basic actions described in the main clause. (This might also be considered a hierarchical part-whole relationship between the actions.)

> When you wash the glasses, first soak them in hot soapy water and then rinse them.

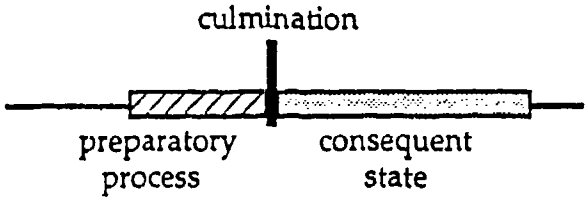

Figure 1. A nucleus.

(5) The action specified in the when-clause may be understood as enabling the action or state specified in the main clause

> When the handle is lowered, the cleaning nozzle swivels for either regular cleaning or low profile cleaning.

(6) The action specified in the when-clause may be understood as generating the action specified in the main clause. (That is, the two clauses may be taken to be different ways of specifying the same action

> When you typed rm *.*, you told UNIX to delete all your files.

The notion of contingency alone though is insufficient to explain the different temporal relations that appear to hold between a when-clause and its main clause. It also requires that events be seen as structured objects. In arguing this, Moens and Steedman (1988) appeal to the same structure they introduce to explain why a sentence like "John blinked" is understood as describing a single act of blinking while "John blinked for 5 minutes" is usually understood as describing a sequence of repeated acts. This structure, which they call a *nucleus* (see Figure 1), consists of three parts: a *preparatory process*, a *culmination*, and a *consequent state*. Any single clause such as "Wash the glasses" or "They repaired the Walnut Street bridge" will denote such a structure. Given such a three-part structure, contingent relations do not have to hold between two complete event structures: they can also hold between parts of their nuclei. To see this, consider the following pair of examples from (Moens & Steedman, 1988)

> a. When they repaired the Walnut Street Bridge, they used alot of defective materials.
> b. When they repaired the Walnut Street Bridge, they solved many traffic problems.

In the first example (a), a contingent relation will be taken to hold between the preparatory process of bridge-repairing and the entire act of using defective materials. Thus the temporal relation between them will be taken to be "during". (See Figure 2.) In the second example (b), a contingent relation will be taken to hold between the consequent state of bridge-repairing and traffic-problem solving. (That is, the latter is taken to be a consequent of the former.) So the temporal relationship between them will be taken to be "after". (See Figure 3.)

Again the point I want to make is that for people attempting to follow instructions that contain when-clauses, free-adjuncts, and other natural-language constructs that simply convey the existence of a contingent relation between two actions or events, those instructions may be a source of confusion to an agent with no independent information as to the particular contingent relationship involved, and hence no idea of the particular temporal relationship involved.

There is one more problem that people have with understanding instructions that I want to return to briefly, since it is relevant to the conclusion I would like to draw in the final section of this paper. As Chapman (1987), Agre and Chapman (1989), and others have noted, agents have a non-trivial job in grounding the object descriptions they find in instructions to objects they're meant to find in the world. This is well-illustrated by an incident that occurred in an experiment carried out by Lucy Suchman, described in (Suchman, 1987). A team of two well-educated scientists was asked to make 50 two-sided copies of an article from a book. The copier would provide them with instructions for carrying out the task. One member of the team would read the instructions, while the other attempted to carry them out. The team's attempt was videotaped for later analysis.

At one point, the reader (A) gives the following instruction

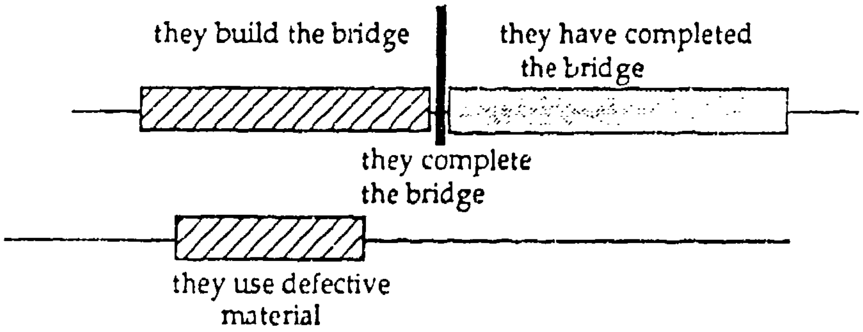

Figure 2. Part-whole interpretation.

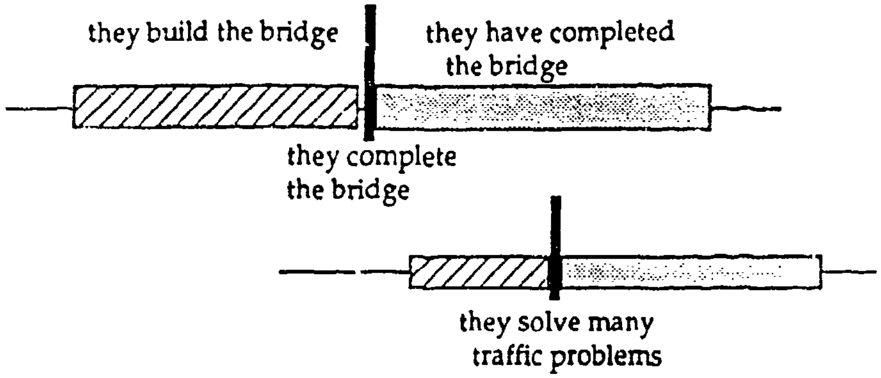

Figure 3. Sufficient-precondition interpretation

> To access the BDA, pull the latch labelled Bound Document Aid and lift up to the left.

The other member of the team (B) struggles with the latch for a while, unable to lift it, before looking at the picture accompanying the instruction that A has read and saying "Oh the whole thing". At which point, A successfully moves it over to the left. The point is that in instructions, referring terms may be as underspecified as the action descriptions they occur in. Thus either the situation itself must be such that any reasonable attempt to perform the action will "reveal" the intended referent or additional help must be given to the agent to resolve the referent. (Commonly, such help is given in the form of diagrams, but that in itself may not be enough.)

CONCLUSION

In this paper, I have given evidence that a set of instructions should not be seen as a program, controlling an agent's behavior. Not only do human agents not use instructions in this way, but instructions cannot be so used because they under-specify actual behavior. This is as it should be. There is no way that instructions written at one place and time can anticipate all relevant features of the world in which the task they describe will have to be carried out.

But natural-language instructions should not be dismissed as irrelevant, because they do have a role to play. Natural-language surpasses all other communicative media in conveying *intentions* – including the purpose of behavior and the reasons for behaving in particular ways. Such intentions cannot be effectively communicated through images alone. For example, while red-slashed icons may be effective in *reminding* people of what behavior is forbidden ("no smoking", "no wearing high-heeled shoes", even "no haunting"), they cannot unambiguously convey the *reason* for forbidden or otherwise discouraged behavior. Thus natural-language instructions serve as a resource for decisions about how to behave in ways compatible with stated intentions. They can serve the same function with respect to high-level control of animation, to communicate the *whys* of task performance. The *hows* require previous knowledge or demonstration. Thus the total communication of task behavior requires a union of visual presentation and language.

And that is the conclusion I would like readers to take from this paper. We should be exploiting the communicative features of multiple media in both designing tasks and instructing agents in their performance, rather than trying to push a single medium to overcome its deficiencies. The long-term goal of our Animation and Natural-Language project at the University of Pennsylvania (Badler, 1990; Badler et al, 1990) is to exploit features of both natural-language and animated simulations to achieve this end.

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TASK COMPOSITION FOR ANIMATION

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ABSTRACT

The task composition for a Human-Centered Design Facility provides an animated, 3D simulation of maintenance activities from high-level natural commands, such as remove and/or replace a selected component on a particular aircraft. The task composition facility allows designers, human factors engineers, maintainability engineers, or design evaluators to view animated maintenance task scenarios and to visualize the complex interaction between maintenance technicians and their work environment. The system integrates multiple software environments such as the Silicon Graphics IRIS 4D workstation and the JACK system developed at the University of Pennsylvania. It also incorporates time data from the Navy's Element Standard Data (ESD) system and Air Force experiments for the Crew Chief model and maintenance instruction from Air Force technical manuals. These capabilities underlie the advanced human-modeling environment that the Air Force's Project DEPTH seeks to build.

This paper describes the task composition technology and outlines the framework of the system and its components.

INTRODUCTION

This paper describes a task composition framework for Human-Centered Design and details the software design. The objective is to demonstrate the feasibility of implementing a task analysis method permitting synthetic creation of high-level molar descriptions of maintenance elements from detailed information about their molecular elements. It also analyzed the feasibility of interrogating relevant data bases to establish performance time data for molecular subtasks and the feasibility of developing software logic to synthesize molar maintenance task time from the underlying molecular task descriptive data.

The hardware selected for the development of the task composition is a Silicon Graphics IRIS 4D Series computer. The software system used to create and display objects graphically is a 3D solid-modeling and animation package called JACK developed by the Department of Computer and Information Science of the University of Pennsylvania (Philips & Badler, 1988).

The task composition software is designed to run outside the JACK environment but it depends on the JACK's facilities and animation capability to perform the dynamic analysis and to display objects graphically. The task composition architecture includes a user interface with a designer facility that allows users to create, modify, or delete menus and icons.

The task composition facility expands the capability of task analysis beyond the detection of isolated problems to more complex tasks. It requires less input of higher level information and links high-level maintenance commands to simulation of maintenance activities.

SOFTWARE DESIGN AND REQUIREMENTS

Software Design Framework

The task composition design framework shown in Figure 1 outlines the major modules and the relevant data bases required for development. A brief description of each module follows.

User Interface Interaction Module. This module provides information and options to the user and accepts all user input, including high-level maintenance commands, data requested by other modules, and options chosen by the user.

Maintenance Scenario Processor. This module assigns a maintenance scenario to the maintenance commands accepted by the system and provides descriptions of maintenance task actions and related information to other modules in the system.

Action Word/Equipment Pairings Processor. This module analyzes maintenance scenario information and processes a breakdown of the task into action word/equipment pairings.

Equipment-Component Processor. This module analyzes the maintenance action word/equipment pairings information and divides the task into the system's basic elements.

Element Time Processor. This module assigns time values to each system's basic elements, processes all time-related data, and provides a total time for the task being analyzed.

Task Simulator. This module reviews the system output and prepares the necessary parameters for the display module.

Display Task. This module contains the graphical information to display the task.

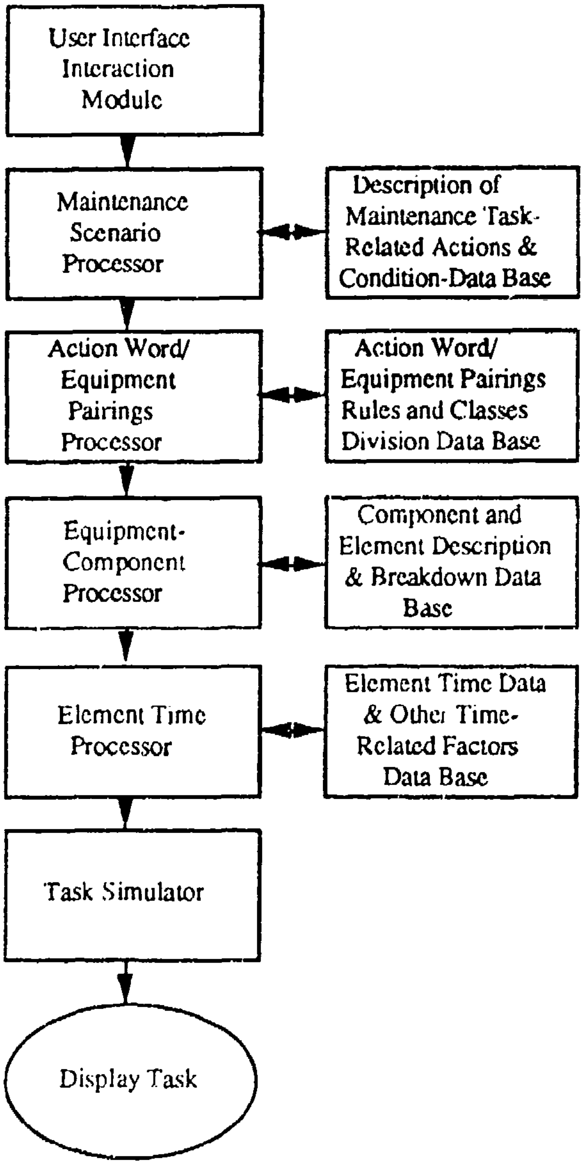

Figure 1. Task Composition Design Framework.

Framework Design-Related Data Bases

The data bases described here reflect the type of data required to accomplish this detailed demonstration of maintenance activities from natural language commands. The JACK environment offers several facilities to store and create some of the required data (see JACK User's Guide, 1989; and Programming with JACK, 1988).

Maintenance Task Actions Data Base. This data base includes the steps involved in performing the maintenance task and other necessary information to develop maintenance scenarios such as:

1. specification of [illegible] area on the system under consideration,

2. the maintenance task to be performed,
3. task precondition, i.e., the maintenance steps required before performing the specified maintenance task,
4. support equipment required, such as a boarding ladder, maintenance stand, and tools, and
5. maintenance crew size and the number of technician(s) required to perform the maintenance task.

Action Word/Equipment Pairings Data Base. This data base includes the natural language instructions and the breakdown of the maintenance scenario. It will also include information about when a series of activities should be executed, the correct ordering of activities, and the instruction for expressive human motions.

Component and Element Description Data Base. This data base includes the workplace geometry and the breakdown to the component and element levels of the workplace geometry.

Element Time Data Base. This data base includes the time line analyses data based on the Navy's Element Standard Data (ESD) system and task time durations based on Fitts' Law defaults (Fitts, 1954). Time data from the Crew Chief experimentation will also be considered and added to this data base at a future date.

Requirements and Related Documents

The task composition software demonstration is integrated with the Silicon Graphics IRIS 4D and JACK environment. Figure 2 shows the relationships between the task composition and both environments. The Silicon Graphics IRIS 4D Series computer was selected as the platform for running the software demonstration and developing the source code. The source code is written in C.

USER INTERFACE DESIGN AND MENU DESCRIPTIONS

User Interface Module

The user interface module is the central control module of the task composition facility. It performs several functions. It:

1. initializes the parameters required for the execution of all their modules,
2. controls data and command flow when a main level or sublevel menu has been selected,
3. communicates with the JACK environment and its facilities,
4. activates the dynamic simulation of maintenance activities, and
5. accepts modification to the maintenance scenario and natural language interface.

The Task Composition Main Menu shown in Figure 3 is designed and displayed by the user interface program.

User Interface Communication. The Task Composition for Human-Centered Analysis user interface controls the execution of all subprograms. Each suboption is a stand-alone program. Communication to programs is handled in two ways: (a) through command line options and (b) through Inter-Process Communication (IPC). The user interface presents a command line filled with options, based on the user's position in the menu, to the program to be executed. These

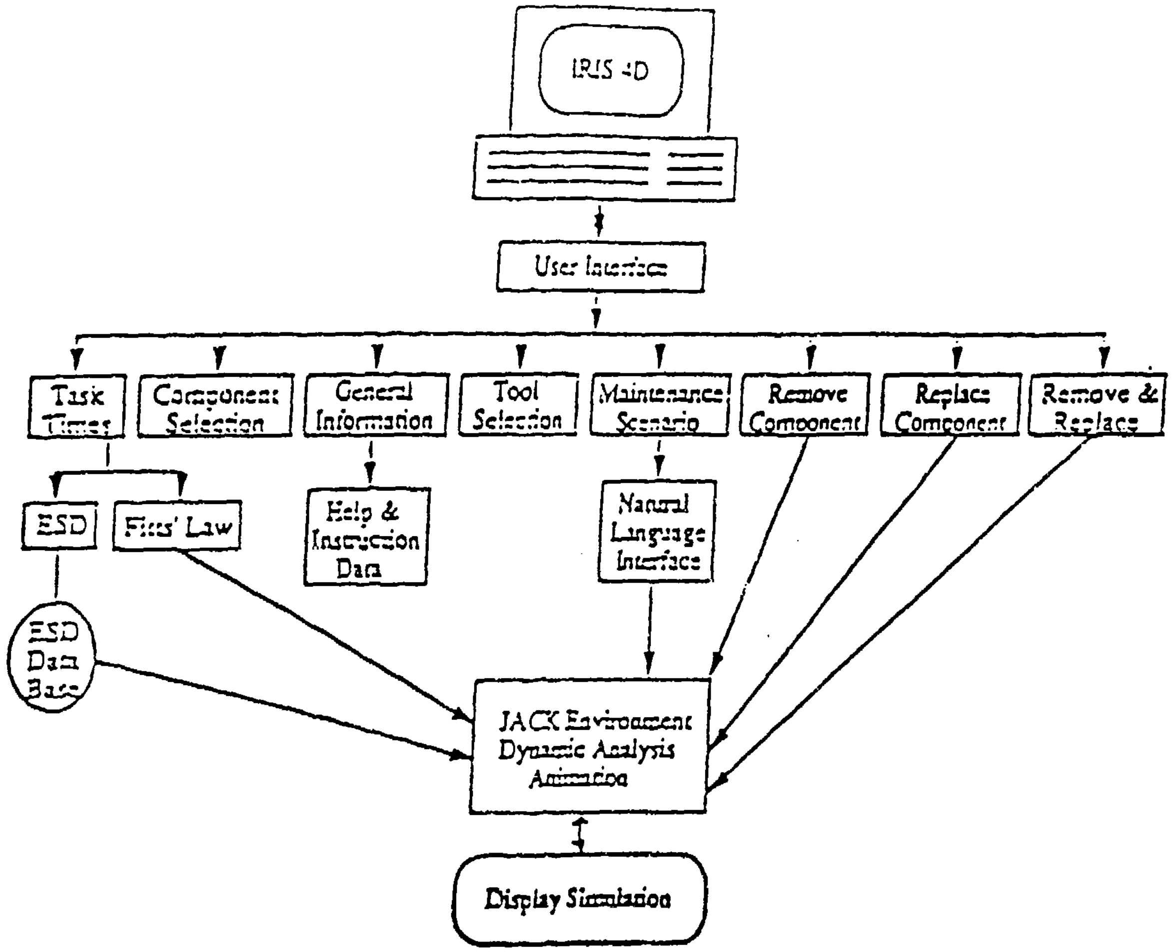

Figure 2. Task Composition Relationships to the IRIS and JACK Environments.

options are expected by the program and cause specific actions to happen, such as the loading of a specific man model. UNIX™ has an IPC facility that permits programs to "talk" to each other. In this way, programs can communicate in a similar fashion to program functions.

Menu Structure and Selection

The menu structure of the user interface is hierarchical. Each option available to the user of the task composition interface is shown as an "icon," which is a graphical representation of each function and subfunction. The mouse operates the user interface and each of the three mouse buttons performs an individual function as follows:

1. Left mouse button - An icon is selected when the arrow is pointed on it and the left mouse button is pressed. If the icon has suboptions, they will be listed. If there are no suboptions, the program attached to the icon will be executed.

2. Middle mouse button - When this button is pressed on an icon, the program prints the context sensitive help attached to the icon. The help screen will provide the user with information pertinent to this option.

3. Right mouse button - When this button is pressed, the user is returned one level in the menu structure. Its function is the reverse of that of the left mouse button.

Task Composition for Human Centered Analysis

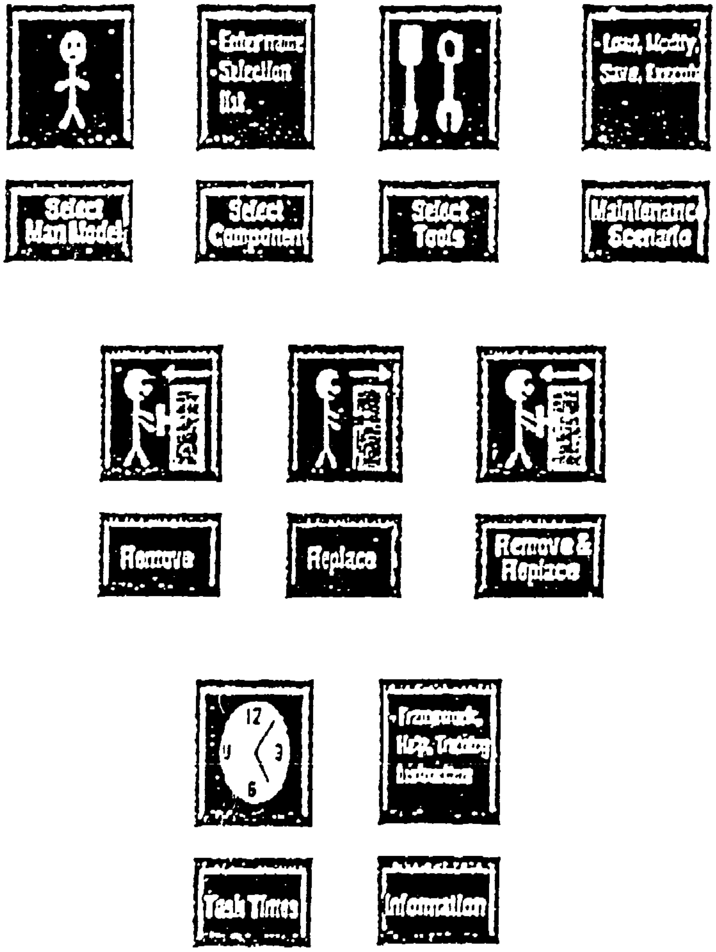

Figure . Task Composition Main Menu.

Menu Descriptions

Select Man Model Function. The task composition for human-centered analysis main menu displays icons of the functions and options available to the user. The select man model function enables the user to select an anthropometric model. Once this icon is selected, the program prompts the user to select either the JACK man model (see Badler, 1990) or the Crew Chief man model (see Ms. Easterly's and Mr. Ianni's paper, this volume, for a description of Crew Chief). Once the anthropometric model is selected, it is used throughout the analysis of the maintenance tasks under consideration. (The program is designed to allow for other anthropometric models to be integrated with the task composition analysis.)

Select Component Function. The select component's icon allows the user to retrieve components and parts from an existing data base. After clicking on the select component icon, the user is prompted to select a component from a list of existing components or to enter the name of existing components, if known. Selected component and parts will be used as the default option for remove and/or replace functions.

Select Tool Function. The select tool function is similar to the select component function. It allows the user to retrieve a tool from the existing data base to be used in the analysis. The user may select a tool from a list of existing tools or enter the name of the tool, if known. This function provides the user the option of a particular specified tool to be used in the analysis of the remove and/or replace tasks. If the user does not wish to specify a tool, the program automatically assigns the appropriate tool as specified in the maintenance scenario for the components already in the data base.

Maintenance Scenario Function. The maintenance scenario function allows the user to modify, load, save, and/or execute existing maintenance instructions. The maintenance instruction is broken down into discrete events. The maintenance scenario of a task can be defined to include motion generation information which is used to create an animation of the task simulation and allow the flow of the animation to effect the subsequent course of task simulation (JACK's YAPS, kinematic, inverse kinematic, and animation functions are required to process the information provided by the maintenance scenario function; (see Dr. Badler's paper for a description of the above-mentioned task functions).

Remove and/or Replace Functions. The remove, replace, and remove and/or replace functions allow the user to activate an animated simulation of maintenance activities from high-level maintenance commands. For example, "remove the water separator on the F-16" command will result in the following considerations and assumptions by the program:

1. Assumes the task preconditions, such as the aircraft has been made safe for maintenance, access panels have been removed, and the access door has been removed.

2. Simulates the following actions to accomplish the removal of the water separator on the F-16:

   a. Disconnect electrical connector.
   b. Remove two couplings and reposition two sleeves.
   c. Remove clamp.
   d. Remove two nuts, two washers, two screws, and bracket.
   e. Remove duct assembly.
   f. Remove and discard four packings.
   g. Remove two clamps and hose.
   h. Remove coupling and reposition sleeve.
   i. Remove nut, washer, and screw.

j. Remove two screws.
k. Remove water separator.
l. Remove and discard two packings.

To complete the task mentioned above, the following support equipment is required:

1. Aircraft boarding ladder
2. Clearing sector holdback tool
3. Emergency Power Unit (EPU)-made knob cover
4. Environmental specialized composite tool kit
5. Adaptor hose
6. Generator
7. Torque wrench

At this time, the program considers hand tools, such as wrenches, to demonstrate the removal of the component.

Similar actions and considerations are included for the replace part of the maintenance activity.

The remove option will demonstrate removal of a specified component, replace will demonstrate the installation of the component, and removal and replace will demonstrate both the removal and installation of the component.

Task Times Function. The task times function allows the users to retrieve a table of the computed times for the maintenance actions considered during the remove and/or replace simulations. The times are based on the Navy's ESD system; task time durations for animation are based on Fitts' law defaults. There is a provision in the function to integrate Crew Chief data at a later date.

Information Function. The information function allows the user to access the help capability of the task composition facility, the training instruction for the maintenance activities included in the data base, and an outline of the task composition structure.

SUMMARY

The above sections described the design approach and the relationships between the design software and the hardware and software environments associated with the task composition analysis. The overall structure is hierarchical in nature. All code is written in C using a top-down modular structure, but can communicate with other routines written in FORTRAN. Subroutines communicate through the UNIX IPC facility. Communication with the JACK environment is performed at two levels. Some subroutines call JACK options; others reside in the JACK option used. Users may add, delete, and/or change the menus and icons available in the user interface. Stepping through the user interface menus is accomplished by clicking on an icon with the left mouse (see Menu Structure and Selection). Finally, the design allows for expansion of existing modules and additions of new without any major changes to the overall structure.

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FROM BIOMECHANICAL MODELING TO BIOMECHANICAL SIMULATION

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ABSTRACT

The leading health hazard that occurs in a manual materials handling (MMH) task involves back pain. The reduction of these incidents is of both humanitarian and economic importance. A typical approach toward solving the problem is to redesign the task to maintain high work performance and at the same time keep stress imposed on the body within acceptable safe limits. Such an approach is dedicated toward the application of motion economy, and anthropometric and biomechanical principles in the design of work systems.

For this approach to be effective, evaluation of stresses on the body in general and the spine in particular is needed. This need resulted in the development of models to estimate the stresses on the spine during MMH tasks. These models approach the problem by tracking the movements of various links and joints of the body and use Newtonian mechanics to arrive at the kinetics of motion and, hence, the stress on the spine.

Because of the variety of tasks to be performed in MMH, another approach would be the simulation of human motion through an understanding of how the human body moves while performing a task. This paper presents an approach to simulate the movement of sagittal lifting activities based on an extension of the minimal principle in biomechanics. This approach utilizes a five-link simulation model of the human body for sagittal lifting. It gives the displacement-time relationship of the five joints included in the model. A comparison between the actual body movement and the simulation is presented.

INTRODUCTION

Biomechanics of human movement has been defined by many investigators over the years. In 1966, Drillis and Contini defined biomechanics as the science which investigates the effects of the internal and external forces on bodies whether in movement or at rest. Since then, many other researchers reported similar definitions, such as Winters (1979), and Frankel and Nordin (1980). Biomechanics uses laws of physics and engineering principles to describe body movements and the forces acting on it. Biomechanics is a multidisciplinary area which requires the combined knowledge from the biological, physical, and behavioral sciences. Many contributing disciplines are called upon in biomechanical analysis: (a) engineering mechanics, (b) engineering anthropometry, (c) kinesology, (d) anatomy, and (e) neuromuscular physiology.

Occupational biomechanics, a more recent term, is concerned with the application of mechanics to the Man-Task-Environment system to reduce mechanical stresses on the worker's musculoskeletal system while maintaining high performance levels. Therefore occupational biomechanics can be considered an applied division of biomechanics (see Figure 1). Occupational biomechanics is quite useful in (a) understanding motion patterns required by jobs, (b) estimating the kinematics and kinetics of these movements, and (c) estimating the stress imposed on various body parts as a result of job performance. In investigating the industrial job-related workloads, it is important to measure distribution of loads and stresses among various body segments and tissues. For example, through biomechanical evaluations of the job-related stresses imposed on a worker, a potential means of reducing the high incidence rates of manual materials handling (MMH) injuries in industry can be realized. Because of the large number of biomechanical studies and models generated in the area of manual handling, especially lifting, this paper will focus on modeling and simulation of lifting activity.

BIOMECHANICAL MODELS

Biomechanical models were an inevitable result of the investigation of body movements and the kinematics and kinetics of these movements. These models are a representation of the actual system to understand the system behavior. Quite often gross simplification and assumptions are made. By constructing a model and comparing the model's behavior with the behavior of the actual system, such as in the case of manual lifting tasks, we may gain an insight into how the system functions and the interactions between its components.

Therefore, through biomechanical modeling of the human activities, the biomechanical stresses imposed on the body can be estimated. A wide variety of models both static and dynamic have been developed to study the stresses of manual materials handling (MMH) activities.

Biomechanical models in general date back to the work of Braune and Fischer (1889) while studying soldiers carrying loads. Another pioneer in the development of biomechanical models and related material is Dempster (1955) who described mass and inertia properties of the U.S. military population in various postures and motions. Although biomechanical model developments were progressing, it was not until the mid 1950s and 1960s that more focus and effort were placed on the development of more sophisticated multilink biomechanical models. Rapid development of these models can be attributed in part to the availability of both high-speed computers and motion tracking equipment. As a result of these developments, several biomechanical models for lifting tasks were developed to estimate stresses on the various body segments, especially the lumbar spine.

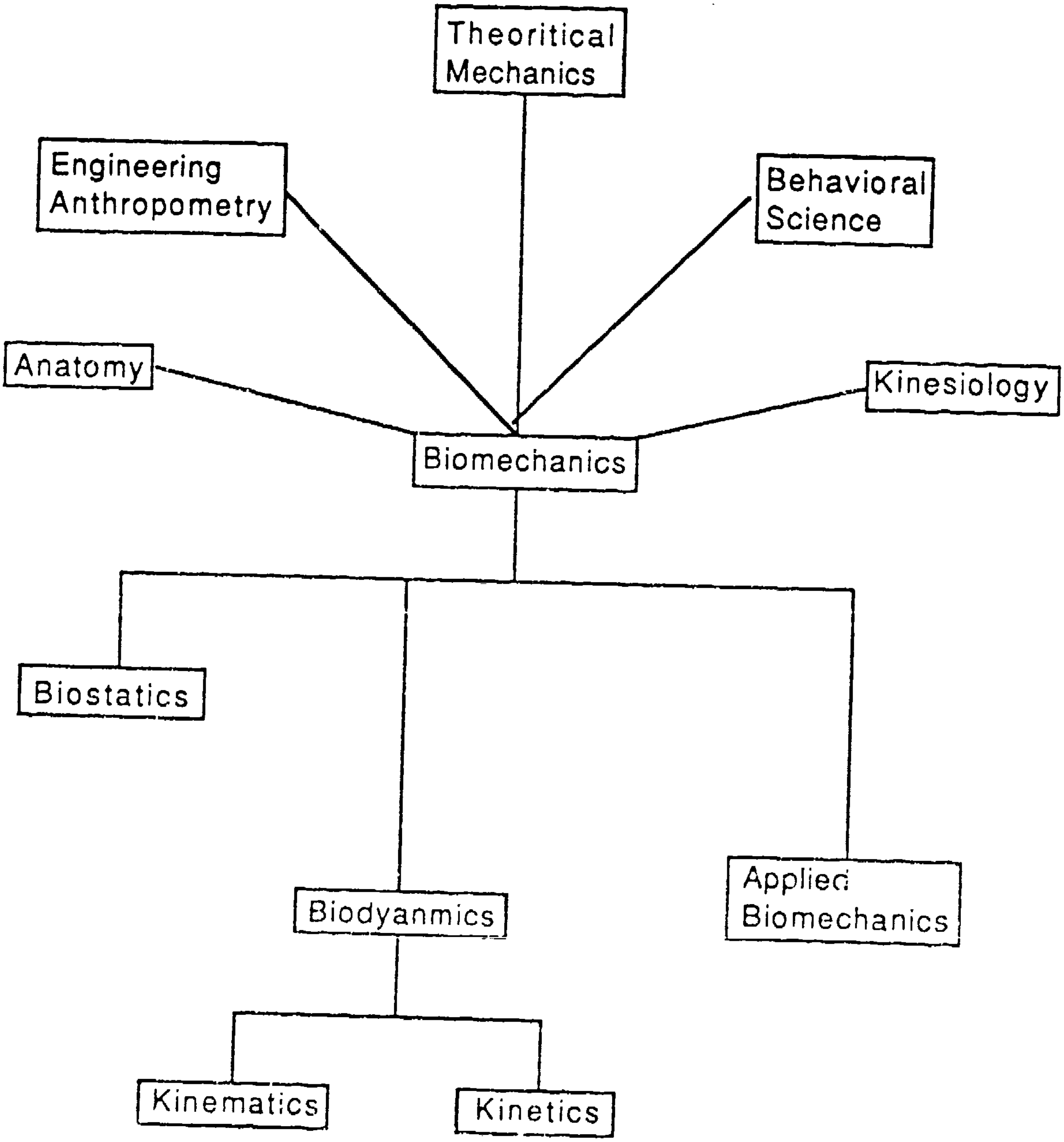


Figure 1. Division of Biomechanics.

Several two- and three-dimensional static and dynamic biomechanical models have been developed to determine stresses on manual handling tasks. Some of these static models include Chaffin (1969), Martin and Chaffin (1972), Garg and Chaffin (1975), and Anderson et al. (1985). Dynamic models include those developed by Fisher (1967), Troup (1977), Ayoub and El-Bassoussi (1978), Garg et al. (1982), Leskinen et al. (1983), Bejjani et al. (1984), Freivalds et al. (1984), McGill and Norman (1985), and Ayoub et al. (1986).

Most of the above-mentioned models were developed using a single muscle equivalent to account for internal trunk muscle forces and resulting compressive and shear forces, based on the rationale that individual muscle models are of limited practical value due to mechanically undetermined systems, and a precise relation between the mechanical and the electric output of muscle is uncertain as reported by Ortengren and Andersson (1977). The two-dimensional models appear to be satisfactory in analyzing two-handed symmetric sagittal plane exertions.

Three-dimensional static models of the trunk show that for symmetrical sagittal plane lifting activities, only the erector spinae muscles are active (Bean et al, 1988; Schultz, Andersson, Haderspeck, Ortengrin, Nordin, & Bjork, 1982). But for tasks that involve asymmetrical lifting, many of the lumbar trunk muscles are recruited. More contemporary models of the back include Schultz and Andersson (1981), Gracovetesky et al. (1981), Schultz et al. (1982), Jager (1987), McGill and Norman (1986), Bean et al. (1988), and Chen and Ayoub (1988). These are three-dimensional biomechanical models based on several muscle groups to more accurately reflect the muscle activities, and compression and shear loads on the spine. Examples of typical two- and three-dimensional models of the trunk are shown in Figures 2 and 3.

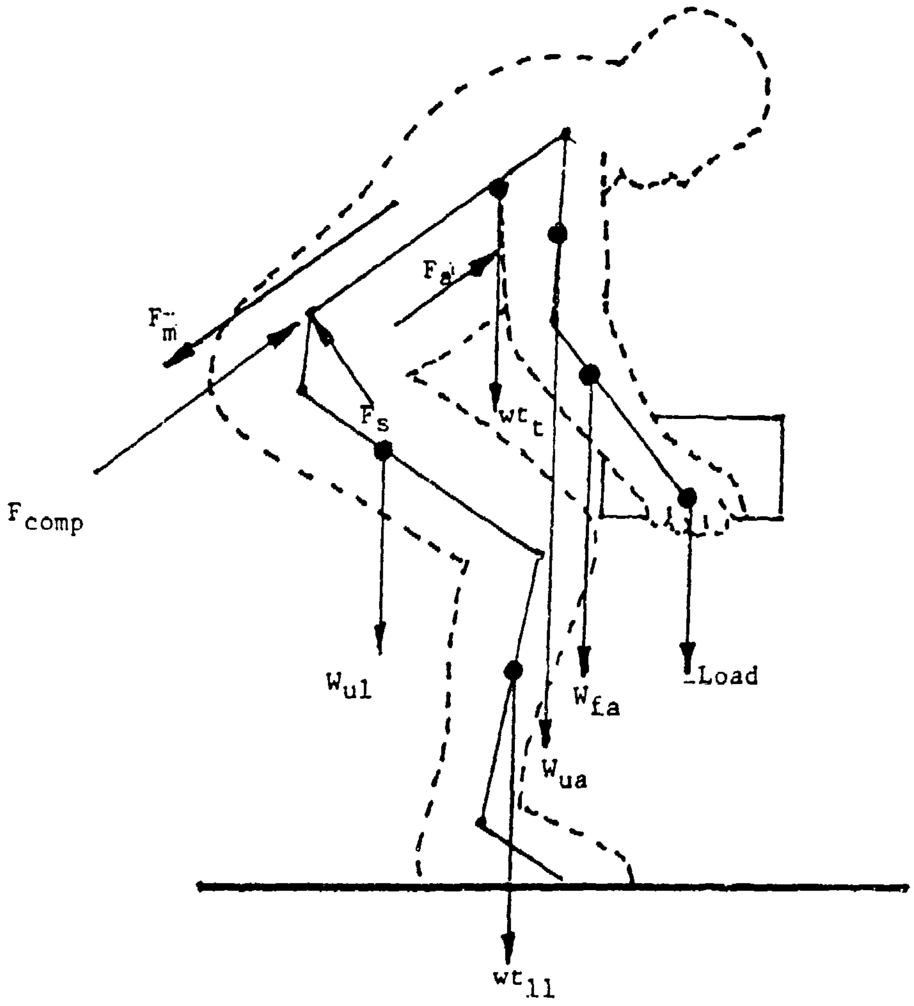
Because of the unknown internal forces and fewer equations of equilibrium, many three-dimensional models of the trunk are statically indeterminate. Therefore, additional assumptions have been made to estimate internal muscle forces. These assumptions need to be validated against experimental measurements or other means, such as myoelectrical activities and intradiscal pressure. Such assumptions include:

1. Assume "zero antagonist" activity and the muscle acts only in tension. Based on this assumption, all the rectus abdominus are given a value of zero. This will tend to reduce the number of unknowns; hence, the system can be determinant. This, however, is not a good assumption and has not been supported by experimental data (Schultz et al., 1981; 1982).

2. Use of optimization techniques such as linear programming to determine those internal muscle forces. Using "minimum compression" force on the spine; as the objective function, Schultz et al. (1981; 1982) found that such techniques produced good agreement between computed muscle tension and measured magnitude of electromyographic (EMG) data.

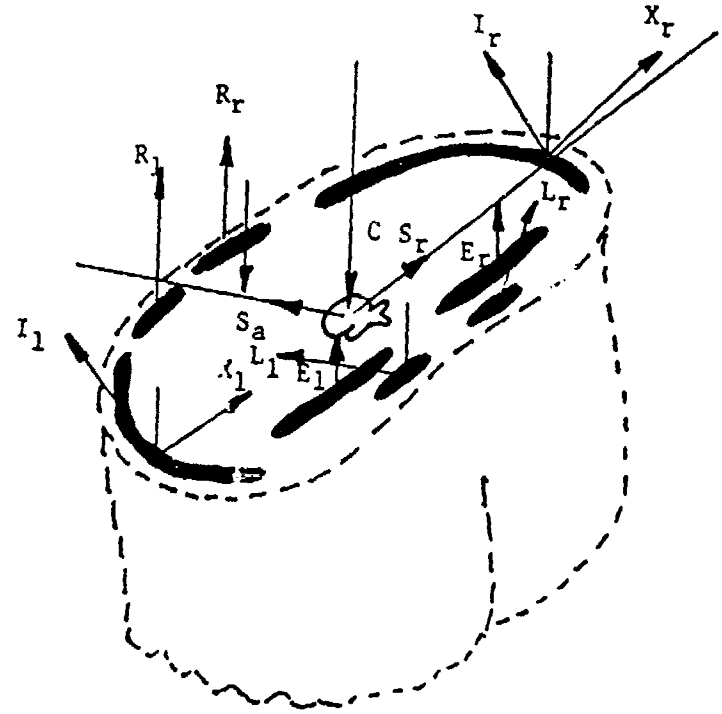
Dynamic Versus Static Models

Due to the complexity of dynamic biomechanical analyses, as well as the limited dynamic muscle strength data to compare with the task produced forces and moments at various body joints (Garg et al., 1983), assessment of the stress of lifting on the musculoskeletal system has most frequently been done with the aid of static models. The comparison of the differences between the dynamic and static analyses has been studied by several investigators. Many lifting motions appear to have substantial inertia components and as a result in biomechanical analysis, body dynamics need to be considered when the inertial forces and inertial moments produced are significant when compared with the forces and moments needed for equilibrium (Schultz, et. al., 1981). The important factor for using dynamic modeling is the fact that jerking of the load may be necessary by the worker. Such jerking of a load produces inertia forces resulting in momentary but potentially high overloads on the back structures that are not identifiable in static analyses (McGill & Norman, 1985).



F_m = Erector Spinar Force
F_{comp} = Compressive Force
F_a = Abdominal Pressure Force
F_s = Shear Force
w_{fa} = Weight of Forearm
w_{ua} = Weight of Upper Arm
w_t = Weight of Trunk
wt_{ul} = Weight of Upper leg
wt_{ll} = weight of Lower Leg

Figure 2. Two-Dimensional Model.



R = Rectus Abdominus (r = right, l = left)
X = External Oblique (r = right, l = left)
E = Erector Spinae (r = right, l = left)
L = Latissimus Dorsi (r = right, l = left)
I = Internal Oblique (r = right, l = left)
C = Compressive Force
P = Abdominal Pressure Force
S = Shear Force (a = anterior, r = lateral)

Figure 3. Three-Dimensional Model of Trunk.

Wood and Hayes (1974) determined the load on the spine using both back and straight leg lifting techniques. The lifting motion was purposely kept slow and simple to reduce the dynamic effects. Despite the relatively low accelerations, the statically derived values of L4/L5 torque were considerably lower than the corresponding dynamic values.

Leskinen et al. (1983) also used a biomechanical sagittal plane model to evaluate lumbosacral compression and stresses on the musculoskeletal system. Comparing the peak L5/S1 compressions in the leg lift and the back lift with the data interpolated from Garg and Herrin (1979), they reported that their data were about 70 percent and 100 percent higher, respectively. They also noted that the reasons for these differences were the dynamic effects and the intra-abdominal pressure.

McGill and Horman (1985) compared the low back moments during lifting when determined dynamically and statically. They found that the dynamic model resulted in peak L4/L5 moments 19 percent higher on the average, with a maximum difference of 52 percent, than those determined from the static model.

The comparison between the dynamic maximum compressive force and static maximum compressive force on L5/S1 showed that the values of the dynamic case were always larger than the static case (Kim, 1990) (See Table 1). Significant differences were found ranging from 4 to 40 percent. On the average, the value of the maximum compressive force for the dynamic was about 120 percent of the maximum compressive force of the static case. Similar results were reported by Marras, Nongsam, and Rangarajulu (1986). They claimed the introduction of a small amount of velocity into the compressive force analysis increases the compressive loading by almost 40 percent.

SIMULATION OF HUMAN MOTION

Humans perform physical activities in a variety of ways. These would depend upon individual anatomical structure, physiological functions, psychomotor control pattern, and associated pathological or chronological changes (Chao, 1986). In addition, many of our physical activities are task-oriented, varying drastically depending upon our personal habits, training and motivation. Interest in the behavior of the skeletal, muscular, and neural control subsystems has grown to such an extent that numerous efforts have been dedicated to simulation of these biosystems and have obtained fruitful results.

In the search for such "optimality" in human motion, theoretical attempts to formulate and demonstrate a "minimal principle" have been provided by Nubar and Contini (1961). In addition, a modeling approach (with experimental data support) based on a minimization principle can be found in Chow and Jacobson (1971); Seireg and Arvikar (1975); Ayoub, et al. (1974); Petruno (1972); Muth et al. (1976); Hatze (1976); Crowminshield and Brand (1981); Redfield and Hull (1986); and Marshall et al. (1985). As a result, the use of optimization, prediction, and quantitative hypothesis testing, the mathematical modeling approaches have generated results within an acceptable degree of accuracy.

Table 1. Comparison of Dynamic and Static Maximum Compressive Force of Subject 2

RANGE	FREQ	WT (KG)	DYNAMIC	STATIC	DYNAMIC/STATIC
FK	2	0	267.71	200.76	133.35%
FK	2	10	433.81	338.61	128.11%
FK	2	20	536.53	463.00	115.88%
FK	2	30	620.58	529.49	117.20%
FK	2	40	722.45	712.78	101.36%
FK	8	0	281.97	204.83	137.66%
FK	8	10	480.29	349.28	137.51%
FK	8	20	537.21	438.10	122.62%
FK	8	30	683.20	612.36	111.57%
FK	8	40	663.26	565.57	117.27%
FS	2	0	256.83	202.52	126.82%
FS	2	10	407.58	345.38	118.01%
FS	2	20	500.12	437.71	114.26%
FS	2	30	632.74	580.00	109.09%
FS	2	40	659.50	632.38	104.29%
FS	8	0	259.11	205.52	126.08%
FS	8	10	466.44	331.97	140.51%
FS	8	20	571.21	445.66	128.17%
FS	8	30	665.38	555.94	119.69%
KS	2	0	172.83	135.57	127.48%
KS	2	10	334.19	294.92	113.32%
KS	2	20	516.72	469.49	110.06%
KS	2	30	489.33	474.50	103.13%
KS	2	40	664.09	633.99	104.75%
KS	8	0	148.65	117.23	126.80%
KS	8	10	305.89	303.65	100.74%
KS	8	20	498.64	477.69	104.39%
KS	8	30	625.14	594.23	105.20%

The Optimal Principle in the Modeling of Human Lifting

The feasibility of using a principle of optimality in the modeling of load lifting is discussed in three points:

1. Considering the minimal principle postulated by Nubar and Contini, in a situation such as infrequent load lifting by experienced industrial workers, it is very appealing to think that the body selects a pattern of motion to minimize stress imposed on it. Muth et al. (1976) developed a lifting model using the minimum principle. Seireg and Arvikar (1975) used a similar principle to address the problem of finding moments of individual muscles producing walking motion.

2. Crowminshield and Brand (1981) and Rohrle et al. (1984) have presented a promising approach to the indeterminant optimal control problem. The general formulation can be summarized as follows:

$$\begin{aligned}&\text{Minimize } f(w_1, w_2, \cdots w_n),\\ &\text{Subject to } g(w_1, w_2, \cdots w_n) = 0,\\ &\text{and } b_i <= w_i <= a_i \ (b_i >= 0) \ i = 1, 2, \ldots, n.\end{aligned} \tag{1}$$

where f is a cost function that can be either linear or nonlinear. The function g represents the equations of motion and other equality constraint relationships based on anatomy and dynamic characteristics of the task. The w_i stands for the moments at joints. The w_i are also subject to inequality constraints.

3. The critical issue in the modeling of human lifting is the determination of a realistic objective function (cost function). The ability of several criteria to predict motion patterns (i.e., the body segment trajectories) has been examined. The criteria were (a) the sum of the muscle effort at joints (Nubar & Contini, 1961; Seireg & Arvikar, 1975) in gait analysis (b) the angular jerk and the sum of the segmental mechanical energies (Marshall et al., 1985) in gait analysis; (c) the sum of the square of mechanical work done at ankle joint (Muth et al., 1976) in lifting analysis; and (d) the joint moments and muscle stress (Redfield & Hull, 1986) in bicycling simulation.

Studies of Human Motion via Optimal Programming

The modeling, simulation, and optimization of the dynamics of the human musculoskeletal system are a real challenge to ergonomists, control engineers, and mathematicians. Chow and Jacobson (1971) formulated an optimization model to describe human gait. The performance criterion was the minimization of mechanical work done at the hip and knees during normal walking.

Ayoub, et. al. (1974) proposed a biomechanical model to predict the path of motion for the arm while performing a simple task. The performance criterion for this model was the minimization of mechanical energy used.

Seireg and Arvikar (1975) tackled the problem of optimal configuration of muscular forces about the hip, knee, and ankle during normal walking. The model, which determined the activity level of muscles at each joint, was formulated as a linear programming problem.

Muth et al. (1976) described a lifting task as an optimization problem with a nonlinear objective function subject to a set of linear constraints. The objective function was expressed as the time integral of torques acting on the ankle joint while lifting. Model constraints were determined by the limitations imposed by the physical characteristics of the human body, the task, and the workplace.

Pedotti et al. (1978) studied the muscular-force optimization problem in human locomotion by formulating four biological optimization criteria for the muscular forces, and comparing the experimental EMG data from the muscle with the muscle force patterns obtained computationally under the various performance criteria.

Marshall et al. (1985) examined the ability of seven optimization criteria to predict the segment kinematics and center of mass trajectory of a normal subject walking at his preferred pace. A nonlinear optimal control program was formulated and a generalized simulation package was used to predict the movement patterns. The results indicated that functions involving either the sum of the joint torques, the angular "jerk," or the sum of the segmental mechanical energies predicted the segmental kinematics and center of mass trajectory most accurately.

Simulation Models Development

To discuss details of human simulation studies, I like to focus on a single study currently in progress at Texas Tech. The study's objective was to simulate human lifting motion trajectories.

Generally, in studies of human motion simulation, the research activities are divided into three phases (see Figure 4).

1. Pre-model development analysis. During this phase, data on lifting kinematics were collected to identify ranges of motion and angular acceleration for each joint (range of lift and container size). In addition, dynamic joint strength tests are conducted to obtain the maximum joint strength values at the joints of interest.

2. Model development. A mathematical model was developed to generate lifting trajectories. The lifting task is presented as a nonlinear programming problem with a nonlinear objective function subject to linear, as well as nonlinear constraints.

3. Model validation and model applications phase. Lifting tasks were predicted using the model. Then, a verification procedure was conducted to justify the homogeneity between the experimental (measured) trajectory of the joint and the corresponding trajectory generated by the model.

Simulation Model Development

In a recent study by Ayoub et al. (1989), a simulation model was developed for sagittal lifting activities utilizing five joints. The mathematical form of the objective function and constraints are:

1. Objective Functions:
opt_obj = MIN
(torque(t,j)/max_stren(j))2 dt. (2)

The objective function (eq. 2) or the cost function is the minimization of the time integral of the sum of the square of the active state of each joint. Use of the ratio as the criterion emphasizes that the optimization process distributes moments to the joints according to their relative abilities. The "square" term provides for a heavier penalty for large deviants (compared to linear) in the minimization process.

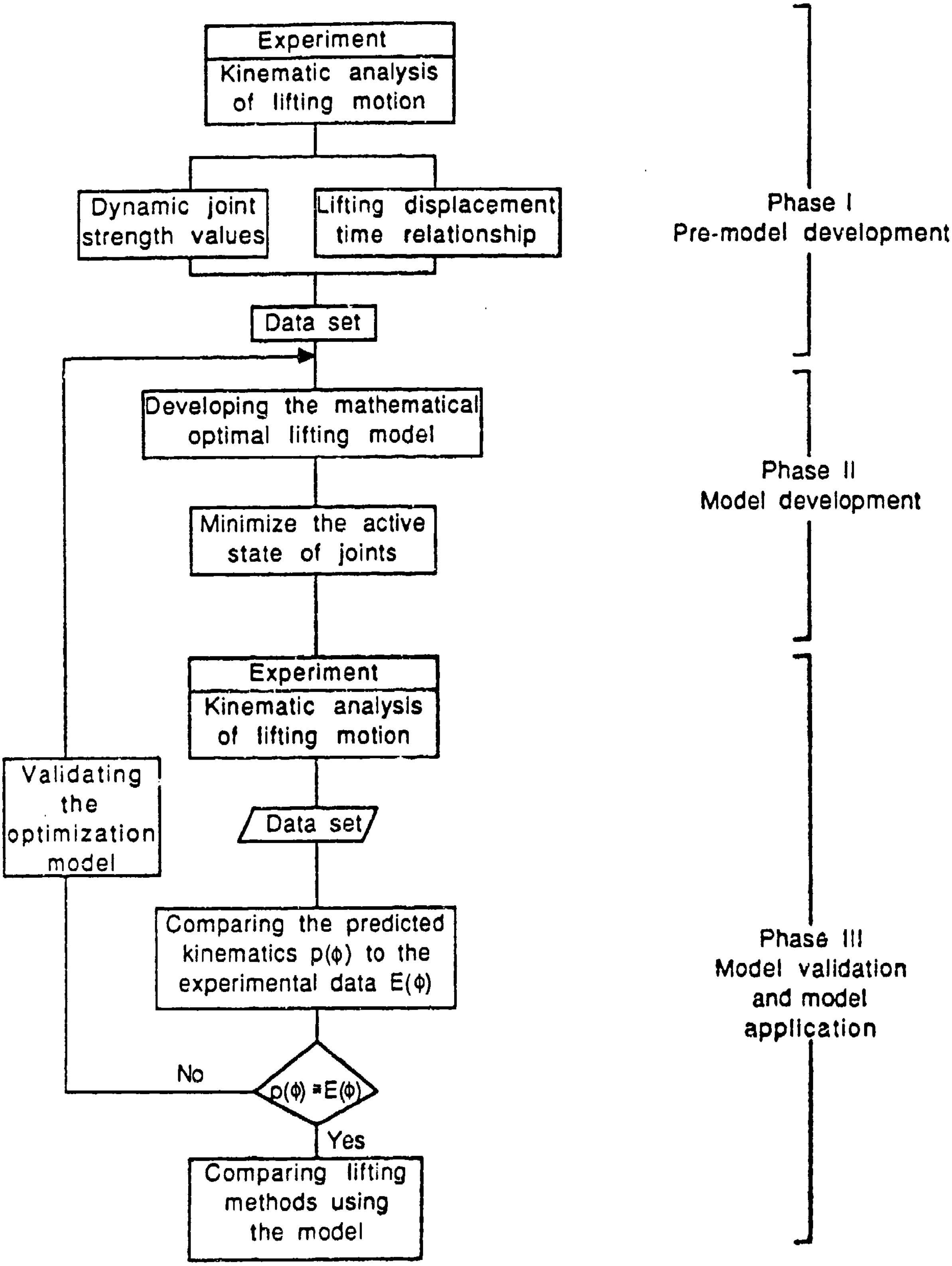


Figure 4. The Flow of Study Activities.

2. Nominal Constraint Set:

The constraints are (a) the constraints imposed by the initial and final joint angles, (b) the constraints imposed by the joint mobility, (c) the constraints imposed by the reaching envelope, (d) the constraints imposed by the workstation, (e) the constraint of the angular acceleration, (f) the constraint of the rate of change of acceleration, (g) the constraint due to muscle strength, and (h) the constraint on the limit on the center of mass of the body and load combination.

Solution Methods

A model such as that described above differs from the traditional nonlinear programming problem in that it requires the minimization of a time integral of a function. In effect, the model is required to "pick" a motion path which results in minimizing the objective function. The method employed to solve these continuous, multivariable, multiperiod, and nonlinear optimization problem involves the use of a dynamic programming procedure and a coarse grid search technique.

From the optimization point of view, the following observations regarding the model can be made:

1. The model has a quadratic objective function and linear as well as nonlinear constraints.

2. The problem is very large in size and is characterized by the number of stages and state variables, as well as the number of coupling, noncoupling, time invariant, and time variant constraints. The formulation results in a dynamic programming problem with states represented by a five-dimensional vector. The number of stages chosen depends upon the precision of the integration approximation required.

3. The problem was solved using the "Trajectory Approximation in State Spaces" technique (Durling, 1984). Computationally, the problem is decomposed into two parts for solution. The first part is to generate initial joint trajectories; the second part is to improve the trajectories to arrive at an optimal or (near-optimal) result (see Figure 5).

Model Application

In an attempt to apply the model to a lifting task, a lifting experiment was performed. The task performed was lifting from the floor to knuckle height (approximately 30 inches above the floor) and lifting from the floor to shoulder height (approximately 50 inches above the floor). Two sizes of containers were lifted, 24 x 12 x 12 inches and 24 x 18 x 12 inches, while the weight lifted was the subject's maximum acceptable weight of lift (MAWL) determined psychophysically. Five subjects performed the lifting tasks while being photographed with the Motion Analysis System. Five joints were tracked by the system. These were the ankle, the knee, the hip, the shoulder, and the hand. In addition, the center of mass of the container was also monitored.

To apply the model the following inputs were provided:

1. The initial and final position of the body based on the initial and final locations of the load,
2. Strength data for the subject,
3. Weight of container (the load), and
4. The physical constraints dealing with range of motion, reach envelope, max accelerations, and first derivative of the acceleration with respect to time, and body balance.

When the model was applied to lifting tasks, the model-generated joint motion patterns were compared with actual motion patterns. Figure 6 shows a sample of the results of this application. Based on the results of several applications of the model, one may conclude that it may be feasible to develop simulation models to predict the path of motion body joints in two dimensions while performing a task. Although the paths generated by the model are not identical to the actual paths, the accuracy of prediction is considered adequate enough with the majority of mean square error constituted by the random error component. However, there is room for improvement.

SUMMARY

With regard to biomechanical modeling, several models exist. These can be divided into static models and dynamic models. These in turn can be divided into two-dimensional and three-dimensional models. The objective in biomechanical modeling is to develop a model of the body or segment of the body which can accurately predict the kinematics and kinetics of task performance and, hence, the risk of injury. Such a model must be provided with adequate data, such as information from EMG studies, muscle strength studies, anthropometric measurements, external forces applied to the body, displacement-time information, internal muscle force vectors, passive tissue data, etc. By examining this list such models do not now exist, but information needed to develop such models are now being pursued by several investigators. The ultimate goal is to develop three-dimensional dynamic models.

With regard to human simulation models, very few models exist which predict the motion pattern a worker may or should follow in the performance of a task. These simulation models differ from biomechanical models in that biomechanical models require input information about displacement-time relationships, while simulation models have the displacement-time relationships as their output. These simulation models depend on optimization theory and techniques to solve problems about the motion patterns required in the performance of a task to minimize a specific cost function or functions subject to a set of constraints.

Both types of models (biomechanical and simulation models) can be combined to provide the ultimate goal of developing a model which cannot only estimate accurately the forces acting on the body, but also predict the motion patterns which will minimize such stresses on the body.

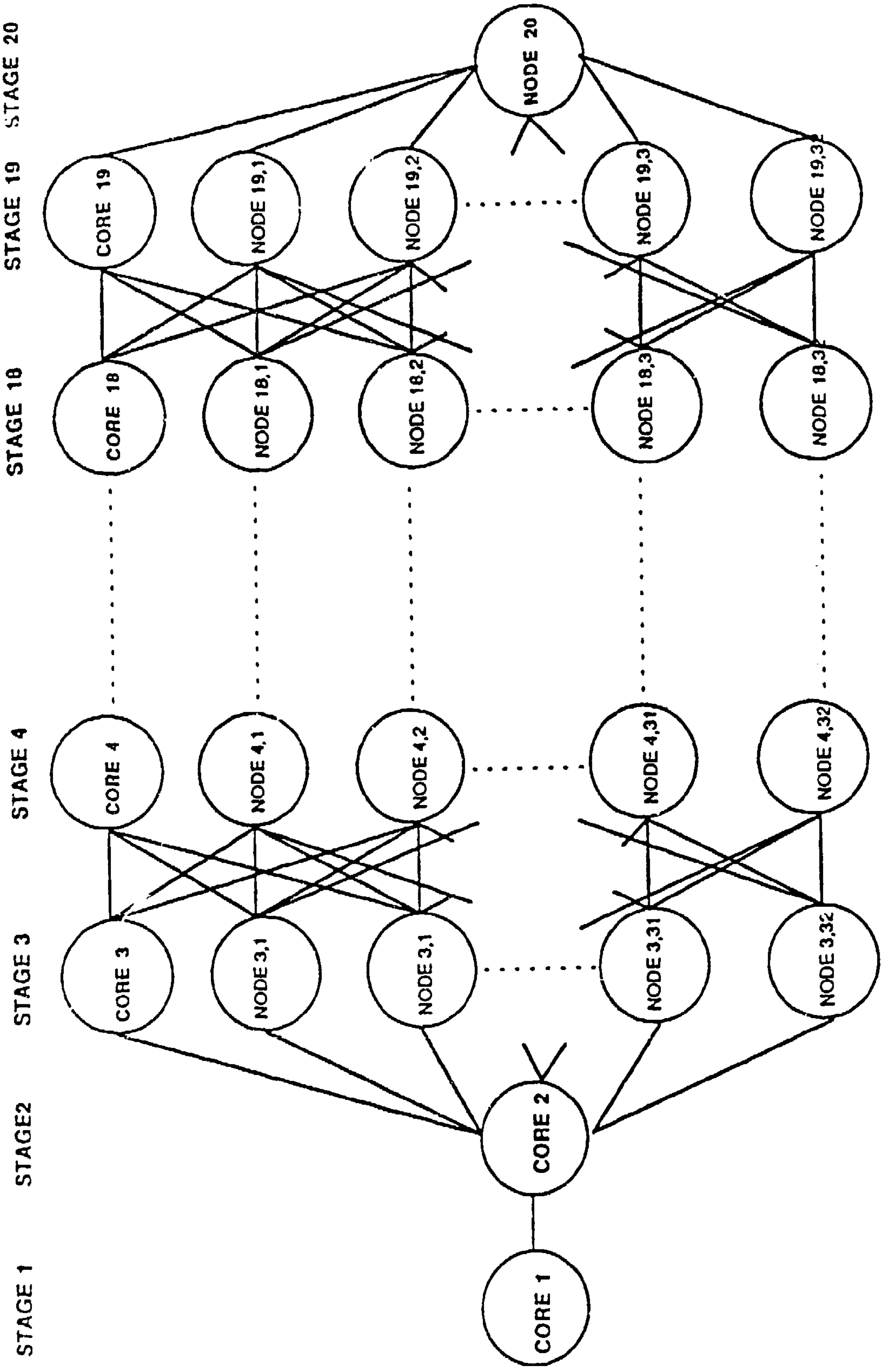


Figure 5. Network for the Model.

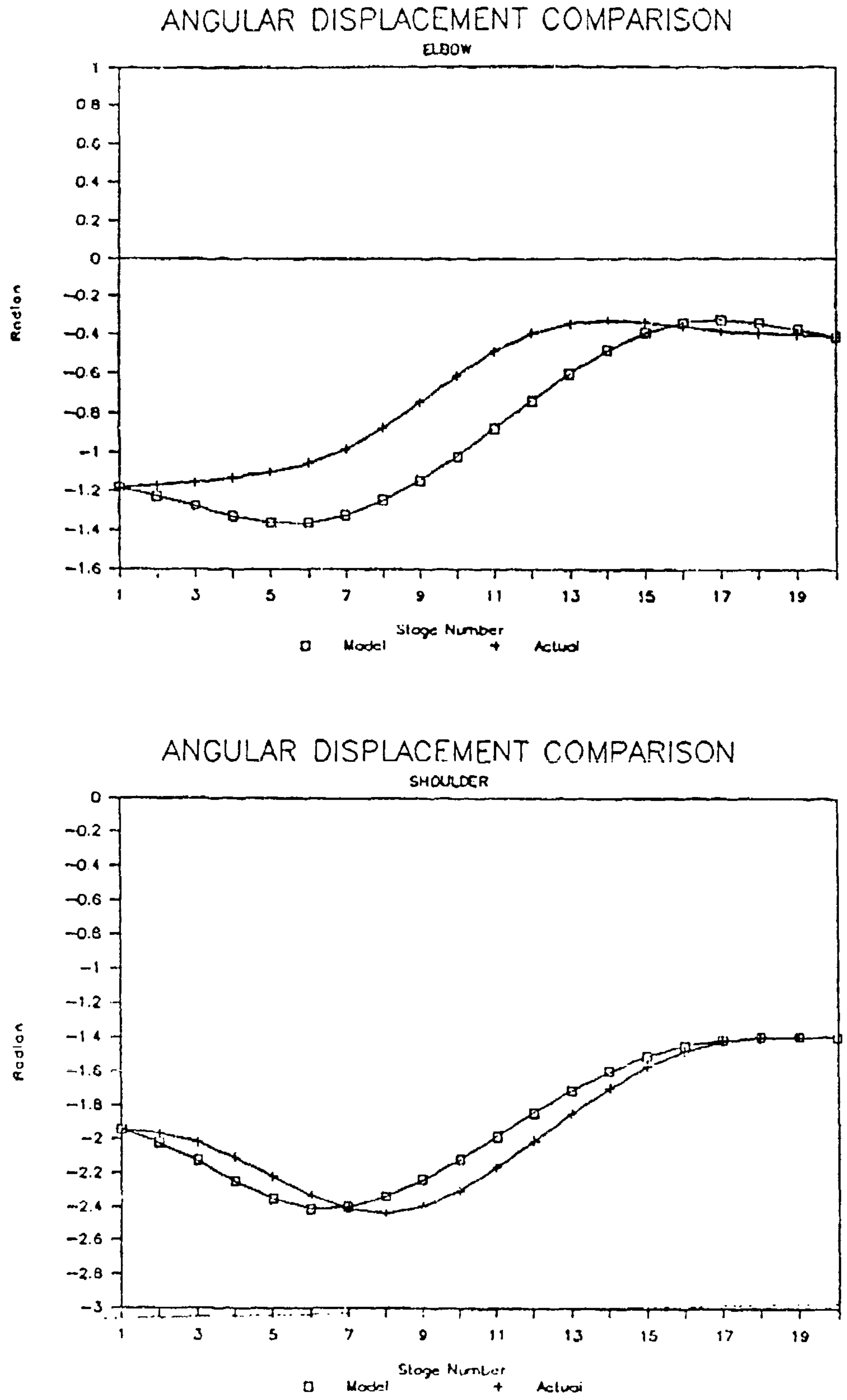
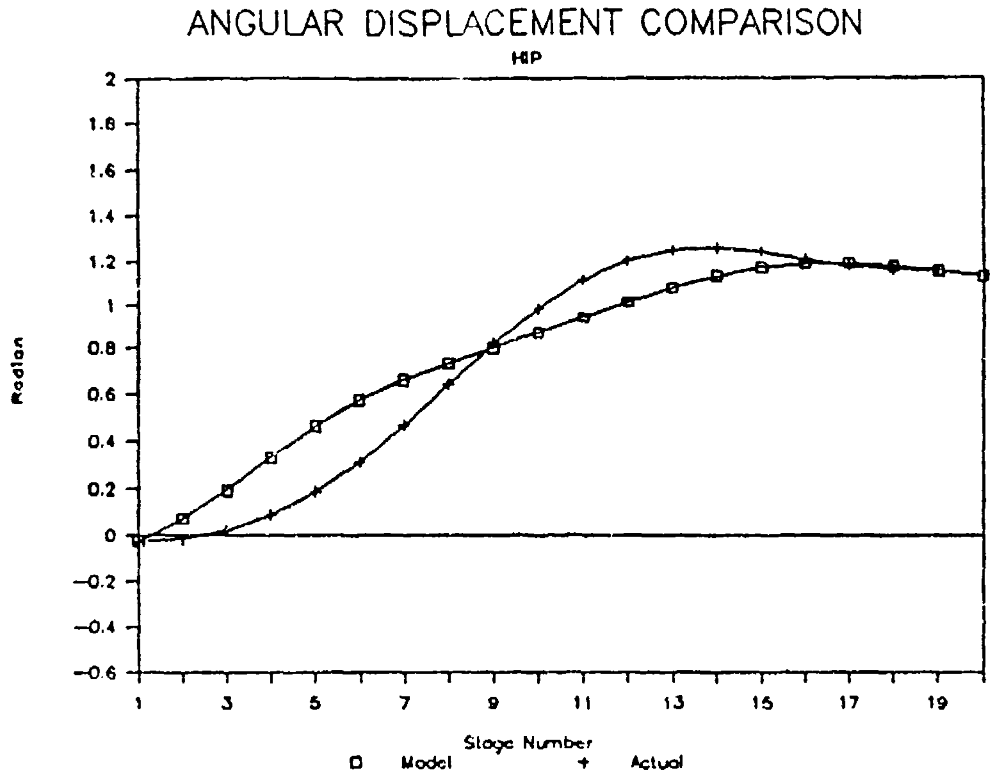


Figure 6. Displacements of the joints and the load.



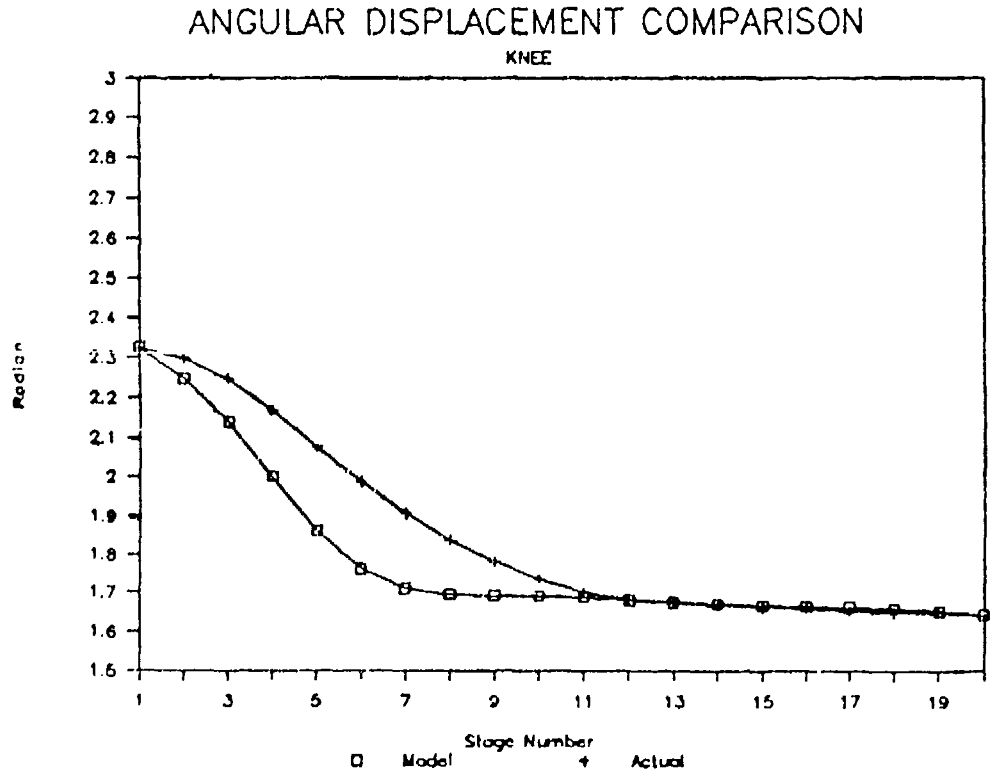


Figure 6 (cont'd)

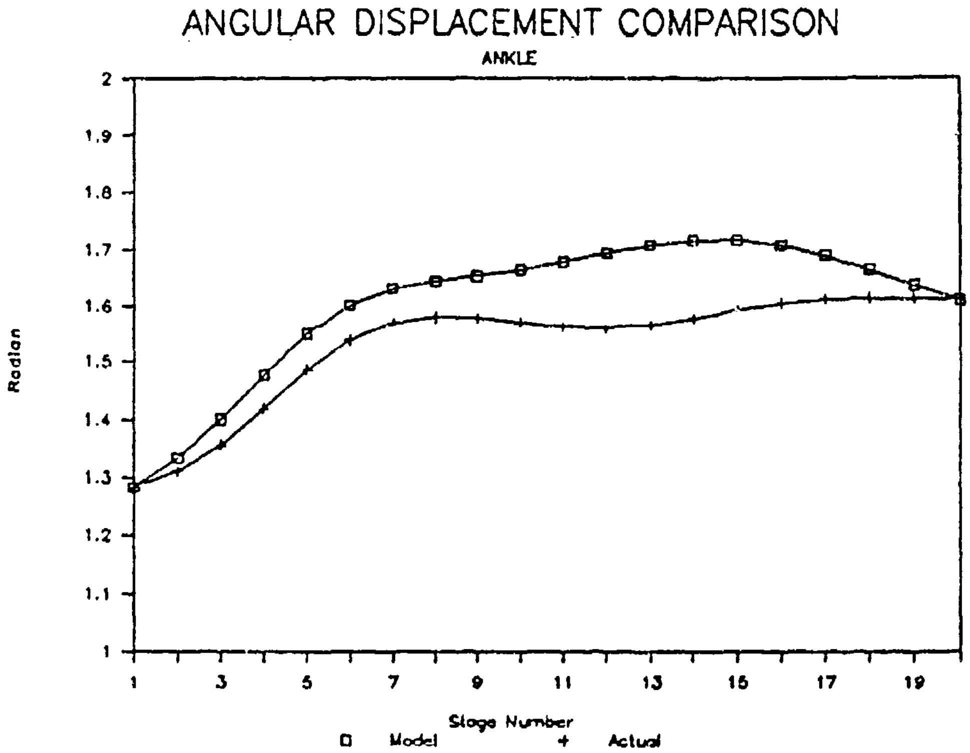


Figure 6 (cont'd)

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SIMULATION PROTOCOLS FOR ANTHROPOMORPHIC MODELS

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ABSTRACT

Task simulation with computer-generated images of humans is examined by contrasting this method with certain aspects of conventional simulation (simulation with languages such as GASP or SLAM). The purpose of this paper is to draw useful ideas from conventional simulation so that human form models may be more effectively used as simulation tools. The commonly accepted stages of development for conventional simulation provide a structure for the discussion. Applications providing examples pertain to aircraft assembly and maintenance. Human form simulation has unique characteristics such as reliance on visualization that make the approach very well suited to spatial questions about detailed task environments. However, additional power and versatility of human form simulation could be realized by employing techniques of experimentation and output found in conventional simulation.

INTRODUCTION

With increased sophistication and versatility, computer-generated anthropomorphic or human form models now have the capability to represent numerous facets of task performance. This capability has introduced a form of simulation with which users intend to improve the compatibility of equipment for human aspects of manufacturing, operation, and maintenance. Examples in this paper pertain to simulation for aerospace applications, especially air vehicle assembly and maintenance.

Throughout this paper, the adjective "conventional" is used in referring to simulation with languages such as GPSS, Q-GERT, SLAM, and SAINT; and "anthropomorphic" or "human form" in referring to simulation with computer-generated images of humans. Conventional and human form simulation appear to have sufficiently distinct characteristics to treat them, at least for present purposes, as different approaches.

Conventional simulation is very widely used. Many people aware of its effectiveness would probably agree that the technique "has been one of the most consistently useful and productive applications of computer science" (Roth, 1983, p. 1327). Therefore, an excellent return on research in anthropomorphic simulation might also be expected.

The purpose of this paper is to draw useful ideas from conventional simulation for human form models so that the latter may be more effectively used as simulation tools; this purpose is based on the assumption that the fundamental goal of human form models is simulation rather than, say, illustration. Two observations support this assumption. First, among the most frequent objectives of designers, planners, and analysts in using human form models is the representation of human performance to understand an operation at the task environment and human interface--in essence the same objective of conventional simulation if "system behavior" is substituted for "an operation at the task environment and human interface." Second, the advantages of conventional simulation, such as study of system alternatives before implementation, and evaluation of operational changes without disturbing an actual system (Banks & Carson, 1984, p. xi), are characteristic of simulation with human forms.

Despite the tradition of simulation behind human form modeling, important contrasts exist between it and models built for conventional simulation. Some of these contrasts suggest needs, or in other cases, advantages, in human form model use. For example, human form models do not allow for straightforward experimentation, while on the other hand, this type of model is oriented to spatial relationships and capitalizes on users' natural ability to visualize.

Because the essential methods of conventional simulation are well known, the stages of development for simulation studies listed by Pritsker (1986, pp. 10-11) provide a useful framework for this discussion. Pritsker lists 10 stages:

1. Problem Formulation
2. Model Building
3. Data Acquisition
4. Model Translation
5. Verification
6. Validation
7. Strategic and Tactical Planning
8. Experimentation
9. Analysis of Results
10. Implementation and Documentation

The following sections define these stages and examine their implications for anthropomorphic simulation. Some sections group pairs of stages together.

PROBLEM FORMULATION AND MODEL BUILDING

In these two stages, the problem is identified and agreed upon by persons involved and an abstraction or model of the relevant system is created. The basic perspective for any simulation is that entities related to each other through some common purpose can be defined as systems, and the interrelationships and behavior of entities can be examined to understand behavior of the entire system. Many systems of interest are complex due to the interrelationship of variables whose levels change without certainty. For example, time required for a fighter aircraft turnaround is not always predictable. Cursory inspection of the aircraft moments after landing can reveal damage that affects refueling, rearming, or reconfiguring the aircraft, and demanding conditions on the ground can affect the movement of ground crew and materials. Thus, the condition of the aircraft will affect the time the ground crew gives to the aircraft during cursory inspection and will set into motion a series of decisions and actions that are affected by events on the ground. Simulation is appropriate for such systems where it is not possible to obtain exact information (i.e., analytic solutions) to questions of interest.

The most commonly used conventional simulation models, termed discrete-event models, are focused on the passage of time and contain entities or functional components called users, resources, demand, and queues (Roth, 1983, p. 1329). One useful item to borrow from conventional simulation is this notion of functional components of a system. For example, if human forms are deployed to model the discrete events of a maintenance or manufacturing task, task elements to be accomplished could be defined as the users, human performance (expressed across time) as the resource, performance requirements as the demand, and waiting task elements as the queues.

However, the associations above (e.g., task elements and users) are abstract. Because human form models are spatial and visual, it is just as important to identify the entities that constitute factors affecting human performance. These factors combine to comprise a system for the purposes of human form simulation. These factors include the structural features of a maintainer's or assembler's immediate surroundings, the human form, task requirements, tools or components related to task performance, and environmental factors. This set of elements leads the human form model builder to focus on highly specific parts of tasks where specified elemental motions take place, such as reaching to a control or using a hand tool. Figure 1 depicts the combination of entities.

It is possible, of course, to define a system more broadly, so that more interrelationships of entities can be examined. For example, in addition to specific parts of some aircraft maintenance task, one might model the movement of ground and support equipment around an aircraft because such movement affects the start times of maintenance tasks. However, broader scope normally leads to less detail in a simulation (Roth, 1983, p. 1328), and one of the primary strengths of human form simulation is its ability to produce insights about detail. A question about the influence of equipment arrival on task start times is more molar, and perhaps better suited to conventional simulation. Simulation with human forms is normally directed at very localized situations where some question exists about person/task environment behavior. Figure 2 presents the difference in scope between conventional and human form simulation and the focus on detail-level questions common to the latter.

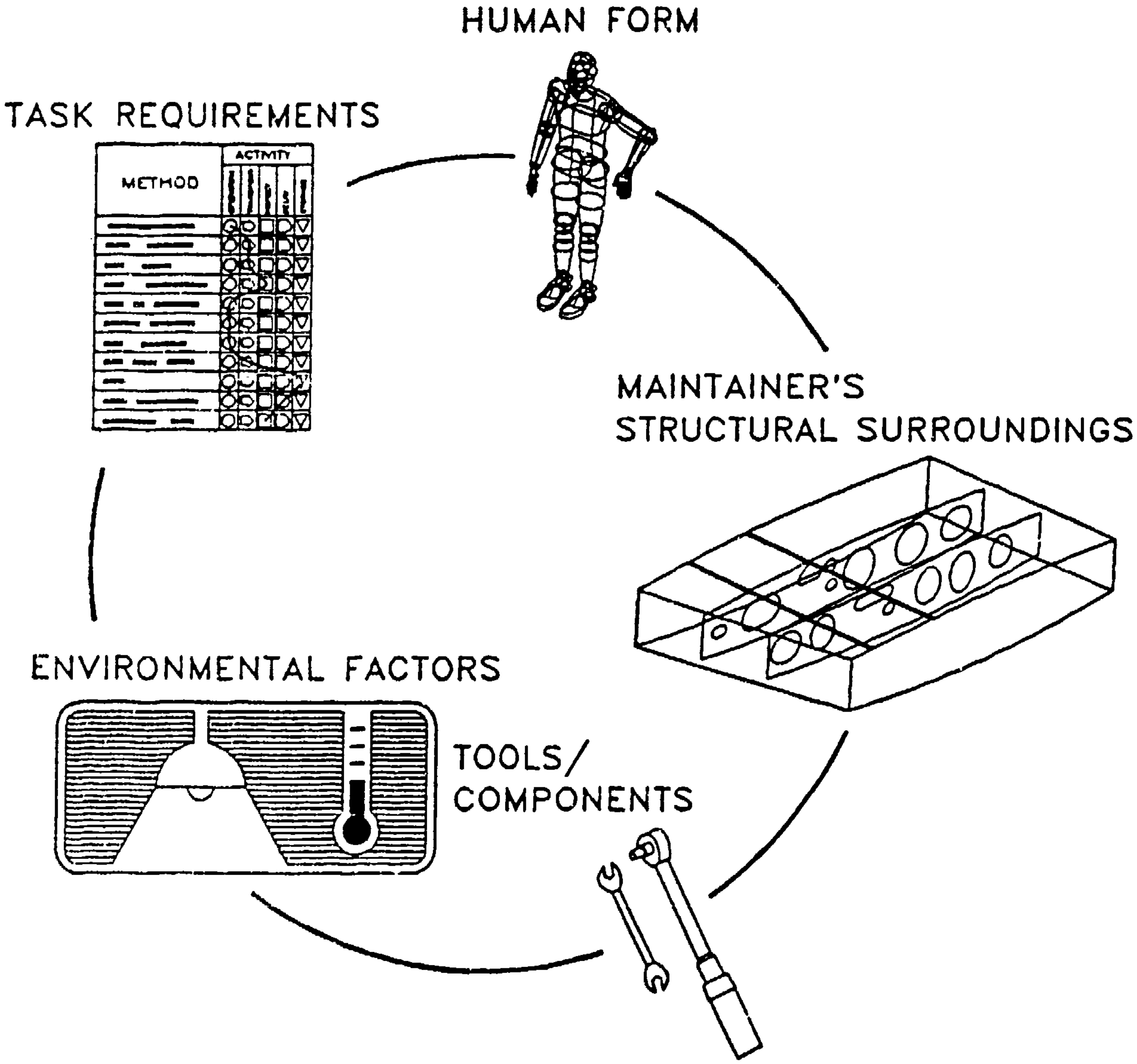


Figure 1. Entities of Systems for Human Form Simulation of Aircraft Assembly or Maintenance.

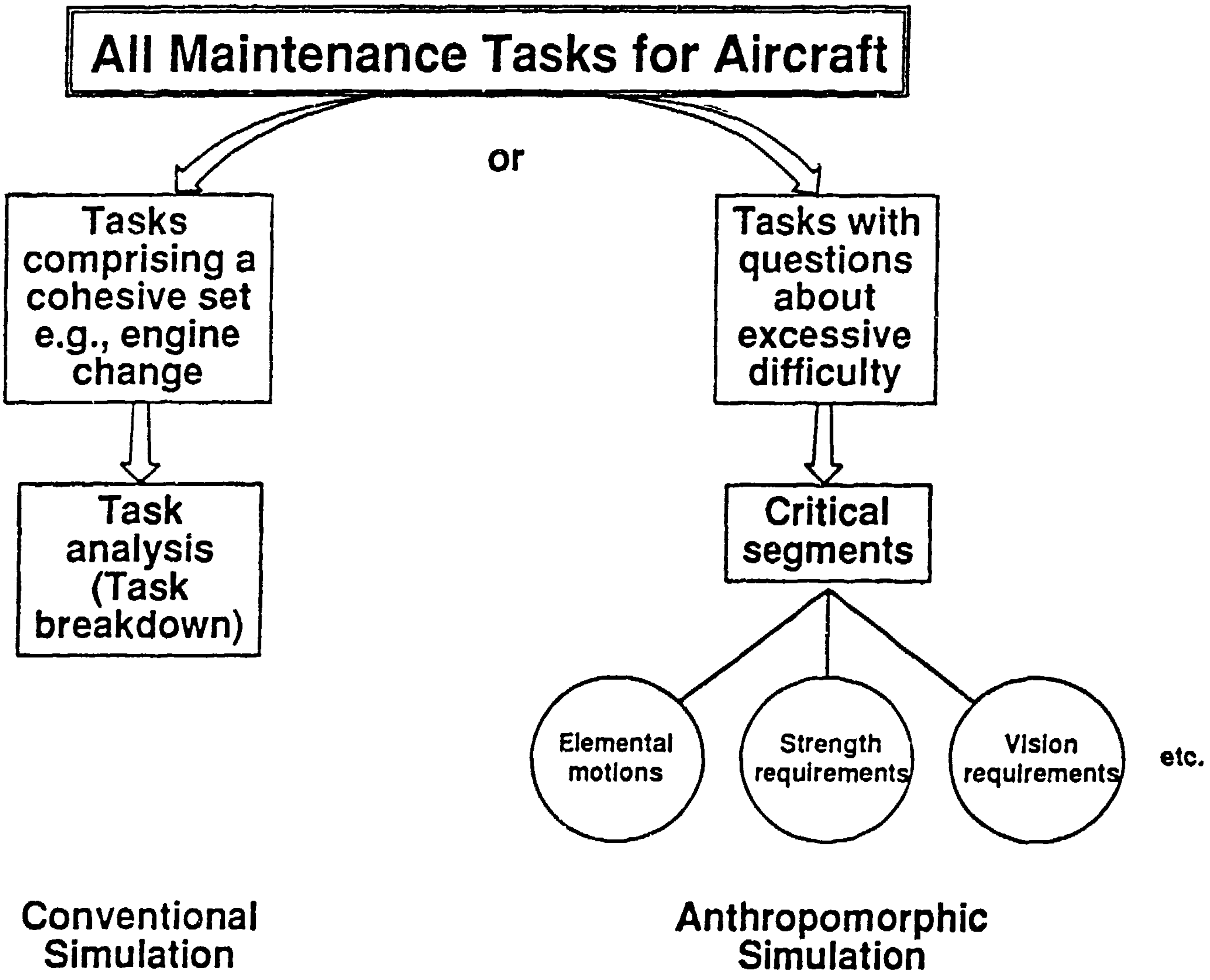


Figure 2. Domains of Conventional and Human Form Simulation for Study of Human Tasks in Aircraft Maintenance.

An economic matter also influences model-building in human form simulation. Where questions do not exist, it is unlikely that models will be built (for example, for exploratory purposes) due to the time-consuming discussion, observation, and frequent revision involved in model building. It is not inconceivable that with thoroughly defined task environments and advanced artificial intelligence, human models could be directed to carry out the steps of a task and identify, for the model user, problem aspects of system behavior. Currently though, expense of model building is one of the disadvantages of any type of simulation (Law & Kelton, 1982, p. 8).

DATA ACQUISITION

This stage involves identifying and collecting data, such as durations, frequencies, and probabilities, that characterize system behavior. In the realm of human form models, this stage is made more straightforward when the model builder narrows his or her attention to critical segments of tasks. Typically, tasks contain many segments or steps, only one or a few of which are likely to be critical. If it appears that a human could not perform a certain segment of a task, an analyst could well assume that the task is nonperformable due to the one (or more) segment(s). Segments of a task are critical if they are likely to prevent completion of the task sequence. When critical segments are identified, the anthropomorphic model-builder can deal with aspects in those segments, such as elemental human motions, to isolate portions of system requirements that challenge human performance. Aspects of critical segments are characteristics arising out of the interaction of structural environment, human capacities, and task demands. They include implications of the segment for strength, vision, body size, fine muscle coordination, perseverance, memory, actual and perceived workload, and so on (see Figure 2).

Thus, the problem-solving focus of human form models applied to aircraft maintenance, for example, brings about a progression from (a) the population of all maintenance tasks on an aircraft, to (b) those tasks with questions about excessive difficulty, to (c) critical task segments, and finally to (d) aspects of critical segments.

It should be mentioned that for human form model building, data acquisition is complicated by the need for engineering data that define the structural features of a maintainer's or assembler's immediate surroundings. Depending on when a simulation is started, these data may be in a variety of locations or forms. For example, logistics analysts may need design data before they are released, or planners may obtain engineering data and find that they are not compatible with their drawing system. Many of the goals of concurrent engineering address these problems.

MODEL TRANSLATION

Model translation is the preparation of a model for computer processing. For human form simulation, this stage is not as distinct as it may be in conventional simulation because human forms and structural environments are often created as part of the data collection process. However, the distinction in conventional simulation between continuous and discrete-event models should be noted. In continuous change models, the state of a system is depicted by dependent variables that change continuously with time. For example, an airplane in flight is in an environment of constantly changing elements, such as spatial location and remaining fuel. In the second viewpoint, referred to as a discrete-event perspective, the state of the system is changed at the time of each event (Roth, 1983, p. 1329). An example of a system that can be modeled as a discrete-event system is the arrival of parts at an inspection station.

Chubb, Laughery, and Pritsker (1987) present the idea that human performance is a "task/network" system that often contains both continuous processes and discrete events. With a task/network model, human performance can be separated into a series of subtasks, and, when the model is implemented in some computer language, "experiments can be conducted by varying subtask attributes or the structure of the network" (p. 1310). This view is often appropriate for simulation of human activity in maintenance and manufacturing. For example, time of day, a continuously changing variable, is clearly related to performance of repetitive assembly and other manual tasks (Dudley, 1968). Therefore, systems encountered in most human form simulation can be considered as combined continuous-discrete event systems if they contain both characteristics. Current human form simulation is oriented to discrete events such as manipulation of a tool or visual accessibility, and would be improved by performance aspects reflecting continuous change. Examples of such factors include time of day, fatigue, and time pressure.

VERIFICATION AND VALIDATION

An analyst constructing a conventional simulation would verify that the computer program running the simulation executes as it is intended. With human form models, the evolutionary process necessary to create a system model normally brings about an incremental verification during model development. As human form simulation versatility and power increase and as the method is applied to more factors or more levels of factors, verification will probably become a more distinct stage.

Validation refers to assurance of some degree of correspondence between a simulation model and an actual system or baseline. Validation occurs at various levels such as data inputs, model elements, and interface points (Wilson & Pritsker, 1982). At any level, questions often arise about what constitutes adequate model validity. For human form simulation, much of the current validation concern involves credibility of the human model itself (e.g., Glenn, Harris, & Zaklad, 1982; Heinze, 1989). It is likely that other issues will arise as multiple factors are examined. For example, an analyst might want to know the probability of human error during aircraft jacking. A human form model for such a question might well contain performance adjustments due to time pressure, maintainer workload factors, and spatial factors. The interaction of these variables depends on valid representation of their individual influence.

Interactions of effects are very characteristic of human performance. An interesting matter noted by Salvendy and Knight (1987) suggests the challenge of validating models of human performance when those models are part of a human body motion scheme. Their point is that "beginning and end points of elemental (motions) do not necessarily coincide with the beginning and end points of the physiological and mental work associated with the performance of an element" (p. 6.1.5).

The validation approach for conventional simulation is to ensure that (a) the internal structure of the model is reasonable, that (b) where possible, assumptions are supported by empirical verification, and that (c) the model predicts the behavior of the real world system (Shannon, 1975). If, as in the case of our example, parameters are not precisely known and must be estimated, a perfectly acceptable model can still result if it has reasonable internal structure and an ability to predict behavior of the actual system. This fact is the same for both conventional and human form simulation.

However, an additional validation level is created in human form simulation by the intentional use of computer images to support users' internal visualization. The objective in the practice of human form simulation is that analysts make decisions or judgments that are applicable to an actual system rather than applicable only to the image presented on the computer screen. The model builder might ask whether different judgments about a system would occur if some analysts studied only the actual system and other analysts studied only a simulation model of the system. An approach for this type of validation is to provide an actual system that can be studied and to compare the products (decisions, judgments, evaluations, etc.) of analysts who study the actual system to products of analysts who study a model of the actual system. Model builders should assure themselves that products from modeled systems are like those or better than those from the actual system.

STRATEGIC AND TACTICAL PLANNING

Strategic planning refers to making general, conceptual plans for answering questions with a simulation model. Tactical planning refers to making plans of strategy execution, efficient use of the simulation model, experimental conditions for using a model, and plans for statistical analysis. Strategic and tactical planning forms the basis for drawing reasonable conclusions about system behavior. As pointed out before, the system under study with human form simulation is normally a human and his or her immediate task environment; the objective is to understand and draw conclusions about the behavior of this detailed, "local" system. With anthropomorphic simulation, this objective is not as much served by statistical experimental design as it is by a Computer-Aided Design (CAD) capability to represent spatial relationships and, just as importantly, by visualization made possible with human forms.

Visualization is the human ability to interpret meaning in complex visual scenes and manipulate internal images. Most people have a natural ability to visualize, and this ability is promoted and put to useful purposes by software for engineering, mathematics, medicine, geology, and many other disciplines. People can interpret and find patterns in visual scenes far more quickly than in numeric formats. For example, it is difficult to determine human posture from a table of human joint angles, but it is effortless to do so by looking at a drawing of a human form with joints set at the same angles. The ease of processing visual information in contrast to the effort of applying deliberate attention to numeric or verbal abstractions (indeed some data are simply too extensive to understand in other than visual format) is one of the primary motivations for continual development in visual representation (McCormick, DeFanti, & Brown, 1987).

In addition to finding meaning in visual scenes, and perhaps more important for anthropomorphic simulation, the manipulation of internal images enables humans to infer effects of spatial conditions. The meaning of this notion can be illustrated by reference to work by Shepard and Metzler (1971). The authors asked subjects to determine whether two geometrical figures shown simultaneously, one a standard and one a target, were the same or mirror images of each other. In pairs containing the same figures, targets were rotated to various degrees as though the viewer had different viewing angles for the standard and the target (see Figure 3). Subjects' time to judge targets was noted; Shepard and Metzler found that the time to judge targets was highly related to the degree to which the figure was rotated. This finding suggested, in concert with subjects' statements, that they mentally rotated their internal representations of the targets (images) to compare them to standards.

The ability to manipulate internal images and related visualization abilities underlies much of the usefulness of computer models of human form. Analysts can position a human form to represent a critical task segment and then envision progressions of elemental motions, goal-directed activities, tool use, and difficult aspects of the task. Visualization builds on available data (in the present case, a computer-generated picture of human form) to create a reasonable mental scenario of human activity (cf. Gregory, 1977; Neisser, 1976). Even such odd effects as the body's response to imagined weight have accurate visualization representations (Kosslyn, 1983). Anecdotal and common human experience suggests that visual thinking can create internal versions of a great array of movement-related phenomena.

Interactive modes of human model movement or animated sequences that capture critical segments further enhance visualization by drawing attention to additional details. Compared to interpreting tables of anthropometric data, construction of a visible human form on a graphics computer supports a pliable visualization of human activity and makes it relatively easy for an analyst to study the effects of a task environment on a maintainer or assembler and to consider various alternatives in system composition. Friedhoff and Benzon (1989, p. 132) find visualization aided by computer-generated forms to be such a compelling tool for understanding relationships between variables that they apply the term "visual experiments" to this practice.

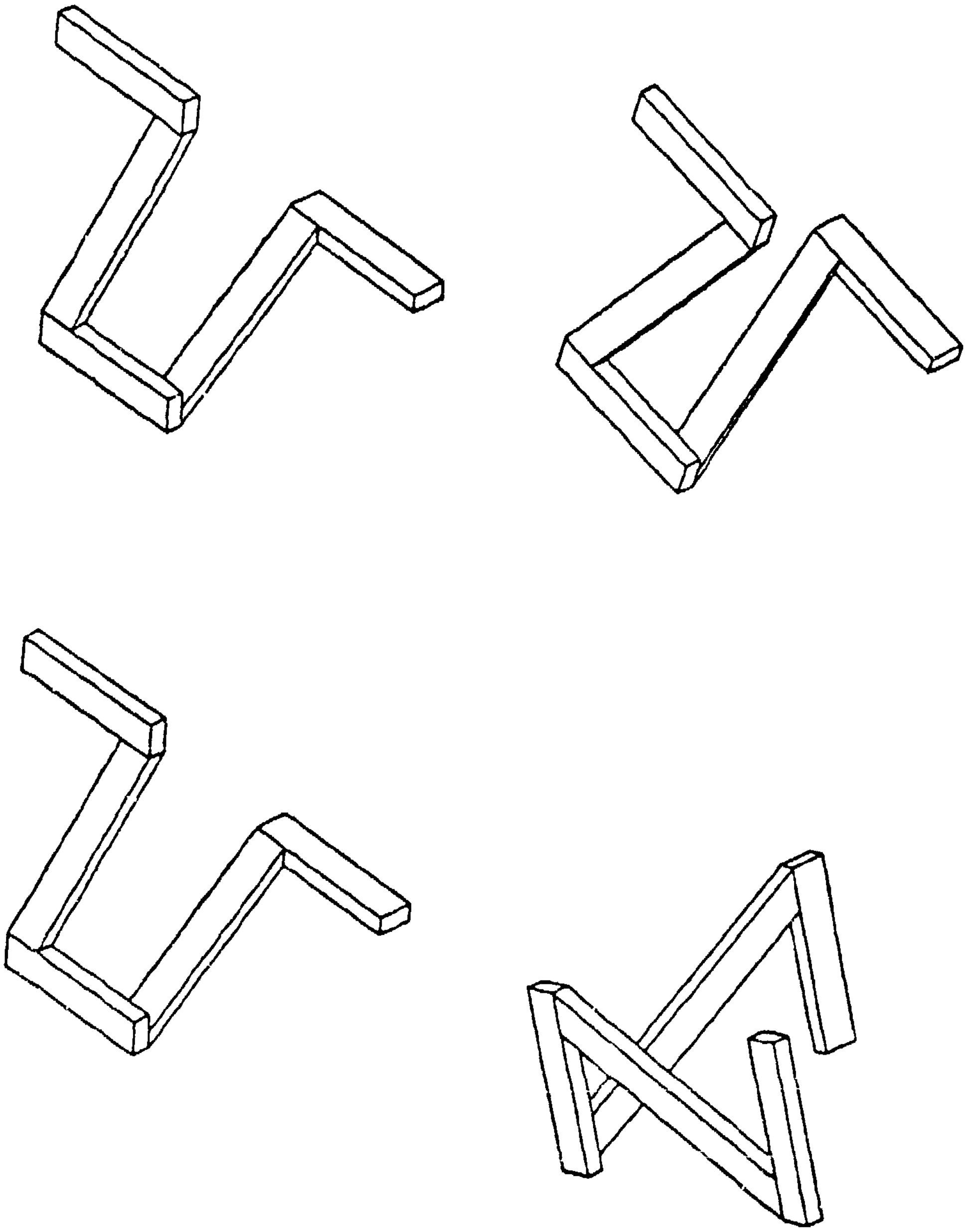


Figure 3. Stimulus Items Similar to Those Used by Shepard and Metzler (1971) to Study Humans' Ability to Perform Operations on Mental Images. (Standard or reference items are on the left; those on the right are the same items but rotated away from the standard position. See text for additional details.)

Visualization, in fact, supports procedures in numerous stages of simulation practice including the following:

1. Identifying critical task segments
2. Determining factors that most strongly contribute to system behavior
3. Reducing the differences between analysts' individual interpretation of a task
4. Identifying qualitative concerns in task performance
5. Pinpointing causes of task difficulty
6. Gaining insight on necessary skill training
7. Determining alternative approaches to task performance
8. Communicating task performance scenarios

Most of the comments in this section are intended to suggest that analysis with visualization is a useful approach to understanding system behavior. However, people always differ in even the simplest of tasks (Massaro, 1975, p. 440) and most likely differ in abilities of visualization and of analysis with visualization (e.g., Glass & Holyoak, 1986, p. 138). Individual differences can lead to different interpretations of the same scene. Therefore, formal experimentation with human form models offers definite benefits. The following section examines issues in experimentation.

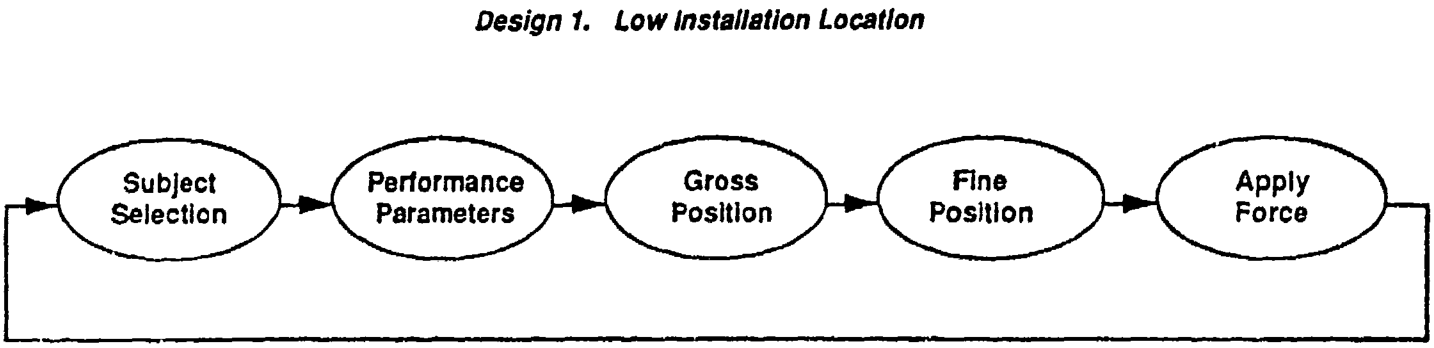
EXPERIMENTATION

Considerations for the variables to be measured and controlled guide the building of a model for conventional simulation. These variables, which can be called factors in the parlance of experiments with physical systems, can be examined with experiments to learn about system behavior. Experimentation is such an expected part of simulation that the point should be emphasized. According to Pritsker (1986, p. 6), "computer simulation is the process of designing a mathematical-logical model of a real system and experimenting with this model on a computer." In the words of another frequently cited writer, "Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies . . . for the operation of the system" (Shannon, 1975, p. 2).

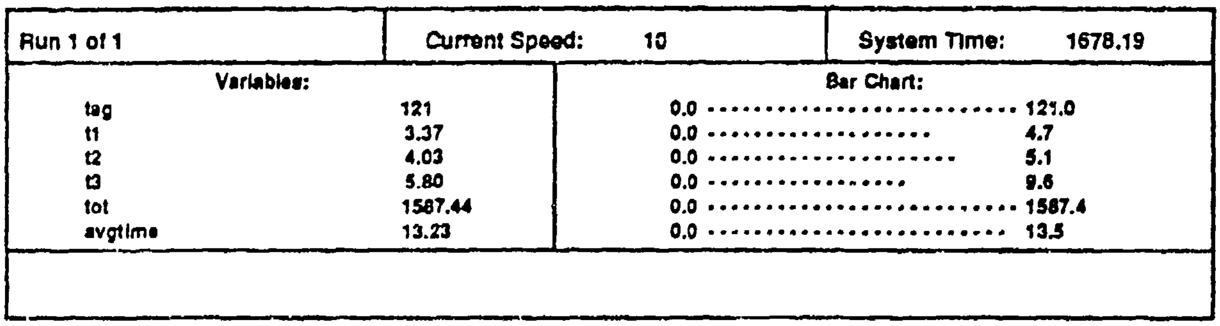
Running a simulation under one set of conditions constitutes what experimental design experts would call a "case study" (e.g., Campbell & Stanley, 1963); if the analyst changes conditions, again runs the simulation, and compares outputs from the two sets of conditions, he or she is performing an experiment. For example, Figure 4 presents elements of an aircraft assembly drilling task (modeled with a human form in Figure 5) where an installation location can be either high in a bulkhead or low.

Examining the effects on drilling time of either a low or high location is a study of either case; comparing the effects across two installation locations is an experiment. Of course, a conventional simulation can be designed to run multiple conditions and accumulate statistically sufficient data to compare conditions or individual factors comprising those conditions. If the conditions are independent of each other, conventional inferential statistical procedures may be used to determine whether conditions affect system behavior. Typical purposes of experimentation include (a) comparing means and variances of alternatives (e.g., how much time is required to reconfigure an aircraft), (b) determining the effect of variables on system behavior, and (c) searching for optimal values (Shannon, 1975, p. 150).

Many factors are normally present that might be examined and, of course, the model builder must select those that are the most likely contributors to system behavior. Most systems appear to operate according to the "Pareto principle," meaning that a few significant factors account for most of the behavior, and many insignificant factors account only for a small addition to



Design 1. Low Installation Location



```
Run 1 of 1          Current Speed:       10      System Time:       1678.19

           Variables:                                  Bar Chart:
     tag                      121          0.0 ......................... 121.0
     t1                        3.37        0.0 ..................        4.7
     t2                        4.03        0.0 ....................      5.1
     t3                        5.80        0.0 ................          9.6
     tot                    1587.44        0.0 ......................... 1587.4
     avgtime                  13.23        0.0 ........................  13.5
```

Figure 4. Diagram and Output Chart of Simplified Micro SAINT Simulation Model of Hand Drilling Task.

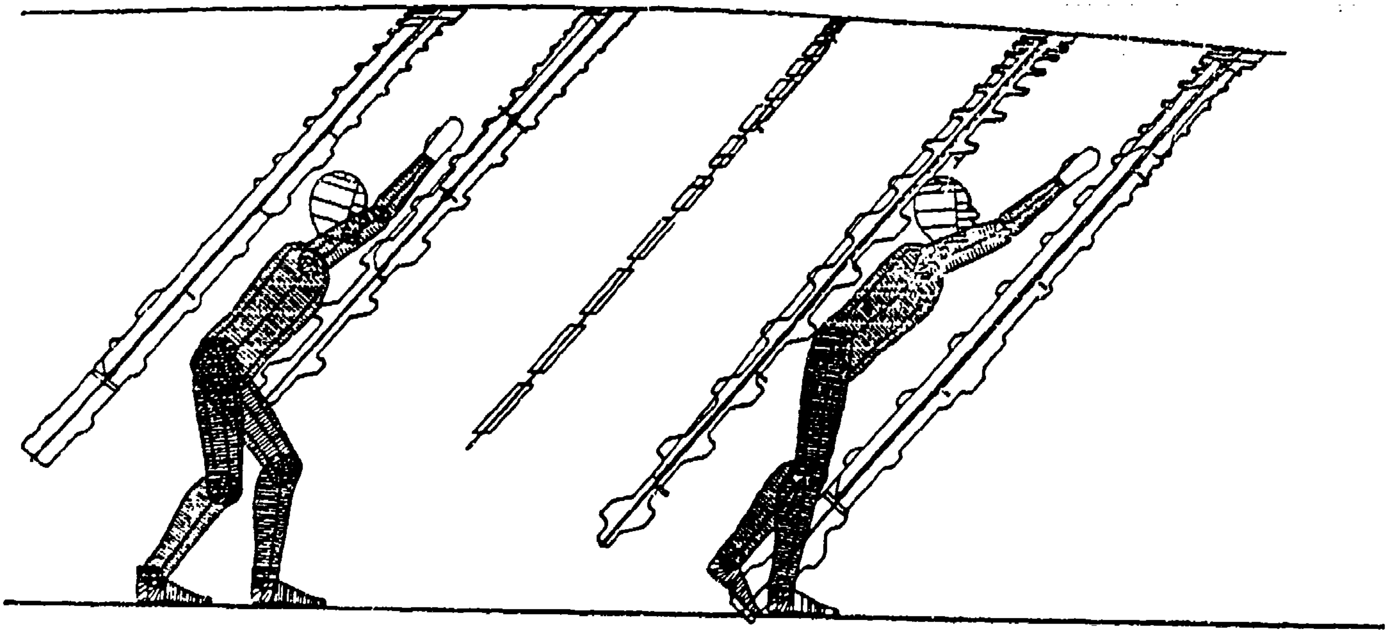


Figure 5. Human Form Model of Aircraft Assembler in Position for Hand Drilling Between Canted Bulkheads.

behavior variability. For example, within a range of typical operating conditions, time to diagnose and repair an aircraft auxiliary power unit (APU) that fails to start is probably affected by many factors, such as weather condition, lighting, strength, agility, stature, skill level, cognitive ability, method of diagnostic reasoning, and clarity of instructions. However, most of the variability is probably accounted for by just one or two factors, possibly the last two listed (cf. Brown, Burrows, & Miles, 1972; Towne, 1984). In the course of experimentation, levels of important factors are either allowed to fluctuate randomly, held at a constant value, or controlled, depending on their perceived role in the physical system.

The importance of experiments is unequivocal in conventional simulation, but in human form simulation, the role of experimentation is less clear. One reason is that with human forms, the need for experimentation can appear less important when visualization provides insights and solutions. Furthermore, some concerns addressed with human form models are qualitative in nature and cannot be resolved through analytic means. Figure 6 shows the method of wing access proposed for retrofit work on bulkheads. Even those unfamiliar with simulation with human forms would agree that the access method illustrated would be a challenge and pulling an incapacitated worker out of the wing could be very difficult; policy decisions might preclude this approach.

However, other common purposes of human form simulation suggest substantial benefit from experimentation. For example, consider a work space matter wherein jet engine fuel controls are mounted on stands for test and inspection. Fixtures that allow fuel controls to rotate for easy access to adjustments would probably reduce the time to complete test procedures, but by how much? In this imagined situation, the important factor might be position of fuel control adjustments, because their positions relative to readout panels on the test stand determine how much time operators spend making adjustments during performance of the test. Currently with human form models, an analyst can (a) position a human model within the electronic representation of the test stand workstation (thereby creating a system model); (b) perform fit, strength, vision, and movement analyses through visualization or through embedded analytic modules; and (c) modify the workstation and repeat analyses.

The analyst's questions would be more adequately answered if experimentation were possible with human form models. For the "as-is" test fixture, the planner collects data on elapsed times between test stand checking and fuel control adjustment and number of cycles of this procedure per test. Then, for the "to-be" test fixture, a human form model is juxtaposed with an electronic drawing of a test stand (again creating a system model) to generate comparative times for the conditions of fixed and rotatable fuel controls. The analyst would provide information about the likely adjustment positions under fixed and rotatable situations and likely frequencies of reaches to any of the positions. The power of the human model comes into play when it is asked to repeatedly perform test stand check and fuel control adjustment trials. Elapsed times for sequences might vary by picking a speed of performance for each trial from an appropriate distribution. The analyst has several valuable outputs from this experiment: (a) a comparison of times for reaching/adjustment under fixed versus rotatable conditions; (b) qualitative information about the two approaches through visualization; and, if the model used can simulate human motion in real time; (c) estimates of time for reaches to adjustment positions where the analyst cannot obtain empirical data.

The experiment above is one with multiple levels of a single factor (adjustment position). It is not unusual for questions to arise about more than one factor (e.g., size of operator, training, availability of assistance from a co-worker), particularly as design and planning cycles merge in concurrent engineering environments. This effect is illustrated in Figure 7. As phases of product definition overlap, types of human model analyses also overlap, and resolutions both need and

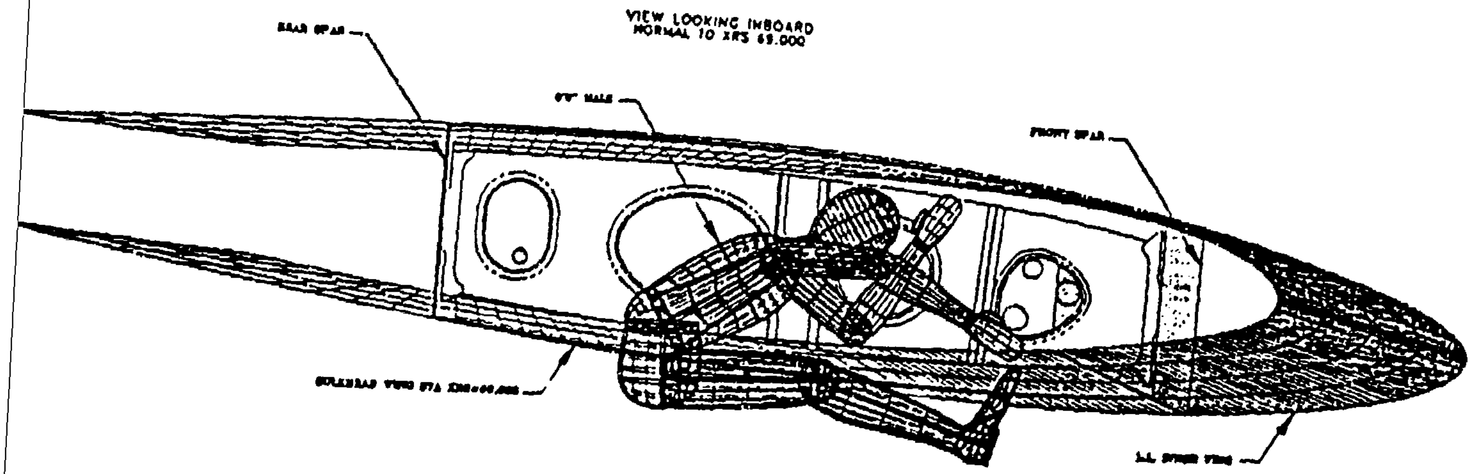


Figure 6. Human Form Model Depicting Worker Entering Wing Cell Under a Proposed Method for One Case of Retrofit Work. Drawing courtesy of Gerald Stone and Thomas P. Jahn, Douglas Aircraft Company.

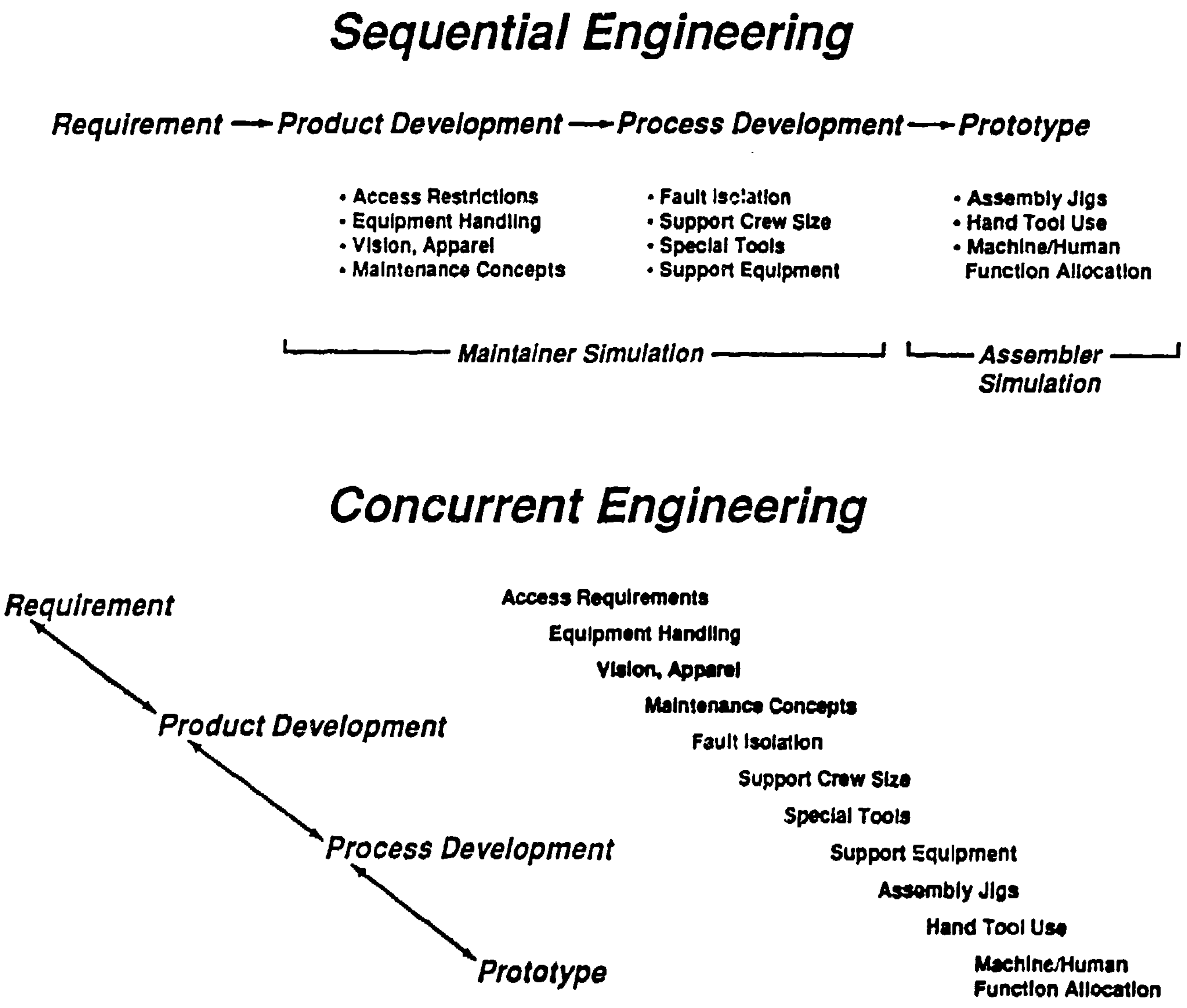


Figure 7. The Effect of Concurrent Engineering on Analysis of Human Performance Variables.

benefit from consideration of multiple factors. With multiple factors, the efficiencies of factorial designs, Taguchi methods, or computer-aided design of experiments (e.g., Hanrahan & Baltus, 1990) can be applied with appropriate planning.

ANALYSIS OF RESULTS

Analysis of results is the process of analyzing simulation outputs and applying them to problem resolution. To put this matter in perspective, consider the simulation introduced earlier of hand drilling during aircraft assembly (see Figures 4 and 5). For our example, we can examine elemental motions in a task so that we can make a reasonable comparison between conventional and human form simulation. This is the level of detail illustrated by Chubb et al. (1987) for manned system simulation, although model-building for this level of conventional simulation is usually prohibitively expensive. The context for this simulation is drilling with a hand-held, air-powered tool while standing between closely spaced, canted bulkheads supported in a large assembly jig. The question behind the simulation is which one of two locations for an installation requiring hand drilling is more efficient: a higher location that shorter assemblers might find difficult, or a lower location that taller assemblers might find difficult.

The sample conventional simulation model depicted in Figure 4, using fictitious data, draws subjects of different heights at random from a population. Then by regressing time on subject height (i.e., predicting performance time from subject height), the model generates times to accomplish each task element (gross positioning of drill, aiming, and applying force while drilling). Element times are added to yield a total operation time for the trial, and each new simulation run adds a new trial to the pool of observations. If enough replications are performed, very accurate estimates of task segment length can be derived, assuming that parameters of the task elements are precisely known. Obviously though, these parameters are very expensive to obtain, so they are usually not well known. (If the scope of the model is changed, so that tasks are examined rather than elemental motions within tasks, parameters might be easier to obtain.)

Outputs obtained with human form simulation, as suggested earlier in the section on Strategic and Tactical Planning, are qualitative judgments about human fit, movement, tool use, perseverance, accuracy, and so on. If they are not qualitative judgments, they are often analyses aided by visualization. The advantages of this type of reasoning help the user to focus on spatial factors that are extremely difficult to examine with conventional simulation.

Some caution is in order with the output of human form simulation because it is so frequently oriented toward information about humans. For example, outputs about human capacity or limitations are common, such as an estimate of the percent of the population expected to accomplish whatever aspect is being analyzed. If the user seeks information about system components other than humans or about design from his or her model and finds such information difficult to derive, there clearly should be some concern about how human form simulation works. In a general sense, this effect is due to the types of questions that have prompted development of human form models. There are also two more specific reasons for this effect. First, variability in human performance is normally just partially accounted for with human form models (although variability in human form itself may be modeled very well). Second, unlike the essentially neutral languages of conventional simulation, anthropomorphic simulation presents a human form which itself is part of the data of any system it is asked to model.

However, human form simulation can be a source of more data for design and planning questions. For example, if human form models are constructed to permit experimentation, outputs relevant to the differences between or among experimental conditions should be expected. Also, data that characterize the human should not always be transformed only into image form; analysts can often gain insight about system behavior by having access to joint angles, movement times, and other information. Finally, prescriptive data regarding acceptable design limits are very helpful for initial design layout and evaluation. Such prescriptive data in the form of guides have been popular for some years and have not yet been replaced by electronic human form models.

IMPLEMENTATION AND DOCUMENTATION

Implementation is the process of applying decisions that emerge out of simulation. All the details of management involvement, acceptance by affected personnel, timing, and other challenges apply equally to conventional and human form simulation.

Documentation refers to description of the model; statement of questions, methods, results; and related matters. For both conventional and human form simulation, documentation is necessary for justifying conclusions and avoiding duplication of work (Roebuck, 1989). For the user of anthropomorphic simulation, little precedent exists to point to the most effective format and, of course, unique requirements of every study affect the content of documentation. For maintenance simulation with human forms, certain minimum information should be expected, including a description of the task under study, illustrations showing key dimensions of the work site, identification of critical task segments, and judgments of task segment performance as a function of system constraints (Majoros, in press). A clear advantage of documentation of human form simulation is the availability of drawings showing human forms in critical task segments. Drawings and graphic presentations have long been a desirable and compelling format for human factors information.

SUMMARY AND CONCLUSION

This paper makes various observations about anthropomorphic simulation by referring to the stages of development for conventional simulation. Examples pertain to aircraft assembly and maintenance. The main themes follow.

Human form simulation is very well suited for analysis of "local" task environments. Conventional simulation is an effective tool for more molar, higher-level systems.

Local task environments contain five classes of entities that comprise a system: (a) structural features of a maintainer's or assembler's immediate surroundings, (b) the human form, (c) task requirements, (d) tools or components related to task performance, and (e) environmental factors.

Critical task segments are a cost-effective focus of human form simulation.

Human form simulation would be improved by performance aspects reflecting continuous change, such as fatigue and time pressure.

Human form simulation depends on visualization on the part of the user. By manipulating internal images, a human form model user can anticipate the problems in critical task segments. Visualization supports numerous additional procedures in human form simulation practice.

To consider multiple factors and be responsive to concurrent engineering, levels of structural, environmental, task, and tool factors that contribute to task performance should be manipulated in experimental design just as are human form factors.

The output of human form simulation is often oriented toward information about humans. Enhancements in output is one way to derive more information relevant to design questions.

It is hoped these observations will generate interest in the development of human form models for increasingly effective simulation use.

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CLASSIFYING AND MEASURING HUMAN DYNAMIC STRENGTH

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ABSTRACT

In the past, human muscle strength has been measured almost exclusively under static conditions, in which the body does not move and muscles remain at the same length. This "isometric" condition simplifies the involved measurement procedures and permits fairly easy conduct of the experiments. Unfortunately, such test results are only weakly related to actual dynamic strength exertions, as various authors demonstrated.

Measurement and definition of "dynamic muscle strength" are fairly complex. In dynamics, displacement is not zero, but can assume varying values. Therefore, time derivatives of displacement (velocity, acceleration, jerk) need to be controlled or measured. Furthermore, forces and torques developed by the human change, depending on the displacement derivatives, in addition to depending on the subject's inherent strength. Other experimental conditions, such as masses involved, or number of repetitions, also influence the results.

Cooperation among several researchers has resulted in a categorization of various "dynamic muscle strengths" and has generated a matrix of independent, dependent, and controlled experimental variables. Together with a new motion terminology, this should lay the foundation for a systematic assessment of human dynamic strength capabilities.

INTRODUCTION

For modelling human-machine interactions, knowledge of human dynamic strength capabilities (human dynamic musculo-skeletal performance) is of much research interest and of great practical importance (Kroemer, Snook, Meadows, & Deutsch, 1988), for example, in the design of aircraft and of repair facilities, such as modelled in COMBIMAN and Crew Chief. Even such animation programs as JACK need other than arbitrary algorithms to depict human work capabilities and motions realistically.

A protocol for the measurement of human "static" (isometric) strength has been established and is commonly used. The need for a similarly clear definition, and for well-defined measurement methods, describing "dynamic strength" was addressed by Kroemer, Marras, McGlothlin, McIntyre, & Nordin, 1990.

DEFINITION OF DYNAMIC MOTOR PERFORMANCE

"Dynamic motor performance is the output of human muscles attempting to move body segments." (A simplified definition employs the term "dynamic strength" instead of "dynamic motor performance.") A major aspect of this definition is the reference to the dynamic nature of the exertion. Muscles attempt to move body segments and external objects, and often do move them. Such dynamic activities bring about changes in muscle length and in their mechanical advantages.

To describe completely and correctly the variables present in a muscle strength test, one needs to distinguish between the following groups:

1. Independent variables are purposely manipulated to generate the experimental conditions.

2. Dependent variables are observed/recorded to provide information about the effects of the manipulations of the independent variables.

3. Controlled variables are purposely maintained at defined conditions so that they do not interfere with the relationships between independent and dependent variables.

4. Confounding variables can or do interfere with the relationships between independent and dependent variables. Therefore, confounding variables should be made controlled variables.

A large variety of techniques exist, or are conceivable, by which one can measure human dynamic strength. Current human strength measures can be viewed as having the isometric exertion (static strength) at one end of the performance continuum and free dynamic exertions at the other end, as listed in Table 1. This table (from Kroemer, et al., 1990) shows the variables displacement (and its time derivatives) as well as force, mass, and repetition; and their assignments to either independent, dependent, or controlled variable categories. For example, one may assign "displacement" to be either an independent or a dependent variable. Making displacement an independent variable and setting it to zero generates the "isometric testing condition," in which velocity, acceleration, and jerk are also zero. Mass properties are likely to be controlled. Force and/or repetition are likely to be used as dependent variables.

In the "isokinetic" technique, muscle velocity is set to a constant other than zero. This means that displacement becomes a controlled variable while the time derivatives of velocity, acceleration, and jerk are zero. Force and torque and the number of repetitions are possible dependent variables.

In an "isoacceleration" test, muscle experiences a constant acceleration. Displacement of the involved body parts can be controlled in terms of range of motion, or it may be a dependent variable in which case the range of motion would be measured. Velocity can also be controlled or one may observe the velocity at which one is no longer able to produce a constant acceleration; in this case, velocity is a dependent variable. Force and repetition could be either dependent or independent.

In the "isoforce" technique, muscle strength remains constant ("isotonic") over the testing time. (Note that the term isotonic is often falsely applied to all but isometric test.) Any of the displacement measures can be used as dependent measures, but for practical reasons isoforce tests are often combined with the isometric condition, as in holding a weight motionless.

In the "isoinertial" technique, a mass to be moved by muscular effort is set to a constant. This means that displacement, velocity, acceleration and jerk, force or torque, as well as the number of repetitions, all can be dependent variables. Isoinertial efforts are common in material handling, such as in lifting and lowering.

In a "free" dynamic exertion, no variables are controlled other than possibly mass properties or repetition: The subject is allowed to move freely without restrictions. Free dynamic activity is common in life, but difficult to measure in a controlled manner.

It is conceivable that other experimental conditions than those listed in Table 1 may be used, dependently or independently. Also, control of a variable may be more complex than simply keeping it constant ("iso..."). Hence, Table 1 shows only one set of possible measurement techniques.

Any body motion measurement system requires a precise description of the motion. Thus, a taxonomy is necessary to specify exact positions and motions of body landmarks in three dimensions. This specification must be in such detail that the motion may be duplicated by someone not familiar with the task without any additional documentation. It is often convenient to identify a body motion as a rotation about a particular joint of the body. For example, a forearm rotation may be described by reporting the angular positions of the lower arm relative to the position of the upper arm, using the connecting elbow joint as a "hinge" for that rotation. Another technique is to describe the position of that body segment by using a vector notation. In either case, the taxonomy must include a coordinate system to describe positions and motions of loci. Also, a precise verbal terminology to describe motions is desirable. Such a coordinate system, and a verbal description terminology, has been developed and recently published. This information is available in the publication of the paper in press, referred to earlier, and in the book Engineering Physiology (Kroemer, Kroemer, & Kroemer-Elbert, 1990).

SUMMARY AND CONCLUSIONS

For understanding and modelling the performance of the human, it is necessary to measure and describe dynamic muscular performance capabilities. A procedure to define and measure "dynamic strength" has been developed, as briefly described above. This taxonomy of dynamic strength also indicates methods and techniques for measuring dynamic strength performance. To do so, a reference system to describe locations and paths of movement has been developed in a companion project.

It is believed that this taxonomy and methodology will allow us to establish well-defined assessments, similar to what has been available for "static strength," also for the much more complex topic of "dynamic muscle strength."

Table 1. Independent and Dependent Variables in Several Techniques to Measure Motor Performance

Names of Technique / Variables	Isometric (Static)		Isokinetic		Isoacceleration		Isojerk		Isoforce		Isoinertial		Free Dynamic	
	Indep.	Dep.	Indep.	Dep.	Indep.	Dep.	Indep.	Dep.	Indep.	Dep.	Indep.	Dep.	Indep.	Dep.
Displacement, linear/angular	constant* (zero)		C or	X	C or	X	C or	X	C or	X	C or	X		X
Velocity, linear/angular	O		constant		C or	X	C or	X	C or	X	C or	X		X
Acceleration, linear/angular	O		O		constant		C or	X	C or	X	C or	X		X
Jerk, linear/angular	O		O		O		constant		C or	X	C or	X		X
Force, Torque	C or	X	C or	X	C or	X	C or	X	constant		C or	X		X
Mass, Moment of Inertia	C		C		C		C		C		constant		C or	X
Repetition	C or	X	C or	X	C or	X	C or	X	C or	X	C or	X	C or	X

Legend
C = variable can be controlled
* = set to zero
O = variable is not present (zero)
X = can be dependent variable

The boxed constant variable provides the descriptive name.

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ISOMETRIC STRENGTH MODEL FOR TASKS REQUIRING ACCESS THROUGH OPENINGS

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ABSTRACT

While performing in situ maintenance of sophisticated large-scale systems, the technician often encounters certain accessibility constraints. The needed access to a part located deeper from the outer skin of the system is possible only through openings that permit access for the upper extremities. Under such conditions, the strength exertion capability of the person is generally very much reduced. This paper describes an experimental study conducted to investigate the effects of the access opening location on the torquing strength capability of the individual. Nine opening locations and eight wrench handle orientations were studied in a simulated maintenance task of tightening a bolt. The resulting data are used to develop a biomechanical model of the individual performing the simulated task.

* This research was partially supported by the Crew Chief program, a joint effort by AAMRL and AFHRL of the U.S. Air Force.

BACKGROUND

Human-centered design for maintainability requires appropriate consideration of all ergonomic issues relating to maintenance of the system early during the design and development of the system. Historically, the maintainability ergonomics issues were rarely addressed during the early stages of design. It was most often left to the maintenance personnel to find a way to complete the maintenance task. When the maintainability ergonomics issues are not addressed during the early stages of design, any later design modifications are necessarily very expensive. Either the expensive design modifications are performed, or if no changes are made in the design, additional cost will be reincurred in maintenance and support during the later stage of the life of the system. Thus, either way the total life-cycle cost of the system would be high.

This absence of consideration of maintainability ergonomics by designers may be attributed to several causes. One primary cause is the lack of a tool or technique that would help the designer incorporate the maintainability ergonomics requirements formally in the design process. This is not to say there is a dearth of useful ergonomic data available, but much of the information available is not in a form readily accessible and usable during the design process. There is a notable absence of any systematic procedure to consider such issues during concept development and early design of the system.

The recent advent and growth in Computer-Aided Design (CAD) technology is leading to an environment that can change the undesirable practice of not addressing maintainability ergonomic issues. The concept of concurrent engineering calls for a team approach to systems design. Team members may comprise manufacturing, ergonomics, economics, materials, marketing, and other such specialities in addition to the usual design engineers. Such a team approach will greatly help in incorporating the ergonomic requirements in the design of the system. With a view to helping the design team consider the maintainability ergonomics issues in a formal way, the Crew Chief program was conceived and is being developed by the Air Force Human Resources Laboratory (AFHRL) and Armstrong Aerospace Medical Research Laboratory (AAMRL) of the U.S. Air Force (Korna et al., 1988; McDaniel & Askem, 1985)

Crew Chief is a computerized biomechanical model of a maintenance technician performing his/her regular tasks. The model considers the body size, posture, movement, and strength characteristics of the technician along with the task-related parameters. This paper will detail a research study conducted to collect certain human strength data that are useful for developing the biomechanical model.

EXPERIMENTAL STUDY

The primary objective of this study was to investigate the effect of restricted access to the task point on the ability of an individual to apply strength. The restriction to access was considered in terms of limiting upper extremity reach through a rectangular opening. The task considered was tightening (clockwise) a bolt head with a socket wrench using the right hand only. The measure of effectiveness was the isometric torque applied on the bolt head. The scope of the study was limited to analyzing the variation in the torquing capability of the person due to different locations of the access opening along a frontal plane. A rectangular opening 10.6-inches wide by 8-inches high was used. This particular shape and size were chosen to be consistent with MIL-HDBK-759 recommendations for such access openings. The bolt head was located at a height equal to 60 percent of the vertical reach height of the individual. This height approximates the chest height of the individual.

For the purposes of this study, the following two task-related variables were considered as primary independent variables.

1. Opening Location - Nine different locations of the access opening along the frontal plane were considered. One was directly in front of the task point represented by the bolt head. The other locations were 12 inches apart center to center one row up, one row down, and one column to the left, and one column to the right. Figure 1 shows the opening locations considered for this study. The openings were labeled top left (TL), middle center (MC), bottom right (BR), etc. based on rows and columns.

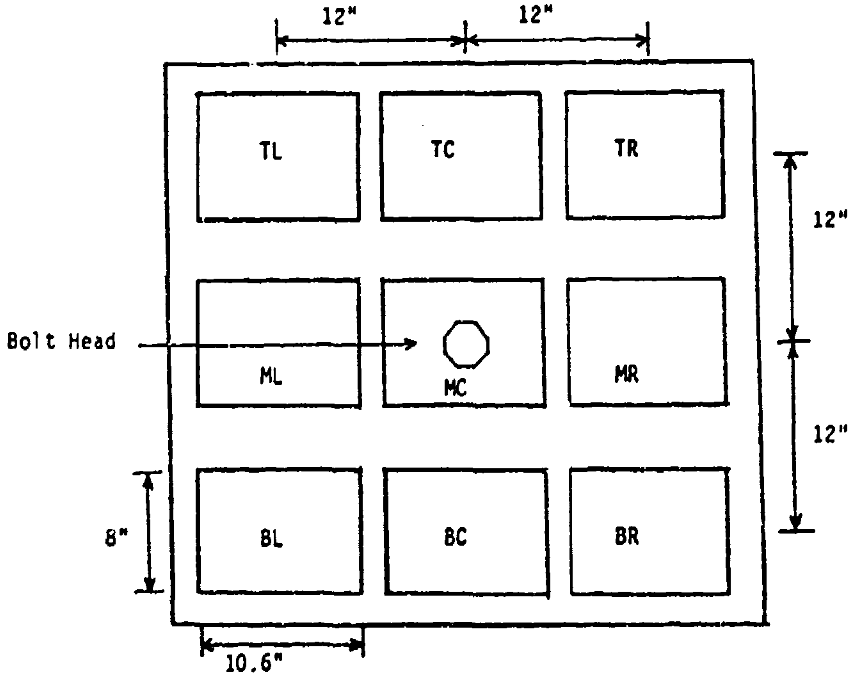

Figure 1. Access Openings.

2. Wrench Position - The orientation of the wrench handle along the frontal plane was considered at eight different levels, as shown in Figure 2. The 0 position was arbitrarily chosen as the handle vertically "up" position and other positions were at 45-degree increments clockwise. All eight wrench positions were considered for the middle center (MC) opening only. For each of the other seven openings, only three wrench positions were considered. These were the three most reasonable wrench positions for the specific access opening location. Figure 3 shows the wrench positions considered for each of the openings.

The above scheme of access openings and wrench locations resulted in a total of 32 test conditions. The maximum torque applied on a 5/8-inch bolt head with a commercially available 10.25-inches-long "Snap-On" branch socket wrench was the dependent variable for this study.

Subjects

Fifteen right-handed male volunteers in the age range 20 to 32 years participated in the study. Each was screened for current health status and previous injury history via a self-reported questionnaire prior to selection as subjects. Each was also informed about the objective of the study and the need for full cooperation for the success of the study at this time. Seven anthropometric and nine strength-related measures were obtained on each subject in a separate session prior to testing. Table 1 presents the summary statistics of the anthropometric and strength data of the subject sample.

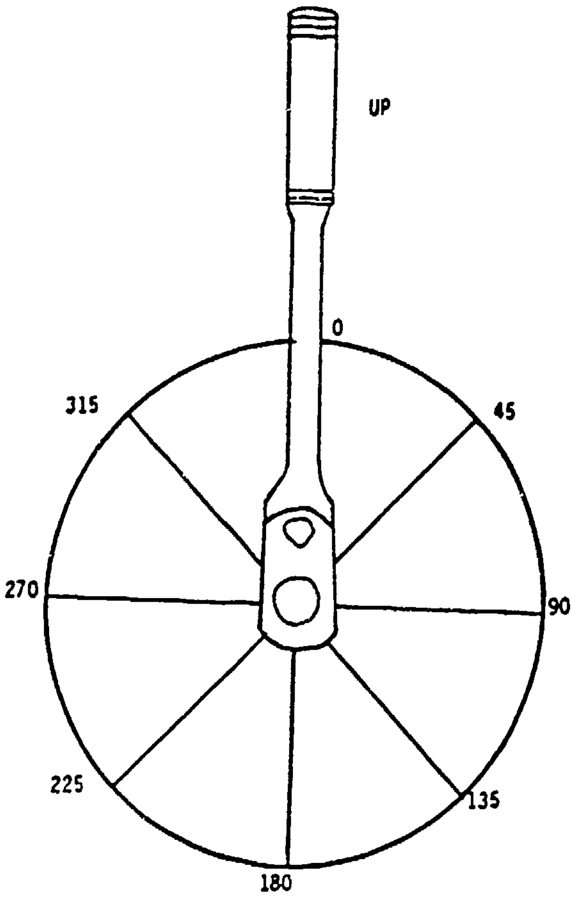

Figure 2. Wrench Handle Positions.

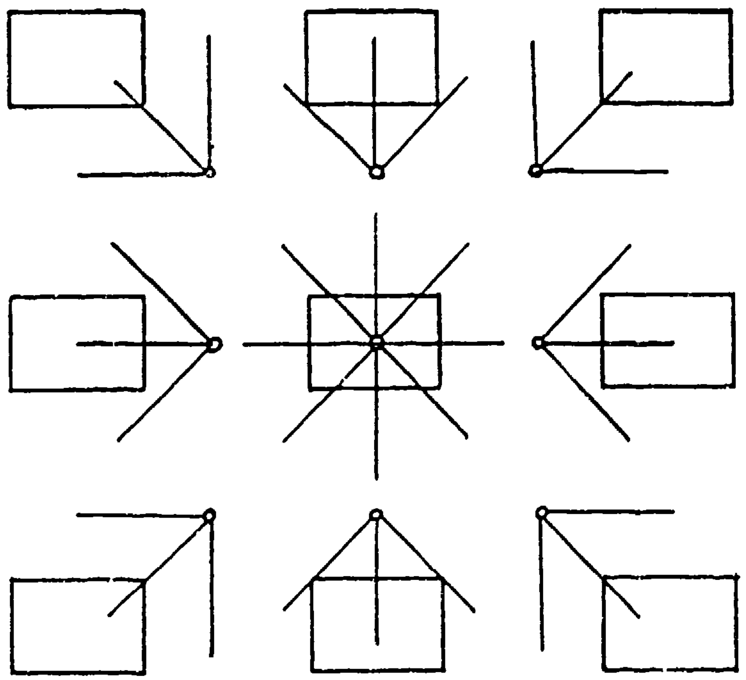

Figure 3. Wrench Positions Considered for Access Openings.

Table 1. Summary Statistics of Anthropometric and Strength Data
N = 15

DATA	MEAN	STD. DEV.
Age (yr)	25.9	3.31
Stature (cm)	175.4	7.78
Weight (lb)	159.9	36.49
6' Inc. wt. lift (lb)	88.0	20.07
Elbow ht. wt. lift (lb)	121.3	26.96
Knuckle ht. wt. lift (lb)	162.0	25.40
40 lb. wt. hold (sec)	88.4	48.70
70 lb. wt. hold (sec)	29.9	22.14
Acromion-Radiale length (cm)	35.0	2.39
Radiale-Stylion length (cm)	27.3	1.36
Biachromial Breadth (cm)	37.2	2.35
Elbow height lift (lb)	72.0	4.20
One hand pull (lb)	107.2	29.02
38 cm lift (lb)	221.8	67.92
Grip strength (kg)	45.0	11.39
Grip length (cm)	54.3	3.56
Vertical reach (cm)	214.7	9.73

Equipment

A torque dynamometer with a built-in strain gauge load cell designed and built at AAMRL was the central piece of apparatus. The dynamometer was mounted on a sturdy metallic framework so that the height of the bolt head from the floor could be adjusted to suit the subject. A Dell microcomputer (AT compatible) equipped with A/D and D/A converters was used for data acquisition. The "TORQUE" computer program developed by the University of Dayton Research Institute (UDRI) was used in the data collection task. Figure 4 shows the schematics of the data collection system. Other pieces of equipment used included anthropometric instruments and strength measurement devices. Please refer to Deivanayagam (1986) and Ratnavelpandian (1989) for more details on the equipment.

The access openings were cut out of a 4-foot-x-4-foot, 3/4-inch plywood board and mounted on a metal frame so that the board could be fixed at any desirable height for the subject. The dynamometer, the access opening board, and the subject positioning are shown in Figure 5.

Procedure

The bolt head location was fixed to a vertical height equal to 60 percent of the vertical reach of the subject. The access opening board was placed in front of the bolt head at a horizontal distance equal to 50 percent of the forward reach of the subject. The height of the board was adjusted to match the center of MC access opening to match vertically with the bolt head height from the floor.

The subject stood in front of the board with the wrench in his right hand and reached through the test access opening to apply torque on the bolt head. The subject was to stand in front of the test access opening but was free to lean his body sideways to help in reaching and applying maximum torque. However, the subject was not permitted to lean on the board or the framework. The subject was required to grip the wrench handle in a specific manner for a given test condition.

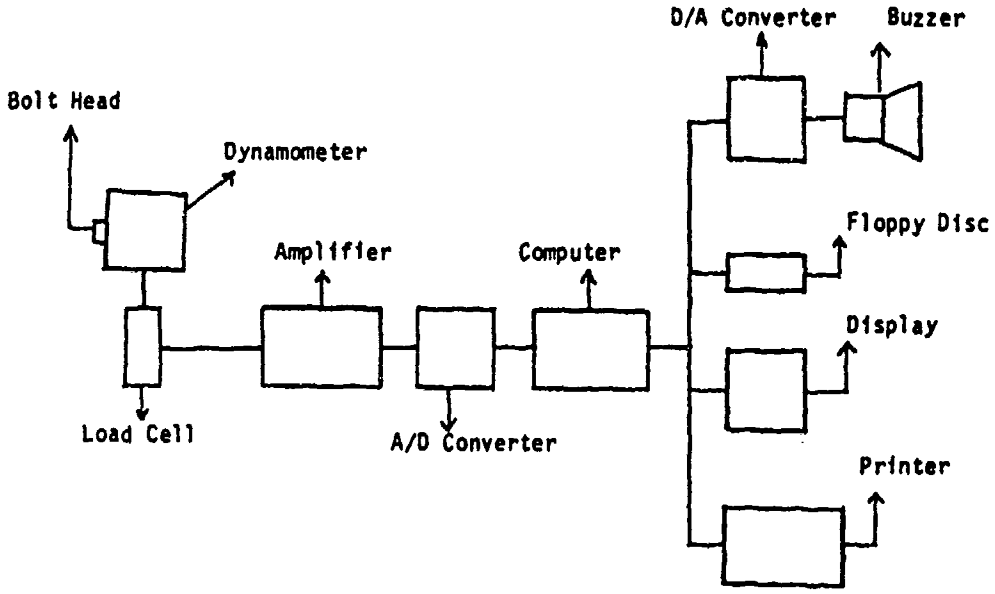

Figure 4. Schematics of Data Acquisition System.

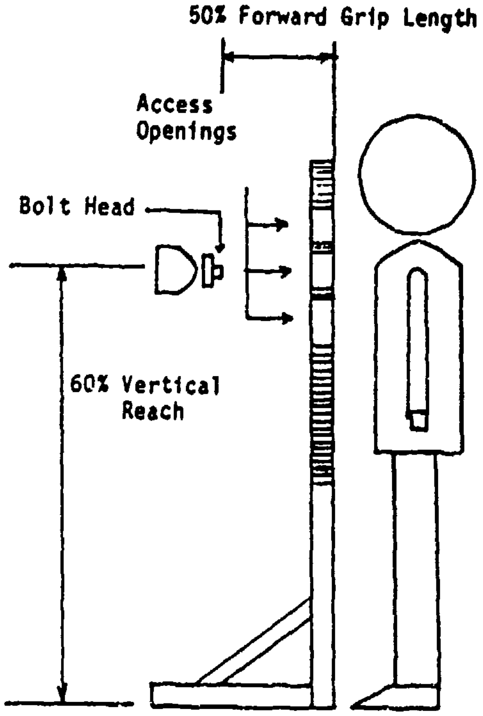

Figure 5. Experimental Setup.

Six different gripping techniques (palm: up, down, away, toward, left, and right) were defined prior to experimentation and each test condition was assigned one of the six gripping techniques. Figure 6 shows examples of the gripping techniques.

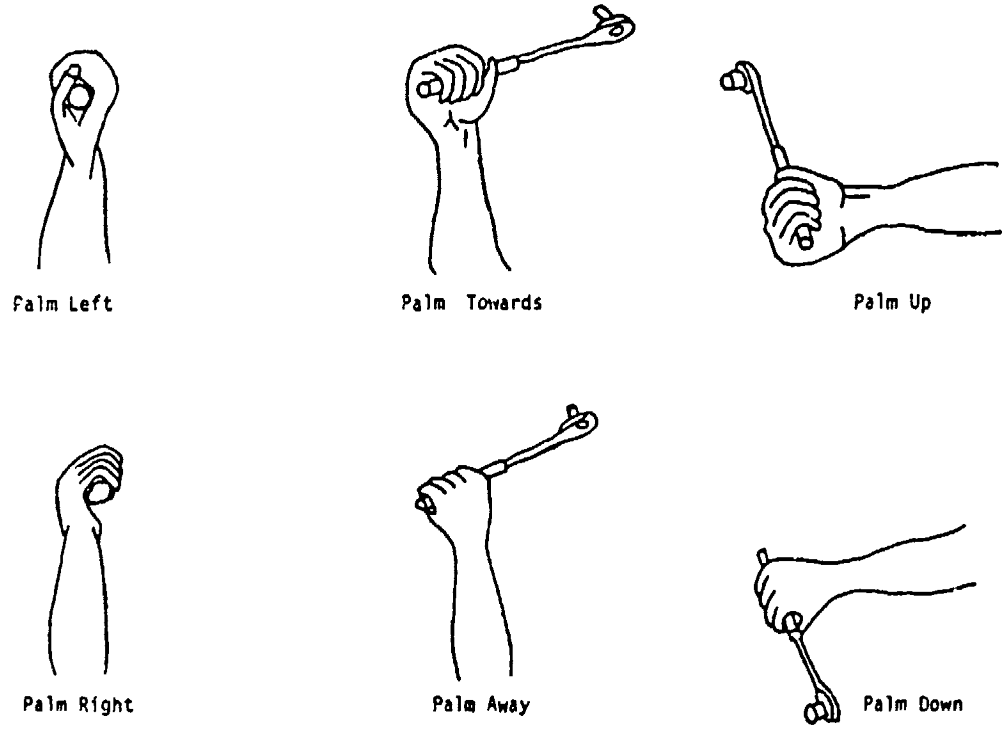

Figure 6. Gripping Configurations.

On a signal from the experimenter, the subject applied his maximum force on the wrench handle so as to result in a clockwise torque on the bolt head. The subject was instructed to develop the maximum isometric force in a smooth manner in about one second and hold that level steady for three more seconds, at the end of which a buzzer sounded to indicate the end of trial so that the subject can relax. The average torque applied during the last three seconds was considered the maximum isometric torque for the trial. The average was computed by sampling at the rate of 10 per second. If for any reason the force application was not smooth and steady, the trial was repeated immediately. The decision to repeat was made based on certain statistics computed from the torque profile, such as peak-to-average ratio and the number of sampling points that fall outside the plus or minus 10 percent limits of the average. Between successive trials, a minimum two minutes of rest break was provided to the subject. The torque data collection session lasted approximately two hours per subject.

Results

The summary statistics of the torque strength for the test conditions are presented in Table 2. The strongest (32.1 ft. lbs.) test condition was while accessing through the bottom right opening with the wrench position at 90 degrees. This may be explained by the fact that it was possible in this test condition to make use of one's body weight to a considerable extent to pull down on the handle. The weakest (13.2 ft. lbs.) test condition was found to be the middle center opening with 0-degree wrench position. The need to reach through the opening directly in between

Table 2. Statistics of the Observed Torque Strength (ft. lbs.)

Exertion	Average	Standard Deviation	Coefficient of Variation %
BC135	28.83	9.14	31.7
BC180	23.23	5.11	22.0
BC225	27.64	7.54	27.3
BL180	28.35	6.65	23.4
BL225	25.45	7.00	27.5
BL270	23.42	8.73	37.3
BR090	32.11	10.87	33.8
BR135	25.40	6.38	25.1
BR180	23.90	6.02	25.2
MC000	13.24	3.76	28.4
MC045	19.79	4.23	21.4
MC090	22.44	6.00	26.8
MC135	19.32	5.63	29.1
MC180	19.21	5.02	26.1
MC225	22.62	4.77	21.1
MC270	19.60	3.98	20.3
MC315	14.26	4.43	31.1
ML225	23.21	5.49	23.6
ML270	23.45	6.15	26.2
ML315	21.64	6.01	27.8
MR045	25.64	6.89	26.9
MR090	26.01	6.44	24.8
MR135	25.10	6.57	26.2
TC000	17.41	4.49	25.8
TC045	18.97	6.67	35.2
TC315	17.76	5.13	28.9
TL000	20.28	7.06	34.8
TL270	16.89	5.34	31.6
TL315	20.92	4.49	21.5
TR000	16.61	5.57	33.5
TR045	19.94	6.14	30.8
TR090	28.68	8.82	30.8

the subject and task point makes it difficult to gain much biomechanical leverage for the upper extremity. In general, reaching through the bottom row of openings resulted in higher torque values than the top of middle rows.

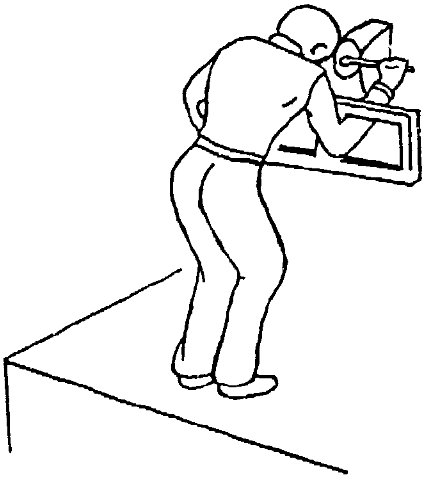

Figure 7a. Example of Test Exertion Posture (BR 90).

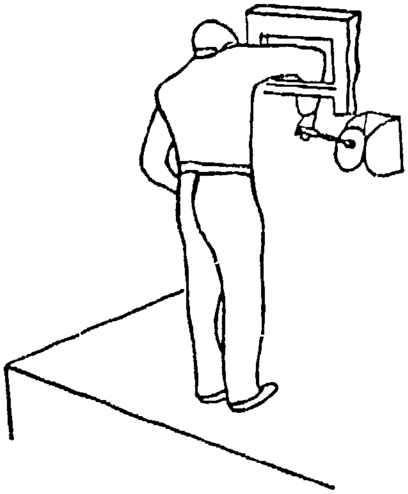

Figure 7b. Example of Test Exertion Posture (TL 270).

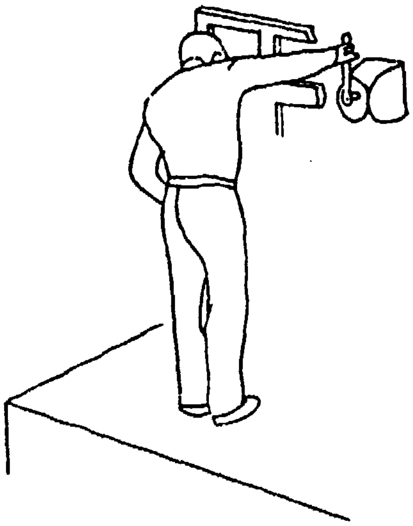

Figure 7c. Example of Test Exertion (TC 0).

A linear regression model for torque strength was developing using a stepwise procedure with selected strength and body size data of the subject, the access opening location, and the wrench position as independent variables. The technique of "dummy variables" was employed to represent the task conditions. The coefficients for the best model (R^2=0.7303) are listed in Table 3.

Table 3. Coefficients for the Variables Included in the Model

Variable	Coefficients
1. Intercept	44.15
2. Stature	-0.37
3. Weight	0.11
4. Six feet incremental weight lift	0.13
5. 70 lb. weight hold	0.06
6. Acromion-radiale length	1.17
7. Radiale-stylion length	1.84
8. Biachromial breadth	-1.06
9. Grip length	-0.58
10. Top left opening	-3.77
11. Top center opening	-5.87
12. Top right opening	-4.55
13. Middle left opening	-1.97
14. Middle center opening	-6.87
15. Middle right opening	-2.31
16. Bottom left opening	0
17. Bottom center opening	0
18. Bottom right opening	0
19. Wrench position 000	-1.48
20. Wrench position 045	2.36
21. Wrench position 090	7.11
22. Wrench position 135	3.33
23. Wrench position 180	1.76
24. Wrench position 225	3.31
25. Wrench position 270	0
26. Wrench position 315	0

Discussion

The primary interest in this study is to assess the effect of restricted access through an opening on the torque-applying capability of the maintenance person. Thus, it is worthwhile to compare the results of the present study with similar data obtained with no accessibility restrictions. An earlier study was conducted under the direction of the principal author at the University of Texas at Arlington (UTA) several years back. This study used very similar hardware and procedures and was also sponsored by the Crew Chief program. Except for the accessibility restriction and the fact that the actual subjects were different, the two studies are very comparable. The details of the UTA study may be found in Deivanayagam (1986).

Table 4 shows the percentage reduction in torque strength for various test conditions when the access is restricted through the openings. The torque strength reduction was significant in all 32 test conditions. The reduction ranged from a high of 63.7% for MC-135 position to a low of 15.8% for ML-270 position. Figures 8-11 made comparisons of torque strength values between the two studies for each opening location.

Table 4. Percentage Reduction in Torque Strength when Access is Restricted (TTU Study Compared to UTA Study)

Opening	Wrench Position							
Location	000	045	090	135	180	225	270	315
TL	34.9	-	-	-	-	-	39.3	28.7
TC	44.1	46.0	-	-	-	-	-	39.4
TR	46.7	43.2	39.3	-	-	-	-	-
ML	-	-	-	-	-	34.3	15.8	26.3
MC	57.5	43.6	49.9	63.7	58.3	36.0	29.6	51.4
MR	-	27.0	42.0	52.8	-	-	-	-
BL	-	-	-	-	38.5	28.0	15.9	-
BC	-	-	-	45.8	49.6	21.8	-	-
BR	-	-	28.4	52.3	48.1	-	-	-

The following general statements may be made, based on the results of this study.

1. Considerable (up to 60 percent) reduction in torquing capability of the individual may be expected if access is restricted through an opening of the size studied.

2. Openings below the level of task point with wrench handles extending downward are preferable to openings above the level of task point, when the task point is about chest level.

3. Access openings offset to the right or left are preferable to openings directly in front of the task point.

The location of the access opening and the wrench position influenced the optimum upper extremity configuration to a large extent so as to affect the torquing capability. It is believed the size of the access opening and the distance of the task point away from the opening will also have such significant effects.

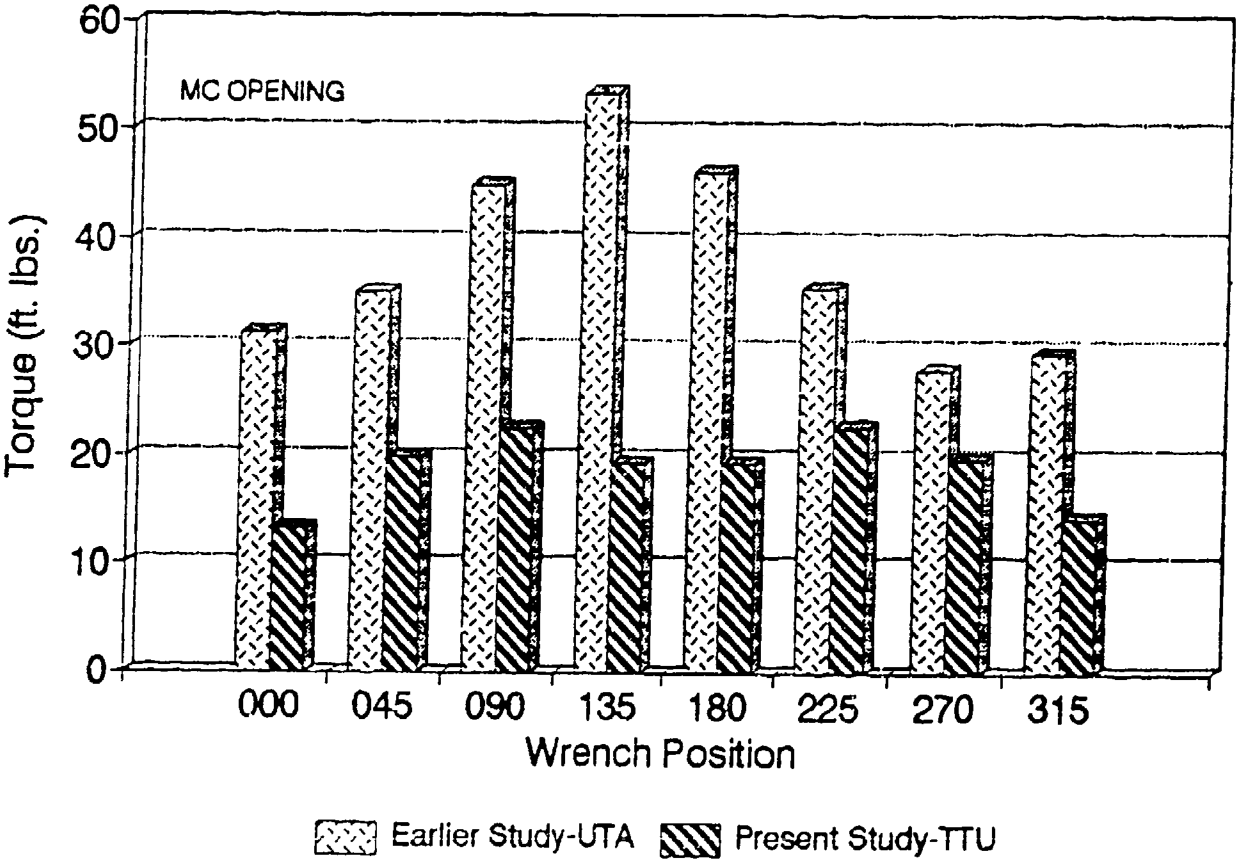

Figure 8. Effect of Restricted Access on Torque Strength.

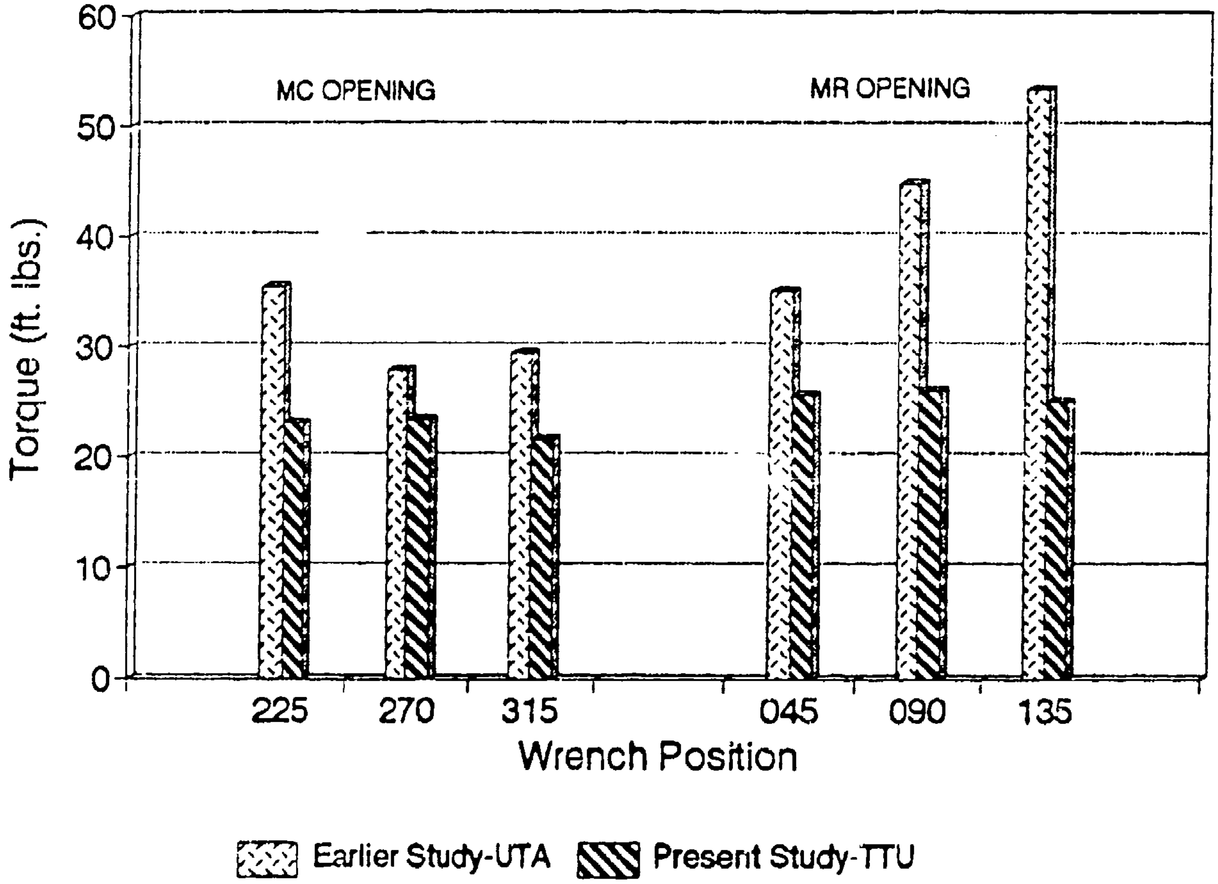

Figure 9. Torque Strength Comparison.

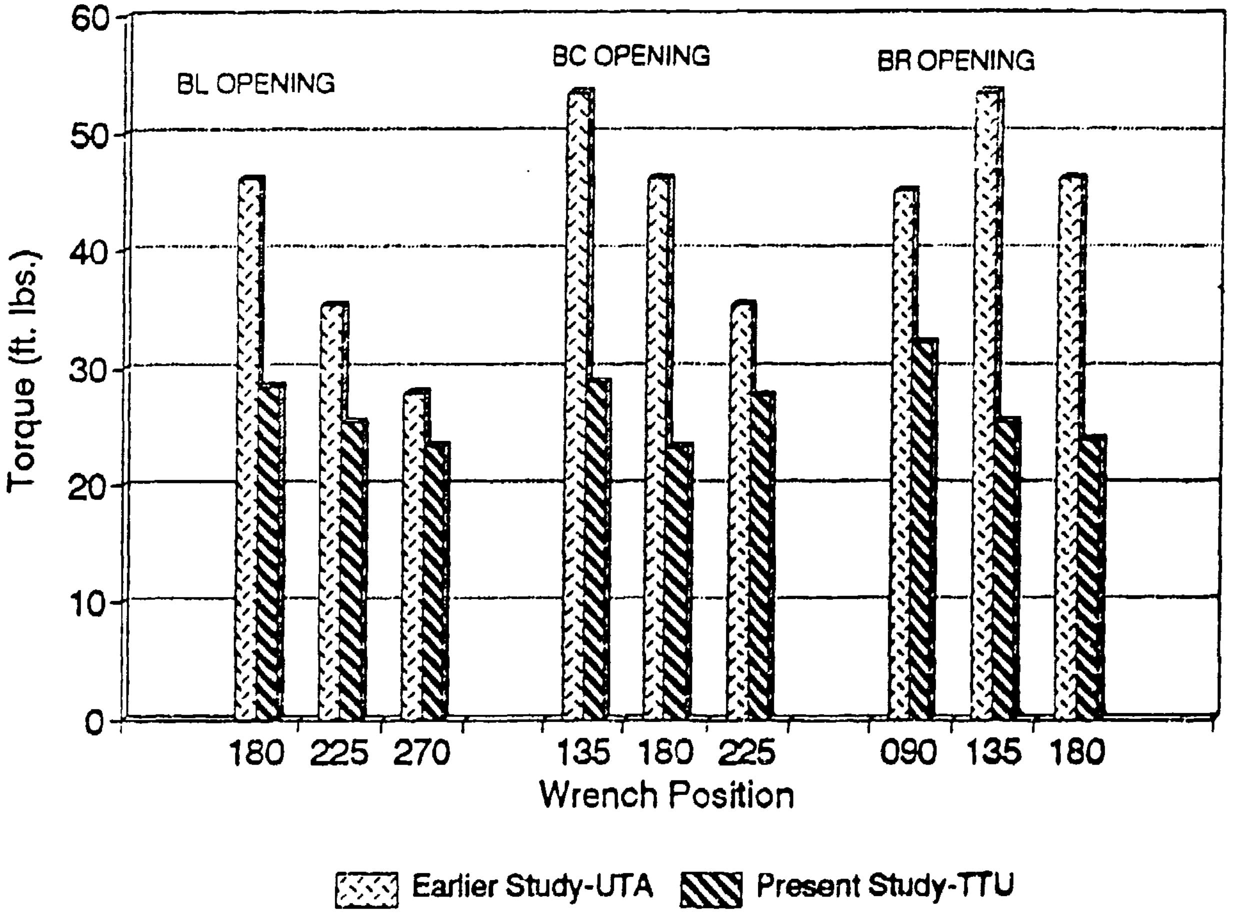

Figure 10. Torque Strength Comparison.

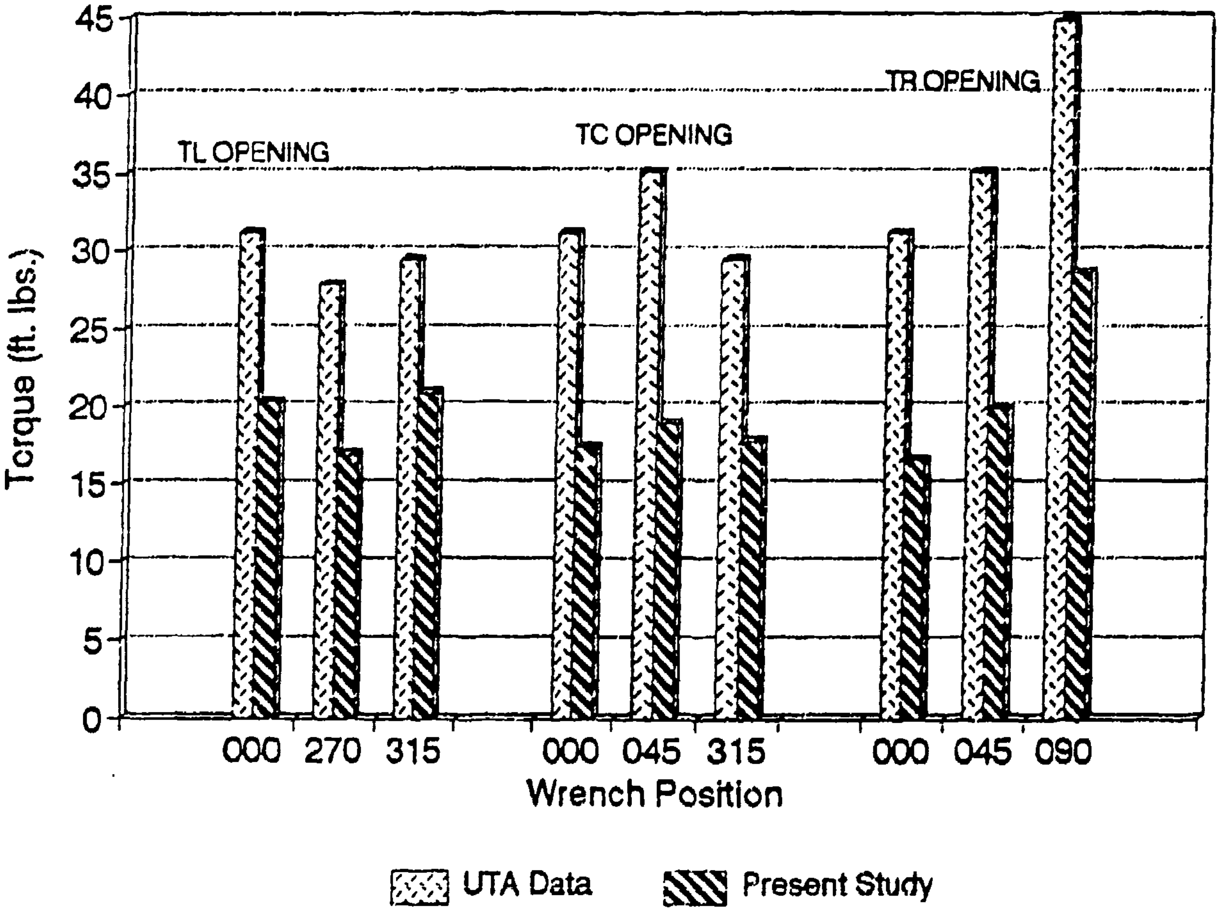

Figure 11. Effects of Restricted Access.

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MODELING OF HIGH-RESOLUTION HUMAN SURFACE DATA

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ABSTRACT

High-resolution human body 3D surface data are now being used in the design process for close-fitting equipment. With a resolution of about 1.5 mm, the detail available permits the custom design of some equipment and the capability of summarizing human shapes to produce representative faces, for instance, without sacrificing detail of the surface features. Using a Cyberware Laboratories Echo 3D digitizer, a data base of the recordings of more than 650 heads has been established, along with the recordings of hands from more limited samples. Three projects that represent some of the potential uses of the data are (a) the design of a head form for a new Navy SEALS diving helmet, (b) assistance in the custom manufacture of astronauts' EVA gloves, and (c) the computer modeling of fit testing a new low-profile night vision goggles design.

In the first project, the Navy wanted to design a diving helmet able to fit all divers with the minimum interior clearance. We designed a head form by displaying the data base head shapes to a common orientation, then projecting a mesh from an interior vertical axis to find the maximum extent of any subject's surface at each mesh point, defining the minimum clearances necessary at each point.

NASA astronauts' EVA gloves are custom made and must fit the fingers precisely to permit precision work. We digitized the plaster hand casts of an astronaut and the data were used to produce fabric patterns.

For the new night vision goggles design, which must fit precisely over the upper face, we digitized the goggles and performed automated fit-testing of them on our subject data base. Not only could individuals be evaluated in terms of potential fit, but we could measure and statistically summarize the distribution of clearances between the faces and the inner surfaces of the goggles.

INTRODUCTION

A series of projects that use high-resolution digital recordings of the human body surface to evaluate and design close-fitting equipment for use by the U.S. military are in progress at Wright-Patterson Air Force Base (WPAFB), Ohio. The work is being performed by a team of Air Force civilian employees and contractors at the Armstrong Aerospace Medical Research Laboratory (AAMRL) at WPAFB. The people involved have combined their expertise in the fields of anthropology, anthropometry, statistics, computer software development, biology, and mechanical engineering to produce the capability to record, analyze, and apply these high-resolution data.

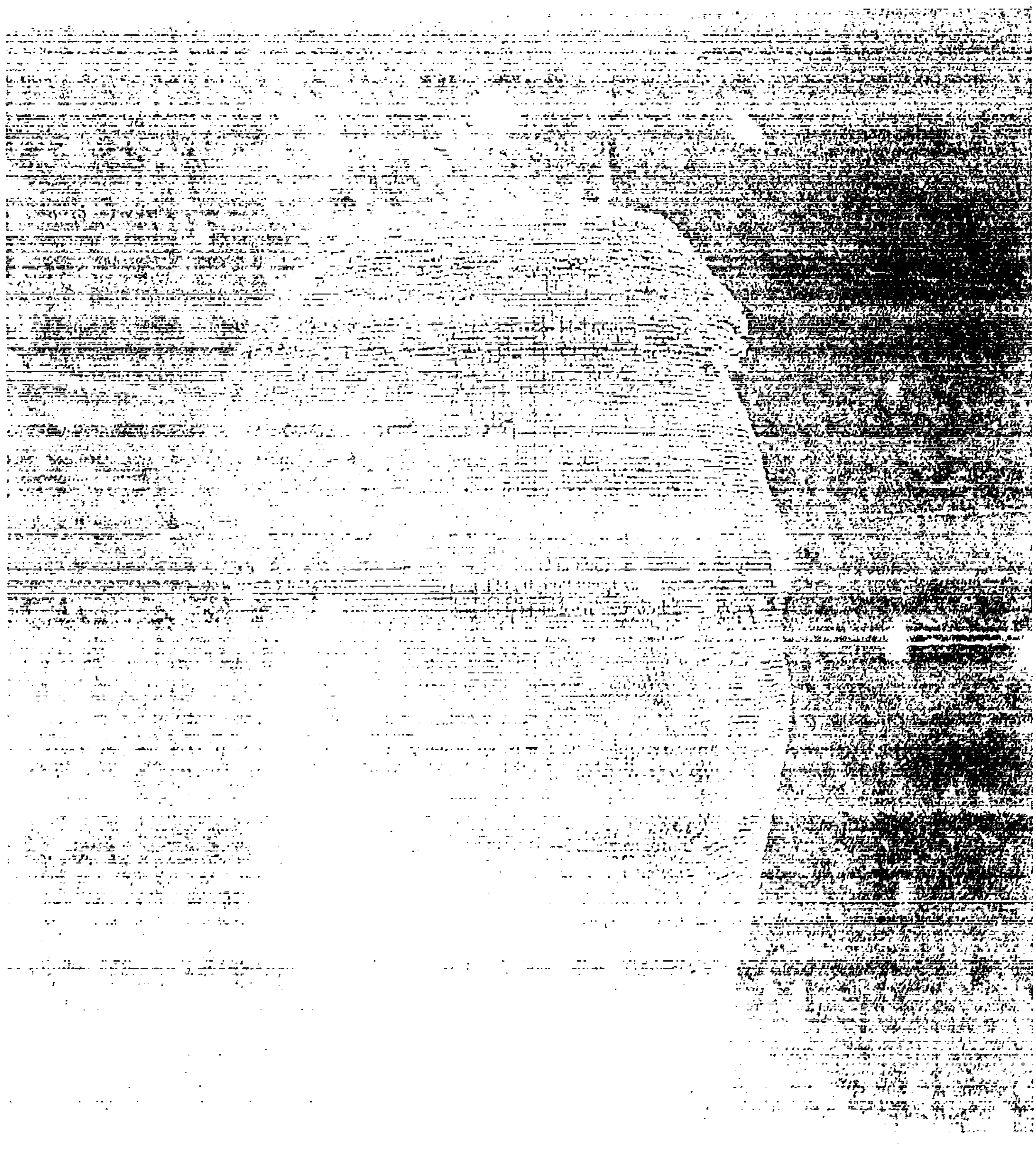
The principal organization leading this effort is the Workload and Ergonomics Branch of the Human Engineering Division, AAMRL. Contractors working with the branch include Anthropology Research Project, Inc., of Yellow Springs, Ohio, Systems Research Laboratory of Dayton, and Beecher Research Company, also of Dayton. AAMRL's role has been to organize the program, seek out appropriate applications, and direct the technical effort of the tasks through development to completion. Contractors have provided technical expertise in data acquisition, archiving, modeling, and graphics display. In each case, the technical problem was new, requiring the team to continually develop unique approaches to solve the problem. However, each task is also leading to the development of techniques and capabilities which will have generalized applications to future tasks in the field of human equipment design.

This paper will concentrate on recent work using high-resolution surface data, specifically, work in fit testing through the use of a computer model, and the effort to develop methods to summarize three-dimensional surface shape. This work has been sponsored by AAMRL. Human surface data were recorded using the Cyberware Laboratory (Monterey, California) Echo 3D Digitizer. This device uses a low-powered laser line and digital camera to record an object about the size of a human head in about 10 seconds. The resolution of the recording is about 1.5 millimeters, and is accurate to the limit of resolution (Figures 1 and 2). In an effort to build a data base for use in various applications, our team, principally involving staff from Anthropology Research Project, has recorded over 400 mostly civilian men and women. For a project to assist in the design of low-profile night vision goggles, and as part of a minisurvey, over 350 USAF flying personnel have been recorded. For other projects, and as experiments, we have recorded small samples of other body areas including hands, arms, legs, and skeletal material.

Because each recording comprises up to 130,000 Cartesian points, the logistics of data handling are a real issue. High-performance graphics workstations manufactured by Silicon Graphics, Inc., are being used to perform both data modeling and display. Almost all the software used to model and visualize the data has been custom written. This has been necessary both because of the huge amounts of data to be handled and because the techniques needed to accomplish our tasks have not been developed elsewhere, or at least have not been implemented in software capable of dealing with these types of data.

NIGHT VISION GOGGLES DESIGN PROJECT

The project to be discussed in detail here is the development of the padding surface shape for the Eagle Eye low-profile night vision goggles (NVG) at AAMRL. These goggles are to fit under the face shield of flight helmets and are to be ejection-compatible. Hardware and optical constraints mean that the goggles cover a large part of the upper face and the lenses are ideally located about 1.4 centimeters from the pupil of each eye. Fit testing of the existing prototypes revealed that the bones surrounding the orbits, lying under a thin layer of soft tissue, were uncomfortable pressure points, so much so that the goggles would be difficult to wear over a long period of time. Our task has been to design and construct a padding surface that will permit the close fitting of the goggles, yet be comfortable for all wearers over an extended period. Our role in this project has been to develop techniques to computerize the fit testing using 3D recordings of the



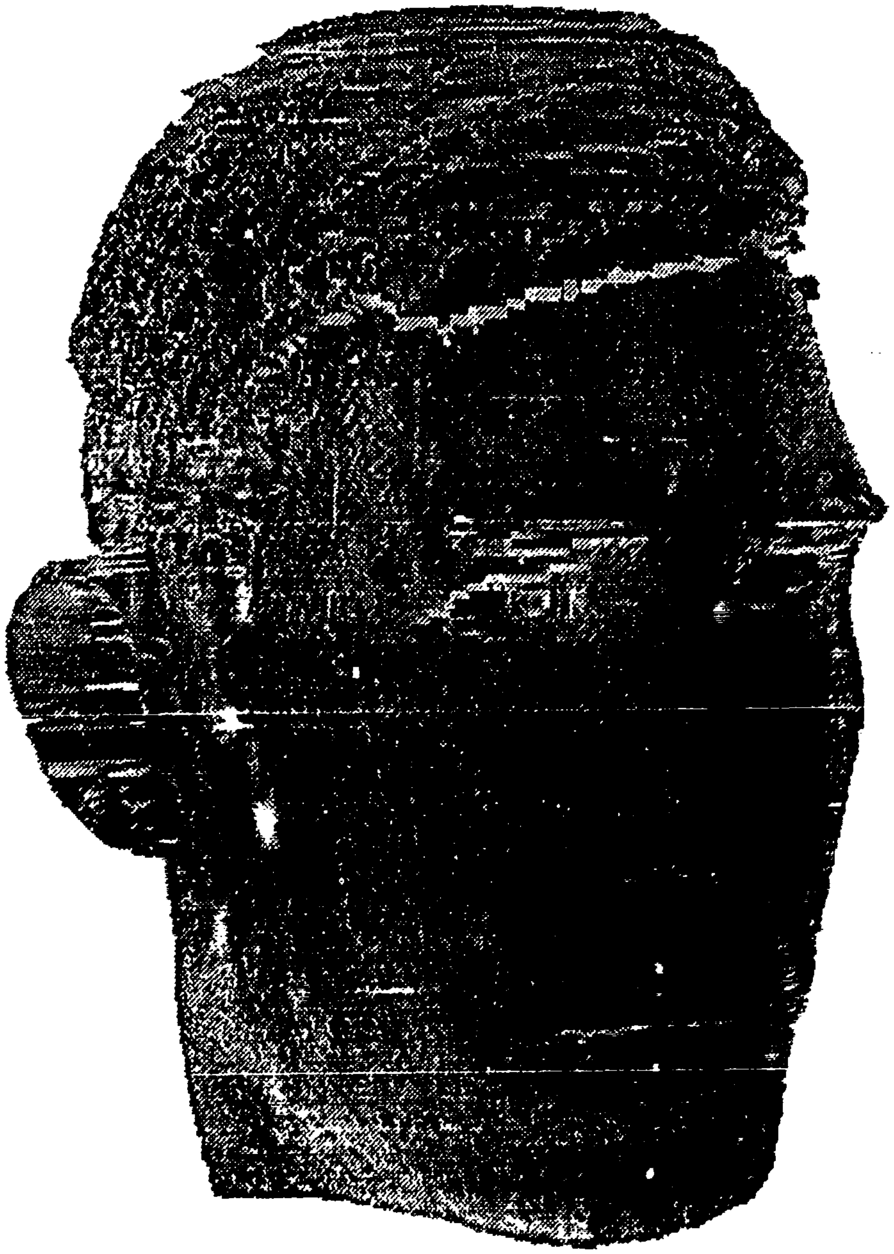


Figure 2. The Same Data as Shown in Figure 1, With Filled, Shaded Polygons Computed from the Surface Points.

goggles and human faces, to produce a 3D representation, or average, of the face shape in those areas where the padding will contact the goggles, and to create a 3D data model of the goggles where the hardware surface under the padding took the shape of this average face.

Automated fit testing has two principal advantages over the use of real subjects. First, the availability of subjects is not a factor, since their digitized images are available at all times. Second, the fit can be quantified in terms of the clearance of the equipment from the body surface and in terms of the precise orientation of the equipment with respect to surface landmarks or features critical to equipment performance. The biggest disadvantage is not being able, at this point, to quantify the degree of comfort or discomfort.

Our first task was to perform an automated fit test on individual subjects, to accurately identify and quantify problems in the clearance of NVG hardware from the face surface. The data for the NVGs were acquired using the Cyberware Digitizer. The inside surface of the goggles, minus any padding, was recorded and represented by about 6500 points (Figure 3). From this set, subsets representing the lenses and padding area on the surface were extracted, so that their separate relationships to the face surfaces could be measured. Because the crucial orientation was that of the lens to the pupil of the eye, we also recorded the coordinates of the lens center, and two other points on the lens surface to define a plane that could orient the lens, and accompanying goggle and padding surfaces. On each face, we recorded, in addition to many other landmarks, points that defined an axis system coplanar with the Frankfurt plane, and we located the pupil. The initial orientation of the hardware and face surface transformed the face data into the Frankfurt plane with an origin at the right pupil. The NVGs, using the right lens points, were initially oriented orthogonal to the Frankfurt plane, with the lens center coincident with the right pupil. Then, the NVGs were rotated 8-degrees downward, so the lens has the ideal angle with respect to the pupil, as defined by the optics group at AAMRL.

With the pupil and lens at the same starting point, our strategy was to move the NVGs away from the face along an axis which maintained the 8-degree orientation. The movements were made in one-millimeter increments, and at each increment, the NVGs were permitted a token 5-degree rotation around a transverse axis. At each increment, vectors were projected from a vertical axis lying six centimeters posterior to the pupil. The projected vectors formed a mesh with equal vertical and rotational increments. The distance from the axis behind the eye to both the face surface and NVG surface was measured at each vector point, and the difference was the clearance, or, if negative, the lack of clearance. The goggles were moved incrementally away from the face until all measured points had a positive clearance. These clearances were then recorded in a goggle-shaped array for each of the 183 subjects used in this part of the study. After all the subjects had been tested, the arrays were summarized and printed (Figure 4). As a goggle-shaped printout, with the lens center-pupil point also indicated, we had a map of the clearances. We could easily correlate minimal and maximal clearances with aspects of the NVG hardware, thus confirming quantitatively where problems may and may not occur. One result was in finding that for the lens to maintain an ideal orientation, the part of the NVG hardware with the intensifier tubes would be very close to the eye.

We wished next to fit the goggles to a data model representing the several hundred flying personnel we had recorded. The problem of summarizing, or averaging, three-dimensional shapes is very real and not yet satisfactorily solved. I used a method which has yielded some interesting results in past small studies. This method is in two steps: data alignment, then data summarizing. Data alignment was approached in two ways: first, to minimize the distance between each point in the data set and its nearest neighbor in every other data set; second, to displace all data sets into a Frankfurt plane orientation with a common origin.

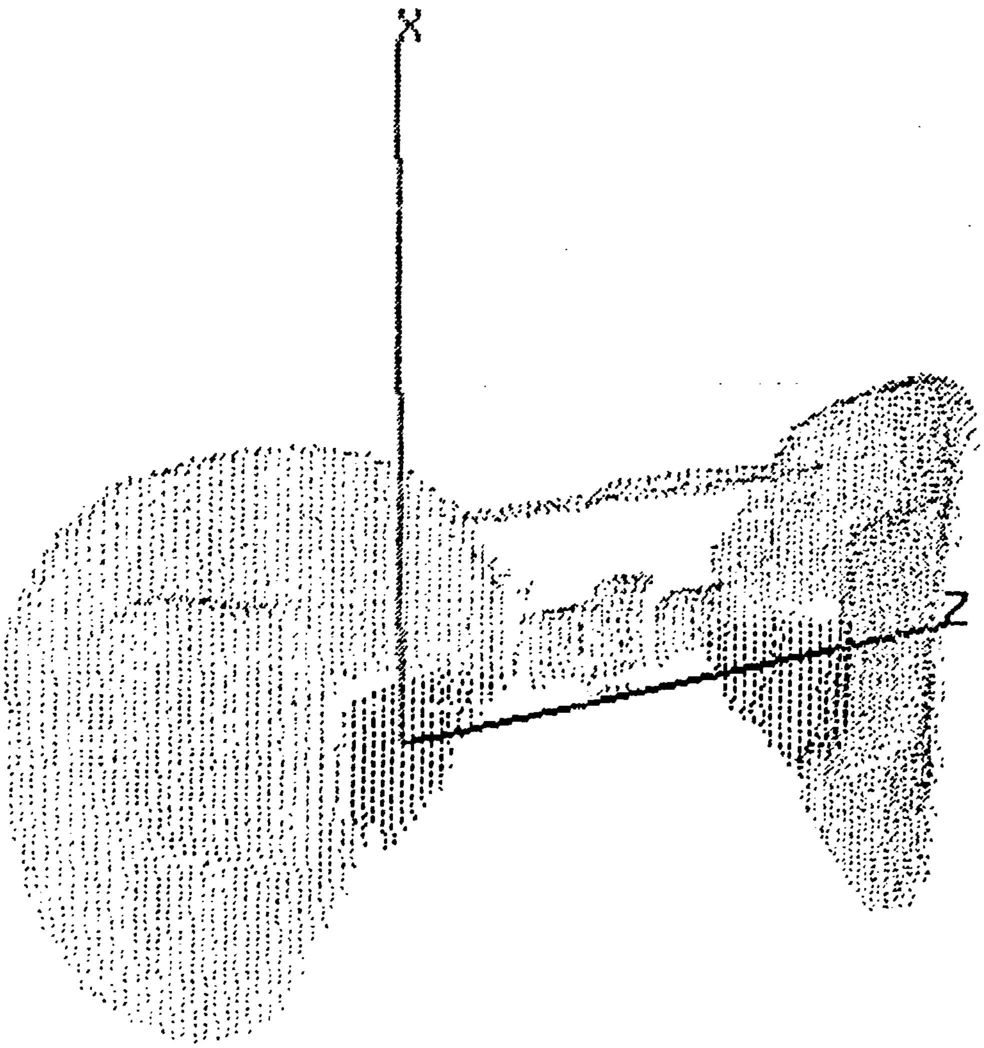


Figure 3. Recorded Surface Points for the Interior Surface of the Eagle Eye Night Vision Goggles. The darker points are from the lenses. The origin of the axis system is the center of the lens, and the X-Z plane is parallel to the right lens. The photo-intensifier tubes occupy the square region in the center on each side; that structure protrudes back toward the eye.

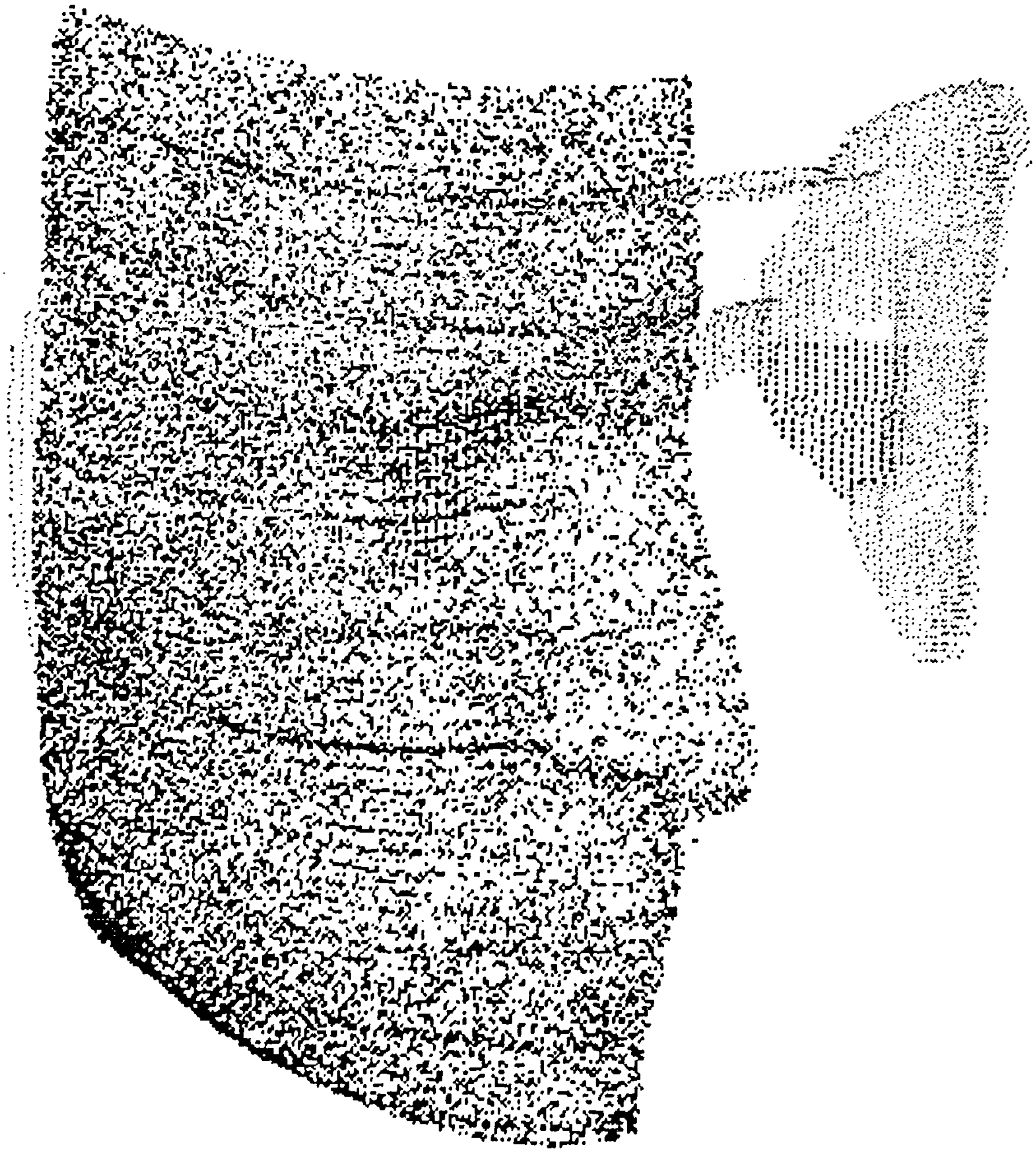


Figure 4. Average Face Clearances for the Eagle Eye Night Vision Goggles, Calculated After Automated Fit Testing on 183 Subject Face Surface Data Sets.

The first technique is an iterative move-and-test strategy, where each data set is in turn given the opportunity to be displaced through a series of rotations and translations, continuing movement in any one direction as long as the distance between the set and all others grows smaller. When the series of incremental movements fails to reduce the distance, the next subject is run through the same series of movements, and so on through all subjects. At the end of the cycle, the incremental rotations and translations are reduced by some fractional amount, and a new cycle begins. This continues until some minimal distance is achieved, or an allotted number of cycles have been run. This technique is computationally very intensive, and, with large data sets, the processing time can stretch to several days. The processing time can be reduced by not testing every point in every data set. Using only every tenth or twentieth point seems to provide results indistinguishable from higher density testing.

The second alignment technique is to simply displace the data sets into a common axis system. This method was used here because it was judged more appropriate for this particular problem. Because the orientation of the faces with respect to the NVGs was critical, it was best to maintain that orientation of face data sets with respect to each other during the process of shape summarization. As in the fit testing, we again chose an axis system parallel to the Frankfurt plane with an origin at the right pupil. Before aligning the face data, a subset of the surface was extracted. To make our final results right-left symmetrical, we used only the right side at this point, with the intention of mirroring the data after summarization.

From these aligned data sets, a summary, or representative set for fit testing was produced (Figure 5). While the procedure involves the averaging of data, we are not ready to call the results an "average" in the mathematical sense. Thus we are using the terms "representative" and "summary." Computation of the representative data set is very simple, but very intensive and time consuming: For each point in each data set, find the nearest point in each of the other data sets, then average the x-, y-, and z-coordinates to produce a point which is a member of the representative data set. The representative data set then contains the same number of points as the total of all constituents. The shape of the result fits neatly into the middle of the displayed and aligned constituent data sets, and is average in appearance and size. Because so many data sets were used in the summarization (350), the procedure was broken down in to subsummarizations. Aligned data sets were summarized in groups of 25, and after summarization, only every tenth point was written out to a file. This kept the size of the resulting data sets manageable. After the groups of 25 were summarized, their summaries were themselves summarized to produce a final representative data set.

Because all the data sets had been aligned at the pupil, the pupil was still at the origin of the axis system for the representative data, and the shape aligned in the Frankfurt plane.

The final part of this phase was to mold the shape of the padding surface, that is, that part of the hardware to which the pads would be affixed. The shape of the surface would be that of the underlying summarized face, and the position of the padding surface would take into account the thickness and compressibility of the padding, as well as clearance problems discovered during automated fit testing.

The NVG template was positioned so that the lens was ideally positioned with respect to the pupil, plus three millimeters to ensure clearance of the intensifier tubes for all subjects (Figure 5). Allowing for the thickness and compressibility of the padding, a one-half-inch clearance of the padding surface was desired when the NVGs were in use. To transfer the face shape to the padding surface hardware in the model, vectors were projected in a mesh pattern from a vertical axis behind the right eye, as in the original fit test.

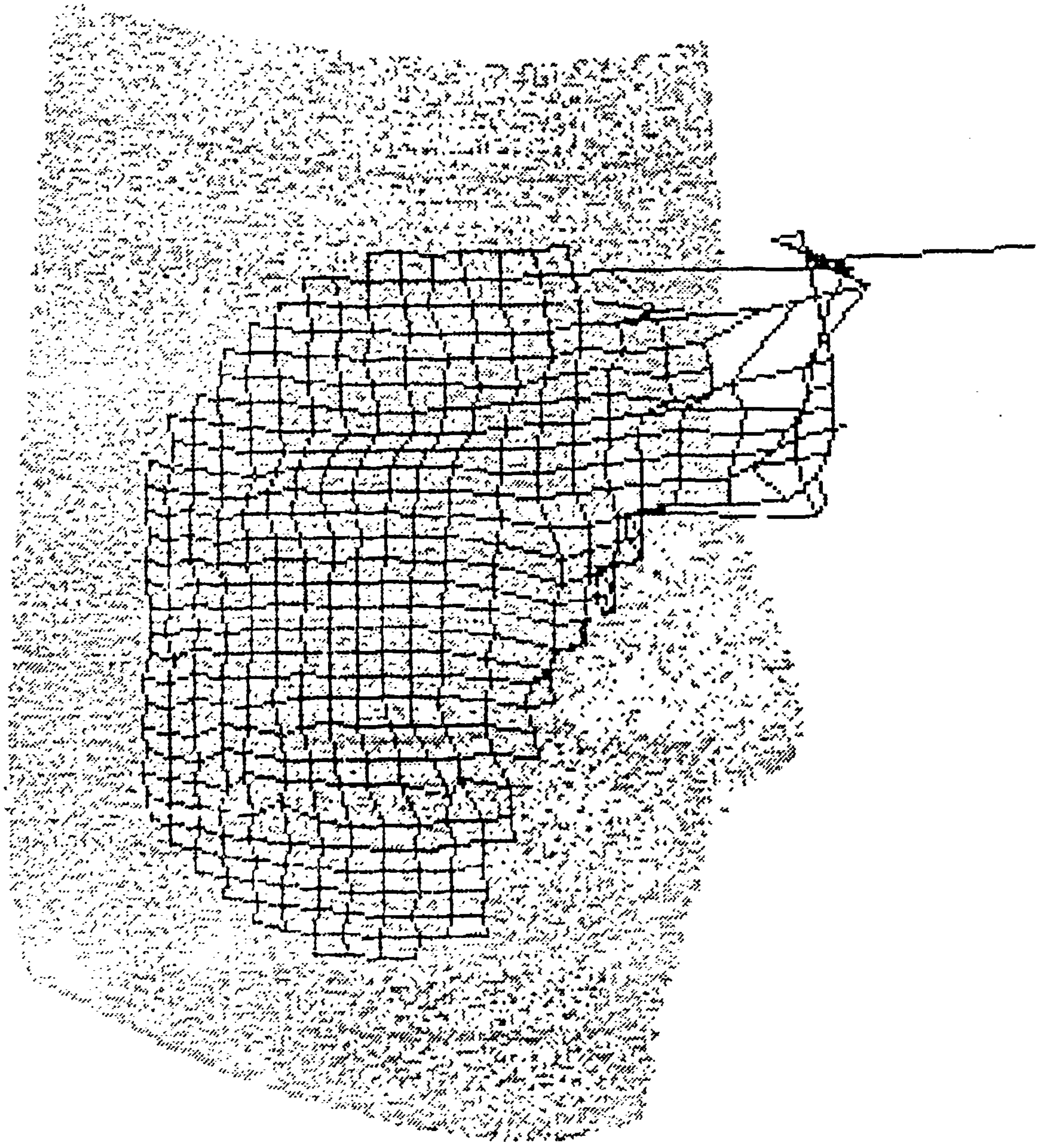


Figure 5. The Representative Half-Face Data Set, Computed from the Recordings of About 350 Air Force Flying Personnel, with the NVG Interior Surface Positioned for Fit Testing.

At the mesh points where the intensifier tube or lens surfaces were found, the 3D locations of those points where stored in a file. When the mesh point was on the padding surface, the 3D location of the underlying face surface - extended outward one-half inch - was stored. Thus, a hybrid data set composed of the surfaces of the lens and intensifier tubes joined to a surface with the shape of the summarized face (Figure 6). This right-side shape was then mirrored to yield a complete NVG template, and the hardware data shape is being made into a dummy NVG for fit-testing and further design.

Other projects which have used these high-resolution surface data include the recording of hand surfaces for use in the manufacture of custom EVA gloves for NASA astronauts, and the production of a head form for the manufacture of a new Navy SEALS diving helmet, the comparison of prototype versus production flight helmets, and the measurement of volumes and centers of volume of the heads of subjects who participate in acceleration sled tests. One proposed project will record the progress of wound healing using hyperbaric treatments at Wright-Patterson Hospital. The detailed surface data will permit the quantification of the changes in wound shape and volume during the course of treatment.

CONCLUSIONS

High-resolution human body surface data have proved valuable in the realistic computer modeling of fit-testing and equipment design. Further developments of these capabilities will provide a powerful tool that can shorten the design cycle and result in better expensive equipment.

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               AVERAGE FACE CLEARANCES FOR THE EAGLE EYE NIGHT VISION GOGGLES

     The right NVG template was positioned over each face so that the lens was in a near optimal
position, but there was minimal clearance of all NVG hardware   Clearances are in millimeters, number of subjects   183
                                          20  20  19  18  17  16  16  15  15  15  14  16
                              19  20  19  17  17  17  16  16  15  14  14  13  13  14  17  23  22  22  21  21  22  19
                          10  18  17  18      16  15  15  14  14  13  12  12  11  11  18  17  22  21  21  20  21  18
                      18  17  16  16  16  15  15  15  14  13  12  12  11  10   9   9  10  10  10
                  18  16  15  15  15  15  15  14  14  13  12  11  11  10   9   8   7   6  10   6
                 PADDING SURFACE
              17  16  14  15  15  15  14  14  14  13  12  11  10   9   8   7   6   6   5   8   5   6
          17  16  14  14  14  14  14  14  13  13  12  11  10   8   7   6   6   5   5   4   5   5   6   9  13  12  11  10
          16  14  14  14  14  14  13  11  10   9   8   7   6   5   5   5   4   4   4   4   4   5   7  11  13   9   9   9
      16  14  13  13  14  14  12  10   8   7   5   4   3   2   2   2   4   4   4   4   5   5   6   8  11  11   8   8   8
  16  14  12  13  13  13  12  10   8   7   6   4   3   2   1   1   2   4   5   5   6   6   7   8  10  12  12   9   7   8
                                     PHOTO INTENSIFIER
  14  13  12  12  13  12  10   9   7   6   5   3   2   2   1   1   2   5   6   7   8   9  10  10  12  15  15  11   9   8
  13  12  12   0  13  11   9   8   7   5   4   3   2   2   1   2   3   7  11  12  11  12  12  12  14  16  19  15  12
                                         TUBES
  12  12  12   0  12  11   9   8   6   5   5   4   3   3   3   3   5   9  14  13  12  12  13  14
  11  11  11   0  12  10   9   8   7   6   5   5   4   4   4   4   6   1  15  14  13   0  14  15
                                                                             LENS
  11  11  11  12  11  10   8   7   7   6   6   6   5   5   5   6   7  11  16  15  14  14  14
  10  10  11  11  11   9   8   7   7   6   6   6   6   6   6   6   7  10  16  15  14  14  14
  10  10  10  11  10   9   8   7   6   6   6   6   6   6   6   6   7  10  15  15  14  13
   9   9   9  10  10   9   7   7   8   8   8   5   5   6   5   5   7   9  13  14  14
   9   9   9  10   6   9   8   8   5   5   4   4   4   4   4   4   5   8   9  11
   8   8   8   9   9   9   8   7   5   4   3   3   3   3   2   3   4   6   7   8
   8   8   8   8   8   8   8   6   6   5   5   4   4   4   3   3   4   5   6
   9   8   8   8   8   8   8   9   8   7   7   8   6   6   5   5   5   5
   9   8   8   8   8   8   7   8   7   8   6   5   5   5   5   4   4   4
  11   9   8   8   8   8   7   7   6   6   6   5   5   4   4   4   3
      10   9   8   8   8   7   7   6   6   5   5   4   4   3   3   2
                 PADDING SURFACE
          10   8   8   8   7   7   7   6   5   5   4   4   3   3
              10   9   8   7   7   7   6   6   5   4   4   3   3
                  10   9   8   8   7   6   6   6   5   4   3   3
                      10   9   8   8   7   6   6   5   4   4
                                   8   8   7   6   5
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Figure 6. The Representative Half-Face Data Set with the Hybrid NVG Hardware-Face Surface Represented by the Mesh. The padding area around the perimeter of the NVG hardware has the contour of the underlying face, offset away from the face to allow for padding.

HUMAN-CENTERED DESIGN EVALUATION FOR ENHANCED SYSTEM SUPPORTABILITY

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ABSTRACT

The application of Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) to design of weapon systems provides design engineers the ability to create and/or modify a design several times in the time previously required for a single iteration. Traditional methods for assessing design supportability characteristics and human interfaces, such as demonstrations on hard mock-ups, can no longer keep pace with CAD design changes. Consequently, supportability assessment is often delayed until the availability of prototype hardware, too late for substantial hardware design changes. There is a need for technologies to integrate performance-oriented CAD/CAE design processes with human performance and supportability analyses. Simulation of the maintenance environment and of the performance of maintenance tasks, using three-dimensional computer mock-ups of developmental hardware and the maintenance technician, is a powerful methodology for this analysis. It provides a means of communication between the maintainability engineer and the designer in a common media, and allows rapid assessment of the design and proposed changes for supportability enhancement. This paper addresses the development and application of the simulation modeling capability at General Dynamics Convair Division.

Today's sophisticated and technically complex weapon systems and austere operating environment require a high degree of availability and sustainability to meet requirements for readiness and survivability at forward basing locations. Weapon system supportability characteristics influence operational effectiveness by driving readiness for battle, sustainability during battle, and use of personnel, material, equipment, and transportation during training and battle.

Good supportability characteristics improve the tactical mobility of forces because there are fewer people, less support equipment, and fewer spares to move. Reduced requirements for facilities, equipment, and personnel for support and decreased downtime for maintenance also reduces system vulnerability in forward deployment areas. In recognition of the importance of supportability to today's weapon systems, Department of Defense (DoD) policy has shifted in all sectors, giving supportability equal consideration with performance in the weapon system acquisition process.

The advent of Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) has had a profound impact on the ways in which design and support engineers interface to ensure development of supportable products. All personnel who influence the supportability characteristics of a product, including design as well as supportability specialists, have become "on-line" with the integrated design process through the use of a shared electronic representation of the product.

Early CAD analysis of proposed hardware offers the greatest potential for cost-effective integration of performance and supportability characteristics before investment in prototypes and production hardware. Therefore, at General Dynamics Convair Division, we have applied CAD/CAE, robotics, communications, and data base management technology to help integrate maintenance and supportability issues with traditional design for performance requirements.

We have developed a Supportability Analysis Workstation (SAWS), integrating CAD and robotic simulation techniques with attendant network communications, data base management, and graphics capabilities. Principal elements are robotics surface-shaded software, relational data base management system, network communications, and our own application software, hosted on a high-speed graphics workstation.

The designer or support engineer can be either a 95th percentile male technician model, as defined by Military Standard 1472, or a 5th percentile female model for assessment of hardware and technician interfaces. The technician models' limbs are anthropometrically modeled to human joint and limb constraints. Rotation exceeding human limitations is displayed through a color change of the respective limb and joint. The models have the capability to assume kneeling, stooping, and sitting positions required for performance of maintenance and support tasks (Figure 1.) SAWS can also show the view of the work area as seen through the technician's eyes. This capability facilitates assessment of visibility of labeling, test points, connectors, and fasteners (Figure 2).

SAWS communications enable the designer or specialty engineer to access the CAD design files for new designs or changes to existing designs for assessment of supportability characteristics. The SAWS data base management system imports the CAD model to the workstation. Once resident on SAWS, the CAD model can be rotated and the viewpoint changed. Additionally, portions of the model can be depicted as transparent to provide full visibility of the work area under analysis.

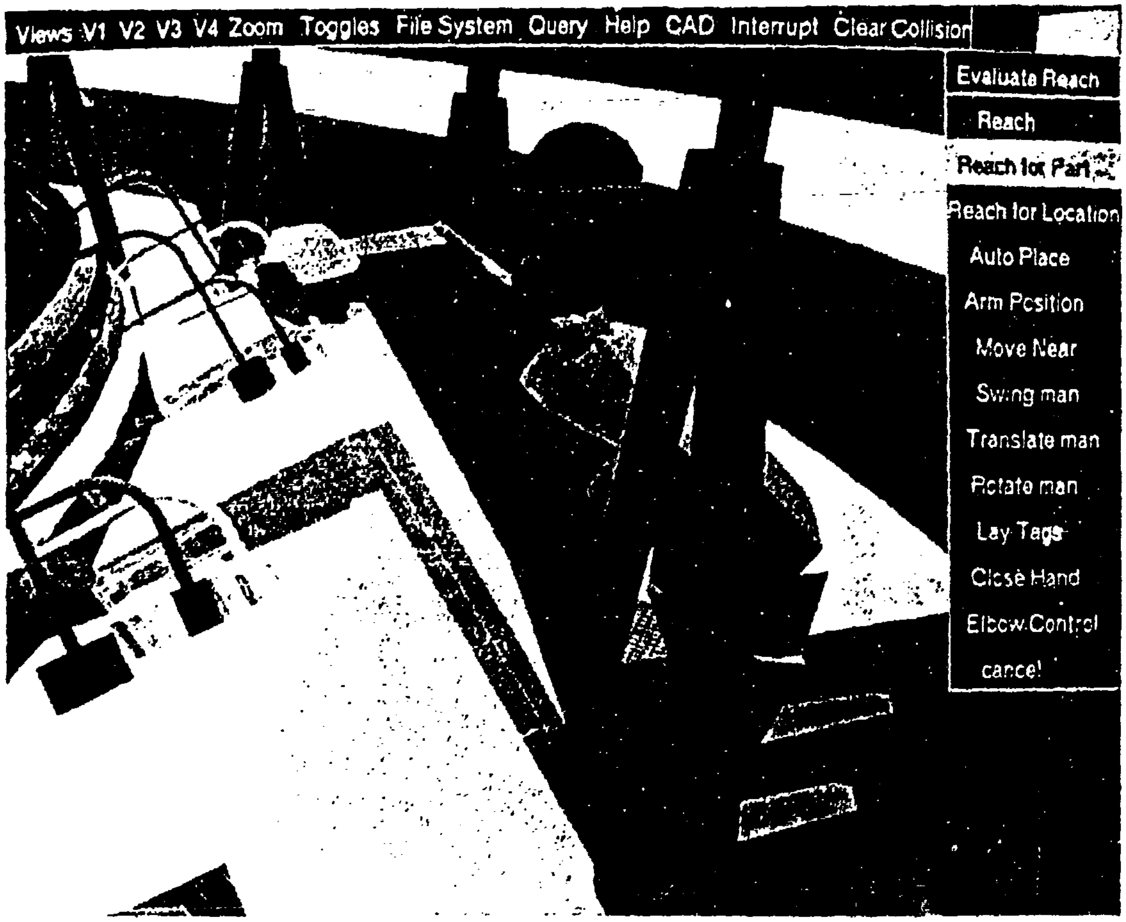

Figure 1. The CAD technician is fully modeled to human anthropometric constraints. It can simulate any position required for performance of a task. High-fidelity models have been developed on SAWS to evaluate detailed tasks such as connecting electrical harnesses.

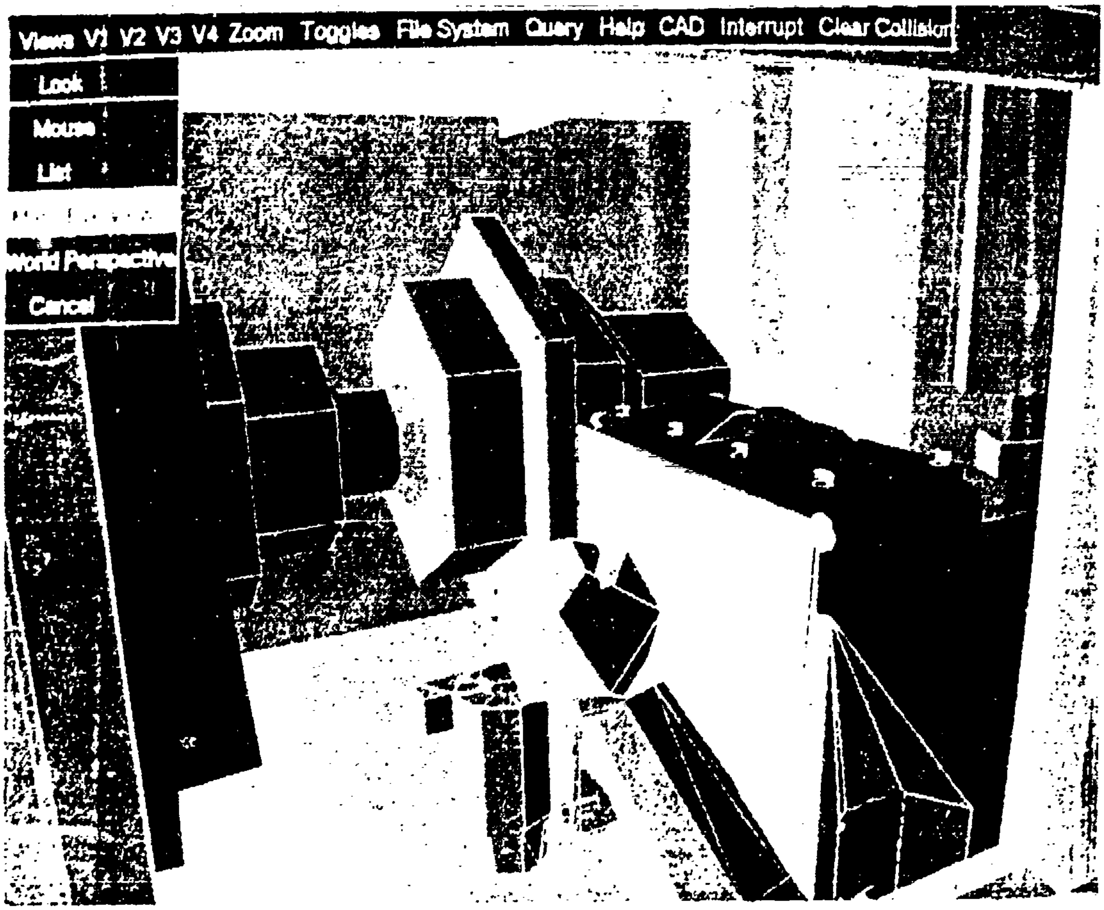

Figure 2. We can provide the technician's viewpoint of the CAD model. This is used to evaluate adequacy of displays and control layouts and visibility of test points, connectors, and fasteners.

Because SAWS locally creates surface-shaded models from the design data base, we can use wire-frame models produced by existing CAD systems as well as solid models which are gaining increased acceptance in the design community. This provides SAWS with the flexibility to remain compatible with a wide range of present and future CAD systems. Additionally, CAD models have been created on the workstation from existing paper drawings or by writing translators for vendor or associate contractor CAD tapes.

CAD models were created from drawings of the proposed redesign of the turbine generator system for the Ground Launched Cruise Missile (GLCM) system. This generator provides electrical power to the GLCM launcher and Launch Control Center. The incorporation of design recommendations for improved supportability characteristics in the final generator system design resulted in a substantial increase in GLCM system operational availability.

A typical supportability analysis is performed as follows: An assessment is to be made of the removal and replacement of a weapon into system subassembly, for example, the fuel pump from the GLCM turbine generator. Attaching fasteners for the fuel pump are first checked for compatibility with standard tools, to avoid development and support costs associated with designing, testing, and stocking special tools for maintenance. SAWS has a library of standard tools which are correlated with the geometry and location of attaching hardware. Tools which will fit the fastener and have sufficient clearance for required operation, such as wrench rotation sweep ranges, are identified (Figure 3.). The tools are then listed for inclusion in instructions for repair and scheduled maintenance. If no tool meets the criteria for a particular fastener, that fastener is highlighted and reported to the designer. Although this analysis is shown on the screen for demonstration purposes, fastener checking may be performed in background, freeing the workstation for other tasks.

Once the correct tools have been identified, reach and manipulation analyses are performed to verify that there is sufficient access to allow the technician to remove all required fasteners and lift the fuel pump from the generator cabinet. A collision detection algorithm highlights impacts with supporting structure as the analysis is being performed. As the fuel pump is being removed, a static analysis capability provides assessment of the forces on the technician's limbs and joints. This information will indicate whether the technician can generate enough torque on the fasteners, and whether he or she has the strength to lift the pump out of the generator cabinet.

The hands-on time to perform the removal task is recorded during the simulation to provide input to a system mean-time-to-repair calculation. This information is also used to develop elapsed time estimates for maintenance planning and cost analysis.

The simulation may be saved in the data base for playback on the workstation screen to demonstrate maintenance problems or to verify the adequacy of access provisions without repeating each command at the keyboard. The saved simulation can also be used for development of training materials and identification of views to be incorporated in technical manuals.

In addition to task analysis, SAWS can be used to perform "quick-look" analysis of interfaces between a weapon, support equipment, and facilities. For example, analysis was performed to evaluate storage of missile containers in a weapons magazine aboard an aircraft carrier. A model was developed on SAWS from drawings in less than a week (Figure 4.) Support equipment models were mechanized, to demonstrate feasibility of using existing handling equipment and overhead rails to maneuver and stack the missile containers within the confines of the weapons elevator and magazine.

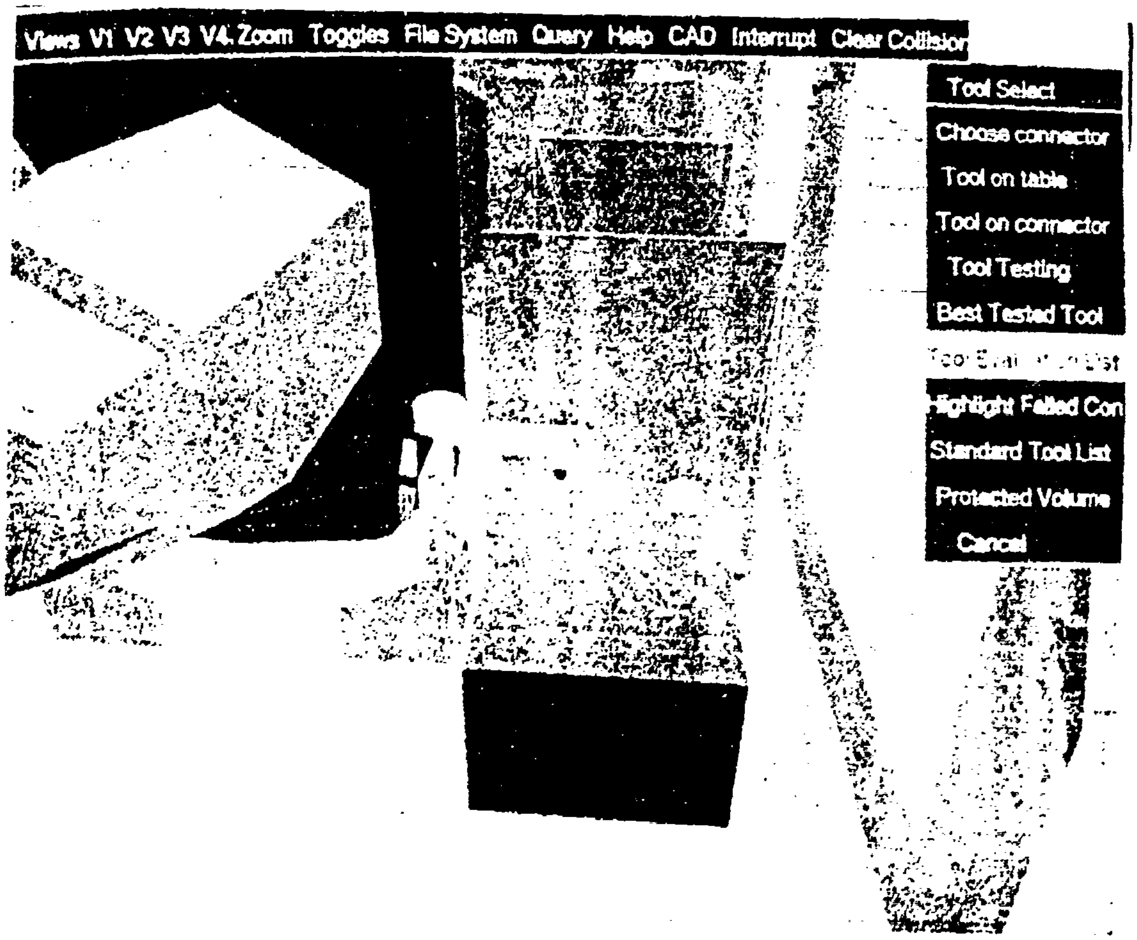

Figure 3. SAWS has a library of standard tools which are correlated with the geometry and location of attaching hardware. Tools which will fit the fastener and have sufficient clearance for required operation, such as wrench rotation sweep ranges, are identified.

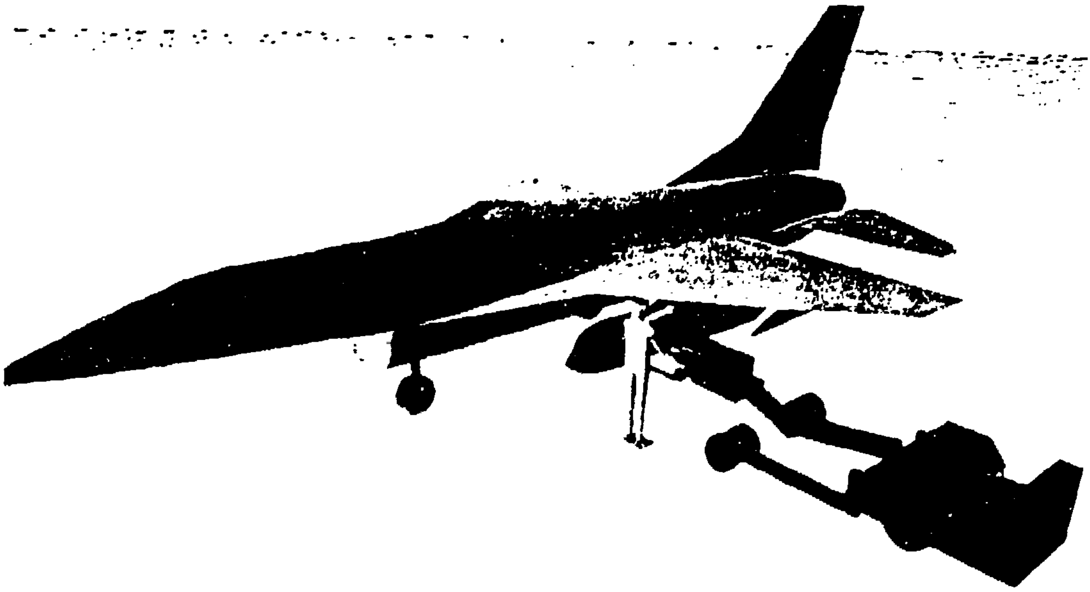

Figure 4. This model of an aircraft carrier munitions magazine was developed in less than a week to evaluate the feasibility of using existing support equipment to strike down missile containers in the weapons elevator and stack them within the confines of the magazine.

Mechanized support equipment models are also being used to evaluate interfaces for missile loading on aircraft pylons. This analysis will result in designing missile and aircraft interfaces to minimize aircraft turnaround time, maximize operational availability, and minimize vulnerability while loading (Figure 5).

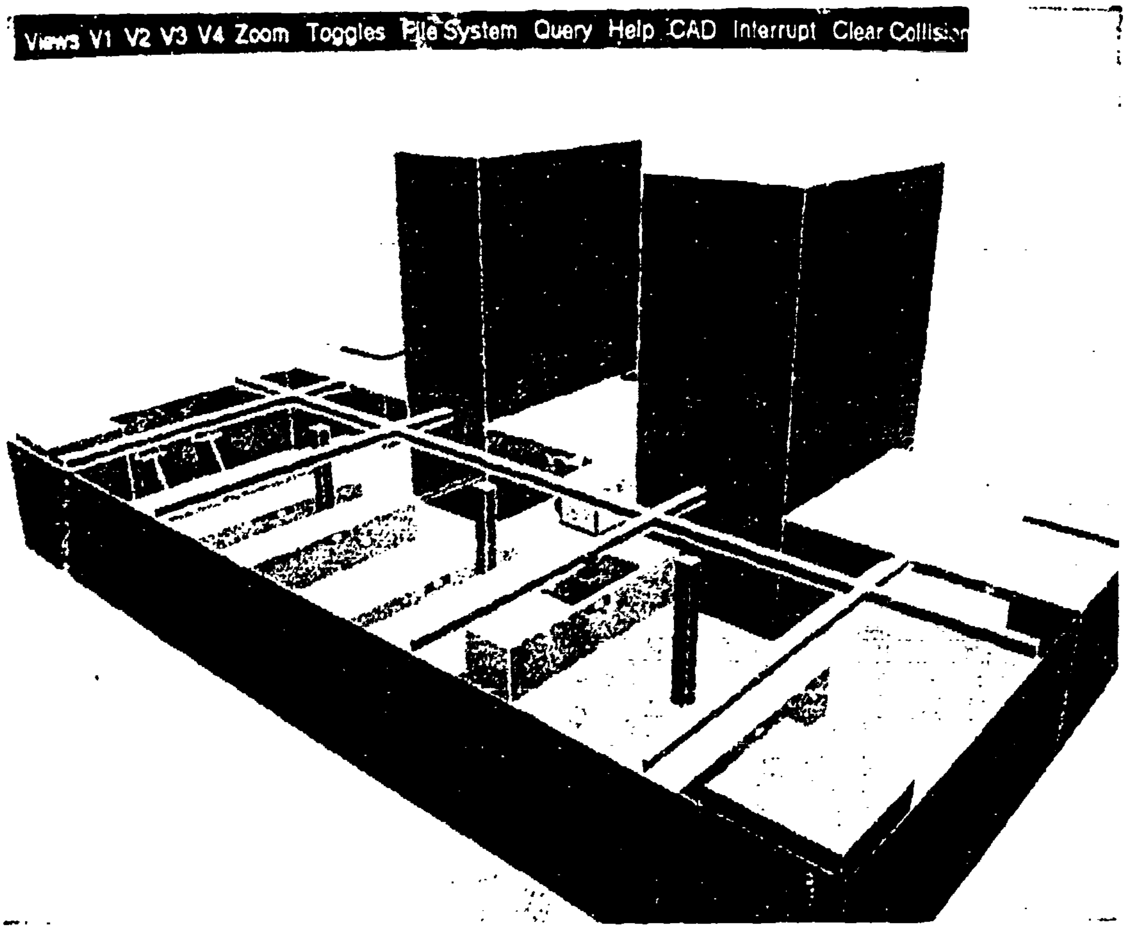

Figure 5. Through the use of mechanized support equipment models and aircraft models, SAWS can also be used to analyze aircraft weapons loading interfaces and turnaround tasks.

SAWS has been integrated into the CAD design environment at General Dynamics. In one example, thermal data plotted on the SAWS workstation have been used to determine the change in temperature of a component caused by relocation within the thermal environment. The new temperature is passed to the electrical design workstation, where a warning message notifies the designer that the reliability of the relocated component may have been changed. The designer then uses software communications interfaces developed under the Reliability, Availability, and Maintainability in Computer-Aided Design (RAMCAD) program to calculate the reliability impact of the proposed component relocation.

The DoD is now applying a heavy emphasis , through the Computer-Aided Acquisition and Logistics Support (CALS) and Total Quality Management (TQM) initiatives and programs to bring the "ilities" into the mainstream of the design process. At General Dynamics Convair Division, we are moving forward to implement these initiatives today through development of an integrated concurrent engineering CAD design and analysis environment, and a focus on continuous improvement of our products and their supporting processes to "do it right the first time."

INTEGRATING TASK NETWORKS AND ANTHROPOMETRIC MODELS

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ABSTRACT

Over the past decade, there have been significant advancements in the development of general purpose tools for the modeling of humans. From our perspective, there have been two key "fronts" for this technological growth -- dynamic human performance models and anthropometric models. Dynamic human performance models explore human performance over time and are used to study aspects of human behavior such as time required to perform a set of tasks, combined task error rates, and human/system interaction and performance prediction. Anthropometric models, on the other hand, have focused on the relationship between the human and his workplace. Anthropometric modeling tools have provided the means to determine whether the relationship proposed by a designer between the human and the controls and displays he must use is technically feasible within the constraints of human body dimensions and movement constraints. Additionally, anthropometric models have begun to provide, through the use of computer graphics, "pictures" of the human at his workplace. Since pictures are, indeed, worth a thousand words, this capability has proven very useful in conveying man-machine anthropometric relationships to designers.

So we have rapidly evolving technologies for studying human performance dynamics as well as technologies for depicting the human in his workplace. What has not yet occurred is the linkage between these technologies. Probably the simplest way to imagine the potential of this linkage is to think of a tool which would allow the creation of a computer graphics-generated "movie" of the human performing his tasks in his workplace. Recent developments in the two human/system modeling technologies have made their merger much more possible. This paper will discuss these developments as well as a specific project to build a bridge between anthropometric models and dynamic human-performance models.

BACKGROUND

Over the past decade, there have been significant advancements in the development of general purpose tools for the modeling of humans. From our perspective, there have been two key "fronts" for this technological growth -- dynamic human performance models and anthropometric models. Dynamic human performance models explore human performance over time and are used to study aspects of human behavior such as time required to perform a set of tasks, combined task error rates, and human/system interaction and performance prediction. Anthropometric models, on the other hand, have focused on the relationship between the human and his workplace. Anthropometric modeling tools have provided the means to determine whether the relationship proposed by a designer between the humans and the controls and displays they must use is technically feasible within the constraints of human body dimensions and movement constraints. Additionally, through the use of computer graphics, anthropometric models have begun to provide "pictures" of the human at his workplace. Since pictures are, indeed, worth a thousand words, this capability has proven very useful in conveying man-machine anthropometric relationships to designers.

So, we have rapidly evolving technologies for studying human performance dynamics as well as technologies for depicting the human in his workplace. What has not yet occurred is the linkage between these technologies. Probably the simplest way to imagine the potential of this linkage is to think of a tool which would allow the creation of a computer graphics-generated "movie" of the humans performing their tasks in his workplace. Recent developments in the two human/system modeling technologies have made their merger much more possible. This paper will discuss these developments as well as a specific project entitled Micro Saint/HOS whose purpose is to build a bridge between anthropometric models and dynamic human performance models.

The dynamic human performance modeling approach being used in this project is task network modeling. The specific tool being used in this project is Micro Saint. However, since Micro Saint alone does not provide some of the specific human performance features that are central to modeling human anthropometry, this effort will link Micro Saint with the Human Operator Simulator (HOS) to develop a tool that will provide a set of modeling constructs that overcome this shortcoming. Using this combined Micro Saint/HOS tool, we believe that we will be able to generate data which can be directly entered into an anthropometric modeling tool. Through these passed data files, Micro Saint/HOS will prepare the input required by the anthropometric models to define human body location and position *over time*. This, we believe will (a) serve as a basis for ensuring that the human movement requirements are feasible and (b) allow the development of a computer-generated "movie" of the human performing his activities. The ultimate product of our efforts will be a tool for studying and illustrating human performance dynamics and anthropometry as the human works.

This tool is currently in the development stage and is scheduled to be completed by June 1992. The product of our efforts will not be a completely new product but, rather, a recombination and integration of existing dynamic and anthropometric models of human performance. A brief summary of the lineage of this tool is presented in Figure 1.

The remainder of this paper will discuss the two underlying technologies of human performance dynamic modeling, Micro Saint and HOS, and the conceptual design of the product linking dynamic human performance models to anthropometric models.

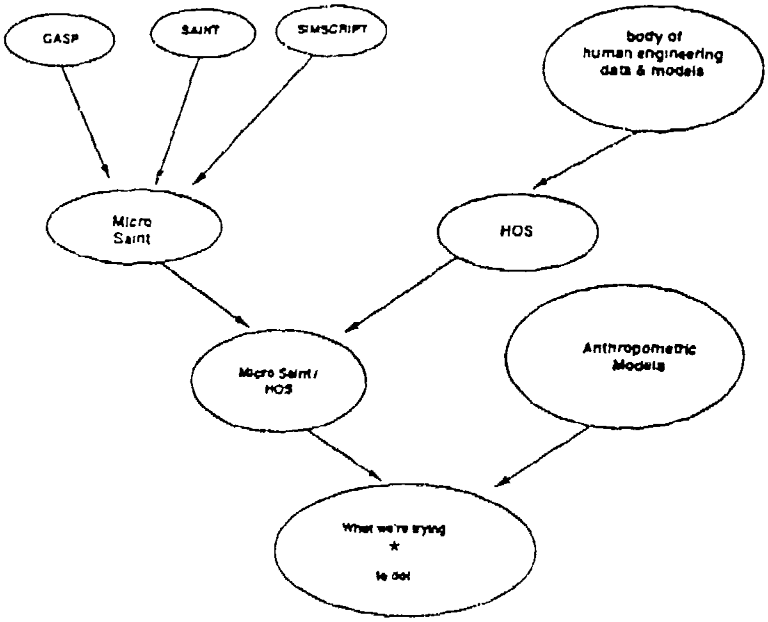


Figure 1. Lineage of the Integrated Task Network and Anthropometric Model.

THE UNDERLYING TECHNOLOGIES FOR HUMAN PERFORMANCE DYNAMIC MODELING - MICRO SAINT AND HOS

Micro Saint

Micro Saint is a discrete event, network-based simulation system that has gained widespread use as a tool for modeling human performance in military systems. The advantages of Micro Saint, from a human performance modeling perspective, are (a) it is relatively easy to use compared to traditional simulation languages and (b) it allows the user to model a system at any level of detail as dictated by the questions to be addressed by the model. This makes Micro Saint a very flexible modeling tool. However, Micro Saint is also a "blank piece of paper" in that no human performance models are inherent to the software. For example, when a user must estimate a task's time, Micro Saint provides no assistance to the user on how to estimate this time. The user must either obtain data from the task or a similar task, use motion time study methods, or ask a subject matter expert for an estimate.

The underlying approach to modeling with Micro Saint is a technique called task network modeling. Task network modeling of human performance is a technique that has been under development over the past 10 years. Essentially, the performance of an individual performing a job (e.g., driving a tank) is decomposed into a series of subfunctions which are then subsequently decomposed into tasks. This is, in human engineering terms, simply the task analysis. The sequence of tasks is defined by constructing a task network. An example of a task network is in Figure 2, which presents a task network for an M60 tank crew.

The level of system decomposition (i.e., how finely we decompose the tasks) and the amount of the system which is simulated depends on the particular problem. For example, in a study to analyze operator workload in a helicopter crew, we constructed autonomous networks for the operators, the aircraft, and the threat environment. While the networks associated with the humans' tasks were far more detailed than those for the helicopter and threat environment, we were able to capture enough of the critical elements of the helicopter and environment to permit a study of closed-loop human performance.

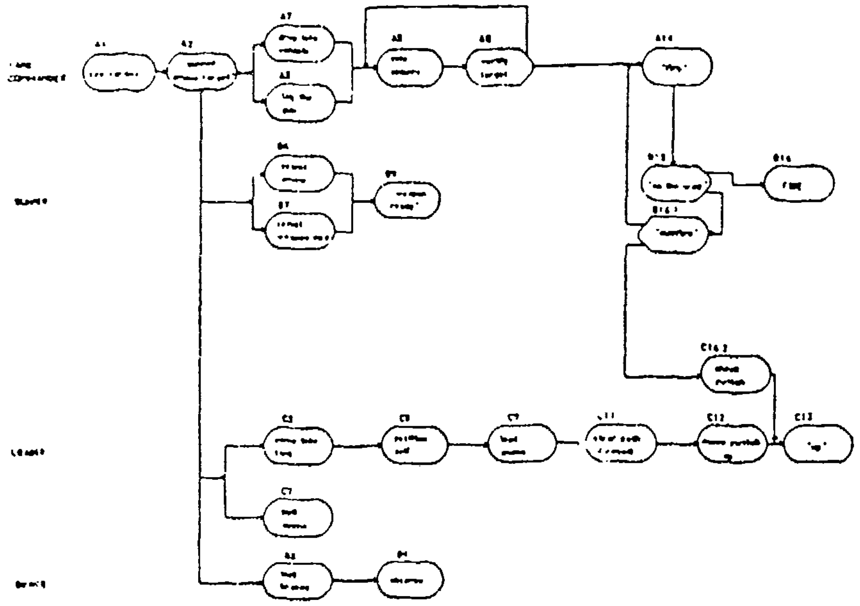


Figure 2. Example of a Task Network for an M60 Tank Crew.

While the task networks in a model may be independent, performance of the tasks can be interrelated through shared variables. Once the network is defined, the modeler must determine what variables are relevant to the modeling problem and how those variables are affected by tasks in the networks. The relationships among different components of the system (which can be represented by different segments of the network) can then communicate through these shared variables. For example, when a helicopter pilot initiates a pop-up activity, the variables associated with operator controls would be changed by that task to reflect the increase in power applied to the engine. These new values would then indicate to the helicopter portion of the model that it must start executing tasks associated with increasing the aircraft's altitude, which is represented by another variable. Once the altitude is above the threshold required for the threats to observe and begin firing, the threat portion of the model begins executing tasks associated with shooting at the aircraft. Representing task sequencing through a network and interrelationships among tasks through the changing values of variables associated with tasks forms the foundation of all network models.

Of course, the strength of task network modeling is that the dynamic aspects of task networks can be simulated on a computer. That is the purpose of Micro Saint. We will use the Micro Saint menu for defining a "task" within a task network presented in Figure 3 as an example of the information required in a task network simulation. If a user provides the information required on this menu for each task in the network, he will have built virtually all of a task network model. Following is a brief discussion of the most important parameters that are defined for each task in the network. Please note that this is not intended to be a primer on Micro Saint, but illustrative of the tool's flexibility in modeling complex human-machine systems.

The Release Condition is a value that can be used to prevent a task from executing if certain conditions in the model are met, such as the availability of a resource or completion of other tasks. Often, the Release Condition value is represented by a variable that changes depending on varying conditions in the model.

The simulated task execution time is a random number generated by the Micro Saint software by Monte Carlo sampling from a distribution. To define the distribution, the user must specify its type (i.e., normal, exponential, etc.) and the parameters such as mean and standard deviation. Like the Release Condition value, the parameters of the execution time distribution can be calculated as a function of some variable value. The variable can then be modified either by the use or by changing conditions in the model.

The sequence of task execution in a network is determined by specifying all the potential tasks that can be executed following the completion of each task and the logic for selecting one or more following tasks. Following tasks may be selected probabilistically or according to some user-specified tactical logic. It is also possible for a task to be followed simultaneously by more than one task. Again, when specifying the following task or branching logic, the user can use variables that can be changed to represent changing conditions in the model.

A primary way that variables representing relationships between tasks change is as a result of a task beginning or completing execution. These "Beginning" and "Ending Effects" are defined by the user by entering mathematical and logical expressions that change the variable values.

A final note on the menu in Figure 3 is that any value that appears on the screen can be not only a number but algebraic expression, logical expressions, or groups of algebraic and logical expressions that would essentially be analogous to a subroutine.

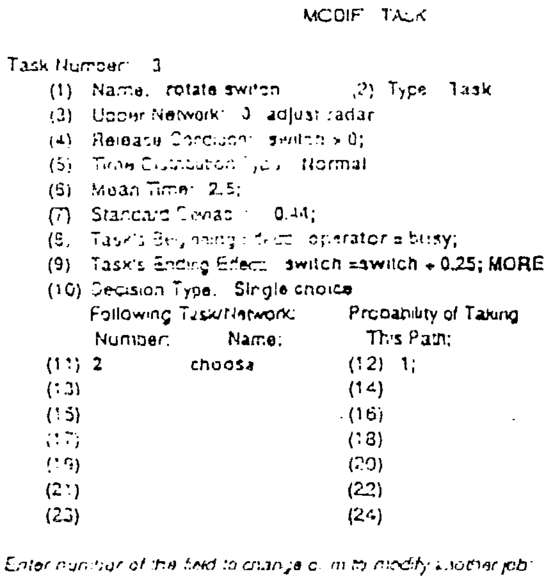
If the reader were to conclude that task network modeling is a straightforward concept which is a logical extension of task and systems analysis, he would be right. Task network modeling is an evolution, not a revolution. It does, however, greatly increase the power of task analysis in that the ability to simulate a t[illegible] work with a computer permits prediction of human performance rather than simply the descrip[illegible] of human performance that task analysis provides.

In summary, Micro Saint is very much a top-down systems modeling tool that was designed for simulating human performance in systems. It is a shell for modeling human performance. However, as stated earlier, it does not provide a detailed data base or specific set of modeling constructs for human-machine systems. The task of defining these constructs and collecting the necessary data is left to the modeler in Micro Saint. This approach provides great modeling flexibility, but creates greater demands on the user to build human performance models.

The Human Operator Simulator (HOS)

As task analytic techniques for using simulation to evaluate human performance were being developed, another approach was being pursued by the Navy in the form of HOS. HOS uses a "bottom-up" approach whereby basic elements of human performance are defined. Then, human performance in a system is modeled by aggregating these basic elements into higher levels representing system operation and control activity. HOS provides an ideal environment for determining the values of human performance parameters based on a detailed analysis of task elements.

To build a HOS model, the user constructs a model of human activities by linking together the elemental human behaviors (identified by what are referred to as micro models) These elemental human behaviors affect aspects of the human and his environment via changes in object attribute values. The execution of these elemental aspects of behavior are mitigated by the interference matrices. These concepts are discussed in further detail.



```
                         MODIFY TASK

Task Number: 3
   (1)  Name:  rotate switch          (2)  Type:  Task
   (3)  Upper Network:  0  adjust radar
   (4)  Release Condition:  switch > 0;
   (5)  Time Distribution Type:  Normal
   (6)  Mean Time:  2.5;
   (7)  Standard Deviation:  0.44;
   (8)  Task's Beginning Effect:  operator = busy;
   (9)  Task's Ending Effect:  switch =switch + 0.25; MORE
   (10) Decision Type:  Single choice
        Following Task/Network:        Probability of Taking
         Number:         Name:           This Path:
   (11) 2             choose           (12)  1;
   (13)                                (14)
   (15)                                (16)
   (17)                                (18)
   (19)                                (20)
   (21)                                (22)
   (23)                                (24)

Enter number of the field to change or m to modify another job:
```

Figure 3. Micro Saint Modify Task Menu.

Micro Models

The basic uses of the micro models are to:

1. determine task times
2. determine error rates
3. change the attributes of objects

Micro models are, essentially, special functions included as part of the software that estimates performance attributes of the elements of human performance. Some of the micro models included in HOS are:

1. Eye Movement
2. Memory Store
3. Speaking
4. Right Hand Move
5. Right hand manipulate toggle
6. Right hand manipulate track ball
7. Left hand manipulate track ball
8. Visual Perception
9. Memory Retrieve
10. Walking
11. Left Hand Move
12. Listening
13. Decide
14. Printing

Objects

The use of objects and the orientation of the simulation toward objects is central to HOS. Objects are normally conceived of as physical things such as switches, dials, hands, feet, eyes, etc. They can also be thought of in a more abstract sense and used effectively in simulations. For example, in studying attentional demands and workload, objects called "Visual Channel," "Auditory Channel," and "Cognitive Channel" could be defined. Since the primary purpose of HOS is to model human operators, there is a set of objects associated with the human (e.g., hands, feet, the various channels, [illegible]) defined [illegible] model. The user can eliminate these as needed. As we will [illegible] this [illegible] provides the linkage to anthropometric models.

The key aspects of objects are discussed below.

Object Structure. In HOS, each object has attributes associated with it. For example, the right hand will have x, y, and z position coordinates. Each of the attributes is then defined in terms of its type (e.g., integer), value (e.g., 30), units (e.g., inches), and acceptable values (e.g., 15 to 45). Objects may be grouped into sets and subsets for better organization. For example, the objects representing the workstation may be a set, and it may have controls and displays as subsets. The characteristics of the object structure are elaborated on below.

1. Object Sets - Object sets are defined by the user and perform no function within the simulation. They simply help the user to organize information.

2. Object Name - The object name provides the label to address the object in the simulation. It also defines the existence of the object.

3. Attribute - The attributes are the characteristics of the object that define the state of the object, for example, the coordinates for the object's location in the environment or the color of the object. These attributes are manipulated by the simulation and reflect the object's change in state during the course of the simulation.

4. Type - Type defines what kind of variable the attribute is (i.e., integer, real, alphanumeric, or an array of one of these).

5. Value - Value reflects the current value of the attribute. It is this value that changes during the simulation execution.

6. Acceptable values - Acceptable values are the specific values or range of values to which the attribute can be set. For example, a speed indicator may have an acceptable range of 0 to 100 mph; or a switch may have acceptable position indications of "on," "off," and "standby."

Interference Matrices

HOS uses an interference matrix to prevent illogical applications of micro models (e.g., moving and writing with the right hand at the same time). They can also be used to reflect more abstract kinds of interference such as the multiple resource theory of workload.

In summary, HOS provides a solid framework for modeling the human. However, because it is so strongly oriented in modeling from the "bottom up," it is inflexible and sometimes very cumbersome.

Micro Saint/HOS

HOS provides an excellent way to estimate the parameter values of task performance by combining the predicted performance of the individual task elements. The disadvantage of this approach is that it forces the user to a very low level of detail which is not always appropriate. Micro Saint allows flexibility with respect to the level of detail modeled. The disadvantage is that it does not provide a way to estimate the values of task performance. The potential for synergy between the two products is obvious.

In mid 1988, Micro Analysis and Design, under contract to the Army Research Institute, began a project to integrate Micro Saint and HOS. This project was funded through the Small Business Innovative Research (SBIR) Program. Currently, there are two cooperative Phase II SBIR efforts underway as part of this Micro Saint/HOS integration effort, one being performed by Micro Analysis and Design and one by CHI Systems, Inc., of Blue Bell, Pennsylvania.

Functionally, the combined Micro Saint/HOS product will be based on Micro Saint. This decision was largely because the discrete event simulation used in Micro Saint is computationally more efficient than clock-driven simulation used by HOS. Also, it is easier to embed the HOS modeling constructs within Micro Saint than vice versa. The project is, however, a mix of Micro Saint and HOS. What were considered to be the best features of each of these parent products have been incorporated into the design of the bridge product. The primary features taken from each of these products are outlined below.

Micro Saint

1. Task network event-driven simulation approach
2. Basic task structure (i.e., mean time, standard deviation, following tasks, etc.)
3. Basic functional characteristics (i.e., develop, execute, analyze; tasks, variables, functions, etc.)
4. Basic data analysis feature (i.e., graphics, statistics, etc.)
5. Content-specific help

HOS

1. The use of objects to define the simulation environment
2. Micro models
3. Interrupts
4. Additional analysis features related to object data
5. Conflict matrices

The software environment selected for this combined product was UNIX with an X-Windows graphical user interface. This was selected to maximize portability as well as power of the software. The software is currently being designed to operate on an 80386 IBM PC computer operating under Interactive Systems UNIX.

As of the writing of this paper, the combined Micro Saint/HOS product was in detailed software design with software development scheduled for completion in mid-1992.

THE OPPORTUNITY - INTEGRATING MICRO SAINT/HOS WITH ANTHROPOMETRIC MODELS

Early in the design phase of this project, we realized that this combined package opened another door: the integration of three-dimensional anthropometric models with the dynamic human performance modeling tool of Micro Saint/HOS. Tools for anthropometric modeling of the human in his workplace have been in existence for almost two decades (e.g., Bonney and Schofield, 1971). Recent advances in computer technology, including low-cost, high-resolution displays, have increased the opportunity to use this approach. Furthermore, the increasing use of Computer-Aided Design (CAD) tools by the engineering community has made it even more imperative that human engineers also be able to use this type of CAD technology.

There has also been an increasing interest in linking anthropometric models to the dynamic aspects of human behavior, thereby creating an animation of the human figure (e.g., Badler, 1989). We believe that there are anthropometric models that contain hooks to facilitate this motion as a function of the tasks the humans are performing. However, the anthropometric models lack the means to predict changes in human geometry over time (i.e., movement) as a function of task performance. Task network modeling tools, such as Micro Saint, are good for simulating human task performance but they contain no clear link between Micro Saint tasks, body parts, and their location in three-dimensional space.

However, as part of our investigation into the concept of HOS objects during our Phase I effort, we concluded that this was an ideal means for linking task network-type models to anthropometric models. The anthropometric models need to know the location and orientation of critical human body parts. Objects in HOS can include human body parts. Attributes of these objects can include their location and orientation in three-dimensional space. Tasks can affect object attribute values. So, as a human moves his hand to adjust a switch, the object attribute values associated with the hand would be changed accordingly. We believe that, through these objects, we can directly link a task-oriented simulation tool, Micro Saint/HOS, to three-dimensional anthropometric models.

For example, the polyhedral figure presented in Figure 4 could be linked to a Micro Saint/HOS model. As the Micro Saint/HOS model executes, tasks would affect object attribute values. As those object's attribute values affecting body parts change, so would the anthropometric model. As the human reaches for a control, we could watch the figure move until it reached a position such as that presented in Figure 5. If we want to explore a change in task sequence or reallocation of tasks, we could simply change the Micro Saint/HOS model and watch the impact of this change on the animation of the anthropometric model.

THE STEPS TO BE FOLLOWED LINKING MICRO SAINT/HOS TO ANTHROPOMETRIC MODELS

Seeing this opportunity, the Army Research Institute funded integration as part of Micro Analysis and Design's Phase II SBIR effort, which began in June 1990.

Our approach for this augmentation of Micro Saint/HOS has the following four steps:

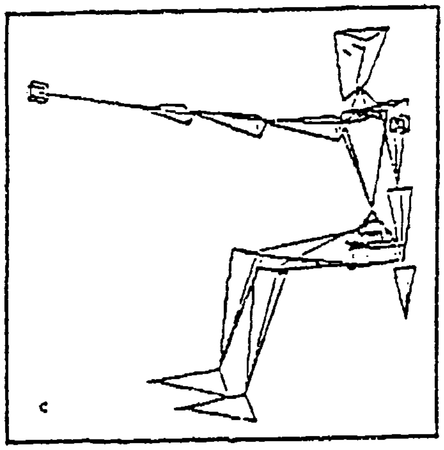
1. Determine the best candidate anthropometric model for linkage into Micro Saint/HOS.
2. Define parameters which must be passed between Micro Saint/HOS and the anthropometric model.
3. Add software to Micro Saint/HOS to permit passing of parameters.
4. Test and refine.

We will discuss each of these steps individually.

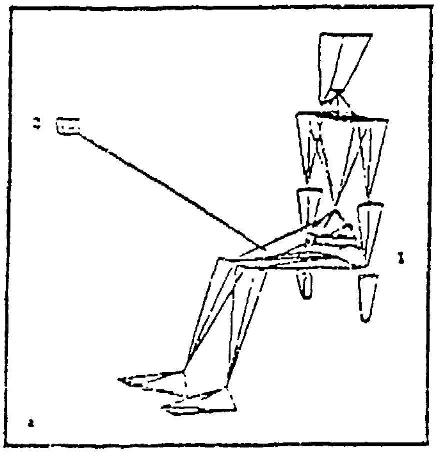
1. Determine the best candidate anthropometric model for linkage into Micro Saint/HOS. Several anthropometric models exist which are already candidates for integration with Micro Saint/HOS. The selection for integration will be based primarily on three factors: (a) the host hardware and software environment, (b) the availability of built-in hooks to external task simulation, and (c) freedom from proprietary encumbrances.

The host hardware and software environment of Micro Saint/HOS is UNIX/X windows. Our first choice would be to find an anthropometric modeling tool in this environment at this time.

Two candidates are models under development at the University of Pennsylvania (Badler, 1989), TEMPUS and JACK. Both of these models are UNIX-based and have been developed largely with government funding. More important, they were developed with specific consideration given to their use in human task animation. Currently, the graphical display of human anthropometrics in TEMPUS and JACK is mature, as are many of the essential constraining factors on human body movement, such as reach assessment, view assessment, collision and interference detection, and strength or reaction force assessment. What these models are currently lacking is an effective means of conveying high level task descriptions such as would be provided by Micro Saint/HOS, to quote Badler.



<u>Figure 4</u>. Sample Polyhedral Model of Human.



<u>Figure 5</u>. Movement of Anthropometric Model.

> An alternative source of task descriptions (that is needed by these models) is an external task simulation. For example, ... a helicopter mission is simulated by a planner, the tasks required of the helicopter pilot are output in a conventionalized format and transferred to the pilot model in JACK. (Badler, 1989, p. 385)

It would appear that Micro Saint/HOS is an excellent task simulation environment to provide that type of information to JACK and TEMPUS. In addition to simply task descriptions, the objects and their attributes in Micro Saint/HOS can be defined to conform to the "conventionalized format" discussed by Badler. We propose these models as the preliminary selections for integration with Micro Saint/HOS.

2. Define parameters which must be passed between Micro Saint/HOS and the anthropometric model. Once we select the anthropometric modeling tool which will be employed, we must determine the attributes which must pass between the dynamic task performance and anthropometric models. Most of the information flow will be from Micro Saint/HOS to the anthropometric model since there will be no task simulation inherent in the anthropometric model. Therefore, we must determine the parameters required by the anthropometric model to execute human animation. These parameters will then be represented as object attributes in Micro Saint/HOS.

We will determine the required parameters by reviewing documentation and meeting with software maintainers for the selected anthropometric modeling system.

3. Add software to Micro Saint/HOS to permit passing of parameters. The final step will be to add software to Micro Saint/HOS to dump the parameter values that are to be passed to the anthropometric model in a standardized format. Again, this format will be based on discussions with the software maintainers for the selected anthropometric modeling system.

At this point, full integration of the software for Micro Saint/HOS and the anthropometric modeling system into a single executable program may not be desirable for several reasons. First, it may require rehosting of the anthropometric modeling tool or Micro Saint/HOS. Second, the combined product, even if the software were effectively partitioned, may be larger than could be accommodated by the RAM available for the Micro Saint/HOS operating system. Finally, and most important, it is probably unnecessary. The only need to create a closed loop between the task model and the anthropometric model is to determine whether certain body movements or locations are feasible. The anthropometric model can check this feasibility and create a data file of "infeasible movement demands" without being on the same computational platform. The task model can be used to create a data set reflecting human body positions over time independently of the anthropometric model. Then, this data set can drive anthropometric model human motion. Since, except in cases of infeasible movement demands, the anthropometric model would not provide information back to the task model which would affect task model behavior, the integration of the software itself is not essential. Figure 6 presents a high-level description of the flow of data between Micro Saint/HOS and the anthropometric model.

We will attempt to create a single executable module if the above problems can be overcome. However, if a single executable integrated software module is not possible, other levels of integration will be pursued. If the animation software hardware environment is the same as Micro Saint/HOS, we will create software to facilitate the transfer of data between these applications. If the operating system is also the same, then we may create menu software which makes the transition between the Micro Saint/HOS task model and the anthropometric model relatively seamless.

4. Test and refine. Once we complete the modifications to the software, we will operationally test it with the anthropometric modeling system. During this testing, we will look for areas of improvement whereby more realistic human animations can be created. Changes will be implemented as allowed by available time and resources

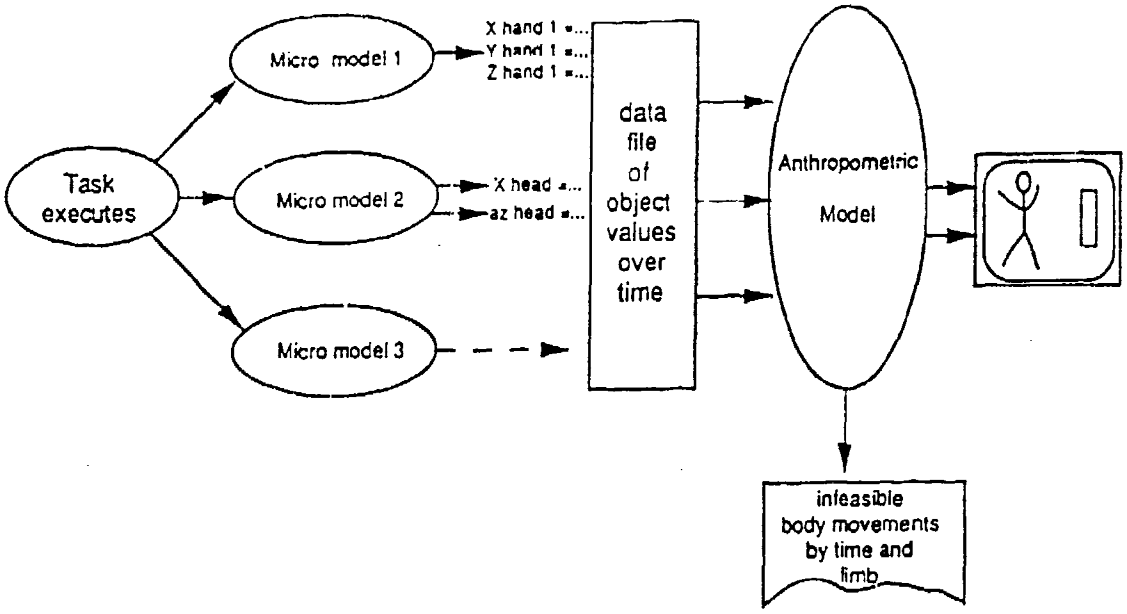


Figure 6. Data Flow Between Micro Saint/HOS and the Anthropometric Model.

SUMMARY

To summarize, our objective of this augmentation of Micro Saint/HOS will be to finally complete the bridge between the dynamic models of human performance, such as HOS and Micro Saint, and the graphically-based anthropometric models of the human. The integration of these technologies will, we believe, represent another step forward in the development of technology-based human-performance modeling systems.

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SYNTHESIZING THE EFFECTS OF MANPOWER, PERSONNEL, TRAINING, AND HUMAN ENGINEERING

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ABSTRACT

All human factors methods are attempts to understand systems in which human beings play a role. As such, the various human factors fields (human engineering, manpower, personnel, and training) and their methods should be able to relate to each other. However, typically this is not the case. Each piece of the human factors field provides analytically useful results, but it is in the synthesis of their outputs that significant meaning is found. The U.S. Army Research Institute (ARI) is developing a suite of methods based on relating the various human factors fields. This method is called HARDMAN III. This paper describes the HARDMAN III program's concept for this relationship.

INTRODUCTION

Organizations acquire *operational* hardware, software, and people to accomplish some desired operational ends. In this context, an end can be thought of some level of system or unit performance time and accuracy that is wanted by that organization.

Organizations acquire *maintenance* and *support* hardware, software, and people to allow the accomplishment of operational ends. Maintenance and support never have independent ends of their own. Their ends always are intermediate and lead to operational ends. Normally, these intermediate ends are described as levels of system Reliability, Availability, and Maintainability (RAM).

Human Factors, Manpower, Personnel, and Training (HMPT) dimensions of a system become significant by demonstrably linking them to operations and maintenance ends--performance time and accuracy, and Random Access Memory (RAM). Each of these dimensions is a different driver in the interaction of human operators and maintainers with system hardware and software. Therefore, to predict the results of adding a human operator or maintainer to such hardware and software, all these dimensions must come into play and their effects must be accumulated. Looking at any one of these HMPT dimensions by itself cannot result in an accurate prediction. Such a unidimensional approach is quite useful for isolating the cause of inadequate performance. However, the realistic identification of such performance requires that all the dimensions come into play at one time. Said in another way, analysis according to individual HMPT dimensions is a very useful tool for diagnosing the cause of inadequate performance or RAM, but the real predictive power of HMPT is in the synthesis of these dimensions. However, to synthesize HMPT dimensions, one should have a concept of what the HMPT data will support and the limitation of such synthesis.

One example of the HMPT synthesis approach is the HARDMAN III (HM3) program. HM3 consists of a number of linked, software-based HMPT prediction methods that run on personal computers. The overall purpose of this suite of methods is to improve the hardware and software design and acquisition processes by raising the probability that realistically available people will be able to operate and maintain hardware and software to acceptable levels.

Many of the HM3 methods are based upon user-friendly modelling. Three rules were followed to make modelling simpler for users:

1. Do not ask users for information they are very unlikely to have.
2. Orient methods to the solution of HMPT problems, not to modelling for its own sake.
3. Make the creation of models sufficiently simple that significant amounts of training are not needed.

Two approaches were provided to implement the first rule. When available to the method developers, libraries of data appropriate to methods were included. If data were unavailable, then the models were simplified so that they were not required. To implement the second rule, completely new, HMPT-oriented interface software was developed and modelling software was embedded. Two approaches were provided to implement the third rule. In the first approach, context-sensitive help screens, glossaries, and data source screens were developed for all methods. In the second approach, it was determined that potential users found it much easier to alter existing models into new models than to build new models from scratch. Therefore, real models were included to serve as both working examples and bases upon which new models could be constructed.

The following is a description of individual HM3 methods and how they interact to synthesize HMPT predictions in a meaningful way. A simplified, graphical representation of the interaction HM3 methods is provided as Figure 1.

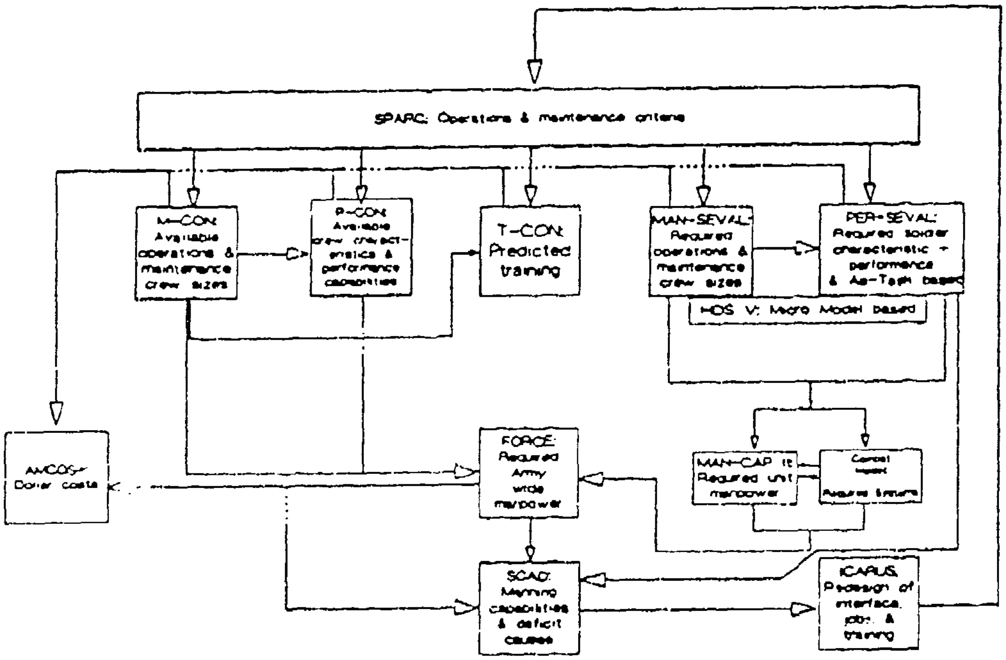

Figure 1. Simplified HM3 Interaction.

CONSTRAINING HARDWARE AND SOFTWARE DESIGN

To constrain hardware and software design, HM3 helps its users develop four general classes of information: (a) criteria, (b) available manpower numbers per system, (c) characteristics of available personnel, and (d) probable training.

Performance criteria are developed by using a relatively easy simulation modelling environment called the System Performance and RAM Criteria Aid (SPARC). SPARC contains operations item models of 21 classes of Army systems. The purpose of these models is to simplify the creation of new models by alteration, and by cutting and pasting across models. In these models, subfunction-level time and accuracy are combined to produce system mission-level predictions. The underlying assumption of SPARC is that design takes place at the subfunction level, but that it is the mission level of performance that gives those subfunctions meaning. Therefore, one can recognize a subfunction criterion because it leads to mission success.

Three methods for developing RAM criteria are provided. In the first method, a quick, spreadsheet aid is provided in SPARC. This method is developed at the subsystem level. In this method, the RAM relationships among subsystems are held constant, but the specific values alter as system-level numbers are changed. In the second method, RAM relationships are modelled for an individual item. The modeling is done at the component level. This method is resident in the Manpower-based System Evaluation Aid (MAN-SEVAL). In the third method, RAM relations are modelled at the unit level for units up to division. This method is resident in the Manpower Capabilities model (MANCAP II). In all three methods, data are provided to simplify the development of new models. The MAN-SEVAL and MANCAP methods were developed primarily to evaluate designs rather than set criteria, but they can be used for this purpose. They allow users to model the relationship between required manpower and system availability, reliability, and maintainability. They require detailed information about the system being modelled. This information is relatively easy to obtain as a function of the design process, but more difficult to obtain during criterion formulation.

Manpower availability, as distinct from requirements, is predicted by one of two methods. In the first method, the user accesses a data base of existing Army manpower and assumes that existing manpower availability will translate into future availability. In the second method, the user accesses a personal computer version of the Army Long Range Planning Model which predicts manpower availability into future years using a modified Markov Chain. Both methods are resident in the Manpower Constraints Aid (M-CON). Inherent in the first method is the notion that soldiers are quite similar to each other in terms of aptitudes. Therefore, if a smaller manpower pool is available, but you need just as many people, you accept people with lower aptitudes. This assumes no significant performance cost will result. Inherent in the second method is the notion that specified, existing soldier aptitude distributions are required by a level of performance or system availability. In this notion, it is preferable to have fewer soldiers who can operate or maintain a system to a specified level than to have more soldiers who cannot. In the second method, which uses the Army Long Range Planning Model as a predictor, the existing soldier aptitude distribution is held constant in the MOS being projected.

In the Personnel Constraints Aid (P-CON), personnel availability is predicted using two types of descriptors: (a) soldier characteristics and (b) task-level performance. The Army Long Range Planning Model is the mechanism for predicting soldier characteristics up to 20 years in the future. In P-CON, the Planning Model does not hold soldier characteristics distributions constant while varying MOS end strength, as it does in M-CON. In P-CON these distributions are allowed to vary while end strength of each MOS is fixed.

One of the classes of soldier characteristics predicted by the Planning Model is Armed Services Vocational Aptitude Battery (ASVAB) score distribution. The Army created the Project A Database to renormalize the ASVAB battery by comparing aptitude scores to performance, knowledge, and supervisor opinion scores. As part of the HM3 project, the hands-on task performance and aptitude data were extracted and regression analyses performed. As a result, P-CON can first predict the ASVAB distributions of available soldiers in a given MOS for some future year. Then it can take the resulting scores and use them as a basis for making task-level predictions for those available soldiers using the equations derived from the analysis of the Project A Database.

EVALUATING INDIVIDUAL SYSTEMS

Most military organizations view performance as a function of units rather than individual systems. From this point of view, HMPT dimensions are only important to the extent that they affect unit-level performance and availability. However, units are constructs of individual systems, and, except for command and control, it is the individual systems with which individual soldiers interact. Therefore, if one wants to make realistic unit-level predictions, and see the effects of HMPT on units, one first has to see these effects on the individual systems and then accumulate the system predictions to the unit level. It is at the system task and subtask levels that HMPT effects manifest themselves. One may describe unit-level performance from the top down, rather than accumulating task-level effects to predict systems and system-level effects to predict units. However, in this case, it is very likely that the HMPT effects will be lost in the reduced resolution of such prediction, and realism will suffer significantly. Therefore, HM3 supports bottom up evaluation from the individual system level.

To evaluate systems, HM3 provides two item-level methods to predict manpower, personnel, and field training requirements and system performance. Manpower requirements and the effects of varying manpower on system performance are dealt with by MAN-SEVAL. Personnel and field training requirements, and the performance and availability effects of varying personnel characteristics and field training are dealt with by the Personnel-based System Evaluation Aid (PER-SEVAL).

MAN-SEVAL consists of two manpower based methods: (a) the Maintenance Manpower Analysis Aid (MAMA), and (b) the Workload Analysis Aid (WAA). Both methods assume that personnel characteristics are "average" and are held constant. MAMA is used only for maintainer manpower predictions. WAA could be used for either operator or manpower, but its greatest use is for the former.

MAMA is an individual system-, or item-, level modelling-based method that runs from the component level. It comes with models for 21 classes of Army systems. The existing models can be used, altered, or pasted together by using a cut-and-paste facility. New models can be constructed by altering old models or building from scratch.

Each component of the system being evaluated is identified. Each component has reliability, maintenance time, MOS, maintenance level, and abort status data. The user sets up a scenario by describing the number of missions run, mission time, time between missions, number of rounds shot, miles traveled, and hours on. When the model is run, it predicts (a) achieved and inherent availability of the system; (b) man-hours required for maintenance per component, subsystem, MOS, and maintenance level; (c) maintenance ratio per subsystem; (d) reliability per subsystem; and (e) the distribution of required manpower per MOS at various maintenance levels. Since manpower and man-hours are associated with availability, it is possible to alter component reliabilities, task-level maintenance times per component, or the maximum maintenance crew size *available* per MOS and maintenance level, and see the effects on system availability.

This approach is based on the position that to predict the amount of manpower required to maintain a system, one has to understand the context of the word "required." The reason one maintains equipment is to use it. To use equipment, it must be capable of working and, thus, be available for use. It would be a good thing if all equipment were always available whenever one needed it, but this might require so many maintenance personnel that it would not be possible. This suggests that something less than an availability of 100 percent is cost effective and permitted. This means that the number of maintenance personnel required is driven by the required level of system availability.

MAMA predicts inherent and achieved, rather than operational, availability and does so for an individual system. This provides a method that runs in relatively short periods of time; thus allowing many runs and what-if scenarios. In addition, achieved and inherent availability are much more sensitive to differences in system design than is operational availability. Operational availability at the unit level takes account of all the major factors that influence system availability whether or not they are functions of the design. As such, operational availability is potentially a much more accurate predictor of reality. HM3's approach to operational availability will be described in the next section.

WAA is an individual system-, or item-, level method for determining operator workload. This workload can be used either to determine required numbers of operators, or to determine how to configure jobs so as to to keep overloads to a minimum. It is based on simulation modelling of individual systems. A given model generates a mission time line. That time line specifies how many tasks were being done by each member of a crew per unit time. If the user desires, he can use a version of the McCracken-Aldrich workload technique as part of WAA. In this case, the user inputs workload estimates per task for each of several channels (cognitive, motor, perceptual, etc.)

according to the McCracken-Aldrich scales and anchors. Then, when the model runs it generates the time line and accumulates the workload associated with the various tasks in the time line. If the user so desires he can use WAA as a pure time line generator that describes numbers of tasks per unit time, but eliminates McCracken-Aldrich workload. The user has the option of defining overload. If the user defines overload, he has the option of telling the method how to reallocate tasks in a high workload situation, automatically, or doing it manually.

PER-SEVAL brings the relationship between human differences and system performance to the evaluation of individual systems. It should be remembered that the MAN-SEVAL methods assume average personnel in each job. PER-SEVAL imports the MAMA and WAA models and, through the use of equations derived from the Ballistics Research Laboratory's AURA Model and the ARI Project A Database, allows users to ask new classes of questions of those models:

1. If average soldiers could not reach performance or availability requirements, what ASVAB levels would be required to do so?
2. If average soldiers are better than the system requires, what ASVAB levels would still result in mission or availability success?
3. What is the effect of changing CAT level(s) on system performance and on system availability?
4. If operators or maintainers had to perform their tasks with varying levels of field training under varying level of environmental stressors, what effect would it have on system performance or availability?
5. In terms of mission performance or availability, what are the trade-offs among soldier quality, field training, and the effects of environmental stressors?

MAN-SEVAL and PER-SEVAL are bottom up prediction methods with tasks at the bottom. For them to function, each of their tasks must have time and, in some cases, accuracy data. The purpose of both methods is to evaluate a manned system. Therefore, logic dictates that the task times and accuracies apply to that system. The problem is--Where do these data come from?

If the system is at the concept development stage, there is neither a prototype, nor a real design from which to extract the data. In this case, data could be obtained from, what are thought to be, similar systems' tasks, or from subject matter experts (SMEs). During and following the design phase, data could be obtained from the design itself. Once system hardware has been fabricated, data could be obtained from actual tests. However, for specific, critically important tasks, similar system data, SMEs, and design data may be inadequate.

There is always a question about the reliability and validity of pure SME input. The adequacy of similar system task data is dependent upon the level of similarity between the systems. When a task is critical and the level of similarity is low or, as is often the case, unknown, the risk of using these data may be too great. If one is evaluating a design, often the design provides task-level time and accuracy. However, these data are produced and sent through various levels of management by an organization that is trying to build the system in question. If specific tasks are highly critical to the overall performance or availability success of a design, it may be unsafe to use that design's time and accuracy data, for those tasks, without some mechanism for checking them. HM3 provides the Human Operator Simulations V (HOS V) component for this purpose.

The HM3 version of HOS V provides its user with a facility to model individual tasks down to the subtask and task element levels. A given task, subtask, or task element can then be loaded with time or accuracy data produced by one or more HOS Micro Models (MMs). HOS MMs are equations or factors that predict extremely small elements of performance, for example, hand movement time, head movement time, decision time, identification accuracy, etc. Typically HOS MMs are derived from the experimental psychology literature, but they can come from any source which resulted from this type of performance measurement. Usually, HOS MMs predict performance in relation to objects. There are interface, body part, and external target objects. Interface objects are individual controls or displays or their elements. For example, a switch is an object as is an individual symbol on a CRT. Objects have attributes used by MMs. Examples of attributes are location, color, size, etc.

In this way, detailed elements of the man-machine interface that apply to a specific, critical task can be modelled to produce a performance prediction, and that prediction can be sent to become task data in MAN-SEVAL or PER-SEVAL. The purpose of MAN-SEVAL and PER-SEVAL is to predict the relationship between variation in dimensions of manpower, personnel, field training, environmental stressors, and system performance. When MAN-SEVAL and PER-SEVAL data come from HOS V, the result is that interface design variation is added to this dimension list.

EVALUATING MULTIPLE SYSTEMS

With MAN-SEVAL and PER-SEVAL, one can determine the manpower and personnel required by one system. However, when evaluating design one wants to determine the total required manpower for those individuals with the required personnel characteristics.

In the case of system operations, if one system requires a crew of three, all else being equal, 10 systems will require 30 operators. Unfortunately, the additive assumption does not hold for maintainers, so that one cannot assume that if one system requires five maintainers, 10 systems would require 50. To go from a prediction of required maintenance manpower for one system to a total prediction, one has to predict first at an appropriate unit level. When unit requirements have been predicted, it is possible to use the additive assumption across units.

HM3's method for predicting unit requirements is the Manpower Capabilities model (MANCAP II). MANCAP is a hybrid method that uses simulation modelling to predict required maintenance manpower and resulting operational availability, and standard factors that relate to maintenance hours to predict required supervisory and support personnel. MANCAP also has the capability to predict maintenance manpower requirements resulting from combat damage of systems under varying combat intensities. MANCAP can model unit manpower requirements for any size unit up to division level.

MANCAP uses the MAMA component of MAN-SEVAL as a preprocessor. MAMA is run at the component level for an individual system. This generates a table of component and subsystem failure probabilities plus associated maintenance data per component. These data include MOS and maintenance task times per maintenance level.

MANCAP runs at the system level. When a system is predicted to require RAM-caused maintenance, the subsystem and component and related maintenance data are determined from the MAMA output. MANCAP includes a combat damage generator that predicts the probabilities of component damage in varying levels of combat intensity. When a component is predicted to have sustained combat damage that requires maintenance, the associated maintenance data per component, including task times, are determined from MAMA output. In addition, MANCAP is capable of reading maintenance task times from PER-SEVAL. These task times will have been predicted according to differences in personnel characteristics, environmental stressors, and field training. Thus, MANCAP can make predictions of unit manpower requirements considering varying aptitudes of personnel, under varying environmental stressors, and following varying field training.

MANCAP is able to predict the relationship between maintenance manpower and system availability taking the the PER SEVAL dimensions into account and trading off among them.

Further, it should be remembered that MAN-SEVAL and PER-SEVAL can both use HOS V task-level predictions which take account of interface design variation. Since MANCAP reads from MAN-SEVAL and PER-SEVAL, its predictions can include the effects of maintenance interface design on the prediction of the relationship between manpower, personnel, and system availability.

MANCAP deals with operations personnel through a spreadsheet model. Thus, if four people are required to crew a tank, and a unit had 100 tanks, the number of people required would be 400 people plus additional people predicted by factors for the effects of illness, injury, shifts, being in training, etc. Since MANCAP assumes the user inputs some number of tanks, the problem of required operations manpower is relatively trivial. However, much more significant questions are:

1. If you knew the performance of one manned system, with soldiers of specified characteristics and field training, how many such systems would you need to win a battle?
2. If you altered the characteristics or field training of soldiers who crew existing systems, would you be able to reduce the number required?

Such questions require a combat model that either is sensitive to personnel and training variations or accepts inputs from item models, such as PER-SEVAL, that are themselves sensitive to these variations. As part of the HM3 program, this possibility is being studied.

Once one knows the number of operators and maintainers required by a system at the unit level, it becomes possible to use a form of additive method to determine the force or Army-wide requirements. The HM3 method for accumulating unit-level manpower and personnel requirements into Army-wide requirements is FORCE.

FORCE users are given information as to the units in which predecessor systems are located and the number of systems per unit. This information is extracted from one of the M-CON data files. Assuming that some units have different numbers of systems than the unit originally modelled in MANCAP, the FORCE user is given the choice to revise the initial model or to use multiplicative factors on the output generated by the initial run of that model. This procedure continues until manpower and personnel requirements of the system for all units of interest are computed. FORCE then adds the result producing an Army-wide requirement for the system.

It should be remembered that FORCE's Army-wide, or force-wide, predictions are based on input from MANCAP. MANCAP's unit level predictions are based on input from MAN-SEVAL and PER-SEVAL. MAN-SEVAL and PER-SEVAL can have input from HOS V. Thus FORCE's Army-wide predictions for total required manpower can take into account: (a) personnel characteristics, (b) field training, (c) environmental stressors, and (d) interface design for high driving tasks. Further, its maintenance manpower requirements are based on computing the relationship to a required level of system operational availability taking these HMPT dimensions into account.

IDENTIFYING THE PROBLEM AND CLOSING THE LOOP

With FORCE, one can identify the total manpower and personnel required by a system design. The next logical system evaluation issue is: Will we have access to that required number of personnel with those required characteristics in the years of system fielding? This issue is dealt with by the HM3 method called the Soldier Characteristics Availability Data method (SCAD).

SCAD will receive manpower requirements numbers, MOS, and associated required ASVAB data from FORCE. One should remember that the M-CON and P-CON versions of the Army Long Range Planning Model predict the available numbers of soldiers with various ASVAB levels in each MOS up to 20 years into the future. SCAD will read the required MOS data it receives from FORCE and run the Long-Range Planning Model for those MOS for a year entered by the user. It will compare the required numbers with the required ASVAB scores to the available numbers of people with or above those scores. If an adequate number of people with required characteristics are predicted to be available, manning should not be a problem. The problem arises when the prediction is for a manpower shortfall.

When SCAD predicts a manpower shortfall, that does not mean that there will not be enough people available in a given year to man a system. It means there will not be enough people with the required characteristics to man that system. Therefore, if there were such a shortfall, it would be for one or more of those required characteristics. It should be remembered that the relationship between operations and maintenance tasks, and personnel characteristics will have been developed in PER-SEVAL. Therefore, once SCAD identifies the personnel characteristics (and their levels) that produced the predicted manpower shortfall, it will access the appropriate PER-SEVAL file to identify the system tasks that required those characteristics at or above those levels. When a SCAD analysis is complete, it will output:

1. The relationship between required and available soldier manpower per MOS taking characteristics into account.
2. The aptitudes and their levels that caused any shortfall.
3. The system design tasks that required the shortfall producing characteristics.

If a shortfall is predicted, one knows what system tasks were responsible for it and what personnel characteristics are required by those tasks, but are in short supply. If one alters those tasks in the appropriate way, it may become possible to eliminate the predicted shortfall. In HM3, the Integrated Characteristics and Availability Redesign Utility System (ICARUS), aids its users in making these alterations.

When a shortfall occurs, ICARUS imports a file from SCAD that describes that shortfall, the high driving personnel characteristics and their levels, and the system operations and maintenance tasks that required those characteristics at those levels ICARUS offers the user individual or combinations of approaches to alleviate the shortfall by:

1. Allocating the task to another MOS, with a higher aptitude distribution, that will be part of the system's crew and will be available in the required numbers.
2. Identifying sources of personnel with the required aptitude levels in other MOS and reassigning them to the MOS with the deficit.
3. Allocating the task to a computer.
4. Eliminating the task.
5. Restructuring the job in which the task is done.
6. Altering the personnel intake and career pipeline structure to make more personnel with the required characteristics available in the years needed.
7. In the case of maintenance tasks only, raising the reliability of the component associated with the task.
8. In the case of maintenance tasks only, improving the resistance of the component associated with the task to enemy fire.
9. In the case of maintenance tasks only, altering the operations scenario to reduce the breakage of components associated with the task.
10. Increasing field training for the task.
11. Reducing environmental stress on the crew member doing the task.
12. Altering the interface design that applies to that task, thus reducing its personnel requirements. This alternative is made simpler by being able to identify the specific soldier characteristic(s) that are heavily stressed by the interface design that applies to the task.

Once an approach or combination of approaches has been determined, ICARUS will route the user to the appropriate HM3 method. Each approach can be tried and tested in one or more of the HM3 methods. For example, the user can search for MOS with the required characteristics and restructure the personnel pipeline in M-CON and P-CON. The user can reallocate tasks, restructure jobs, change the operations scenario, and change the characteristics of components in MAN-SEVAL and MANCAP. The user can increase field training, alter soldier characteristics, and reduce environmental stress in PER-SEVAL. The user can alter the interface design in HOS V.

Thus, ICARUS makes HM3 a closed-loop HMPT evaluation method. Design constraint information is developed and given to system designers. A concept, design, or prototype is developed. It is evaluated using HM3. A shortfall of manpower with required characteristics is predicted. The high driving tasks and deficit personnel characteristics that caused the deficit are identified. Alternative individual and combinations of HMPT fixes are suggested. Fixes are tried in the HM3 simulations. The fixes are evaluated. This loop continues until fixes result in predicted success, or it becomes evident that no successful combination of fixes is possible.

At this point, HM3 questions the dollar cost of the HMPT portions of the original system and its various alternative fixes, if they are required. This will be done using an enhanced version of the Army Manpower Cost model (AMCOS). The enhanced AMCOS will read the files from the various HM3 methods that describe numbers and type of required soldiers, training, and interface design alterations plus the years in which the system is to be fielded and the number of systems. It will predict the dollar costs including assumptions for inflation. If more than one alternative fix would be successful, users can use this information to do cost-benefit trade-offs among candidate fixes.

FALLOUT FROM SYNTHESIS OF HMPT

When the HM3 project began, the general HMPT problem facing the Army was difficulty in getting enough of the right kind of people to operate and maintain weapon systems to appropriate levels. Now, other HMPT problems have arisen as a function of shrinking forces and budgets, but the flexibility afforded by the synthesis approach in HM3 allows these new problems to be dealt with by the existing methods.

One of the major problems now is--How can you reduce the force without destroying its effectiveness? This appears to be the opposite of the previous problem. In reality, it is another version of the underlying problem that is common to both--What is the relationship between performance and the synthesis of HMPT dimension effects?

An example of the application of HM3's synthesis approach to this problem is as follows. One can use M-CON and P-CON to predict the reduced numbers and resulting characteristics of personnel who will be available due to changing Army accession policy. One can model the operations and maintenance of the individual system of interest in MAN- SEVAL. One can study the system-level effects of the reduced operator and maintainer crews on performance and achieved availability based on average soldiers in the various MOS. If the reduced crews produce unacceptably reduced performance or availability, one can import the models to PER-SEVAL. In PER-SEVAL one can study the effects of assigning soldiers with higher aptitudes, more field training, or reduced environmental stress to these reduced crews. If the results continue to be inadequate, one can take individual, inadequately performed operations or maintenance tasks and import them to HOS V. In HOS V, one can study whether operations or maintenance interface improvements would allow the reduced crews to perform the tasks significantly better. If this turned out to be the case, one could rerun the operations and maintenance system models to see if the task-level improvement made a meaningful weapon system-level improvement with the reduced crew.

Once it appeared that the individual system could be operated or maintained adequately with the reduced crew, the effects of this on unit-level operations or maintenance would be studied. Operations effects of the reduced crew on unit-level performance could be studied by importing the PER-SEVAL output to an existing operations combat model. Maintenance effects could be studied by MANCAP in either of two ways.

In the first way, MANCAP could be run with the user varying manpower numbers needed to reach required system availability, as was described earlier. These manpower and personnel requirements could be run through FORCE to produce the required Army-wide number, and then through SCAD to compare requirements with soldier availability. If the first stage of fixes, made in MAN-SEVAL, PER-SEVAL, and HOS V were adequate, there will be enough people available. However, it is possible that when the individual system effects are accumulated to the unit level, manpower will be inadequate and will have to be raised. At this point, SCAD will describe a manpower shortfall since there will be a reduced number of available soldiers. It will send this information plus the design tasks and high driving soldier characteristics to ICARUS which will offer alternative paths to fix this shortfall.

In the second way, the MANCAP user could enter the unit-level maintenance manpower that will be available in reduced circumstances. In this approach, manpower would become a fixed dimension in the analysis. If system availability were unacceptably low with reduced manpower, the user could immediately apply the various HMPT approaches to raising the performance effectiveness of individual soldiers in MAN-SEVAL, PER-SEVAL, and HOS V. The outputs of these approaches could then be read in another MANCAP run.

The underlying problem dealt with in HM3 is the relationship between performance and the synthesis of the effects of HMPT dimensions. Each of the HMPT dimensions appears to be quite different from the others, and, therefore, to have different problems However, the importance of each dimension lies in its effect on task performance, and the importance of task performance lies in its effect on mission performance and RAM. Once this underlying problem can be dealt with, the apparently different problems of each of the HMPT dimensions can be resolved. In this way, the power of HMPT synthesis can be brought to bear.

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LESSONS LEARNED IMPLEMENTING CREW CHIEF

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Abstract

McDonnell Aircraft was used as a beta test site for the system-independent version of Crew Chief and has since installed the first production release of Crew Chief. Crew Chief has served as a design tool for Advanced F-18, used as a data base for tool creation, and its mannequin data have been used as input to a human animation project funded by the Air Force Human Resources Laboratory. With the variety of implementations of Crew Chief, McDonnell Douglas has compiled a list of lessons learned. These lessons include (a) installing Air Force software into production systems, (b) the complexity of graphic simulation of human modeling, (c) the need for a validated human modeling tool for it to be useful, and (d) some improvements that could be made to Crew Chief to make it a more useful tool. Based on these lessons learned, recommendations are provided on what a good human modeling system should entail.

The Harry G. Armstrong Aerospace Medical Research Laboratory (AAMRL) and the Air Force Human Resources Laboratory (AFHRL) of Wright-Patterson Air Force Base, in conjunction with the University of Dayton Research Institute (UDRI), have developed Crew Chief. Crew Chief is a suite of programs that allows assessment of a system's maintainability through the interaction of a computer graphics simulation of the physical characteristics and capabilities of a maintenance technician. McDonnell Aircraft Company served as a beta test site for Crew Chief and has installed the first production release onto our proprietary Computer-Aided Design Drafting (CADD) system.

BACKGROUND OF CREW CHIEF

The Crew Chief programs have many good features and can help a user answer maintenance questions while at a graphics terminal. Once a user has identified a task to be performed, he can run the specific task in Crew Chief and obtain information such as the following:

1. Can a technician perform the task at the specific percentile and specific posture?
2. Did the technician collide with any part of the Computer-Aided Design (CAD) model, and if so, where?
3. Is there anything obstructing the technician's view?

Crew Chief provides the user a choice of five percentile body sizes (1%, 5%, 50%, 95%, and 99%) for each gender (see Figure 1), four types of clothing, and 12 initial present postures. Crew Chief was designed so that it can be implemented on various CAD systems.

The types of programs available in Crew Chief are (a) Vision Analysis, (b) Accessibility Analysis, and (c) Maintenance Task Analysis. The Visibility Analysis program plots the limits of visual acuity and the azimuth and elevation angles of a Crew Chief technician. Vision analysis can be invoked from either Crew Chief's point of view or from a user-defined point of view. The Accessibility Analysis function can detect interference between the Crew Chief man-model and the elements of the CAD drawing.

Maintenance Task Analysis consists of three functions: (a) Tool Analysis, (b) Manual Material Handling Analysis, and (c) Connector Analysis. The Tool Analysis function allows a user to evaluate the ability of a technician to reach for a specific point with a tool while in a given posture. Crew Chief provides the user with the selection of 105 different tools. The Manual Material Handling Analysis function allows a technician to evaluate the ability to carry, lift, hold, pull, push, and reach an object. The Connector Analysis function is similar to Tool Analysis, except that it uses a connector instead of a tool.

IMPLEMENTATIONS OF CREW CHIEF

The McDonnell Aircraft Advanced F/A-18 program was the first user of Crew Chief at McDonnell Aircraft. They found Crew Chief to be quite helpful in their analyses. The following are some comments from a user on the Advanced F/A-18: "Crew Chief provided the design engineers with a good perspective on possible maintainer positions in relation to the various work areas around the aircraft. It was useful to have a means of providing a pictorial representation when discussing accessibility problems and solutions." Some other remarks worth noting are comments concerning the ease of use of Crew Chief. "The menus were straightforward enough that a user could become competent enough to use Crew Chief in design evaluations with minimal training. The only prerequisite to using Crew Chief would be a basic understanding of the CAD system that is implementing Crew Chief." The menus mentioned are really interface menus developed at McDonnell Aircraft for Crew Chief, but credit must also go to the Crew Chief developers as they provided customers the ability to develop a good user- friendly interface.

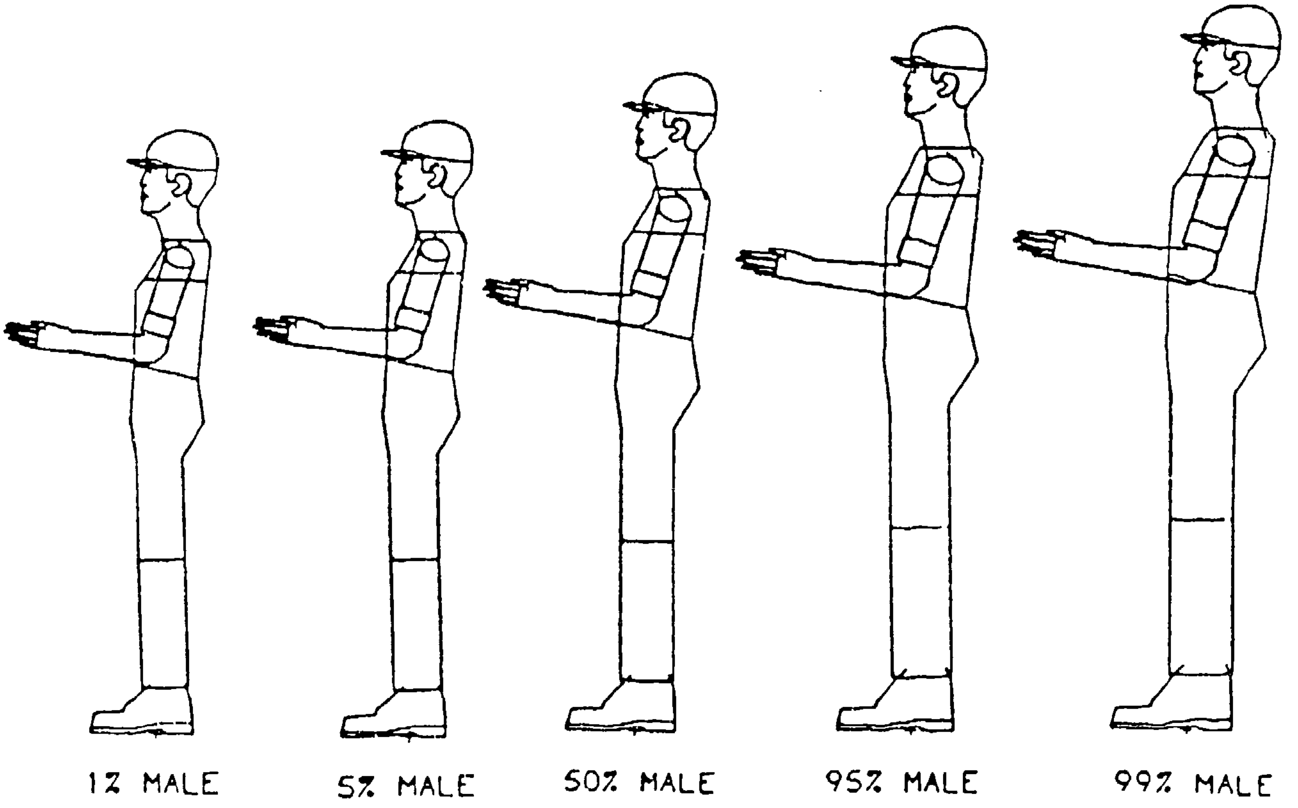

Figure 1. Pictorial Representation of Crew Chief's Five Percentile Body Sizes.

Though they were pleased with Crew Chief, they found Crew Chief too limiting in certain situations. For example, they could not use Crew Chief to determine if a design was absolutely acceptable or unacceptable because the Crew Chief model has not been validated. This is a serious problem with Crew Chief because it limits its usefulness. It would be advantageous if Crew Chief or some other human modeling tool could attain the level of usefulness that Crew Chief has and also be validated. It will be difficult to promote a human modeling tool until this occurs.

The Advanced F/A-18 program also identified other limitations with Crew Chief. Presently, it limits the user to the creation of one mannequin at a time. They need to display two mannequins on the graphics screen since most maintenance tasks usually require two technicians. Having two technicians performing a task would also require the program to provide strength data for a two-person task. They would also like to have the ability to create bivarient mannequins. For example, they may want to select a mannequin that has a 50 percentile torso and 95 percentile arms and legs. Crew Chief only allows the user to use one of the five standard percentile mannequins from either gender.

Another limitation is the inability to modify the posture of the Crew Chief mannequin. For example, after a user has selected a specific task to perform, he notices that the technician's shoulder is interfering with an element of the CAD drawing. The user knows from experience that a technician should be able to perform the task without interfering with anything; so to demonstrate this, he would like to lower the shoulder a few inches so that he can verify that the task can be performed without any interference. Currently, this cannot be done with the Crew Chief programs.

The Crew Chief programs require a large amount of memory to execute. We have encountered problems running Crew Chief because of its size. Users are having to delete sizeable portions of their CAD drawing so that they can run Crew Chief. Typically, a user identifies the area in the CAD drawing of interest and then deletes all nonrelated areas of the drawing. The user is then able to execute the Crew Chief programs. The time required to perform this outweighs the advantages achieved with using Crew Chief. An alternate solution to this problem has been to disable some of the Crew Chief programs that users are not interested in. For example, the Advanced F/A-18 users had no desire to run Vision Analysis; therefore, this program was disabled and they were then able to run Crew Chief with their large CAD models. Admittedly, the CADD system that McDonnell Aircraft uses is quite large and does contribute to this size problem. Additionally, we implemented Crew Chief a little differently than the Crew Chief developers envisioned. They run each Crew Chief program as a separate module, whereas we combined all the programs to create one large module. This was necessary to integrate Crew Chief in our CADD system.

Another feature that Crew Chief offers is that when exiting Crew Chief, the current Crew Chief mannequin displayed is saved in an external file. The next time the Crew Chief programs are executed, the user can regenerate this mannequin and it will be displayed in the exact location and in the same posture as it was during the last Crew Chief session. Comments from our Advanced F/A-18 users were that it would be nice to have the ability to save multiple versions of Crew Chief postures. This would save them time as it would give them the ability to retrieve these different examples for future reference without having to duplicate the effort.

Douglas Aircraft Company participated in a Maintenance and Ergonomic Modeling project, and a portion of this project was to develop a hand/tool modeling capability to enable the simulated maintainer to grasp, position, and apply a hand tool. The second implementation of Crew Chief was to extract all the tools from the Crew Chief data base for this project. Crew Chief was not designed for this type of an implementation, and therefore, it was cumbersome to extract the tools from the data base. This tool information is valuable and could be more of an asset if Crew Chief could be modified so that it would be easier to retrieve the tools from the data base. Another option would be to make the source code available for Crew Chief so that individuals needing access to the tools could provide their own interface.

The last implementation of Crew Chief was a proof of concept program funded by AFHRL called Turnaround and Reconfiguration Simulation Extension (TARSE). TARSE demonstrated animation, collision detection, and human factors analysis. For this program, the Crew Chief mannequin data were used. With assistance from UDRI, we were able to obtain the data of a 50% Crew Chief mannequin with its link system. The Crew Chief Vision Analysis program was also used for the TARSE program.

TARSE was not able to take advantage of all the potential benefits that Crew Chief offers. TARSE could not use the Crew Chief joint limit programs and the enfleshment programs because the algorithms for these programs are embedded in the source code of Crew Chief. Both of these had to be developed because the source code for Crew Chief is not available. TARSE also ran into size problems while implementing the Vision Analysis. A separate module had to be created to run Vision Analysis.

Supplying source code to the customer does pose an interesting question. If the man-modeling data are embedded into the source code (as Crew Chief's are), is the validation of the man-model jeopardized or destroyed if the source code is distributed to each customer? If so, these type of data should not be embedded into the source code. A possible alternative to providing source code would be for Crew Chief to provide a lower level of functionality than is currently available to the customer. This would allow the users of Crew Chief to have more control of the programs by calling low-level routines. For example, let us look at extracting a tool. To obtain the data of a tool, one has to run the Crew Chief Tool Analysis program and it will display the mannequin along with the tool. In the suggested lower-level approach, one might call a specific Crew Chief routine with the argument of a certain tool and get back the coordinates of the tool. The user of the system can then do whatever he wants to do with the data, such as displaying the tool or storing the tool data in an external file. The same type of approach could apply to obtain joint limit data or enfleshment information.

LESSONS LEARNED IMPLEMENTING ROBOTICS SOFTWARE FOR ANIMATION

The BUILD and PLACE robotics programs, developed by McDonnell Douglas Systems Integration, were used for the animation portion of TARSE. BUILD enables the user to quickly describe new robots in high-level terms. Using BUILD, the geometric model of a robot or a device is automatically combined with its unique kinematic (motion) description for animation in PLACE. The data output files from BUILD eliminate the need to perform custom kinematic analysis. PLACE is designed to create, analyze, and modify robots and associated data. PLACE determines if required motions can be accomplished by the robot.

A few problems were encountered using robotics software for animation. This software is limited to one degree of freedom (DOF) joints. These joints were chained to give the appearance of two DOF or three DOF joints. A human animation system requires true two DOF and three DOF joints. Systems which have only one DOF or "chained" one DOF joints may produce realistic looking movements in some cases, but in general they do not resemble movement of people. Also, joint limit checking in the one DOF systems cannot be implemented in a straightforward manner. The "chained" one DOF joints must be combined into two DOF or three DOF joints before joint limit checking can be performed.

The mannequin hierarchy for TARSE was developed by creating a robot for each joint and then chaining them together to create the mannequin. While creating the mannequin hierarchy, several possible solutions were tested in an attempt to find the best base location for the mannequin hierarchy. While investigating different base locations, it was discovered that the base of the system should change as the mannequin changes position. For example, when walking, one foot should be the base for the first part of the step while the other foot should be the base for the second part of the step.

The TARSE animation was created by interactively positioning each degree of freedom for each moving limb. This required a great deal of time. Future animation systems should incorporate a higher level of automation so that the user does not have to explicitly define each joint/angle position.

The use of available robotics software as an animation driver is quite poor with respect to anthropometric correctness. That is, robots do not move like people. Joint ranges are very dynamic and in many cases are dependent upon locations of other joints to determine the full range of the joint in question. Human modeling systems implementing animation must employ multiple degrees of freedom.

WHAT ARE THE ELEMENTS OF A GOOD HUMAN MODELING SYSTEM?

By taking a look at the different implementations of Crew Chief at McDonnell Aircraft, some lessons have been learned and characteristics of a good human modeling system have been identified. The following list summarizes these characteristics:

1. The most important quality of a human modeling system is that it must be validated. Otherwise, it is not a cost-effective way to analyze a maintenance activity or a design drawing.

2. The system should also be able to run on multiple platforms. McDonnell Aircraft has another potential user for Crew Chief, but they require a VAX-based version of Crew Chief. This is not currently available. To avoid situations like this, portability must be an essential component of a human modeling system. This is especially true today since the industry is moving toward an open systems environment.

3. Human modeling users need the ability to manipulate the mannequin size for their specific needs. They should not be constrained by a limited selection of postures and percentiles.

4. Human modeling systems should have the ability to use more than one mannequin for their analyses.

5. A useful feature for a human modeling system would be to allow for users to use selected parts of the mannequin. For example, a user may only be concerned with the arms of the mannequin and does not want to deal with other parts of the body. With this feature, the user should also have the ability to position the body part(s) in the location that he desires.

6. Animation is an important element in human modeling. Crew Chief does an excellent job demonstrating the starting and ending positions of a task, but there is a need to visually verify that the task can be performed. There may be obstructions that may interfere with the man-model or perhaps the man-model would have to perform some movement that would cause one or more joints to go out of range. Neither of the items would be obvious to the user since his only point of reference is the starting and ending points.

7. As with most systems, the program must be easy to use and have a quick turnaround time. A system that requires a great deal of time to set up and evaluate a task, or that takes a significant time to process the information cannot be a candidate for a useful system.

8. Shading would be a desired component in a human modeling system since it is often very difficult to differentiate parts of a complex wire-frame CAD drawing.

9. The provision of source code can help customers of human modeling systems get the maximum use of the functionality available. It can also help in developing a good interface between their CAD system and the human modeling system.

10. Other functions that should be provided are (a) collision detection, (b) obstacle avoidance, (c) strength analysis, (d) vision analysis, (e) tool analysis, and (f) maintenance tasks analysis.

CONCLUSION

Crew Chief is a good human modeling analysis tool. Its structure is modular, allowing each program (Vision Analysis, Tool Analysis, etc.) to run independently. Crew Chief is fairly easy to implement on CAD systems. Users felt the response time to calculate an answer was satisfactory. As stated above, Crew Chief is helpful in that it provides a pictorial representation of accessibility problems. Crew Chief is a good starting point, but it needs to be expanded to include the items discussed above.

The most important of these items are (a) a validated man-model, (b) portability, (c) flexibility to modify the mannequin, and (d) animation. A validated man-model is very important. Providing this capability will allow the human modeling system to cross the threshold from being a "good" human modeling system to a "useful" human modeling system. Animation is an important element for a human modeling system because users want to visualize the man-model performing the task; a starting position and an ending position of a task are not sufficient. The system must allow users to interact with the man-model, that is, they must be able to modify the mannequin, whether it be its posture, location, or orientation. Last, portability is an essential element in a human modeling system. Since we are moving into an era where customers are demanding open systems architecture, we must have a system that is platform independent.

A special note concerning Crew Chief: The comments referring to Crew Chief are for Release 1.0 of the System Independent version of Crew Chief. Future release of Crew Chief may have resolved some of the shortfalls mentioned in this paper.

COMPUTER-AIDED ACQUISITION AND LOGISTIC SUPPORT - HUMAN SYSTEM COMPONENTS (CALS-HSC)

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ABSTRACT

Computer-aided Acquisition and Logistic Support (CALS) is a Deparment of Defense (DoD) and industry initiative to transition the paper-intensive acquisition and logistic processes to a highly automated and integrated mode of operation for the weapon systems of the 1990s and beyond. CALS addresses the generation, access, management, maintenance, distribution, and use of technical data in digital form in the design, manufactur , and support of weapon systems, including ships and military equipment. These include the technical data related to the human system components (HSC)—i.e., the data on manpower, personnel, training, safety, health hazard prevention, and human factors engineering. This paper deals with the human system components of computer-aided acquisition and logistic support (CALS-HSC).

INTRODUCTION[1]

In September 1985, the Deputy Secretary of Defense issued a statement to the Secretaries of the military departments approving recommendations of a DoD-Industry Task Force on CALS. The recommendations were designed to achieve major improvements in supportable weapon system design, and to improve the accuracy, timeliness, and use of technical information.

A strategy was initiated to effect these improvements and to transition from the current paper-intensive weapon system design, manufacture, and support processes to a largely automated and integrated mode of operation. All component elements of the entire DoD were directed to establish plans to acquire, process, and use technical information in digital form, and to begin to develop CALS-compatible acquisition strategies for all major weapon system new starts, developments, and modifications.

In August 1988, the Deputy Secretary of Defense issued another memorandum to the Secretaries of the military departments stating that major steps had been taken towards routine contractual implementation of CALS throughout the DoD and Industry. The memorandum upheld the issuance of CALS military standards for digital data delivery and access, and it required that an option for access to, or delivery of, technical data in digital form, be provided in each weapon system entering development during Fiscal Year 1989 and beyond.

THE CALS CONCEPT: EVOLUTIONARY DEVELOPMENT

The concept of CALS development is to evolve the desired digital data and data bases from the paper-intensive processes that are currently employed. The evolution is to continue until it has produced a highly automated CALS capability that integrates fully the weapon system acquisition and logistic support processes. These processes include activities in three domains—engineering, manufacturing, and logistic support. Specifically,

Engineering:	Analysis, Design, Test and Evaluation.
Manufacturing:	Tooling, Material, and Process.
Logistic Support:	Maintenance, Modification, Provisioning, Reprocurement, Spares and Support Equipment Ordering, Supportability Analysis, Technical Manuals, and Training.

In addition, the training activity has been designated (and is understood in the listing) to connote all human system components (HSC) and their integration (manpower, personnel, training, safety, health hazard prevention, and human factors engineering).[2] The CALS-HSC evolutionary path is represented within the same conceptual frame as that of the overall CALS initiative—namely, as a progression from the current paper flow state, through an intermediate digital flow stage, to a final integrated and shared-data state.

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[1] Based in part on an undated brochure on *Computer-aided Acquisition & Logistic Support* (CALS), published by the Office of the Secretary of Defense, Washington DC 20301.

[2] See DoD Directive 5000.53, "Manpower, Personnel, Training, and Safety (MPTS) in the Defense System Acquisition Process," December 30, 1988. See also DoD Instruction 5000.2 (Draft), "Defense Acquisition Management Policies and Procedures," which will supercede DoD Directive 5000.53. It includes specific guidance on Human System Integration.

Examples of the sorts of HSC paper-flow data required in the current acquisition process include those necessary for conformity with the relevant Military Standards[3] and Specifications[4] as well as specific inputs at each of the Defense Acquisition Board (DAB) milestone reviews (0 though V).[5] Existing HSC information and data, some of which are already in digital form, include the many manpower, personnel, and training records and data bases used and maintained by the separate Military Departments and Services, the Defense Manpower Data Center (DMDC), and the Defense Training and Performance Data Center (TPDC). Although administered as parts of the Defense Logistics Agency (DLA), both DMDC and TPDC report to and receive guidance from the Assistant Secretary of Defense for Force Management and Personnel.

Among the analytic models or tools that are currently used in resolving HSC issues are the following:

Manpower:	Logistics Composite Model (LCOM)
	Authorization Projection Model (APM)
	Manpower Standards Development System (MSDS)
Training:	Instructional Systems Development (ISD)
	Training System for Maintenance (TRANSFORM)
	Training Analysis Support Computer System (TASCS)
Design and Safety:	Crew Chief (CC)
	COMputerized BIomechanical MAN-Model (COMBIMAN)
Costing:	Life Cycle Cost Models (LCC-2, LCC-2A, LCCH)
	Logistics Support Cost Model (LSC)
	Cost Oriented Resource Estimating Model (CORE, ZCORE)
Logistic Support:	Logistics Support Analysis (LSA)
	Logistics Support Analysis Record (LSAR)

Thus, for some years now, CALS-HSC has progressed by converting from paper to digital-flow data, data bases, and analyses. Integration efforts have begun, both among the HSC elements themselves and between them and other components of the CALS initiative. Of all the CALS-HSC constituents, the logistics support area of training has progressed most, especially in the post-system design phase of training system development.

In accordance with the overall plan, the focus of CALS-HSC development is to broaden beginning in Fiscal Year 1991. It will go beyond its past near-exclusive concentration on training and post-system design issues to emphasize coverage of all HSC constituents and their integration with other CALS components at earlier stages in the system design and development cycle. Thus, it will stress more aggressively the progress to be made towards the CALS and CALS-HSC goals.

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[3] For example: Military Standard No. 882B, "System Safety Program Requirements," No. 1379B, "Contract Training Programs;" No. 1388-1A, "Logistics Support Analysis;" No. 1388-2A, "Logistics Support Analysis Record;" No. 1472C, "Human Engineering Design Criteria for Military Systems, Equipment and Facilities," and No. 1474B, "Noise Limits."

[4] For example: Military Specification No. T-23991, "General Specifications for Military Training Devices," and No. H-46855, "Human Engineering Requirements for Military Systems, Equipment and Facilities."

[5] See paragraph 2 (pp. 2-3) and Enclosures 3 (p. 3-1), 4 (p. 4-1), and 5 (p. 5-1) of DoD Directive 5000.53, ibid., as well as the other relevant DoD Instructions and Directives cited therein.

WHY EMPHASIZE INTEGRATION?

The weapon system acquisition process typically generates an enormous flow of paper.[6] In order to reduce the paper-flow requirements, and to improve overall productivity and quality, both the DoD and Industry have agreed to invest in the automation of processes in the acquisition-relevant functional areas of the CALS initiative. From the very beginning, the integration of these processes was recognized as essential for systems to be designed and prototypes built "right the first time," thereby avoiding costly design changes and ensuring producibility and supportability.

Many different automated systems are currently used by weapon system contractors and government agencies to enter, update, manage, and retrieve data from relevant data bases. For the most part, the automated systems in current use are incompatible. In many cases, information that is ultimately delivered to the government is created from disparate data bases, reduced to paper, and then rekeyed into other data bases or even recreated. The process is inefficient, costly, subject to error, and overly dependent on paper.

The data bases themselves are often unidimensional or even unique in the sense that they fail to take into account (known) relations with other factors. For example, among the CALS-HSC constituents, the design of the equipment and its user interface (human factors engineering data) often determines the numbers of operators and maintainers required (manpower data), their task difficulties and the skills required to perform successfully on their jobs (personnel and training data). These all interact, for if the aptitude level of personnel selected for the job is lowered, the training requirement is increased, and vice versa, and if the job difficulty is increased, so is the aptitude or training requirements. Likewise, requirements for the protection of health and life (safety and health hazard prevention data) are likely to place constraints on the design (human factors engineering data), and, therefore, on the numbers, aptitudes, and skills of the people who are to operate and maintain the system (manpower, personnel, and training data).

The CALS (and CALS-HSC) goal will eventually be reached when the information, data bases, and models are capable of including all the information needed for weapon system design, manufacture, and support in an automated mode accessible through electronic means to all authorized DoD and Industry users, and fully integrated for use at the right times in the design phases and, indeed, throughout the weapon system's entire life cycle.

CALS OBJECTIVES

The objectives of the CALS initiative are to improve the timeliness and quality of weapon systems and their supporting technical data, while reducing their cost, and thereby increasing operational readiness and industrial competitiveness.

Nine specific examples of the objectives to be achieved through CALS development and implementation are listed in Table 1 on the following page. They are associated with the three major CALS objectives to reduce time, reduce cost, and improve quality in the engineering, manufacturing, and logistics support of future weapon systems. Examples of the same objectives applied to CALS-HSC development and implementation are listed in Table 2; comparison of the two tables shows the real commonality of purpose and objectives of CALS and CALS-HSC.

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[6] For example, a single weapon system may generate on the order of 3,500 new technical manuals, thereby adding a million pages to the current inventory. On average, 200 thousand (20 percent) of these pages will be changed each year. Present day paper-oriented processing systems are hard-pressed to keep up with the additional volume and to provide accurate and timely technical information needed for weapon system acquisition, logistics, and support activities.

Table 1. CALS Objectives

Reduce Time:	• Improved industry responsiveness will result from the development of integrated data, automation of plant facilities, and industrial networking. • Shortened weapon system design, development, production, and resupply times will be possible through the creation of a shared-data environment designed to generate and transfer required data. • Reduced "out-of-service" times for repairs and overhaul will increase combat capability. These results will be obtained from integrated planning, automated tool design and set-up, and more rapid parts support.
Reduce Cost:	• Elimination of the labor-intensive development of duplicate data used for separate processes in design, manufacturing, and support, will be one result. • The use of paper will be dramatically reduced and replaced by accurate, timely, and cost-effective digital technical information for acquisition, logistics, and field operations. • Data will be shared by multiple systems; common system applications will help achieve interoperability.
Improve Quality:	• Fewer errors in weapon system design and manufacturing will result through the integration of key data bases that support these functions in near real-time environments. Producibility, reliability, maintainability, sustainability, and other "ility" considerations will be integrated with computer-aided engineering and design tools. • Data consistency will be significantly enhanced as data bases are linked together.

The challenges of successful development and implementation of CALS are substantial, but so are the expected rewards. That is especially true of the CALS-HSC constituents, since in many cases the HSC data do not yet exist in forms or formats suitable for engineering applications. In those cases, algorithms for data inversion and analytic techniques for use in design trade-off decisions at the engineering workstation will have to be developed, tested, and verified. Only then will the CALS-HSC effort have fulfilled its role as part of the CALS initiative.

It will be necessary, at some future time, to document the actual benefits and payoffs of the CALS and CALS-HSC efforts with criteria and figures of merit related to the cited objectives. Although difficult to do now, that should eventually be an easier task to accomplish. In the meantime, there is much work to be done and progress to be made towards those objectives and their promise of substantial benefits and payoffs.

Table 2. CALS-HSC Objectives

Reduce Time:	• Improved industry responsiveness will result from the availability of HSC data in automated digital-flow form networked to and from the engineering workstation.
	• Shortened weapon system design, development, production, and resupply times will be possible through the sharing and automated transfer of data regarding the human system components of weapon systems.
	• Reduced "out-of-service" times for repairs and overhaul will increase combat capability. These results will be obtained partly from integrated planning with data on maintenance, technical personnel, and technical training.
Reduce Cost:	• Elimination of the labor-intensive development of duplicate data used for separate HSC processes such as the personnel and training requirements, will be one result.
	• The use of paper will be dramatically reduced and replaced by accurate, timely, and cost-effective digital technical information for all HSC operations within the full life cycle of the weapon system.
	• HSC data will be shared by multiple systems; common system applications will help achieve interoperability.
Improve Quality:	• Fewer errors in weapon system design and manufacturing will result through the integration of key HSC data bases that support these functions in near real-time environments. Producibility, reliability, maintainability, sustainability, and other "ility" considerations will be integrated with computer-aided engineering and design tools.
	• Data consistency will be significantly enhanced as HSC data bases are linked together and with other data bases.

The CALS-HSC Goal-Oriented Schedule

The CALS-HSC effort is addressing the issues as part of the CALS initiative by progressing along the CALS-defined evolutionary developmental path to make substantial improvements in the system development processes used by the DoD and Industry. In the near term, until the mid-1990s, the effort will concentrate on the development of digital file exchanges to replace paper document transfers. In the longer term, beyond the mid-1990s, the relevant advanced information technologies, integrated data bases, and information models for the CALS-HSC constituents will be developed and integrated with the other CALS components for use in the applicable engineering, manufacturing, and logistics support processes.

Through Fiscal Year 1990, the CALS-HSC effort has been centered mainly in the area of training, and more especially in the subarea of training system development. Considerable progress has been (and is still being) made in developing automated, digital flow data, data bases, and decision support systems for training system design and development during the design phase of the weapon system development cycle. Beginning in Fiscal Year 1991, the effort will be broadened to give increased attention to the full range of CALS-HSC constituents; i.e., to the manpower, personnel, training, safety, health hazard prevention, and human factors engineering components. The thrusts of the effort will parallel the CALS strategic thrusts.

CALS Strategic Thrusts

The strategy of the CALS initiative is aimed at developing the means to transition from the paper-intensive, nonintegrated weapon system engineering, manufacturing, and logistic support processes to a highly integrated and automated mode of operation. There are five main elements of the CALS development strategy, as follows:

1. Standards. Standards are crucial to the creation of an integrated environment for electronic data access and transfer. CALS will facilitate the transfer of logistic and technical information between Industry and the DoD by leveraging existing international and national standards and accelerating the development of new standards to support future requirements.

2. Technology Development & Demonstration. Development and demonstration of new technologies that can support the creation, storage, and secure dissemination of a large volume of digitized data are essential to the successful implementation of CALS. The CALS environment will support the development of integrated data base technologies that displace paper and enable redefined processes over the entire weapon system life cycle.

3. Weapon System Contracts & Incentives. DoD weapon system contracts with Industry form the basis for implementing CALS standards and integration requirements. An objective of the CALS initiative is to provide an orderly transition to a new way in which the DoD and Industry will do business, and to facilitate Industry investment in automation and integration.

4. DoD Systems. Ultimately, the capability of the CALS environment to improve readiness will depend on the modernization of the DoD support infrastructure. DoD information systems must be able to receive, transmit, and use digital technical data in weapon system life cycle management support activities. Recent (and still current) efforts include development of a corporate architecture and plan that is providing a framework for modernization of DoD information systems.

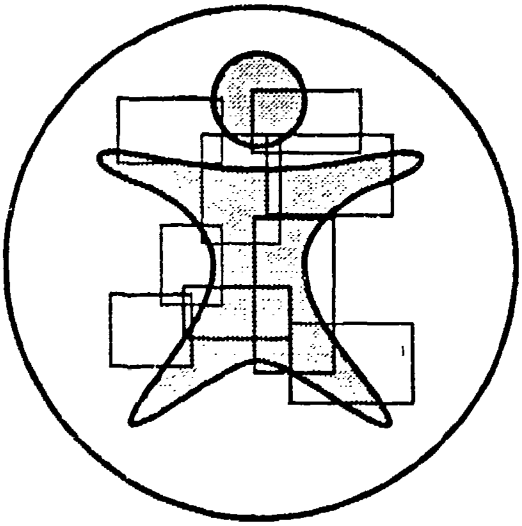
5. Management. The DoD is developing the corporate architecture and plans to establish the overall strategic direction for CALS implementation. An important aspect of this strategy is to maintain close liaison with other government agencies and Industry. DLA and all four military services have prepared plans, are educating and training their program managers, and implementing the CALS environment and products as they are developed.

The Future of CALS-HSC

As part of the CALS initiative, the CALS-HSC effort is also committed to address all five of the CALS strategic thrusts each across the HSC subareas of manpower, personnel, training, safety, health hazard prevention, and human factors engineering. The specific steps already taken, and those planned for the future, are substantial. To succeed on a schedule reasonably consistent with that of the CALS initiative, many more members and organizations in the HSC community will have to be involved with commitments to contribute in their own domains.

The model that appears most appropriate is one that calls for each of the HSC communities (manpower, personnel, training, safety, health hazard prevention, and human factors engineering) to construct, with "Operations and Management (O&M)" resources, the digitized data bases that best serve their O&M functions. Next, data element dictionaries will have to be developed so that terms are used in meaningful and consistent ways within and across areas and communities. Then, it will be possible to link the data bases to support the digital flow of information.

All of these steps should be underway in FY 1991, so that by the mid-1990s, real progress will have begun on HSC integration, in relational data base modes, and with any data conversions that may be necessary to make HSC information meaningful and effective for decision making at the engineering design workstation, and vice versa.



DESIGN FOR MAINTAINABILITY PANEL DISCUSSION

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Mr. Cream: To make the last session of the workshop exciting and interesting, what we're going to do is follow a life cycle of a panel. The way this will work is each individual will express his viewpoint on the key issues of this workshop. These are: What are the technical challenges that will move us from the "as is" world of today to the fully integrated "to be" world of human-centered design technology of the product life cycle. Each individual will give a short presentation about 15 minutes or so.

Dr. Askren's Remarks:

Our instructions had two parts. First, what is our reaction to what has been presented? And, then, what is our vision of the "as is" and "to be" world? What are the technical challenges? My overall reaction to what has been presented today and yesterday is that the scope of what has been happening in human modeling in the last five years is very impressive. The quality of the people doing this work is just outstanding.

I'm particularly happy about Crew Chief. If I may be permitted a little history here, as some of you may know, I had a hand in getting Crew Chief started. During the early 1980s, Don Tetmeyer was Division Chief of AFHRL/LR, and I was a Branch Chief. We had many conversations about how to get human factors inserted in the design world. This was part of our mission, getting human factors integrated with design. So we decided to take a systematic look at what the aerospace industry was doing in the area of design engineering to see if we could link into it. So I took a round-robin trip and visited a number of aircraft companies to see what was happening in the world of engineering design. I found that CAD was beginning to take hold as the new design method. So Don and I hashed this over and we decided that CAD looked like the way to get human factors into design.

We tried a number of things. One of the early ideas was discussed today by Pete Glor of General Dynamics. This was the idea of trying to get a man-model incorporated into the Ground Launched Cruise Missile (GCLM) design program. Another effort, discussed by McDonnell Douglas, was the CAD simulation of F-15 field deployment in Europe: the Combat Turn Model. These demonstrations showed the potential for CAD integration of human factors evaluation.

But I guess the thing that I really liked and really enjoyed was Crew Chief. Don and I realized that maintenance was our field, our mission. The folks in AAMRL had the operator side, the cockpit design side. They have some models called COMBIMAN that have to do with the cockpit. We wondered if we could do something like that for maintenance. So I visited with Dr. Joe McDaniel of AAMRL. I wish Joe were here to share some of this. I said "Joe, we're interested in maintenance. You're working the cockpit. Do you think we could adapt your COMBIMAN to the maintenance field?" He said "I don't know. Let's try." So we scraped up some money. AFHRL put up some money and AAMRL put up some money and together we embarked on what is now an eight-year program to develop a maintenance man-model called Crew Chief. It's growing admirably. I think what you folks are doing with it is just outstanding.

An amusing side note on the name Crew Chief. You might not believe this but it took three months to come up with the name Crew Chief. I remember writing many names on the blackboard and looking at them for long periods of time trying to come up with something. We had Maintenance Man, Repair Man, and others. We wanted a name that would apply equally to male and female maintenance personnel. Then one day, almost an inspiration, we remembered the name Crew Chief, and that name was a perfect fit.

Now as far as the future, I have a copy of Dr. Kroemer's National Research Council study.[1] This study summarized the progress of man-modeling in eleven areas. Based on the presentations I have heard at this workshop, it appears we have made progress in four of these areas. Let's look at these.

Predictive Models of the Effects of Platforms. We don't have good models which show how vibration, acceleration, and other environmental factors affect performance. We've heard some discussion of these sorts of problems here, but in general I think it could be said that we've not progressed very far with that.

Dynamic interface models. This is a second area in which we still appear to be woefully inadequate. I'm aware that there is a movement beginning in this area, but of course a limiting factor continues to be computer memory. But this appears to be an area where good work could be done.

Stress and motivation have still not been brought into these models. There has been some work here, but in general these factors have not been adequately modeled.

Fatigue, trauma, and injury are still not adequately dealt with. I'm intimately familiar with this problem. Some years ago in the Air Force we tried to bring these factors into studies of nuclear missile handling operations. We tried to bring fatigue factors into the evaluation, but there just wasn't sufficient data or models to use. So apparently there is still a lot of room for work in these areas.

Complex aspects of vision, audition, and speed and accuracy of response to sensory inputs need to be explored. This is obviously a very complex area but one where new simulation technology for virtual realities may pay off.

Sociological factors, such as habitability, on human performance are largely unquantified. This could be important to submariners, outer space operations, and people who live in the Arctic conditions. For that matter, think of Desert Shield. What are the effects of heat on performance?

Model validation is still an unresolved issue.

So out of the list of eleven discussed by Kroemer and his colleagues I see at least seven still needing work.

What are my key technical challenges? My challenges overlap somewhat with Kroemer's study, but with a slightly different flavor. I see three challenges that come out of the experiences I have had.

First, we need to gain as good an understanding as we can of the user's needs. That is, the designer's needs. In the design world, the better understanding we can have of the design process the better our models will be. My research over the years has shown that there are different types of engineers. Different styles of work. Some engineers are serial workers who deal with things sequentially. Our models work well for them. But there are also engineers who work in a holistic fashion. They get a problem, think on it for a few days or weeks, draw on their experience, and then all of a sudden they create a design. How does something like this relate to our modeling work?

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[1] See Kroemer, K., Snook, S., Meadows, & Deutsch, S. (Eds.). (1988). Ergonomic models of anthropometry, human biomechanics, and operator-equipment interfaces, proceedings of a workshop. Washington, DC: National Research Council.

In the design world there seem to be two concepts that guide the engineers. One is *constraints* that the engineer must design to. However, complementing this are *trade-off* studies. To achieve a constraint an engineer might look at many alternative designs. Our modeling must be compatible with the way the engineer works. So my first point is that we must put as much energy as we can into understanding the user's world in which our models are applied.

My second point is: *Do as many practical demonstrations as you can.* I love what Pete Glor is doing at Convair with those practical demonstrations. This is a great way to sell our products. However, one thing that inhibits us is the caution of human factors people. I think sometimes we're too timid about getting in with the engineering or design folks and making contributions. I think we're afraid that what we have to offer is not good enough. Well, my experience has shown that very often it is good enough.

My third point, which is related, has to do with *the quality of the data*.. We're very concerned about the scientific precision of the data here today. I understand this. After all, we're scientists. But we also need to consider the engineering usefulness of the data. Quite often they're different ends of the continuum. Where we might be concerned about two millimeters, in the practical world several centimeters might be sufficient. The payoff of this is that it's often cheaper to get less precise data.

My first experience with this came many years ago when I was a human factors engineer in the original B-1 bomber program. An aerodynamical engineer came to me and said that he had to design the structure to provide a good ride for the pilot. Therefore, he wanted to know what g-load the pilot could tolerate for a 10-hour, low-level flight. I went to the literature and all the experts and there was no research data on 10 hours of g-load tolerance, only for 30 minutes. Therefore, I did an extrapolation from 30 minutes to 10 hours. The scientific community wouldn't like this. I went back to the engineer and gave him my extrapolation - my specs - for a 10-hour profile. I told him I could be off by 100 percent. He said that's OK. He would put in a safety factor to account for this variance. What I learned from this experience is what somebody here said today: An 80 percent answer today is oftentimes better than a 100 percent answer tomorrow.

Dr. Pew's Remarks:

All models are wrong. Repeat for emphasis: All models are wrong. However, models are useful. We can't make models useful unless we know what they are useful for. We've talked about a number of areas where models might be useful in the domain of human factors in design. We've talked about them with respect to reliability and maintainability. We've talked about them with respect to manpower, personnel selection, and training. We talked about them with respect to cockpit layout and design. We talked a little bit about safety although I think we may have to put more emphasis in the area of safety analysis. And this morning we even heard a very interesting talk about equipment fit and the requirements for very detailed models and data for fitting night-vision goggles.

I came here - and in fact Ed Boyle and I sort of teased about this. He said if I invite you to speak on the panel I know what you'll say. You'll say we need more cognitive models. After listening to the presentations and discussions for two days I've come to this conclusion: Yes, we need cognitive models. However, I used to think we should put a cognitive front-end on an anthropometric model. Now I think that's wrong. I no longer think that's a useful thing to do. In terms of Ron Laughery's presentation, I predict that when you connect MicroSAINT to the anthropometric models, you will use the task-modeling representation in order to say "Assemble" and this breaks down into a set of things that you want to represent in an anthropometric way; but you will find that the pieces you are alluding to in the Human Operator Simulator, the human performance and the information processing pieces, will not be terribly useful for the analysis of anthropometric issues.

I think one of the most useful things we've heard in the last two days is the discussion of users and real applications. First of all, I've come to believe that anthropometric modeling really is useful for maintenance design. But second, I've come to believe that those people who are interested in the design of spaces for maintenance--hand holes, tools, forces, all the things related to the maintenance activity--are not very much interested in the thinking part of that problem. This is not a criticism. It's just that the people who do this sort of analysis are different from the people who do the functionality analysis of a crew station to see whether the equipment is appropriate. And because these things are done in different places, there is no reason for us to integrate models at that level.

The second thing I see -- which I think is healthy and not dysfunctional -- is that people are talking about models at many different levels of detail. That's fine. I think that's the way it should be. And in fact the richer the levels of detail we have with these models the better able an individual need can be met by looking for the right data representation at the right level. My feeling is that the kind of thing that Dr. Kaplan talked about and the talk by Dr. Evans on EDGE, both of which are focused on manpower, personnel, and training, are the highest level of representation that we've seen. They are further than I would want to go but they are not further than one needs to go to make these kinds of predictions up front.

It's hard to talk about this next level because in one sense it's a detailed level and in another sense it's not as detailed. We talked about the utilization of equipment, the functional utilization of equipment. This is what Mike Young talked about and something we've had a part in. And it was also part of the A^3I discussion. This is the notion of looking at cockpit design and layout from the standpoint of functionality. In these cases I think we need a human performance model that gets into intellectual and cognitive performance as well as the physical performance. The anthropometric models are more incidental here. They are not inappropriate. We do need reach, but we don't need the kind of detail--force and stature and such kinds of representations for the anthropometry-- if we are interested in the functional design. Functional design may not be the right term. What I mean is that aspect of the design of equipment that requires both physical and mental interaction in order to operate. I think you understand what I mean.

Then, clearly, when you get down to the level of equipment fit, I think you're getting down to a level more detailed than even the anthropologists aspire to. It's really going down to a level of very great detail.

With that thought in mind, I want to reflect on the DEPTH program, at least as it was presented here. I don't know much about it other than what I have heard. But I had the feeling that DEPTH is trying to be too many things to too many people. Maybe it could be more focused. But then I thought about what Detroit does with concept cars. You build a concept that you know will never be put on the road but you build it because it contains a lot of ideas, some of which may ultimately prove to be worthwhile. So I decided that the DEPTH program is like a concept car. In this sense it's a demonstration of lots of different things. I think the people who are doing DEPTH shouldn't try to be all hooked up together. Because the people who are going to be doing the different kinds of analysis--manpower, personnel, and training on the one end, and anthropometry on the other end--don't necessarily work at the same time, and they're working at different levels of detail. While it's nice to have all those parts in DEPTH, I wouldn't offhand expect them to be connected up together.

HARDMAN III is a different case because it's trying to produce a single kind of prediction out of an integrated collection of things, and for that purpose that's OK. But it appeared that DEPTH was also trying to do the anthropometry at the most detailed level at the same time.

Now, two points about data. The first is a topic I did not hear discussed very much in the last two days but that I think is absolutely critical. It was referred to in a backhanded way a couple of times. This is the data entry problem. Particularly the equipment data entry problem. The discussion has suggested that the equipment representation is resident in the CAD system and they just bring it up and it's there. One person did mention that he would like to have a representation of the support equipment as well as the representation of the primary hardware configuration. I think we should be thinking a lot about the designer's workstation design from the standpoint of data entry. Entering the equipment specifications is potentially a very labor-intensive process.

With that in mind I would suggest the following kinds of things:

1. Supplying templates for standardized pieces of equipment.

2. Providing baseline cases. You might have a baseline cockpit that can be modified to correspond to the new design. You might also have a baseline wing that can be specialized to the wing whose maintenance is under study.

Then the critical thing is that you make it very easy to modify. The focus on the data entry process should be on change introduction rather than initial coordinate introduction. You want to be able to manipulate the representation not by going back to the original coordinates of the thing but by shaping it, making it bigger, smaller, and so on; treating these things as objects and being able to manipulate them in ways that make them look like the ones you want to represent in your particular case.

Also, I think it becomes extremely important that these objects be transferable across different data bases. In this way a data file or a particular system specification can be translated to another system. And that may require a careful definition of primitives. Not just graphics primitives but primitives at a little higher level describing the nature of the objects that are being ported from one system to another.

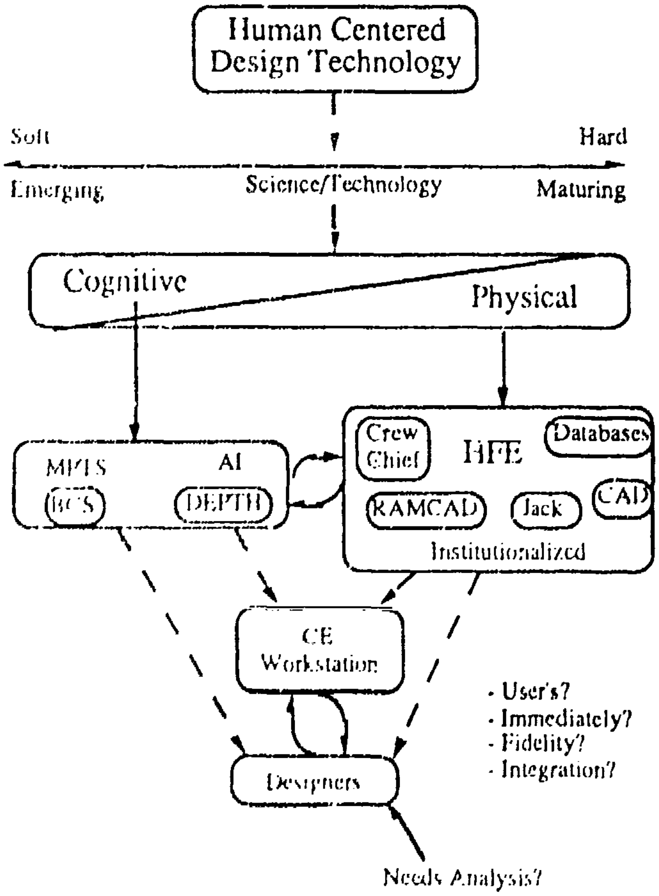
The final point I want to make is this: "Don't forget the beef." The "beef" in the anthropometric modeling case are the data, the data on human characteristics. I was absolutely fascinated by Dr. Roebuck's talk. He really highlighted some of the weaknesses of the current data and some very ingenious ways for solving some of those problems that don't require going out and getting more data from another sample of 10 thousand people.

I have the feeling that the Air Force, and the Army as well, could make the best investment by improving the quality of the anthropometric data. The General Dynamics and the McDonnell Douglas and the Boeings of the world, as you have seen, are already putting these things into CAD/CAM systems and are making them work in their own context. But they can't afford to collect those data. They can't afford to go out and get the detailed kinds of data needed to make these models accurate. Therefore, I think that's the place where the most cost-effective investment by the government can be made. Thank you.

Dr. Gould's Remarks:

My comments will be kept at a very macro level. I'm going to chat about three highly related issues. First, who are the users we're really targeting for all these tools and data bases? Related to that is what level of detail is to be provided and when is it needed? Because the answers are all intricately entwined, I'll end up talking just a little bit about some integration issues.

In the macro view we were all talking about getting human-centered issues into the design process. That was fairly clear. Then I took a look at the issues and the tools as they were starting to emerge. They can be placed on a continuum which has two dimensions. One dimension is the soft sciences and technologies to the hard sciences and technologies. Directly related to that is the status of the research. There is a continuum describing that which is mature and being used and that which is just starting to emerge. If you look at the cognitive as the soft, gradually emerging side, and the physical human factors side as harder and more mature, you can break this down into two broad camps. The human factors or physical side, which I understand has many subdisciplines within it, has some mature technologies that are already being institutionalized in the design process. I understand this might have been a very hard fight to get in there to make people believe you need to be there because the designers already have a very full plate.



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human factors-oriented physical side, you can break this down into two broad camps. The human factors or physical side, which I understand has many subdisciplines within it, has the mature technologies that are already being institutionalized in the design process. I understand this might have been a very hard fight to make people believe you need to be there. The designers already had a very full plate and weren't looking for something to complicate the design process.

But there are many emerging analysis tools and data bases from the softer science side, the side I come from. We have manpower, personnel, and training folks. These people don't routinely interact with each other for the most part. Then we have safety people and hazardous materials people who have their own language, chains of command, and lines of communication. These are all totally separate and unique disciplines. Finally, we have information processing folks and those involved in applying artificial intelligence technology. Yes, we have data bases such as the performance task-level baseline comparable systems (BCS), and analysis tools such as DEPTH are coming along. But working from the softer cognitive side of science, we have had little success in breaking into the design process, much less convincing our fellow scientific method colleagues that we are scientists. If we just take a look at the tools and data bases on the human factors side, we have these very minute and specific data bases. I envy you the hard stuff you have to work with.

But at the same time I want to chide you a little bit. Several of you stood up and talked about your detailed data bases applicable to different populations. You have Army and Air Force populations, you have civilians and military, pilots and maintainers, males and females, and different ethnic groups. There were some hinted-at questions from the floor about what's the difference, the delta between these different populations? Nobody could answer the question. Some talked about not having needed data that others said they had, but the needed data couldn't be used because it's from a different population. Many described the terrible dollar costs of collecting the data or updating aged data since the work force is getting larger at the rate of one centimeter each year. So it seems to me that somebody should undertake a major effort to develop the broad view, the whole range of anthropometric and biomechanical data needs. I can't tell the difference between those two terms, by the way.

All of your data need to be brought together some way to represent the whole American work force so you can start sharing information. Maybe this idea will appeal to some of you contractors. How about asking for access to all these data bases, collapsing/merging them and using regression techniques to fill in the missing cells for various populations? Give free subscriptions to the updated data bases for those organizations who contribute data and charge the rest a subscription fee. Use the fees to update the data base and, of course, to line your pockets. Dealing with the "missing cell" problem, the data specificity problem, should be doable if resources are pooled. But believe me, you are in much better shape than we are on the other, cognitive side of the fence.

I think one of the main purposes of this workshop is to start bridging the gap between these human centered technologies, cognitive, and human factors technologies. Notice the unconnected link between the MPTS and HFE technologies. Our hosts have started to make that link up. We now recognize them for such things as Crew Chief, RAMCAD, and other work from the so called harder science side. On the other side of the fence we now see them talking about DEPTH, which I'll list more to the MPT side than the concrete, physical aspects side. So there they are with their feet firmly planted on both sides. But actually it's more like standing on a banana peel on the one side and a wet piece of soap on the other. My hat is off to them for what they're trying to do to bring these two broad disciplines together. As I'll discuss, making that link is vital to all of our success in making each part of the human centered technology usable in the design process.

If we take a look at these various tools and data bases and ask who the users are, each developer can tell you who his or her user is. But the thing that dismayed me as I sat and listened was that people talked about passing the information to a designer directly or even having the designer conducting the analysis. Only a few of you expected other experts or mediators to use your analysis tools and send refined summary results to the designer. I'll take RAMCAD as an example of the latter. RAMCAD developers talk about needing an R&M (Reliability and Maintainability) engineer to work the information and feed the results back immediately to the designer. Others of you talked about giving task-level data directly to the designer.

I remember when I first started giving briefings about the MPT issues in design. The audience asked me how much information could be used in design. I gave my off-the-cuff answers. Coming back immediately was the remark that it would never work. Those designers already have a full plate. During this conference, I never once heard anybody talk about the fact that if designers already have a full plate, what is the chance that designers can actually use the tools we are building for him.

Each one of us is developing technologies for his or her own areas. We're producing a very wide range of tools and we each seem to have the notion that designers are just chomping at the bit for our technology. I think the chances of getting designers to use them is probably not great. What we're really doing is we're sending, or planning to send, too much information or analysis capability. We are focusing on what we think is important from our parochial vantage point.

I think we need to identify what the designer needs and what he can possibly use. We need a more detailed analysis of the engineer's job. What degrees of freedom does he have to change the way he does business today? We may be building tremendous tools that don't have a snowball's chance of ever being used. True, the acquisition environment is changing rapidly with the introduction of automation technology. Computer-Aided Engineering (CAE) is coming along, and we heard a lot about the elimination of paper and speeding up the process through CALS and CAE. Information will be created and transferred rapidly. Subcomponent designers will have their designs critiqued by an engineer at the component level and returned with modification instructions overnight. It looks like the designer in the future is going to be on a very fast revolving wheel.

At the same time, though, many of the tools we have on hand, and are developing, to critique that design will still take weeks and even months to devise a solution in reaction to a specific design. So, for many of our efforts, while we're busy getting estimates down to the third decimal place of precision all that can be used are whole numbers. Can it be that our tools are not very well adapted to the target design technology or the information processing skills of the designer? We're back to the data specificity problem here, but in this case no one has a clear picture of what can be used.

Several times during the conference, I heard reference to lessons-learned data bases. "We will place our analysis results in a lessons-learned data base for use by the designer." Well, I give that same response to those doubters who ask, "How can the designer possibly use the outcomes of your analysis tools?" "I'll place them in a lessons learned data base so the designer can be guided by the information," I answer. Maybe my answer is right, but as I listened to the many references to the lessons learned data bases, I realized that we must be talking about over a dozen such data bases and that my answer was naive. But I have never met a single lessons-learned data base that had a structure suitable for efficient use in a digital medium. Have you? Also, do you think a designer will consult a dozen, maybe two dozen, data bases to uncover the impact of each design decision?

What I am saying here is that we have a major problem which I heard no one verbalize. We need a major research effort to develop a heuristic for lessons-learned data bases. No, not just another Military Standard. That heuristic must encompass the information each of us will place within it. By the way, have you noticed that lessons-learned data bases only contain answers to problems we have solved rather than characteristics which have created unsolvable problems. Also, why don't lessons-learned data bases include the results of good decisions that have been made? Who has taken on this problem to solve? We all need the resolution.

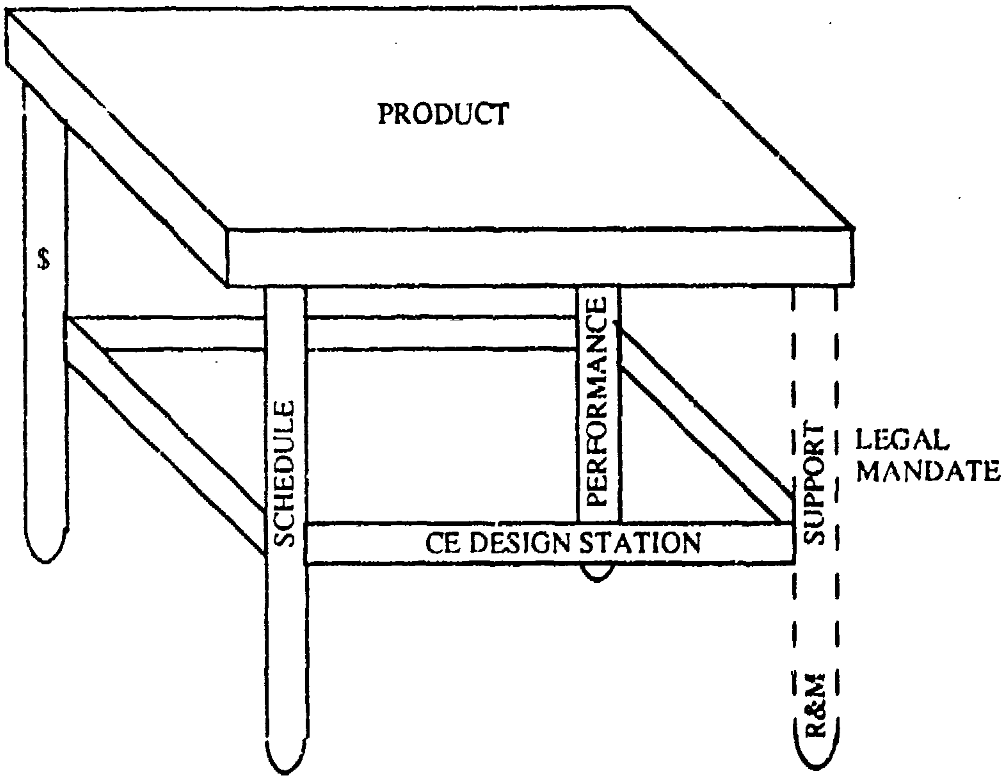
I want to mention that I think most tools being built require the existence of something that I'll call the Concurrent Engineering (CE) workstation idea. I think that's the direction we all need to aim for. There has to be a filter for this tremendous volume of information we're developing. A CE workstation will probably require a team of specialists, MPTS people, and HFE people. Somehow we have to get together--join forces. We must aim our collective analysis results to pass through the same filter if we're going to get our act together, to get our information through, in a usable fashion to the designer. Who is addressing this information cross-discipline integration problem? Also, are most design engineers really going to learn to use all these tools even if they have the inclination?

There's also another integration issue. This one concerns the necessity to coordinate, or integrate the trade-offs across a broad range of concerns. Let me use the RAMCAD presentation as an example. During the discussion there were some statements made that by cutting R&M significantly, there were going to be tremendous reductions in manpower. Well, that's true if you define manpower only in terms of the times to perform tasks. In the MPT community we define manpower as numbers of required personnel. There was discussion about how emerging technology has demonstrated that task performance times were, in fact, reduced by improving R&M. What you're probably doing here is reducing manpower utilization rates, increasing idle time. The fact that the skill is still required, although only for rare events, means that you won't necessarily reduce manpower. You still need someone available 24 hours a day to perform those rare tasks. The result is no manpower saving.

Further, again using the RAMCAD example, at the same time you're improving R&M, you're potentially increasing the training problems, possibly dramatically. When things don't break as often, how are you going to develop and maintain proficiency? In fact, you have possibly increased manpower requirements to keep rarely performed skills current, i.e., required additional personnel in the training pipeline. By removing the simpler tasks or lowering task frequency, you make it more difficult to learn maintenance tasks and hence you may also have increased aptitude levels. Higher aptitude personnel cost more to recruit and tend to leave before reaching the technician level, so you have reduced your maintenance experience base. Lower your experience base and you know what happens to your sortie rates.

All I'm trying to tell you is that what you folks from the hard human factors side do affects us on the MPTS side. You may think you don't need us. You've fought through the issues and are institutionalized and moving toward the goal box. Well, you do need us and we need your support. There have been some recent developments that may change your mind about the relevance of MPTS issues.

I took the idea for this chart from workshop references to the three-legged requirements stool. The reason you must care about MPT and safety is that in the past you had only cost, schedule, and performance requirements. Now we have a fourth leg, the supportability leg. Human factors had a reason to be in the picture under the performance requirement, you had an "in." If the human could not operate or maintain the system, the system would not perform. We soft guys, the MPTS discipline, did not have an "in" under that scenario. There was no mandate for the developers to attend to MPT. The attitude was: "Don't bother me about manpower support." "We'll find the money for training later so I can use the money to buy more units now." "Besides, you only add to the total cost of design."



Suddenly, not only is the supportability side added to the stool, but Congress has come in and made MPT and safety analyses a legal requirement before funding is approved. What this means is that if we can't analyze and document the requirements for MPT early in the acquisition process, the requests for new systems are never going to get to the Defense Acquisition Board (DAB). If you don't get to the DAB, you won't get approval to have a new system and you won't be able to do your human factors design work. So, believe it or not, human factors engineers really do need us MPTS guys now.

Well, where is MPT and S? It's clear we're way behind the human factors technology. We need some help. So whatever you do, please don't push us aside. Leave spaces in your CAD tools to accept the MPTS tradeoffs. Let's jointly address the lessons learned data base problem and do a detailed designer needs/capability study. Help pull us along so we can pull together.

A last point. R&M is one leg of that supportability stool, and R&M has made great strides. But I might point out that when you look at operation and support (O&S) costs, R&M is only one of the smaller elements of system support resources. Forty to sixty percent of the support costs are MPT costs. Congress is looking at these very closely. The requirements and the changes in MPT have to be reported. At any rate, that's where we stand and these are the thoughts I had as I listened to the papers. Thank you.

Mr. Nondorf's Remarks:

After listening to Dr. Gould I'm glad to announce that the Air Force and industry have the very same problems with technology integration. First, I'd like to congratulate the people in this room on the progress they've made since the last conference I attended on this topic four years ago. This was at AFHRL and we all fit into their small conference room. We've obviously grown a lot since then.

Before I discuss the problems, you need an expectation of what we in industry think these tools can do for us. Aside from the obvious impacts of maintainability and human factors, I think there are some other key areas that we see a big payoff for in these areas, especially for tools like DEPTH. And that's in the area of early generation of data. Task analysis, tech data validation, and training are all examples of things that can be done because of animation and so forth. These have been the long poles in the tent and have not only hampered the operability of the systems once we deliver them to you, but also hampered the manufacturing of them in our own facilities. I know at least one instance where we are taking early geometric definition and doing the rudimentary manuals which will aid in manufacturing, and from that developing training plans, technical manuals, and so forth. So this is a genre we have to get into. It's not something we've found easy to do because of technical problems with defining the right geometry, but we have to persist. These are long poles and they add to life cycle cost.

In terms of the implementation I think there's an underlying premise with this movement called Concurrent Engineering, or simultaneous engineering, or Integrated Product Development. Whatever you call it, there must be five or six other terms that refer to the same thing. In order to allow these things to happen, that underlying foundation must be in place. We need to start thinking in terms of design teams. We need to get away from this "my rice bowl, your rice bowl" mentality. Team efforts are becoming more important because of the teaming arrangements we are being forced into in industry.

In general, the philosophy of this workshop is that we need to design in better product quality the first time. This is all doable if we keep in mind that in the future weapon systems are going to be dictated by mission requirements. The next major weapon systems now on the boards will be driven by these requirements. We will be working on unconventional aircraft designs and unconventional equipment installations for new missions. These are things we are not used to working with currently.

In terms of users, I think the real customers of this technology are numerous. The ultimate end user at this moment is the guy who is sitting out in the desert, in Greenland, in the Arctic. This is the guy who needs to fix it and make it happen. He's the one we ultimately have to satisfy. The user before that is the guy on the manufacturing floor putting the system together. We can't closet ourselves by looking at these things only as legs on a stool, as maintainabilty and human factors things in isolation. They also have a significant part in the manufacturing process. I think Dr. Majoros made this point well in his presentation. The initial user is the design team, not a designer. The design team includes maintainability, human factors, reliability, and maintenance task analysts, manufacturing planners, and so on As a team, these people all have different needs and different requirements for different tools. We have to keep these things in mind.

In terms of technical barriers to transition. Probably the biggest one--and it's not just a problem between the government and industry, it also happens within industry too--is the question of portability. Part of the portability issue is the cost of capital. We can't afford to go out and recapitalize. GM did this a couple of years ago. We can't afford that and neither can you. So we have to look at the open system architectures, the standards being proposed by the CALS initiative that Dr. Alluisi will talk about.

We also have to have validated models. The real question is: Can the program manager believe the results of the technologies being developed by the people in this room? This is a very important thing. Many times we propose to program management to use a particular tool on a new system and the thing they always ask is: Has it been used before? If you say it's never been used before, they will send you away. Nobody wants to be the first to use a new but unproven technology. There has to be a track record of demonstrations, as Dr. Askren suggests. It has to be easy to use too. This is an education issue as well. Speed and use of resources is another problem. We have a lot of computer terminals and CAD stations at McAir for people to work on but there are never enough.

In addition, there are compartmented programs because of DoD and security requirements. We have to be able to live in that environment as well. We preach information sharing, but when you have 50 programs and they're all TEMPEST and none can talk to anyone else, so much for data sharing. And some of these are 12 and 15 people, or less. They are not large enough to warrant the investment in the infrastructure needed for information sharing. So we have to think about that small-scale way of doing business.

There are cultural issues as well. Design engineers are design engineers. They design airplanes. They are not human factors people. They are working 12 or 14 hours a day in many cases. They have a schedule to meet and are driven by cost. They are just not going to do these human-centered things. I know we have asked them to do things for us that we didn't think of as major tasks and they say they don't have the time. They don't need the additional burden. We've been fighting this one for seven or eight years. We have not come up with a good way to solve this problem. Design engineers that I deal with don't want additional utilities dumped on their CAD workstations if they have the effect of slowing them down. On the other hand, if you have one CAD station and tell 100 people to use it, nobody ever will because they can't get on it. And even if they can it's another language, more passwords, and other complexities people do not like to deal with. We don't know an easy way around this. But overloading a CAD system is not a good idea. Anything you do to slow a CAD system down is not good for human-centered design.

Translation of academic data about human performance into a form useful to engineers is another big issue. What data are useful to him, how much data can he use? What type of data does he want to see? We can pin this down in some cases with some people in some disciplines but generally speaking these are unknowns. They can tell you what they don't like but generally they will have a hard time telling you what they do want.

Another thing that has to be done, and our Navy and Air Force customers are pretty good about this, is to mandate the use of these human-centered technologies in the RFP. You have to make them hard requirements. If I tell my boss that we need to do this maintainability analysis because it makes a better product and there is not a specific requirement to do it in the RFP, we will not do it. That's all there is to it. Some of the CALS mandates that have been coming out in recent programs that I am familiar with are merely "alluded to" requirements. They have to be firm. You can't let us tailor them or we will tailor them out. It's that simple.

In closing, I'll just say this. Colonel Clark yesterday asked who was in the audience. We had a few designers, a few users, and lots of technology people. I think the ultimate way to incorporate this human-centered technology both in the Air Force and industry is to increase the number of users with designers and technology people so that the ultimate users get what they want.

Mr. Cream's Remarks:

The presentations we have been privileged to hear during the past two days have been impressive in both scope and scholarship. Comprehensive as they may have been, there still remain issues that warrant our attention. Before I introduce our last speaker, I would like to share some of the more pressing of these with you in the hope that they may stimulate and provoke your thoughtful consideration.

Today, and more so in the future, many commercial and military products will be designed in one country, produced in a second, for sale in a third, and used in a fourth.

What technical steps must be taken to ensure that the understanding of end-user requirements, design data and production models used by this international community represent the breath of the intended user population throughout the product's expected lifetime?

How do government/industry initiatives such as Product Data Exchange Standards (PDES) and Computer-Aided Acquisition and Logistics Support (CALS) initiatives fit into the picture for international specifications and standards?

What role can/should academia, government, and industry play?

What forward-looking steps must be taken to ensure that the human models and supporting data now being developed will support this international design enterprise?

From a DoD perspective, consider that all major weapons systems are substantially redesigned and/or rebuilt during their operational lifetime. In some cases only the "shell" remains the same and the population of operators and maintainers that will own and use these systems in later stages of their operation are not yet born. Given this reality, what new technologies are needed to design not only for the initial cadre of users, but for those who will follow. Is this in fact a new technical requirement, "design for change," or just a further refinement of existing capabilities?

It is my opinion that although this workshop has focused on human-centered technology for maintainability, the technology is also directly relevant to design for assembly, disassembly, operation, retrofit, mobility, reprocurement, disposal, and CHANGE. What should we do to ensure that these and other applications and user communities are addressed. How do we ensure that we are not building another set of vertical technical "stovepipes"?

With the impressive sums of money being spent to develop new technologies, what are the technical barriers that slow the transfer of this technology to industry? How can we help the introduction of this new technology recognizing the inherent difficulties with integration of new technology with legacy systems and existing processes and the impressive capital investment required to "join the club"? Moreover, how do we ensure that the thousands of "Mom-and-Pop" machine shops, suppliers, supporters, and others serving as subcontractors have easy electronic access to these critical data if their contribution to the overall product is expected to merge smoothly with the work of the prime? What do we do when these essential elements of the product development infrastructure reside overseas? And what metrics are available and believable that can show industry a real return on investment for these new tools in view of the substantial investment required for them.

Next, how can we interconnect human-centered design technology with the surrounding "ilities" that inevitably impact human performance requirements and eventual system operation?

--We don't want just another "stovepipe" for HCT, but there are real problems in communicating our "ility" with the others, in particular, as Matt Tracy points out, with reliability and maintainability engineering.

--On the "downstream" logistics support processes, we have a large number of integration problems and opportunities. Ed Boyle has made the point that there is, first of all, human resources management--or so called MPT--to consider. Here is the largest single element of weapon system cost, yet we still don't know how to evaluate human resources aspects of design well enough. What must be done to "fix" this problem?

Finally, although there are no limits to the number of issues that could be usefully pursued, in light of the expected reduction in government budget available to support R&D in general, the predicted changes in demographics and manpower availability, coupled with the clear need to improve weapon system maintainability (and hopefully national competitiveness), what are the primary points of technical leverage that must be addressed? Who are the users, what are their real requirements, and what must be done to meet these needs?

Our final speaker will tie together the themes of the previous panel members with a description of the electronic integration vision inherent in the philosophy of CALS .

Dr. Alluisi's Remarks:

The revolution in the midst of which we find ourselves started between 45 and 50 years ago during World War II. The revolution had to do with recognition of the human as an essential element in military equipment and system design and performance. With the creation of the new discipline, variously called "human engineering," "engineering psychology," "human factors," and "human factors engineering," came the realization that *manpower, personnel, training,* and *safety* are key elements of all weapon systems. And Dayton, Ohio—Wright-Patterson Air Force Base, and especially Wright Field—was preeminent as a center of the revolution that first recognized the importance of "human factors" in systems.

But, other revolutions were also taking place. One was in computer technology. The first electronic computers came out of World War II. They were based on vacuum-tube technology—slow, costly, and very large physically by current standards. Computer technology has advanced considerably since then. Today, any of us can hold in our hand a computer that has more power than many universities were able to afford in their mainframes during the early 1960s.

For example, when I joined the faculty at the University of Louisville in 1964, they had two computers—one in the engineering school and the other in the medical school. Both machines were batch-processing IBM 1620s. Today, millions of Americans own and use personal computers that have as much or more power than those 1620s. And the trend is continuing. We are going to have more computer capabilities in the future than we have ever had before, and they will remain "affordable," or become even more so. The advances in computer technology are changing our world and the ways we work in our world.

Fifty years ago some of us were taught that we should design equipment in light of human capabilities—design equipment and systems with consideration of what the human could do, or do best. We have grown up professionally believing that. And now, today—in the present time frame—I believe we are acquiring the capability to do just that. We have come a long way during the past 45 or 50 years, but we still have further to go. Today, I want to talk about the "further to go."

In the 1950s, I "worked the benches" in a large aerospace company as a human factors engineer. Let me tell you what that experience was like. There were bays (large rooms) about four times the size of the room we are in now. Each bay was filled with numerous large drawing stands or tables. These were the engineering design stations. A few of the design stations were associated with racks of equipment and panels, as the designs were either mocked-up or actual "brassboard" prototypes constructed.

I was assigned as the sole human factors engineer in one of those bays. My primary job was to know everything that went on in the bay, and to insert, where I could, the "human factors principles" I had learned from Paul Fitts and others. Of course, I was to do this without seeming to be an intruder to the engineers whose designs I was mandated to influence.

My secondary job was to carry back to colleagues in my department information regarding what was being designed in "my" bay. I was to relay that information to two persons—one who sat in the desk behind mine, and one who sat in the desk in front of mine. The one behind was the *QQPRI* specialist (for "Qualitative and Quantitative Personnel Requirements Inventory"), and the one in front was the *training* specialist. We three, and about two dozen others, were members of the "Personnel Subsystem Department." That was how human factors engineering was accomplished in the middle and late 1950s.

We have had substantial advances in technology since then. The field is now nearly 50 years old. One would expect that we have come a long way since those beginning days—that we should be much more efficient and effective in how we go about doing human factors engineering today. Let us see how far we have come.

During the 1950s, if we had to address an issue of maintainability, for example, a question of accessibility, how would we do it? We would do it empirically. For example, there was one person in our department who was close to the 95th percentile American male in physical stature. (We only dealt with males in those days—there were no female operators or maintainers of military weapon systems then.) We had another person whose physical size was about the same as that of the 5th percentile American male. And, we had access to a mock-up of the system under development.

So, we would take these two people to the mock-up. And we would ask them to do a relatively simple thing, for example, "Reach up there and unscrew that purple cap and hand it to me." We would stand back, watch and write notes regarding our observations on a pad. The note might read something like, "The 95th percentile male is able to perform the task without difficulty, once his hand grasps the cap, but only by bending 90 degrees or more at the waist is he able to see the cap and thereby guide his hand visually to the correct position." (We didn't measure the strength or grip requirements back then, at least not unless someone complained that there was a "problem" in that regard.) The note might go on to say that the 5th percentile man could perform the task only if he had a stool or other stool-surrogate device upon which to stand.

How do we accomplish the same task today? We are more efficient, but we are no more effective, for we are doing the job essentially the same way. The only difference is that we are substituting a computer graphic (model) for a physical mock-up. And I submit that this process is not good enough—it takes too much time, and we human factors specialists are too few in number to meet our responsibilities.

We human factors specialists constitute about two-tenths of one percent of the engineering community.[2] The job that we have to do is a job that two-tenths of one percent cannot do well—if, indeed, that few can do it at all. With our computers and models, we are able do a little more than we could do with only mock-ups and live people, but we cannot do the whole job that needs to be done. We're going to have to enlist the aid of others. Those "others" should be the design engineers—the people who, after all, bear the major responsibilities for designs. We are going to have "to trick" them into doing our work for us. How? By providing the data and models for them to use in doing our work for us. And, it is not to worry about what would be left for the human factors specialists to do. There will still be plenty of work for us to do.

The key to this "trickery" is CALS. CALS stands for computer-aided acquisition and logistic support. Many of us know about CALS, but some of us do not. Those of us in the manpower, personnel, and training communities generally know little or nothing about CALS. Those of us in the logistics and human factors community generally do know about it—some quite a bit.

What is CALS? First, it is not a program. It is an initiative. It is a goal, it is a faith, it might even be a religion. But it's not a program in the usual sense of a government program. It is said to be a "Department of Defense and Industry initiative." Industry and the DoD have agreed to pursue the CALS initiative until the goal of a fully automated, integrated, digital computer-aided

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[2] See E. A. Alluisi, "The Human Factors Technologies—Past Promises, Future Issues," pp. 293-290, in L. S. Mark, J. S. Warm, and R. L. Huston (Eds.), *Ergonomics and Human Factors: Recent Research*. New York: Springer-Verlag, 1987.

acquisition and logistic support capability for weapon system engineering, manufacturing, and logistic support is reached sometime beyond the year 2000. CALS will replace our current paper-flow intensive weapon-system world with a digital-flow intensive one.

The process is to evolve our present-day paper system into a state in which we have digitized data with linkages to provide a digitized flow of information. Then, continuing the evolution, we will move toward a completely automated and integrated system in which industry and government would share access to fully digitized data in relational-type data bases. We would input the data once. The keeper of the data would be the organization that created it.

The objectives of CALS are (a) to reduce the time required to design and get the system on line, (b) to reduce its life cycle cost, and (c) to improve the quality of the system. The "quality" objective was not articulated in the initial CALS goals, but its importance is well understood by both industry and government, and has been been accepted. Industry is expected to be made more competitive by CALS, and in the international marketplace, American industry wants to be able to compete well.

In recent times, we as a nation have been challenged by the competitiveness of other nations' industries. Some have worried that we may be losing our competitive edge. And they might be correct.

We are now the second-largest debtor nation in the world. Money and costs are viewed as more important now than they have been in past years. The cost of a weapon system is now a more critical factor in the decision to develop it or not. World War II was an all-out effort. Nothing could cost too much to help our servicemen win that war. This is not so today!

And so CALS is one of our hopes for the future. A capability that will at the same time ensure an international competitive edge for American industry and affordable high-technology victory-capable weapon systems for American fighting forces. That is a tall order, and it would be well for all of us in the human factors community to take a closer look at the CALS initiative, its objectives and goals, and the part we must play in it if we are to integrate the Human System Components (HSC)—our technologies—successfully within the CALS processes. I shall use some viewgraphs to illustrate.

The overall CALS objectives are simple and clear enough—to reduce the time and costs, and to improve the quality, of weapon systems produced by American industry for all phases of acquisition and ownership by the Department of Defense.

CALS means an integrated environment. This is represented in Figures 1 and 2. CALS will integrate the engineering, manufacturing, and logistics support processes—processes that have been treated as entirely separate or different in the past. The idea is process-integration is similar to concepts in other thrusts—for example, in the Concurrent Engineering (CE) and Integrated Product Development (IPD) initiatives.

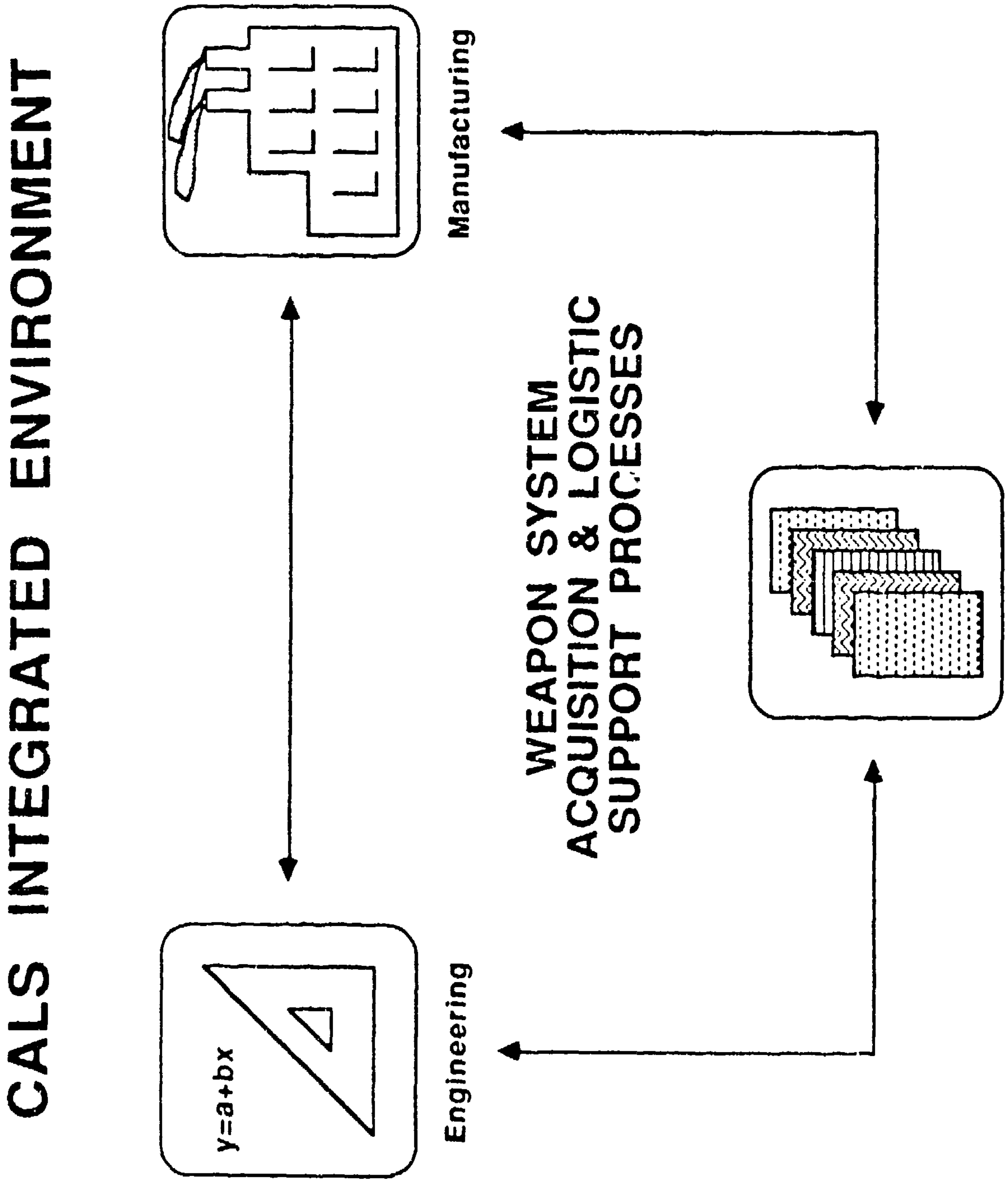

Figure 1. CALS Integration.

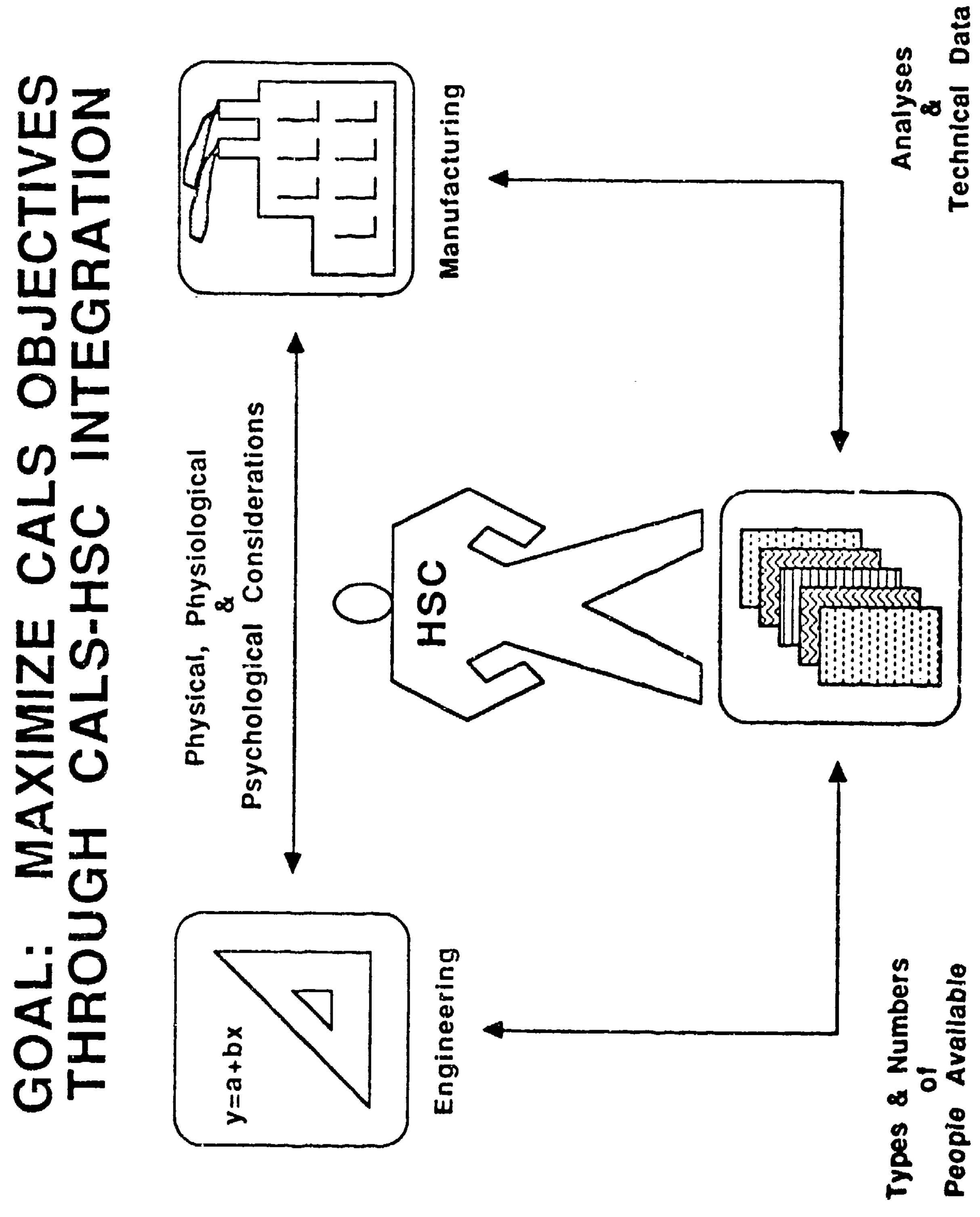

Figure 2. CALS Integration of HSC.

The CALS initiative charges American industry and the Department of Defense to evolve from the current paper-intensive processes and systems, through a stage in which we have digital data bases with linkages connecting them, to the CALS automated and fully-integrated environment. The schedule calls for us to be in the stage of digitizing data bases and developing links until the mid-1990s, and thereafter to be developing the necessary and enabling integrated relational data-base technology.

As a community, we in the human factors technologies have commited ourselves to the goal of maximizing the CALS objectives. We can achieve the goal through CALS-HSC integration—that is, through integration of the human system components—the manpower and personnel, education and training, simulation and training device, and safety and human factors engineering technologies into CALS. To do this the human-centered elements—the analyses and technical data regarding the types and numbers of people available, the physical, physiological, and psychological considerations, etc.—must be digitized, linked, and made "to talk" to each other in relational data base formats. In short, we have to work toward the development of CALS-HSC integration—that is, inclusion of human system components in a CALS integrated environment.

Why? Because acquisition and logistics support impacts on, and is impacted by, not only human factors and safety, but also by manpower, personnel, and training. What we need to develop is the capability of everyone in the engineering, manufacturing, and logistic support systems getting the right data, at the right time, in the right format, and at the right place. Our initial success will depend on our being able to get these data at the engineering design workstation in appropriate design-relevant formats. That's what I think we have to shoot for if we want truly to integrate the human system components into CALS.

We must accomplish two major tasks. The first task is internal to our own community: To identify and organize our CALS-HSC data in the proper form of a CALS-HSC data element dictionary (DED). The DED is necessary for us to be able to communicate digitally, and clearly. The second task is on the other side; namely, to determine, demonstrate, and assess the HSC design data conversions that will be necessary to make our data meaningful in engineering-design terms to the designer at the engineering workstation. Implied in each of these tasks is the building of PDES-compatible architectures to guide our efforts and represent our progress and products.

Our mid term goals in Task 1 should be to identify and organize data. The first step is to extend the charge of the industry-government committee that has been working on "training" as part of the CALS initiative to work on all the human system components. The committee began as the CALS Training Committee because when the CALS initiative started, "training" was recognized and listed as a part of logistics support. The CALS-Training Committee has been doing very good work. Among the other products that it can take at least partial credit for is a project called the ISD/LSAR-DSS, which stands for "Instructional System Development/Logistics Support Analysis Record - Decision Support System." This project is, I believe, the first successful effort to develop an automated decision aid for completing an Instructional System Development (ISD) analysis from use of the Logistics Support Analysis Record (LSAR). This is a big initial step toward the goal of CALS-HSC integration.[3]

So, the first step is to expand the charge of the redesignated CALS HSC Committee from only "training" to all the "human system components"—training as well as manpower and personnel, safety and human factors engineering. The second step is to expand the CALS Training

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[3] The project is based on a proposal made by Don Tetmeyer and carried out initially as an offshoot of the Unified Data Base (UDB) project by AFHRL/LR. Management of the project, now called ISD/LSAR DSS, was later transferred to AFHRL/MO. It has been supported in part by the Office of the Secretary of Defense under a 6.4 Program Element, the *Joint Services Manpower and Training Technology Development* program.

data element dictionary into a CALS-HSC data element dictionary (or dictionaries). The third step is to produce a general framework—information architectures—with which to represent the HSC domain. All three steps are being taken this year.

Our mid-term goals in Task 2 are to develop data conversions. Why are data conversions needed? The "personnel community" does not generally speak the same language as the "engineering community." Neither of these communities speaks the same language as the "manpower community." And none speaks the same language as the "training community." Each community has its own language or jargon, and correctly so. But to communicate we have to be able to translate. The idea of a data element dictionary is to make this translation. More importantly, we deal with our domain in the way that our domain requires. For example, manpower people make projections of manpower needs. But personnel people don't make projections of manpower needs. They make projections of manpower qualifications and characteristics. Each domain has its own data base. But with CALS we shall have the capability of having the different communities communicate, and the different domains interact, in meaningful and useful ways.

The first step is to identify at least some of the potential HSC impacts on system design engineering, manufacturing, and logistic support. The second step is to determine the CALS-HSC data needs (the Who? What? When? Where? and How?) for three demonstrations — one from the manpower and personnel area, one from the education and training area, and one from the safety and human factors engineering area, and to demonstrate and assess the impact of being able to include CALS-HSC integration within the CALS integrated environment. The third step, like that in Task 1, is to produce a general framework—PDES-compatible information architectures—with which to represent the domain and guide further work. All three steps are being initiated this year. If we are successful in these efforts, I believe we shall be able to carry out the trickery that we have dreamed of for the past 50 years. That is, we shall be able to have the design engineers, and the engineering workstations, consider the human system components at the very earliest stages of conceptual design — and make trade-off decisions based on real data from existing validated data bases. The formula for success, having the appropriate data, in design-relevant formats, at the engineering workstation is what CALS-HSC integration is all about!

I take the model of the Air Force Logistics Command's (AFLC's) reliability-maintainability data base. That is a data base created with O&M funds, not R&D funds, to serve AFLC in its O&M functions, namely, by gathering data on the historical reliability of equipment, components, and parts, the data base provides information with which to help AFLC meet its mission — information helpful in determining the number of parts to order, when and where to send them, and so on. In other words, it is a super inventory control aid and more.

By analogy, we need to have the personnel community (and other HSC communities) make their O&M data bases available as part of the CALS initiative. For example, when the relevant personnel data bases are digitized, consistent with an appropriate and valid data element dictionary, and linked, they can be an integral part of the automated CALS integrated environment. The CALS-integration capability will not disturb the HSC (e.g., personnel) files at all. The files will continue to serve their O&M purposes within the specific HSC community just as they do now. The difference is that the data base will be available to the wider communities more directly concerned with weapon system engineering, manufacturing, and logistic support.

Once the data bases are digitized and linked, the difficult job of integration will still face us. The three demonstrations that are planned — each drawn from a different HSC domain — should prove helpful in assessing the scope of the CALS-HSC integration issues and the likely value of their resolution. The development of the algorithms for converting the data into terms meaningful to the engineer will be a substantial challenge. But the challenging jobs are the ones that are "fun" to tackle!

What are the likely benefits of successful CALS-HSC integration? The benefits are quite in line with the overall CALS objectives: We shall contribute to *reduced time* by having the system designed right the first time, by providing relevant data where and when needed, in already-converted forms usable at the engineering workstation. We shall contribute to *reduced cost* by providing efficient data bases, resulting in fewer retrofits or engineering change proposals, and by eliminating unnecessary duplication. We shall contribute *improved quality* by providing consistent data, with which all HSC factors can be considered thereby resulting in fewer design errors.

We must integrate the human system components into CALS, take a proactive requirements-based approach, and demonstrate that it's practical. We'll have a big payoff because we shall then be able to do what we've been aiming to do for the past 50 years. Thank you.

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