CRANFIELD UNIVERSITY

YANG YANG

AIRCRAFT LANDING GEAR EXTENSION AND RETRACTION CONTROL SYSTEM DIAGNOSTICS PROGNOSTICS AND HEALTH MANAGEMENT

SCHOOL OF ENGINEERING

Full Time MSc
Academic Year: 2011 - 2012

Supervisor: Dr. Craig lawson
February 2012

CRANFIELD UNIVERSITY

SCHOOL OF ENGINEERING

MSc by Research

Academic Year 2011 - 2012

YANG YANG

Aircraft Landing Gear Extension and Retraction Control System Diagnostics, Prognostics and Health Management

Supervisor: Dr. Craig lawson
February 2012

HEALTH WARNING

This thesis has been assessed as of satisfactory standard for the award of a Master of Science degree in Aircraft Design. Readers must be aware that the work contained is not necessarily 100% correct, and caution shall be exercised if the thesis or the data it contains is being used for future work. If in doubt, please refer to the supervisors named in the thesis, or the Department of Aerospace Engineering.

ABSTRACT

This thesis contains the Group Design Project (GDP) work and Individual Research Project (IRP) work.

The target of this GDP was to design a long range flying wing passenger aircraft to meet the increasing global aircraft demand. The name of this flying wing aircraft is FW-11. This is a project cooperated between Aviation Industry Corporation of China (AVIC) and Cranfield University. The writer was involved in the conceptual design stage of this project. The author was in charge of the engine market, engine selection, engine sizing and performance.

The target of the IRP is to build a set of health management methods including system real-time monitoring, accurate fault diagnosis and prognosis of major components which are suitable for the aircraft landing gear extension and retraction control system. These technologies have the capability to improve mission reliability of the aircraft and the maintenance costs could be reduced. Simultaneously, aircraft landing gear extension and retraction control system, as one of the most important aircraft systems on-board, could directly affect the flight safety. Consequently, diagnostic, prognostic and health management (DPHM) technology is necessary for the system.

Based on the FHA, FMEA and FTA of the aircraft landing gear extension and retraction control system, each of the catastrophic events, all the root causes and their effects were identified. Synchronously, all the components which are related to the catastrophic events were found. The rule-based expert system diagnostic technology was chosen from the available approaches and it was successfully applied on the system. Appropriate prognosis approach was recommended for each component of the system according to the features of components of the system. Finally, the DPHM architecture of the landing gear extension and retraction control system was built.

ACKNOWLEDGEMENTS

The author would like to take this chance to give special thanks to his supervisor, Dr Craig Lawson, for his continuous guidance and professional support through the author's GDP and IRP, and Dr Fernando Colmenares Quintero, for his patient and professional support through the author's GDP.

The author would also like to take this chance to thank his company, the First Aircraft Institute AVIC, for giving this opportunity to study in Cranfield University and appreciates the staff from Department of Aerospace Engineering.

The author would like to acknowledge the Aviation Industry Corporation of China (AVIC) and the China Scholarship Council for sponsoring his study in Cranfield University.

Thanks are also given to the other members of AVIC aircraft design group for their kindly assistance during the whole year.

Finally, the author would like to thank his families for their understanding, encouragement and patience through the whole year in Cranfield University, especially his mother Zhang Yanhua and his wife Bai Jingyuan.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AVIC	Aviation Industry Corporation of China
ARMA	Autoregressive Moving-Average
BIT	Built-In Test
BITE	Built-In Test Equipment
CA	Criticality Analysis
CFDS	Central Fault Display System
DPHM	Diagnostic Prognostic and Health Management
DOD	Department of Defence
EPS	Electrical Power System
EIS	Entry Into Service
FHA	Functional Hazards Analysis
FMECA	Failure Modes and Effect Criticality Analysis
FTA	Fault Tree Analysis
FMEA	Failure Modes and Effects Analysis
FPR	Fan Pressure Ratio
GBR	Ground Based Reasoner
GDP	Group Design Project
GTF	Geared Turbofan
IVHM	Integrated Vehicle Health Management
IRP	Individual Research Project
JSF	Joint Strike Fighter
LRU	Line-replaceable unit
LED	Light-Emitting Diode

LGCIU	Landing Gear Control and Interface Unit
MDW	Maintenance Data Warehouse
OPR	Overall Pressure Ratio
OMP	Operational Maintenance Program
PDF	Probability Density Function
RUL	Remaining Useful Life
SFC	Specific Fuel Consumption

1. Introduction

This chapter is separated into three parts, the background of GDP and IRP will be introduced firstly, and then the aims and objectives will be presented in the following part and finally the methodology will be given.

1.1 Background of GDP

FW-11 is a project cooperated between Aviation Industry Corporation of China (AVIC) and Cranfield University. This group design project is a new conceptual design and the target of it is to develop a flying wing commercial airliner.FW-11, a 200-seat airliner which the range is 7500 nm, mainly focuses on Asia-Pacific region market. As a part of AVIC MSc program, the FW-11 project is constructed by three phases: conceptual design phase, preliminary design phase, and detail design phase. The author was involved in the conceptual design phase which was divided into three steps: derivation of requirements, design a conventional aircraft as baseline aircraft and design FW-11 comparing with the baseline aircraft.

The major responsibility of the author is the engine market, engine selection, engine sizing and performance. The detailed work will be presented in the Appendix A.

1.2 Background of IRP

1.2.1 DPHM Definition

The competition between airlines is becoming fiercely increased, as a result, high efficiency commercial aircraft is always considered to fulfill this demand. From the operator’s point of view, the reduction of operational cost plays a very important role of aircraft efficiency. Consequently, novel technologies need to be taken into account. In response, diagnostics, prognostics and health management (DPHM) was introduced into aircraft industry recently. International space station and space shuttles applied this new technology for years [1], as well as the Joint Strike Fighter which introduces not only a comprehensive and integrated diagnostics system, but also prognostics, and an information system including decision support tools for the users. [2]

Diagnostics is to determine the state of components to perform their functions according to acquired and detected parameters; prognostic is predictive diagnostics including the determination of the remaining time to failure of components. Health management has the capability to provide suitable decisions in order to instruct maintenance actions according to diagnostics and prognostics technology and operational demand. [3]

1.3 Aims and Objectives

1.3.1 Objectives of GDP

In the conceptual design stage of FW-11, the main target of the author in the GDP work was the engine market, engine selection, engine sizing and performance.

The following objectives will be achieved:

- Research and report on the current engine market and its development in terms of technology
- Employ an appropriate method to estimate the dimensions of the engine
- Utilize TURBOMATCH to calculate the performance of the candidate engine

1.3.2 Objectives of IRP

The main target of this individual research project is to build a set of health management methods which are suitable for the aircraft landing gear extension/retraction control system.

The following objectives will be achieved:

- Research and report on diagnostic and prognostics health management history and trends
- Research and report on the currently available diagnostic and prognostics

techniques

- Use a typical landing gear extension and retraction control system as a case study in order to apply the methodology of DPHM
- Research and report on how can DPHM effect the system maintenance and reduce the cost

1.4 Methodology

1.4.1 Methodology of GDP Work

According to the development procedure of the FW-11 was that a conventional configuration was developed firstly for comparison, and then the flying wing configuration was considered, the design flow of is presented as below:

1) The current engine market and its development in terms of technology was analyzed.

2) For the conventional configuration, an existing engine was chosen from the engine market as a baseline engine.

3) A new concept engine was considered based on the market analysis and development, and then sized with available method according to the aircraft parameters and was built to calculate the performance of the engine. Consequently, the performance of the conventional configuration aircraft could be compared with these two types of engines.

4) For the flying wing configuration, sizing the new concept engine which is the same type as the conventional configuration aircraft use the same method and build a TURBOMATCH model to acquire the performance of the engine.

5) Finally, these engine parameters were provided to the performance team and mass & CG team so that the performance of the conventional configuration and the flying wing configuration could be compared.

1.4.2 Methodology of IRP Work

The design flow is shown as follows:

First of all, the landing gear extension/retraction control system of AIRBUS A330 was chosen as a case study.

Secondly, in order to apply the diagnostic and prognostic approaches, the key parameters and major components need to be identified and monitored. Then the functional hazards assessment (FHA), failure modes and effect analysis (FMEA) and fault tree analysis (FTA) would be performed to verify the failure modes and critical component.

Thirdly, based on the result of the system safety and failure analysis, the writer will utilize appropriate diagnostic methods and prognostic approaches respectively. Then, have a case study according to the chosen diagnostic methods and prognostic approaches.

Finally, the writer will build the architecture of DPHM for the system.

2. Literature Review

2.1 DPHM Development and Functions

2.1.1 DPHM Evolution

From the 1950s to the 2000s, the evolutionary process of the aircraft system health management technologies which were developed in the Department of Defense (DoD) and NASA and is listed in Table2-1.

Table 2-1 Health Management Technologies Evolution [5]

	DoD	NASA
1950s	• Reliability analysis • System Test and Evaluation • Quality Methods	• Reliability Analysis • System Test and Evaluation
1960s	• Modelling • Failure Analysis	• Modelling and Simulation • Failure Analysis • Telemetry of Data • Systems Engineering
1970s	• System monitoring • Reliability Centred Maintenance • Systems Engineering • Built In Test (BIT)	• System Monitoring • On-board fault protection • Redundancy management • Byzantine fault theory
1980s	• Expanded BIT • Data buses and digital processing • Engine Health Monitoring • Total Quality Management	• Expanded BIT • Data buses and digital processing
1990s	• Integrated Diagnostics • Flight Data Recording	• Diagnostics • Vehicle Health Monitoring • Vehicle Health Management • System Health Management
2000s	• Prognostics • Integrated Vehicle Health Monitoring • Integrated Vehicle Health Management	• Integrated System Health Management • Integrated System Health Engineering and Management

Early-generation aircraft, in order to meet their health management requirement, relied on manual detection of failures and only schematic and voltmeter readings were available for maintainers. Over the 1950s and 1960s, as aircraft systems got more and more complicated and integrated, in order to notice the operators and maintainers of safety-critical situations, BIT was employed, which led the implementation of built-in test equipment (BITE), simple alarms and trending analysis. Line-replaceable unit (LRU) which is small light-emitting diode (LED) could indicate a fault when it is detected. This capability could reduce the ground-support equipments which were used to test critical components. However, the reliability of BITE was poor, and it was difficult to use and often confusing. The system operators and maintainers still did not fully use this ability and often depended on the voltmeter and schematics. [4]

In the 1970s, as the break through of computer technology, more and more computers were introduced into complex aircraft systems. These computers called digital BITE have the capability to display different fault by using numeric codes which could identify each type of fault and isolate them as well. This approach was implemented on many aircraft, such as the B757/767, A300/310, etc. [4]

In 1986, as the next phase, the ARINC 604 was defined, providing a central fault display system (CFDS) which indicate all the systems status on the airplane with one display. This approach is capable of accessing maintenance data more consistently to across all systems and replacing the system LRUs on the front-panel displays. Many of the systems on the B737, the A320 and the MD11 applied this technology. [4]

In the early 1990s, as aircraft systems still became more integrated and complex, the ARINC 624 was developed to troubleshoot a problem which a single fault may cause many fault indications for other systems. This provided a more integrated maintenance system which could reduce more ground-support equipment and also consolidate multiple systems fault indication. For instance, the Boeing 747-400 and 777 airplanes introduced this approach. [6]

An example of the current technical status of aircraft DPHM is the Joint Strike Fighter (JSF) program which has extensive DPHM utilizing sensors, advanced reasoning and processing, and an integrated information management system. The JSF PHM system on-board is divided into areas such as mission systems and propulsion system. [7]

2.1.2 DPHM Functions

As Modern PHM systems become very and complex, the main functions are shown in the figure below.

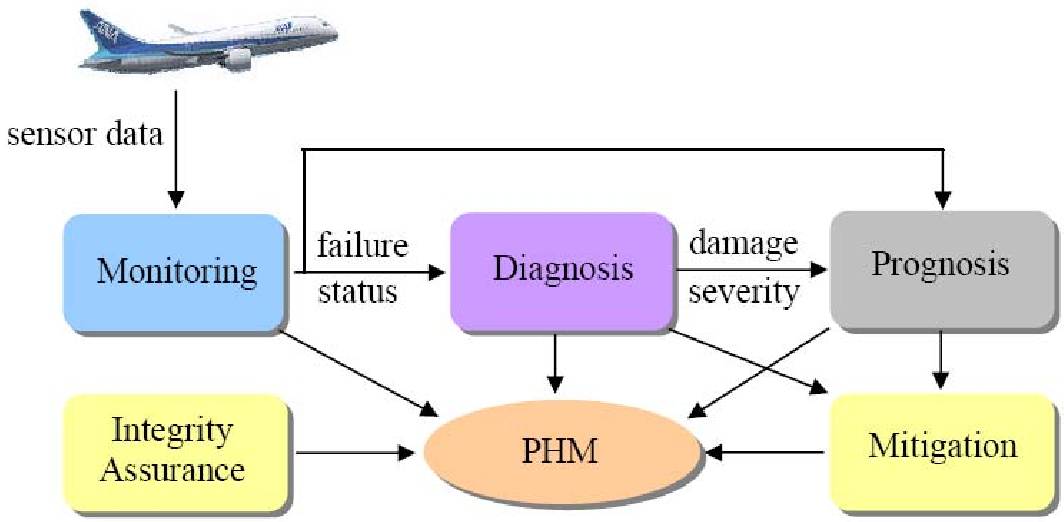


Figure 2-1 DPHM Main Functions [8]

To be more accurate, a DPHM system has many types of functions including fault detection, fault isolation, remaining useful life estimation , component life usage scouting, false-alarm reduction, health status reporting, only notifies the operator what is required to be known immediately, informs the right maintenance information to the right people at the right time, etc. “Through the philosophy and concept of health management, the modern PHM system uses these functional capabilities to complement each other and provide a much larger impact and a broader set of maintenance-oriented benefits than any single function by itself.”[4]

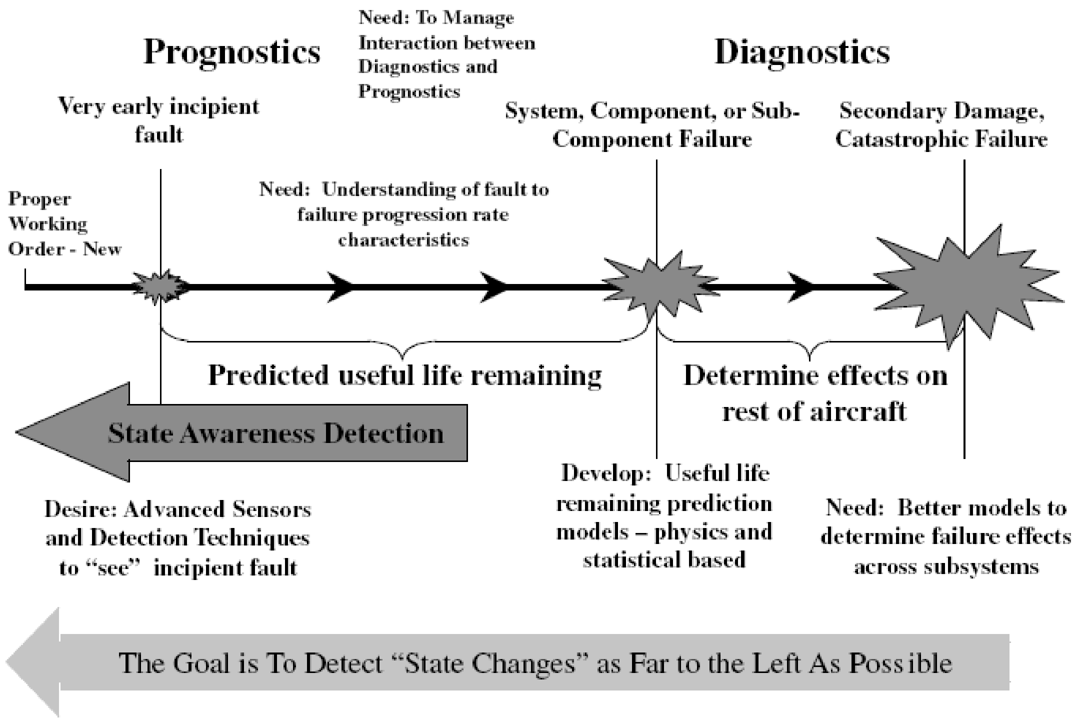


Figure 2-2 Failure Progression Timeline [4]

As it is shown in the figure above, there are three stages of fault, first of all, very early stage of fault, secondly, system, component or sub-component failure and finally, secondary damage and catastrophic failure. It is obviously that the earlier detection of the state changes the more benefit we could get. Diagnostic technology has been applied between the two stages which are more critical. Prognostic technology has the capability to make a prediction of the remaining time to failure of systems or components. In order to achieve that and predict it accurately, many tools such as advanced sensors and incipient fault detection techniques are required.

2.2 Diagnostics Techniques

Diagnosis, which has been investigated over the past decades, detects fault isolates faulty component and decides on the potential impact of a failed component on the system. [4] The prerequisite of diagnosis is to obtain available and sufficient data from a monitoring system.

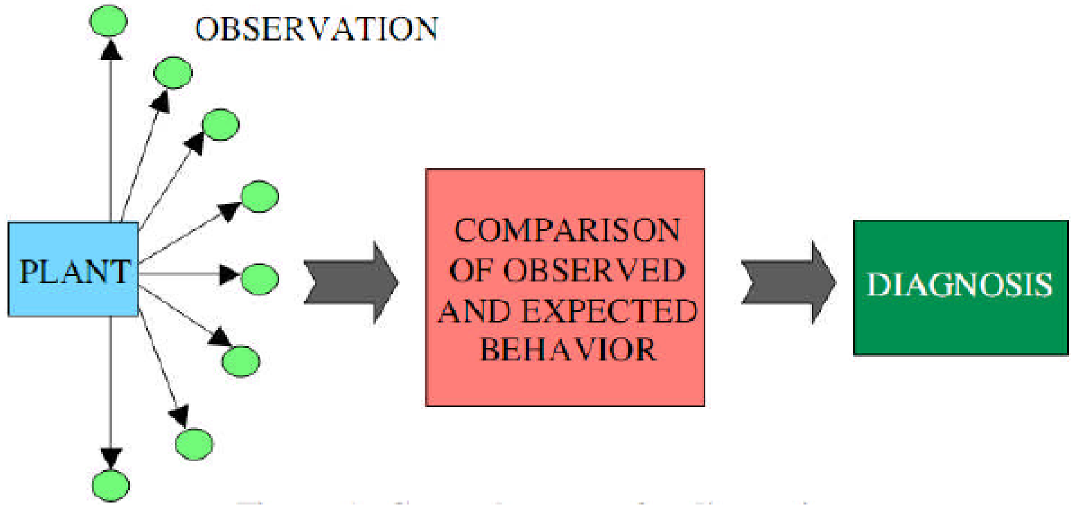


Figure 2-3 General Diagnosis process [9]

The figure 2-3 illustrates that a diagnosis process could be described in three parts: observation, comparison and diagnosis. Through observation, sufficient data could be acquired by implementing diverse sensors measuring physical characteristics such as voltage, current, and temperature. During the second step, the acquired data will be processed, then make a comparison of the processed output and the expected state. Finally, if the result of the comparison indicates the system or component working in an eccentrical way, then the cause of the fault should be diagnosed.

The following parts represent the selection of diagnostics approaches available.

2.2.1 Rule-based Expert Systems

Rule-based expert reasoning system is an artificial intelligence approach using "if-then-else" rule. The reasoning engine utilizes these “rules” and search for modes in the rules matching modes in the data. The "if" means "when the action or performance is true," the meaning of "then" is "take action A" and the "else" indicates "when the performance is not true take action B. [3]

There are mainly two reasoning methods could be applied to generate the result of diagnostics. If the starting point is hypothesized, evidence which support the hypothesis can be collected and verified by using a backward-chaining algorithm. After the evidence is proved, then the hypothesis could be regarded as the diagnostic result. Figure 2-4 illustrates a forward chaining, and the process examines rules to verify which one match the acquired evidence. [9]

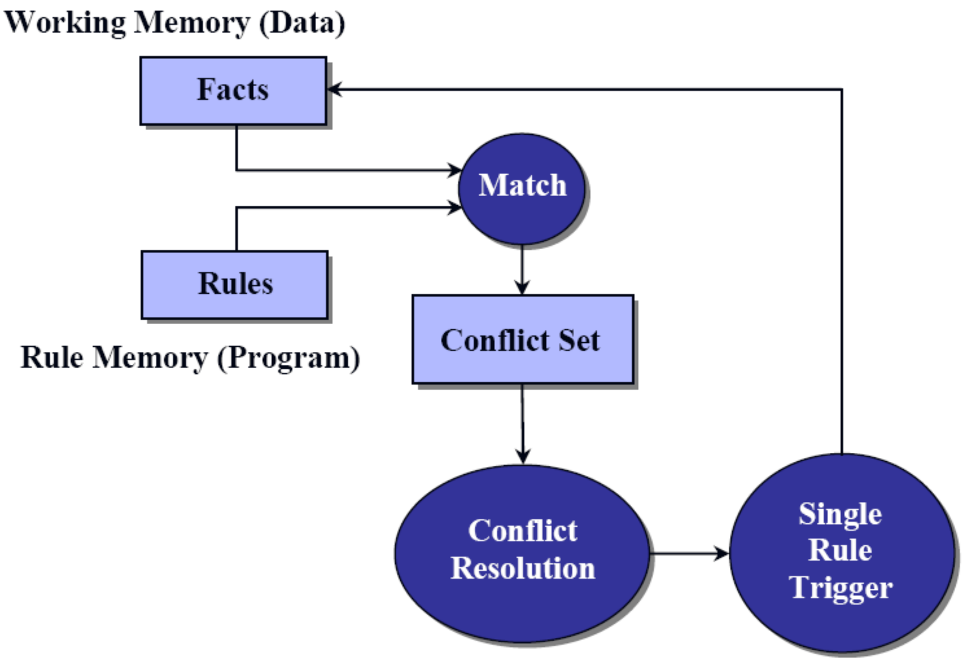


Figure 2-4 Approach of forward-chaining expert system [9]

2.2.2 Case-based Reasoning Systems

A Case-based Reasoning System is a technique using past problems to solve current problems. In addition, a case-based reasoning system has the capability to have possible adaptation of a past solution to fit similar situations by utilizing a learning component. A case-based reasoning system has a case library which describes the problem, solutions, outcomes, methods and their efficacy assessment. This technique is very suitable for poorly understood problems which structured data are available to describe operating conditions. [9]

There are mainly four phases included in the case-based reasoning architecture which are shown in the figure below. The first one is retrieval which could get the best past cases from the case library. Secondly, the differences between the past and current case will be found, then, the old solution would be modified in order to conform the new problem and a new proposed solution will be conducted.

The third step is to revise the proposed solution if it fails, then learn how to avoid that and repair the solution. Finally, the new solution will be incorporated in to the case library. [9]

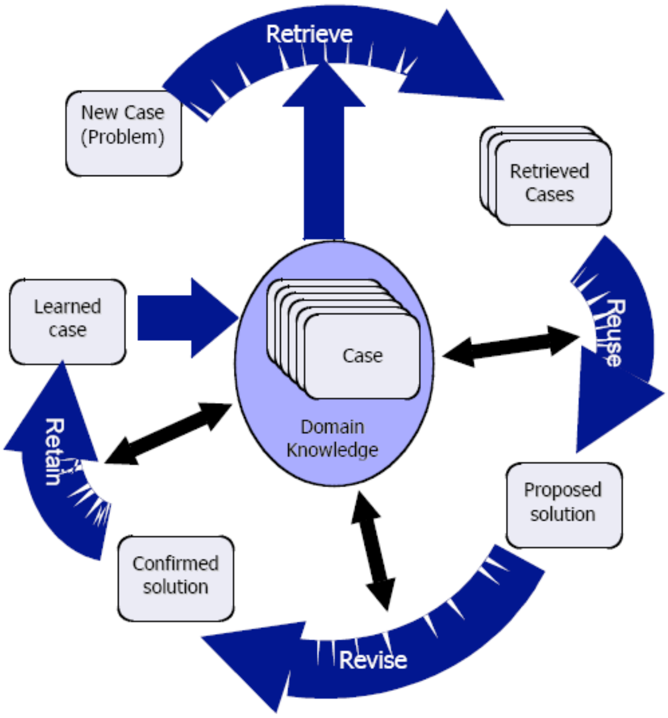


Figure 2-5 Case-based Reasoning Systems Architecture [9]

2.2.3 Learning Systems

Learning systems belongs to data-driven approaches which are developed from system operating data directly which might be power, calibration, temperature, vibration, oil debris, pressure, voltages or currents. Typically, learning system approach is divided into five parts that will be introduced below. First of all, high-impact malfunctions need to be determined according to historical data, understanding of the nature of potential faults, their locations, their severity level and the characteristic symptoms. Secondly, data selection, transformation, de-noising and preparation will be performed to build the final data base for model building and classification. After that, trends, degradation and assess the severity level of a fault for early stage warning should be detected by implementing data processing techniques. The forth step is testing and validation of models ensuring the quality and robustness the data of models. The last step is fusion which has the capability to estimate fault severity level and to evaluate the health status of a system to improve the diagnostic accuracy. [9]

2.2.4 Model-based Reasoning

The model based approach compares the system actual performance and the model expectation performance. If there is a difference between the actual and the expected values, then a discrepancy must be analyzed in order to determine the reason for it. [3] Model-based reasoning is the foundation of the diagnosis knowledge and techniques, which characterizes the widely use of variety of engineering models. [9] In parallel developments, with the implementation of powerful processors, input-output transfer function models, analytic state-based models, physics-based models, fault growth models and quantitative have been found to develop diagnostic software for dynamic systems between different communities. [10] One of the fundamental advantages of model-based techniques is that the model running with the same inputs as the actual engine will only predict the nominal outputs. [11] The figure below shows a typical example of a model-based reasoning system.

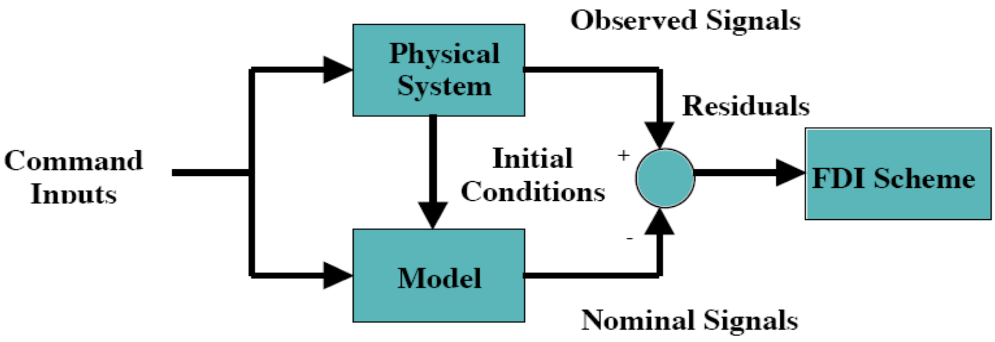


Figure 2-6 Model-based Reasoning System [9]

Table 2-2 Comparisons of Diagnostic Technologies [12]

Diagnostic Technologies	Advantages	Challenges
Rule-based expert systems	Increased availability and reusability of expertise	Domain knowledge acquisition
		Resolving conflicts
	Fast, consistent response	Completeness of rule base
		Maintenance of rule base
Case-based reasoning Approaches	Increased availability and reusability of expertise at reduced cost	Domain knowledge acquisition
	Fast, consistent response	Indexing and retrieving case information
	Increased safety	Completeness of case base
	Learning component enables adaptation to similar situations	Maintenance of case base
	Works well in conjunction with a human operator (system can make suggestions in unusual situations)	Knowledge expressing for a complex system
Model-based reasoning Approaches	Engineering models form basis for diagnosis	Model building and validation
	Interrogation of fault propagation graphs is very efficient	Scalability
	Hybrid approaches use a combination of techniques	Optimizing flexibility can be a lengthy process
	Flexible implementation	Cost
Learning-based Approaches	Data-driven approaches are able to transform high-dimensional noisy data into lower dimensional information	Highly dependent on quantity and quality of system operational data
	Provide monitoring capability	Generalization ability
	Facilitate model-building via identification of dynamic relationships among data elements	

2.3 Prognostics

The target of the prognosis element is to determine a validated estimation of the remaining time to failure of a component or system generated by the diagnosis technology. [7]

The figure 2-7 illustrates a fault progression. If a fault is detected when the severity is at 4%, only the component is required to be replaced. If the severity is increased to 10%, the subsystem is needed to be replaced. More serious is all the system required to be replaced, when the failure occurs. Consequently, it is essential to predict fault severity accurately. [4]

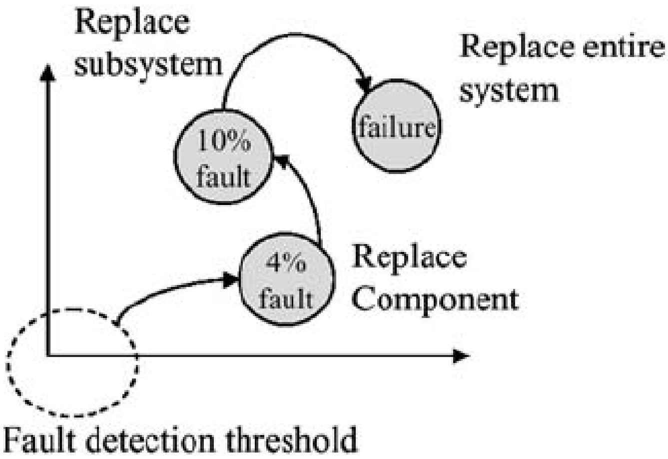


Figure 2-7 Fault propagation [4]

A system could benefit from applying prognostic techniques and the advantages are listed below [15]:

1. Maintenance actions could be scheduled according to advanced warnings of failures.

2. Because of maintenance cycles could be extended if the developed method is proven and validated, the availability of a system will increase.

3. Life-cycle costs of equipments would be lower by reduce inspection costs, downtime and inventory.

After noticing the advantages of prognostic techniques, the challenges should be identified. In order to prognoses accurately, the fault propagation models and sufficient statistical fault data which could assist in establishing prognostic algorithms are required. In the following parts, four challenges of the prognosis technologies will be introduced. [4]

Challenge 1: Normally, the dimension of a fault might not be detected directly; as a result, some measurable parameters which could indicate the fault dimension are required.

Challenge 2: How can it predict the fault progression accurately? A prognosis system might have the capability to settle this problem after an appropriate algorithm; available sensor metrical parameters and models of a system are utilized.

Challenge 3: How can we determine the prediction confidence limits? In this case, probabilistic or other methods could characterize the uncertainty distribution when time is progressing.

Challenge 4: How can we make the prediction more accurate, confident, and precise after the initial uncertainty bounds and the fault progression have been predicted? It is suggested that a learning strategy which could provide corrections according to the actual fault propagation and reliable algorithms of prognosis may be required.

Figure 2-8 summarizes the range of prognosis approaches applied to different systems, and shows the relative cost as well.

George Vachtsevanos, 2006, suggested that there are three approaches could be utilized, which are model-based prognosis approaches, probability-based prognosis approaches and data-driven prediction approaches. [4] These approaches will be introduced below respectively.

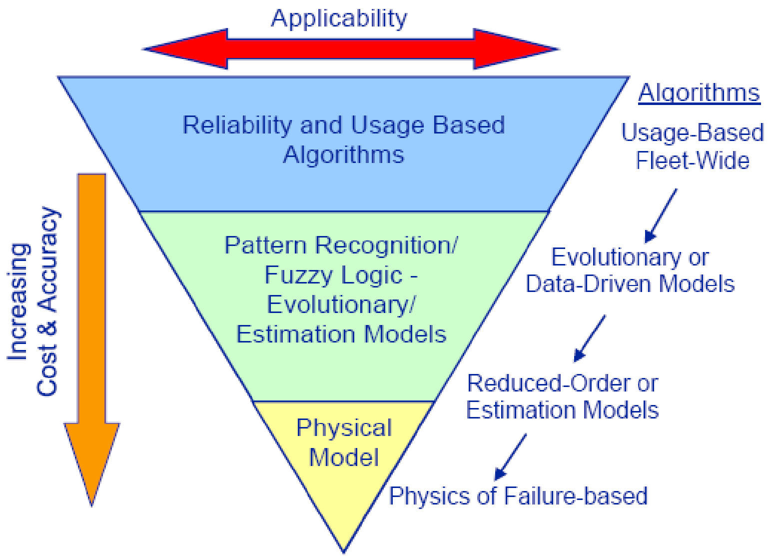


Figure 2-8 Approaches of Prognostic Technology [13]

2.3.1 Model-based Prognosis Techniques

Model-based prognostic schemes mainly include four method which are autoregressive moving-average (ARMA) techniques, physics-based models, empirical-based methods and Kalman/particle filtering, these methods could utilize a dynamic model of the process predicted, which provide a extensive approach which has been used to comprehend progressions of failure modes of components. [4] Figure 2-9 shows a schematic of physics-model based approach.

Model-based approaches to prognosis can make RUL estimated without any measurable event; however, the model usually could be calibrated according to the related diagnostic information which is present. Consequently, a combination of the model-based and feature-based approaches could fully provide prognostic capability over the whole time to failure of the component. [4]

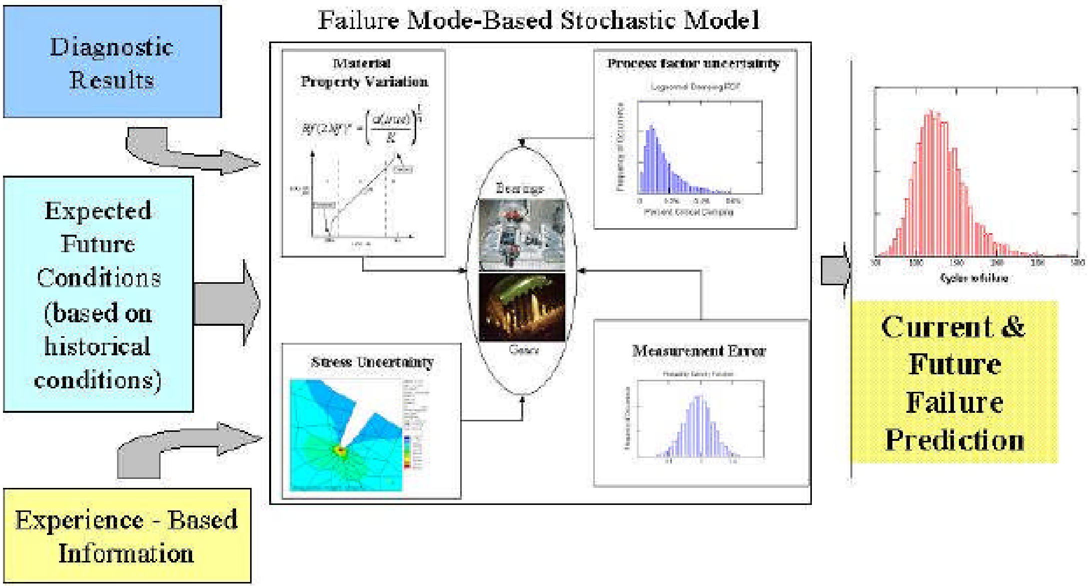


Figure 2-9 Physics-model Based Approach [13]

2.3.2 Probability-based Prognosis Techniques

It is very effective to use probabilistic methods of prognosis when previous failures could be provided by historical data. Compared with model-based techniques, less detailed data and information is required. The reason is that the information required for prognosis comes from various probability density functions (PDFs), instead of coming from dynamic differential equations. There are advantages provided by these methods which the sufficient PDFs could be acquired from statistical data and confidence limits of the result could be given in order to have accurate and precise predictions. [4] Generally, probability-based prognosis techniques include three approaches which are Weibull Distribution model, Bayesian Probability Theory and Probability Density Function of Remaining Useful Life.

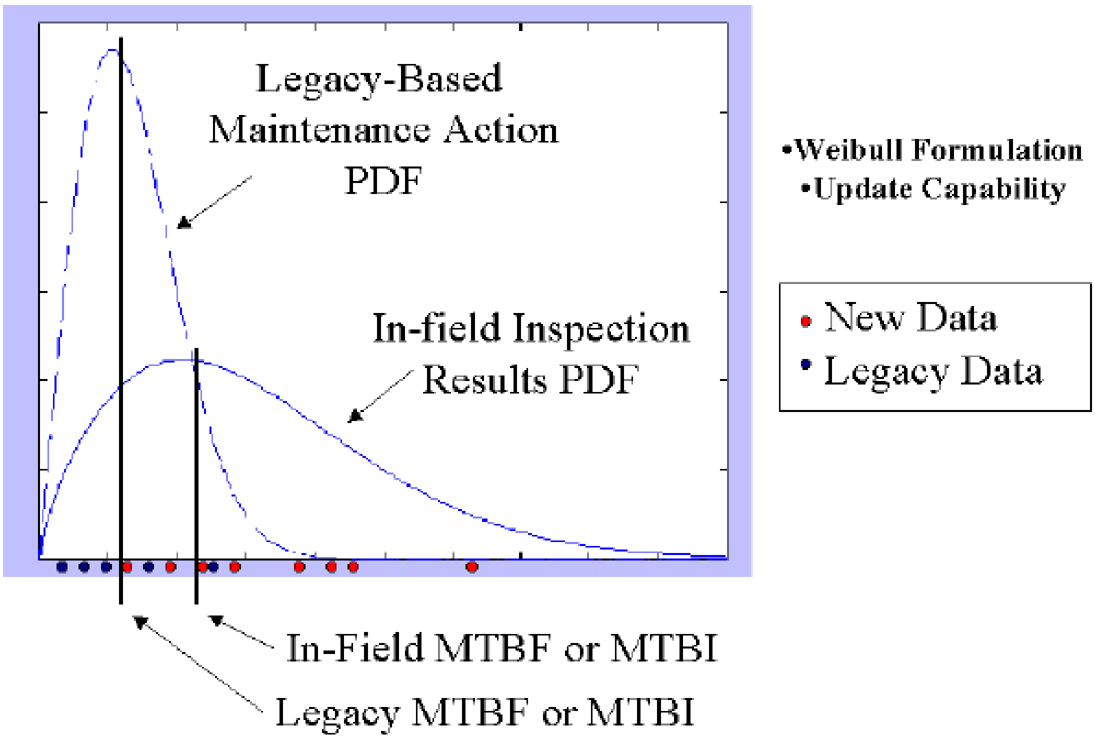


Figure 2-10 An Example of Probability-based Approach [14]

2.3.3 Data-driven Prediction Techniques

In many cases, it is impractical to conduct a physics-based model for prediction when various historical fault data lead to the failure. Nonlinear network approximators could be used, which use well established formal algorithms so that desired outputs would be provided directly. The neural network is included in nonlinear networks; signals could be processed by using techniques in fuzzy logic systems and biological nervous systems, which are based on human linguistic and reasoning abilities. [14]

In this approach, operational data which are related to health status of a system is gathered. This technique is suitable for the situation when the system performance characteristics need to be fully defined to permit complicated models to be developed. There are mainly two advantages could be provided by this approach. The first one is that it can be developed quickly, and secondly, it is cheaper than the model based approach. However, the main disadvantage of this approach is that substantial data are required in order to have the mature analysis. [16]

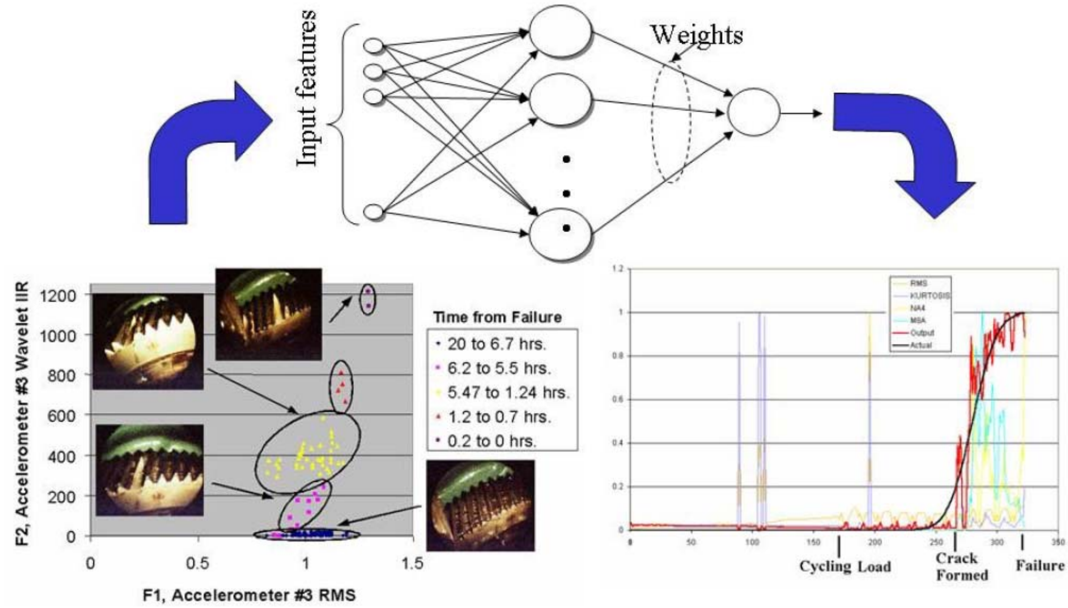


Figure 2-11 Data-Driven Model Based Approach [14]

3 Landing Gear Extension/Retraction Control System Safety and Failure Analysis

The main functions of an aircraft landing gear extension/retraction control system are to operate the main landing gear, nose landing gear and their doors open or close when an aircraft is taking off and landing, at the same time the position of the gears and doors could be indicated on the central instrument panel and shown to pilots.

In order to meet the research objectives, the landing gear extension/retraction control system of AIRBUS A330 was chosen and introduced firstly. All the other research works were depended on this system. After implementing the FHA, FMEA and FTA, the critical component and main parameters of the system were determined and further research could be carried on based on the analysis.

3.1 Introduction of Landing Gear Extension/ Retraction Control System

The A330 is a wide-body twin aisle aircraft which is the most efficient one in operation today, it could be presented in form of numbers such as over1,100 firmed orders, 120 customers and operators, more than 780 aircraft in service, over 17 million flight hours and over 4 million flights. [27]

According to the A330 flight crew operating manual, this aircraft has not currently equipped the advanced DPHM system. However, probably it will be still in service in the next 20~30 years or even longer, consequently, it is possible that the advanced PHM technology will be implemented on the A330 to increase the competitive capabilities.

The landing gear extension/ retraction control system has three main functions, the first one is normal operation function which controlled by the landing gear lever located on the center instrument panel, secondly, the indication function that the position of gears and doors are shown on the center instrument panel, finally, the

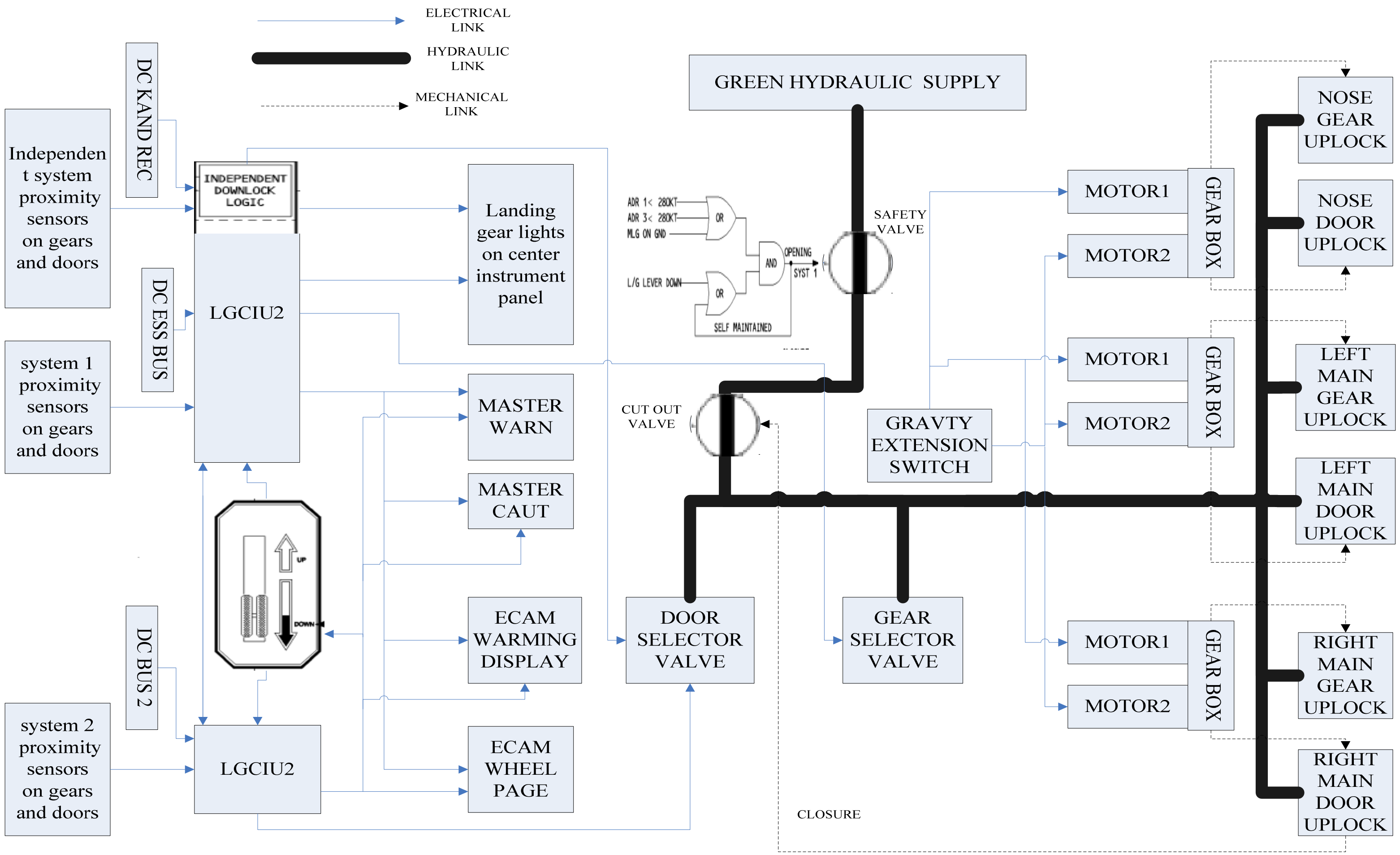


Figure 3-1 Schematic of A330 landing gear extension and retraction control system [26]

gravity extension function which controlled by two selectors on the center instrument panel. [26] The system architecture was introduced based on the three functions respectively.

As it was mentioned above, the normal operation function is controlled by the lever, and gears and doors are electrically controlled by two landing gear control and interface units (LGCIU), the two LGCIU will switch over automatically after a complete extraction/retraction cycle or a failure is detected. All the gears and doors are powered by the green hydraulic system. A safety valve is controlled by two signals which are lever position and aircraft speed. The valve will be open if the lever is at down position and the aircraft speed is lower than 280 knots. [26]

The normal operation architecture is given in figure 3-1 below.

The landing gear position indication and warning function is another important function. The gears and doors position could be indicated by landing gear indicator panel and the ECAM wheel page. The landing gear position indication is still provided by LGCIU1 even when the LGCIU2 is controlling the cycle. According to the hazard class of a failure, warnings and cautions will be performed in many modes such as aural warning, master light, local warning and etc, when a fault is detected. [26] The normal operation architecture is given in figure 3-2 below.

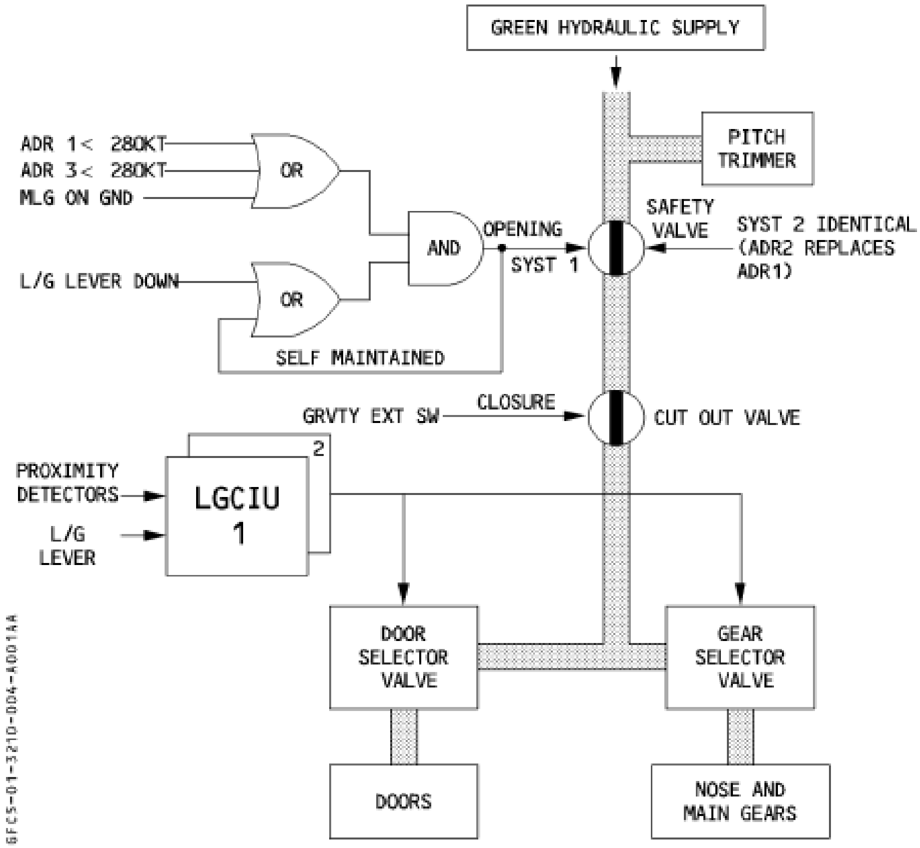


Figure 3-2 Normal operation architecture [26]

Finally, the gravity extension system, when the normal operation failed, permits the nose landing gear and main landing gear extension. When the electrical selector is set to down position, gears and doors are electrically unlocked, and then, main landing gear and nose landing gear could be extended by gravity, after that, gears and doors could be down locked. All the doors remain open after gears are extended. The indication function is still available for gravity extension. [26]

The components of this system are presented in the table 3-1 below.

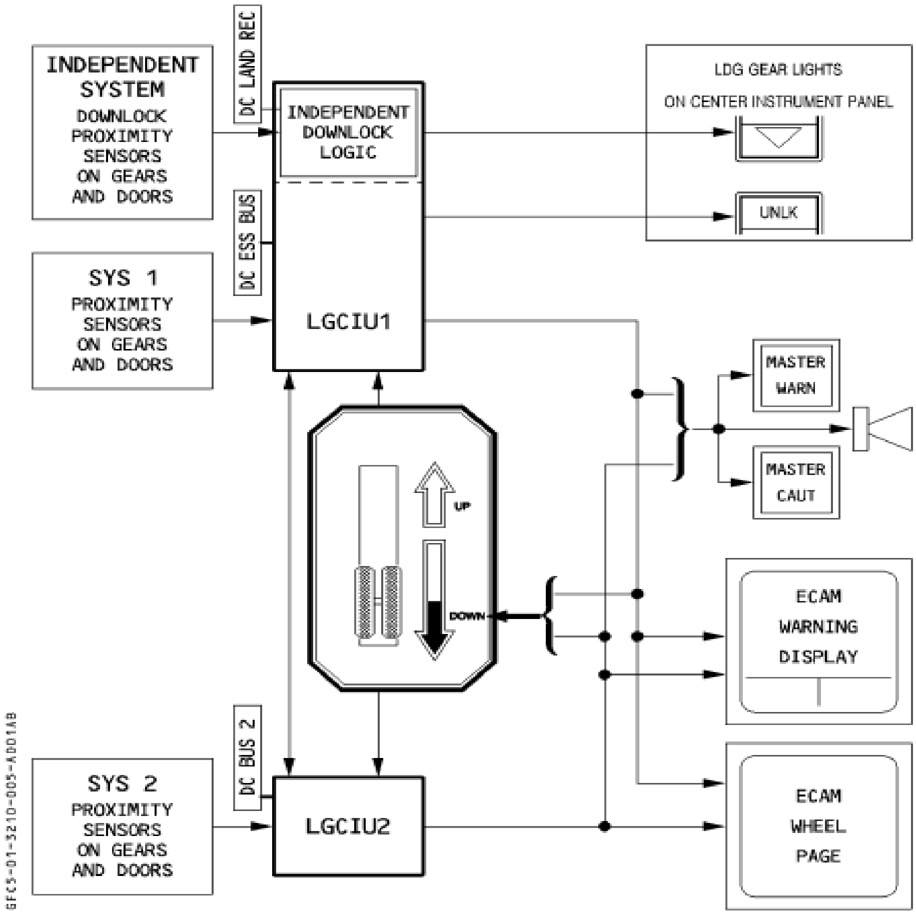


Figure 3-3 Landing gear indication and warning architecture [26]

Table 3-1 Bill of Material

Item	Components	Item	Components
1	L/G Lever	5	Gear selector valve
2	LGCIU1	6	Proximity sensors
3	LGCIU2	7	Gravity extension switch
4	Door selector valve	8	Gravity extension motor

The author was only considered the components of landing gear extension and retraction control system, all the other components such as connectors, wire, hydraulic valves, and structural components were not considered.

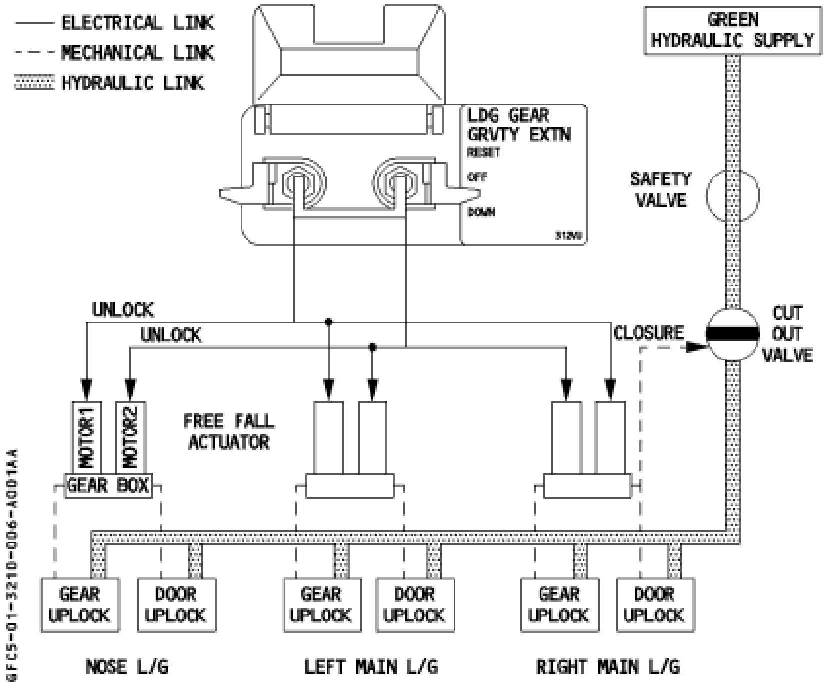


Figure 3-4 Gravity extension [26]

3.2 System Functional Hazard Analysis

The following paragraphs present a Functional Hazard Assessment (FHA) for the system. The purpose of this part is to perform a systematic and comprehensive examination of the function of the landing gear extension/retraction control system, and to identify all catastrophic, hazardous, major and minor failure conditions.

The FHA is also a starting point of the FMEA and related to other analyses, which provide the data on fault symptoms of the system. The FHA is constructed according to SAE ARP 4761. [25]

3.2.1 Failure Condition Severity and Effect Classifications

The severity of failure modes should be classified in order to measure the potential effect caused by failures. The following table represents the failure condition severity and its effect classifications. [8]

Table 3-2 Failure Condition Severity and Effect Classifications [25]

Failure Severity Level	Failure Effect
Catastrophic	All failure conditions preventing continued safe flight and landing
Hazardous	- A large reduction in safety margins or functional capabilities; - Physical distress or higher workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; - Adverse effects upon occupants.
Major	- Significant reduction in safety margins or functional capabilities; - Significant increase in crew workload or in conditions impairing crew efficiency; - Some discomfort to occupants.
Minor	Failure conditions which would reduce airplane safety margin slightly; increase the crew workload and cause some inconvenience to occupants.

3.2.2 Summary of Landing Gear Extension/Retraction Control System FHA

The detailed results of FHA were shown in the Appendix B. The failure conditions related to catastrophic and hazardous events were pointed out and presented in the following table 3-10, because the flight safety would be influenced.

Table 3-3 Summary of system FHA

Failure conditions	Severity Level
Loss of nose landing gear extension	Catastrophic
Lose of left main landing gear extension	Catastrophic
Lose of right main landing gear extension	Catastrophic
Loss of nose landing gear doors extension	Catastrophic
Loss of left main landing gear doors extension	Catastrophic
Loss of right main landing gear doors extension	Catastrophic
Erroneous nose landing gear extension position indication without warning	Catastrophic

Table 3-3 Summary of system FHA(cont.)

Erroneous left main landing gear extension position indication without warning	Catastrophic
Erroneous right main landing gear extension position indication without warning	Catastrophic

3.3 Failure Modes, Effects and Criticality Analysis

Failure modes,effects and Criticality analysis (FMECA) is a bottom up approach that all possible failures should be outlined and the effect of each failure would be determined, and then each failure could be ranked based on the category of criticality. Normally, the procedure is performed in two steps: the failure mode and effect analysis (FMEA), the Criticality Analysis (CA): [28]

1) The failure mode and effect analysis (FMEA)

It is utilized to examine the failure modes on the system to verify the results of failures and to classify the severity level of each potential failure. [8]

2) The Criticality Analysis (CA)

Based on the FMEA, every failure mode would be ranked based on the influence of severity level. [8] The criticality analysis was not performed in this thesis.

3.3.1 Summary of Landing Gear Extension/Retraction Control System FMEA

When FMEA is performed it should be considered that there is only one failure in the whole system. The detailed results of FMEA were shown in the Appendix C.

3.4 Fault Tree Analysis (FTA)

3.4.1 Introduction

The following parts introduce the FTA of the landing gear extension/retraction control system. A FTA is to set one undesired event as a top event and then utilize a method to identify all the root causes of it. The research of FTA is based on the result of the FHA and FMEA developed above. The main functions of FTA are listed below: [25]

a) A comprehensive fault tree analysis represents each failure event that could lead to the undesired event.

b) Assess the system safety while it has been modified.

c) Calculate the probability of a top event.

d) Allocate the probability of lower level events.

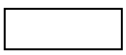
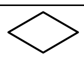
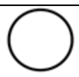
e) Assess the effects of single and multiple faults.

f) Assess the redundant design attributes (fault tolerant).

3.4.2 Symbols of FTA

A fault tree is consisted of two types of symbols, logic and event. The used logic symbols and event symbols are explained in the table 3-4. [25]

Table 3-4 Symbols of FTA

Symbols	Name	Definition
	Description Box	Description of an output of a logic symbol or of an event
	Undeveloped event	An event has negligible impact on top event or details of further event are not readily available
	Basic event	Event which requires no further development
	OR-gate	Boolean logic gate - event can occur if any one or more of the lower conditions are true
	AND-gate	Boolean logic gate - event can occur when all the lower conditions are true

The detailed results of FTA were shown in the Appendix D.

3.5 Conclusions

According to the results of FHA, FMEA and FTA, each of the catastrophic events of the landing gear extension/retraction control system and all the root causes and their effects were identified. Synchronously, all the components which are related to the catastrophic events are listed in the table below. Consequently, the crucial components of the system could be identified and the key parameters of the components could be acquired.

Table 3-5 Results of FHA, FMEA and FTA of the System

Failure condition			
Loss of nose landing gear extension			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Gear selector valve LGCIU1,LGCIU2, Gravity extension switch, Unlock motors	LGCIU1,LGCIU2	Electrical power signal
Failure condition			
Loss of left main landing gear extension			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Gear selector valve LGCIU1,LGCIU2, Gravity extension switch, Unlock motors	LGCIU1,LGCIU2	Electrical power signal

Table 3-5 Results of FHA, FMEA and FTA of the System(cont.)

Failure condition			
Loss of right main landing gear extension			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Gear selector valve LGCIU1,LGCIU2, Gravity extension switch, Unlock motors	LGCIU1,LGCIU2	Electrical power signal
Failure condition			
Loss of nose landing gear doors extension			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Door selector valve LGCIU1,LGCIU2, Gravity extension switch, Unlock motors	LGCIU1,LGCIU2	Electrical power signal
Failure condition			
Loss of left main landing gear doors extension			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Door selector valve LGCIU1,LGCIU2, Gravity extension switch, Unlock motors	LGCIU1,LGCIU2	Electrical power signal

Table 3-5 Results of FHA, FMEA and FTA of the System(cont.)

Failure condition			
Loss of right main landing gear doors extension			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Door selector valve LGCIU1,LGCIU2, Gravity extension switch, Unlock motors	LGCIU1,LGCIU2	Electrical power signal
Failure condition			
Erroneous nose landing gear extension position indication without warning			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Gear selector valve LGCIU1,LGCIU2, Proximity sensors Warning system	LGCIU1,LGCIU2	Electrical power signal, Sensors signal
Failure condition			
Erroneous left main landing gear extension position indication without warning			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Gear selector valve LGCIU1,LGCIU2, Proximity sensors Warning system	LGCIU1,LGCIU2	Electrical power signal, Sensors signal

Table 3-5 Results of FHA, FMEA and FTA of the System(cont.)

Failure condition			
Erroneous right main landing gear extension position indication without warning			
Severity	Related component	Failure detect method	Parameters
Catastrophic	L/G lever, Gear selector valve LGCIU1,LGCIU2, Proximity sensors Warning system	LGCIU1,LGCIU2	Electrical power signal, Sensors signal

4. Diagnosis Technology Research

4.1 Introduction

In this chapter, diagnosis research was developed for the Landing gear extension and retraction control system based on a selected approach. This chapter can be consisted of four parts. First of all, rule-based expert system was chosen from the diagnosis approaches introduced in the literature review chapter. Secondly, the structure and design of this diagnostic research was developed. The third step was to have a case study in order to demonstrate how the diagnosis affects the system. Finally, the conclusion was presented.

4.2 Chosen of Diagnosis Approach

Rule-based expert system was chosen from the four approaches introduced in chapter 2 based on the comparisons given as follows.

The procedures which a rule-based expert system performs can be divided into many steps and translated into rules which describe action that should be taken when a symptom is detected. The advantages of this approach are the increase of availability, reusability of expertise and reliability for decision making, fast and steady response and consistent performance. However, there are challenges of this technique, which are the domain knowledge acquisition and the completeness, correctness and consistency of the rule base. [9]

The case-based expert system is highly dependent on a large amount of domain knowledge from engineering experiences. The main advantage of a case-based system is to make suggestions in new situations which adapt similar cases. However, the indexed and retrieved case information are required to support the case-based reasoning system, consequently, it is difficult to obtain a complete case base. [8]

The model-based reasoning approaches employ engineering model from basis and the interrogation of fault propagation is efficient for a linear dynamic systems.

Nevertheless, the drawbacks of it also exist, sufficient model are required, the model building and validation are very important for its performance and the performance of this approach is unsatisfied for the non-linear and complex system. [9]

Learning system belongs to data-driven approaches which are able to lower the dimension of noise and could provide monitoring capability, but sufficient and available model sets or system operating data which could derived for a long term are needed. [12]

According to the above comparisons, the writer would prefer to choose rule-based expert system for the diagnosis research of landing gear extension/retraction control system. The following parts present the details of the application of this approach for the system.

4.3 Architecture of Rule-based Expert Systems

A routine rule-based expert system is to utilize human expert knowledge to overcome real world problems which human intelligence would be normally required. An expert system explains and organizes the expert knowledge to be rules within computer programme which has the capability of trouble handling. Rule-based expert systems play a very important role in intelligent modern systems and there have been some successful applications in many ways such as strategic goal setting, design, planning, scheduling, diagnosis. The important feature of expert system is that the quick response and accurate diagnosis of any failure or faults when they occurred, it could solve the actual problems by using domain knowledge base. An important advantage of expert systems is that the reasoning process could be explained and handles levels of confidence and uncertainty. [29]

A rule-based expert system utilizes “if-then-else” principle to describe the conditional statements which comprise the knowledge base. The architecture of rule-based expert system is shown below. There are six basic components included in a rule based expert system, they are knowledge base, system data base, inference engine, user interface, knowledge base acquisition facility and explanation facility.

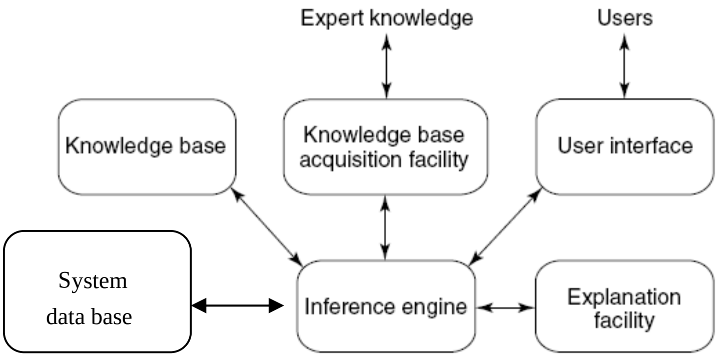


Figure 4-1 Architecture of rule-based expert systems [29]

1) Knowledge base

The basic function of a knowledge base is that all the rules, cases and relevant information are stored and managed. A rule is a translation of a condition of the system and related actions. [30]

2) System data base

System data base is the special place for the storage of the current system operational data which including the real-time system operating status and inputs. [8]

3) Inference engine

The main responsibility of the inference engine is to find an appropriate or related knowledge from the knowledge base according to the data acquired from the system data base, and then present the solutions of problems. [29]

4) User interface

The function of the user interface is for developers, users and administrators to design, update, and use expert systems. [29]

5) Knowledge base acquisition facility

The main purpose of the knowledge acquisition is to translate the domain knowledge into rules to construct the knowledge base, in other words, it takes the responsibility of updating, revising, maintaining and administrating the knowledge base. [29]

6) Explanation facility

The explanation facility is to explain a problem and its reasoning result for users. [29]

4.4 Design of Rule-based Expert Systems

4.4.1 Work Flow of a Rule-based Expert System

According to the architecture of a rule-based expert system, the work flow of it could be presented as a flowchart given below.

As it is shown in the figure 4-2, the work flow could be introduced in the process given below.

1) The fault signals are collected and monitored by sensors when the system is in operation

2) The signals are sent to system data base and be filtered, and then translated into programs which could be identified.

3) The program would be sent to the inference engine, and then a rule could be selected from the knowledge base.

4) If a rule which is match the status of the signal is found, appropriate solution could be suggested to maintainers to take actions and the problem and its reasoning result would be explained to users through explanation facility.

5) If the feedback from maintainers that the solution is not able to solve the failure, the rule would be revised, then a new suggestion will be given to maintainers.

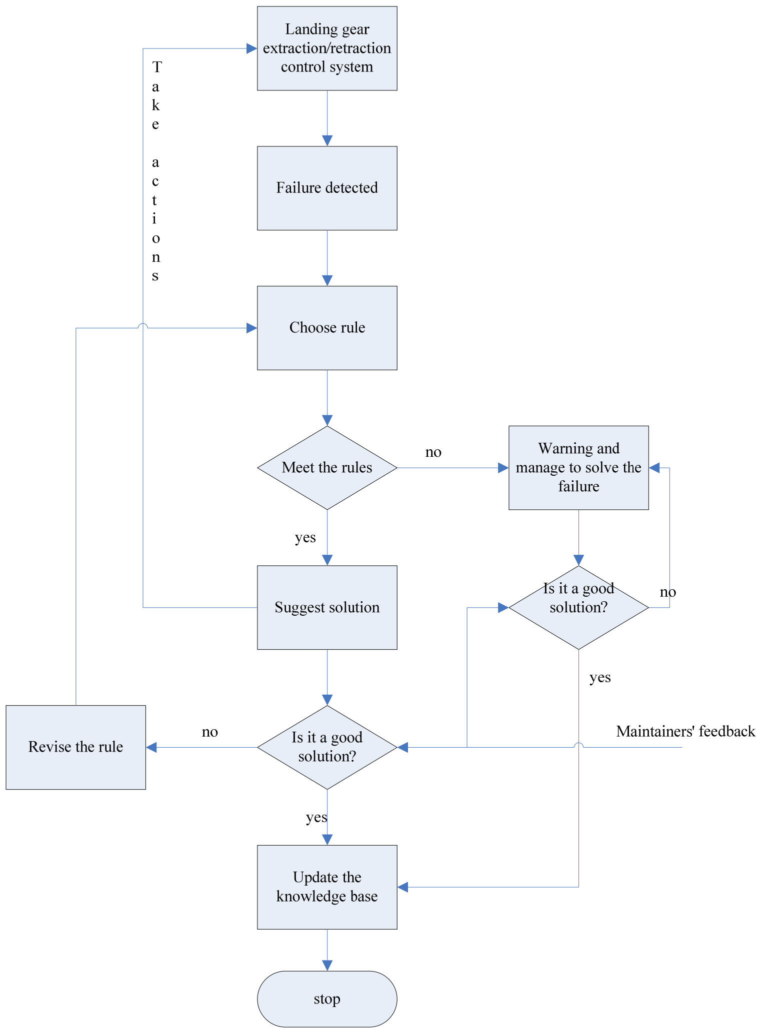


Figure 4-2 Flowchart of a rule-based expert system

6) If there is no rule matching the current status, a warning would be performed to notice the system developer, and a solution would be provided to maintainers, and the feedback cycle should be performed until a satisfied solution is acquired.

7) After the failure has been successfully settled, a new rule would be produced and saved into the knowledge base.

4.4.2 Domain Expert Knowledge Acquisition

According to the work flow, it is clearly that the core element of the rule based expert system is the knowledge base. The system could perform well as long as sufficient and enough available domain knowledge can be obtained. Consequently, the acquisition of comprehensive domain expert knowledge is in the most important factor. The domain expert knowledge could be acquired from three aspects: system operational principle, operational experiences and fault tree analysis. Failure modes of a system could be conducted based on the system operational principle. The domain knowledge could be obtained form the system maintenances, system designers and flight crew. Their experiences could provide large quantities of practical data for diagnostics.

The root causes of catastrophic and hazardous events could be identified and presented by utilizing fault tree analysis. [8]

4.5 Case Study

According to the analysis results developed in chapter 3 and the discussion of diagnosis approach shown above, a case study will be given in the following parts. First of all, the gear selector valve was chosen form the system. Secondly, failure modes of the gear selector valve were summarized. Finally, rule based expert system was applied into the gear selector valve.

4.5.1 Selection of the Gear Selector Valve

There are mainly two reasons that the gear selector valve is chosen for this case study. The first one is that based on the FHA, FMEA and FTA performed in chapter 3, the results shows that most of the catastrophic events of the landing gear extraction/retraction control system are related to the gear selector valve failure. Secondly, a survey was performed and it was found that serious problem and catastrophic events related to the landing gear control system happened in history. For instance, on 14th April 2011, an Air France A330 had an emergency landing because there was a problem of the landing gear [36] and on 1st Nov 2011, a Boeing 767 had an emergency landing without any landing gear was extended [35]. Consequently, the gear selector valve was selected for the case study.

4.5.1.1 Introduction of the Gear Selector Valve

The landing gear selector valve is an electro-mechanical device which could change the hydraulic flow to control the extension/retraction of the landing gear. It is consisted of two parts which are electrical control part and mechanical part. The electrical control part is normally an electromagnetic device which is powered by the two LGCIUs. The mechanical part is a moveable component driven by the electromagnetic device in order to change the hydraulic flow. When the electrical control signal is sent to the valve, the electromagnetic device could drive the moveable component to either the extension position or the retraction position. As it can be seen from the figure below that the component has the electrical interface and the hydraulic interface.

Figure 4-3 Landing gear selector valve

4.5.2 Failure Modes of Landing Gear Selector Valve

According to the FMEA developed in chapter 3, the failure modes of the landing gear selector valve are listed below.

Table 4-1 Failure modes of landing gear selector valve

Failure modes	Local effect	System level effect
Internal leakage	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function
Fails to switch to extension position	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function
Fails to switch to retraction position	Loss of the landing gear retraction function	Landing gears remain at extension position
Selector valve always at extension position	Loss of the landing gear retraction function	Landing gears remain at extension position
Selector valve always at retraction position	Loss of the normal landing gear extension function	Reduce the redundancy of landing gear extension function
Loss the control of actuators	Loss of the normal landing gear extension function	Reduce the redundancy of landing gear extension function
	Loss of the normal landing gear retraction function	Landing gears remain at extension position

4.5.3 Diagnosis of Landing Gear Selector Valve

According to the failure modes of the landing gear selector valve, the internal leakage could be detected by implementing a senor which could detect the acoustic signal caused by the leakage. [31] [32] The failure mode which is fails to switch to extension position could be caused by electrical power and mechanical fault. The electrical power signal could be detected by the LGCIU. The mechanical fault could be explored by utilizing a type of sensor which is available to indicate the position of the core of the valve. The main theory of this type of sensor is the same as the proximity sensor in the landing gear extension/retraction control system. The following three failure modes could be diagnosed by using the same method of the second one. The last failure mode could be diagnosed by utilizing the flow sensor which could indicate the flow rate of the output of the valve. [33]

4.5.3.1 Domain Knowledge Representation

As it was introduced before, the rule based expert system is to translate the domain knowledge into program which has the format of “if-then-else”. The following part introduces the domain expert knowledge of landing gear selector valve failures. According to the failure modes shown in the table 4-1, the latter four failure modes could be caused by electrical fault and mechanical fault, because the LGCIU has the capability to detect the electrical fault, the writer mainly considered the detection of the mechanical fault. In order to present the knowledge clearly, flow chart of each rules was given below as well.

If {“ The internal leakage is detected ” and “ The electrical power of the gear selector valve is off. ”}

Then {Gear selector valve is currently suffering internal leakage.}

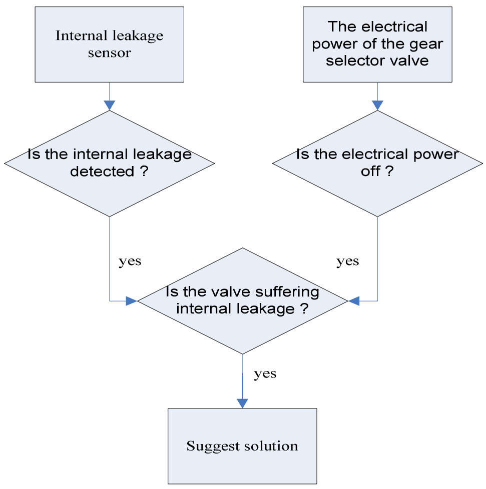


Figure 4-4 Flow chart of internal leakage detection

If {“ The electrical control signal is sent to the gear selector valve to switch to the extension position” and “ The position of the core of the gear selector valve is not at extension position.”}

Then {Gear selector valve fails to switch to extension position.}

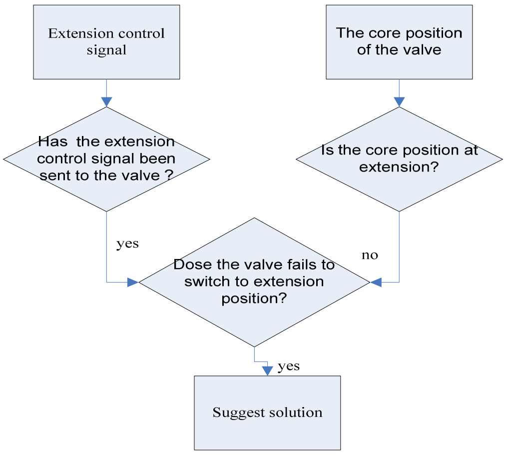


Figure 4-5 Flow chart of the detection of the valve fails to switch to extension position

If {“ The electrical control signal is sent to the gear selector valve to switch to the retraction position” and “ The position of the core of the gear selector valve is not at retraction position.”}

Then {Gear selector valve fails to switch to retraction position.}

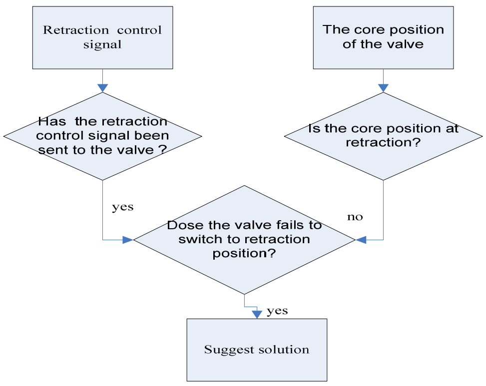


Figure 4-6 Flow chart of the detection of the valve fails to switch to retraction position

If { “ The position of the core of the gear selector valve is at extension position.” and “ The extension control signal is not sent to the gear selector valve.”}

Then {the core of the valve is blocked at extension position.}

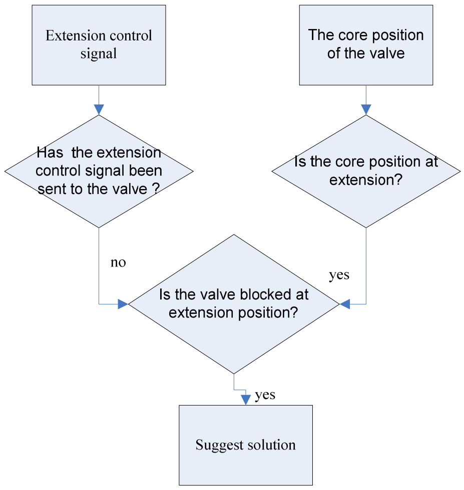


Figure 4-7 Flow chart of the detection of the core of the valve is blocked at extension position

If { “The position of the core of the gear selector valve is at retraction position.” and “ The retraction control signal is not sent to the gear selector valve.”}

Then {the core of the valve is blocked at retraction position.}

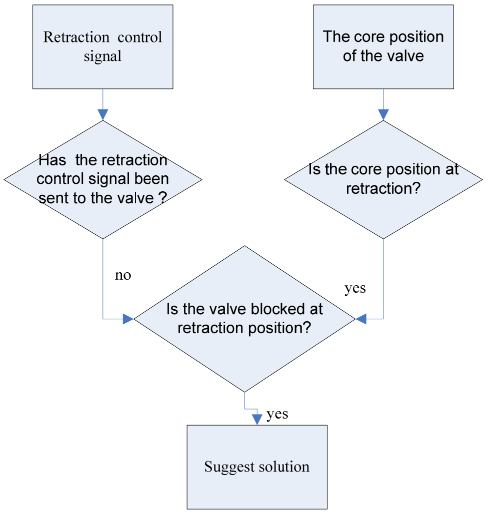


Figure 4-8 Flow chart of the detection of the core of the valve is blocked at retraction position

If {" The electrical control signal is sent to the gear selector valve to switch to the retraction position" and " The flow rate of the actuator is "0" and "The position of the core of the gear selector valve is at retraction position."}

Then { The gear selector valve lost the control of actuators.}

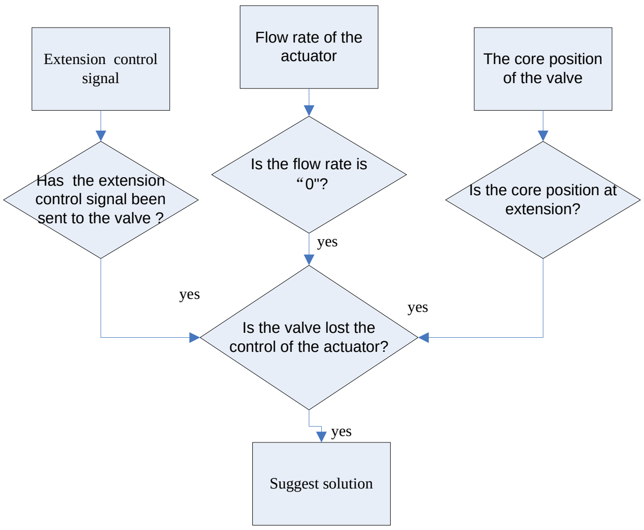


Figure 4-9 Flow chart of the detection of the loss of the extension control of actuators

If {“ The electrical control signal is sent to the gear selector valve to switch to the extension position” and “ The flow rate of the actuator is “0” and “The position of the core of the gear selector valve is at extension position.”}

Then { The gear selector valve lost the control of actuators.}

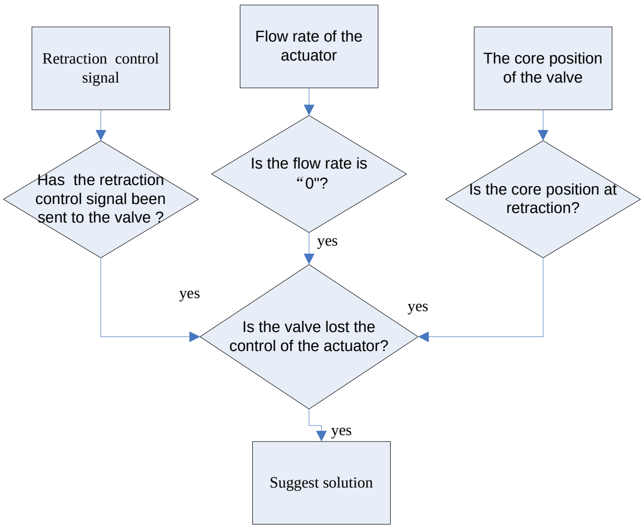


Figure 4-10 Flow chart of the detection of the loss of the retraction control of actuators

4.6 Discussion and Conclusion

Rule-based expert system could increase the availability, reusability of expertise and it has the capability of providing reliable decision making, fast and steady response and consistent performance. It is suggested that this approach is suitable for aircraft landing gear extension/retraction control system to realize the automated failure diagnosis. Generally, six basic components are included in a rule based expert system; they are knowledge base, system data base, inference engine, user interface, knowledge base acquisition facility and explanation facility.

From the architecture of the rule-based expert system, the acquisition of comprehensive domain expert knowledge is in the most important factor, and it could be acquired from three aspects: system operational principle, fault tree analysis and operational experiences of maintainers.

In the case study, according to the FHA, FMEA and FTA, the gear selector valve was selected, and the rule based expert system was applied to the valve. In addition, the domain knowledge was translated into the format of “if-then-else” which could be easily transformed into computer programme. Synchronously, according to the failure modes of the gear selector valve, available sensors could detect the parameters which can indicate the failure. However, these sensors might reduce the reliability of the system and the writer did not consider the installation of sensors, consequently, further research is needed to increase the reliability of sensors and the installation of them should be taken into account as well.

5 Prognostic Technology Research

5.1 Introduction

In this chapter, prognosis research was developed for the Landing gear extension/retraction control system base on the available approaches introduced in chapter 2. This chapter could be consisted of four parts. First of all, the main features of each approach introduced in the literature review part was analyzed and compared. Secondly, the author determined the approaches which might be appropriate for each component according to the features of the components of the landing gear extension and retraction control system. The third step was to have a case study in order to demonstrate the work flow and how the prognostic affects the system. Finally, the conclusion was presented.

5.2 Research and Application of Prognostic Approaches

5.2.1 Model-based Prognosis Techniques

Prognosis for the failure progression could be described in two steps, the first one is to estimate the current state accurately, and secondly, a model is required to describe the fault evolution. In some cases, it is very difficult to acquire a dynamic model according to all the related physical processes. In this situation, it is possible to conceive a dynamic model and then identify the model parameters by utilizing the inputs and outputs of the system. The following figure shows a classic system model identification loop. Prior knowledge leads the experiment design, and data can be acquired from the experiment. A system model is conducted together with a chosen criterion of fit. Data, the criterion of fit and the model set, are used to calculate parameters of the model. After this step, the model will be validated. The identification loop will be terminated if the validation is satisfied; otherwise, the loop will be move back to the fist step until we get a satisfied solution. There are some examples which successfully utilize this approach such as crack propagation of a turbine engine, fatigue models, bearing prognosis and etc. [4]

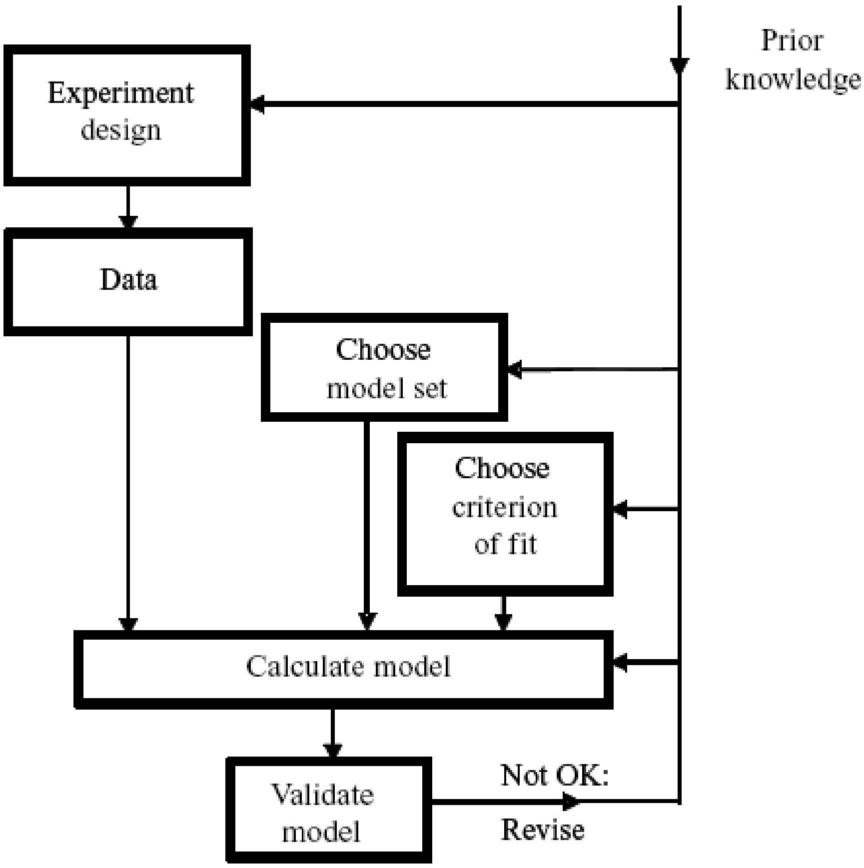


Figure 5-1 System model identification loop [4]

5.2.2 Probability-based Prognosis Techniques

As it was said in chapter 2 that probabilistic methods for prognosis are very effective when previous failures could be provided by historical data. It can be seen from the figure 5-2 that each point means a previous failure. Less detailed information is required than model-based techniques. There are advantages provided by these methods that the sufficient PDFs could be found from statistical data and confidence limits of the result could be given in order to have accurate and precise predictions. However, another issue of this approach is that the remaining useful life PDF might be recomputed according to the new system information if the system has not failed at the time. The prognosis of gas turbine performance and SH-60 helicopter gearbox has successfully utilized this approach. [4]

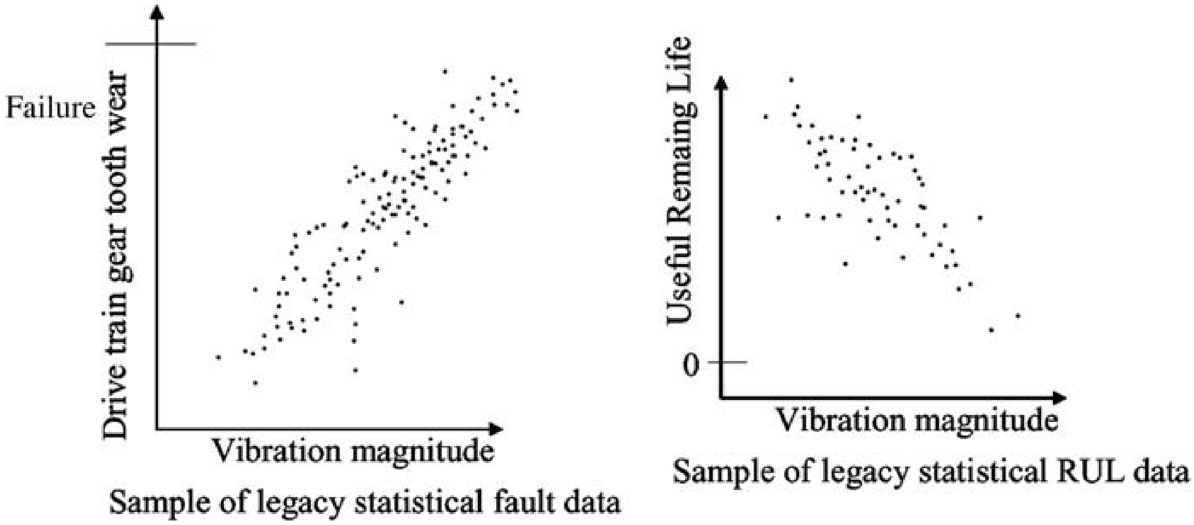


Figure 5-2 Historical data from previous failures [4]

5.2.3 Data-driven Prediction Techniques

In many cases, it is impractical to conduct a physics-based model for prediction when various historical fault data lead to the failure. It is different from the model-based methods that very little estimation is made for the studied problem. These approaches could provide a feasible method but the main problem is that the decisions are not evident. [4] Some researches show that the data-driven prediction approach would suitable for the electronic equipment [34], the Aircraft actuator components [38] and the flight control actuators [37].

5.3 Landing Gear Extension and Retraction Control System Prognostic Approach

5.3.1 Classification of System Components

The landing gear extension and retraction control system components are classified into three types which are electronic, electro-mechanical and mechanical. The detailed information was listed in the table below.

Table 5-1 Classification of system components

Item	Component	Type of Component	Monitoring method
1	L/G Lever	Electronic	LGCIU
2	LGCIU1	Electronic	BIT
3	LGCIU2	Electronic	BIT
4	Door selector valve	Electro-mechanical	LGCIU
5	Gear selector valve	Electro-mechanical	LGCIU
6	Proximity sensors	Electronic	LGCIU
7	Gravity extension switch	Electronic	NO
8	Gravity extension motor	Electro-mechanical	NO
9	Gravity extension Gear box	Mechanical	NO

5.3.2 Prognostic Approach of System Components

As for the LGCIU, the internal structure and the working principle are complicated, and as an electronic device, the data driven approach is recommended. [34] The L/G lever, proximity sensors and gravity extension switch could use the same approach as the LGCIU.

For the door selector valve and gear selector valve, they are electro-mechanical components consisted of two parts which are electrical control part and mechanical part. Consequently, it is suggested that a multiple approach which is a combination of a data driven approach and a model based approach could be utilized on them.

- For the mechanical part, the fault progression could be caused by the friction which the feature of fault progression is similar with bearing, as a result, model based approach might be suitable for the mechanical part.
- For the electrical control part, the data driven approach could be utilized.

A probability based technology has been successfully utilized on SH-60 Helicopter gear box. [4] As for the gravity extension gear box, the same method could be applied.

Table 5-2 Summary of System Prognostic Approaches

Item	Component	Type of Component	Prognostic Approach
1	L/G Lever	Electronic	Data driven approach
2	LGCIU1	Electronic	Data driven approach
3	LGCIU2	Electronic	Data driven approach
4	Door selector valve	Electro-mechanical	Data driven and model based approach
5	Gear selector valve	Electro-mechanical	Data driven and model based approach
6	Proximity sensors	Electronic	Data driven approach
7	Gravity extension switch	Electronic	Data driven approach
8	Gravity extension motor	Electro-mechanical	Data driven and model based approach
9	Gravity extension Gear box	Mechanical	Probability based approach

5.4 Case study

The key of prognosis is to identify the prognostic feature related to the failure progression of failure models. For the gear selector valve, the failure modes were listed in the table 4-1. The failure mode which is “fails to switch to extension position” was chosen for this case study. All the other failure modes could be analyzed by following the same process presented in this case study. The detailed analyses will be introduced below.

In order to identify the prognostic feature of this failure mode, the causes of it must be recognized. As it was mentioned in chapter 4, this failure mode could be caused by the fault of electrical control devices and mechanical parts. On one hand, the electrical control part could be normally consisted of two electrical devices which are an electromagnetic winding driving the core of the valve and a diode restraining the voltage spike caused by the electromagnetic winding. Either the short circuit of these two components or the open circuit of the winding could cause this failure. On the other hand, for the mechanical fault, the core of the valve could be blocked by the metal scraps produced by the friction.

After identifying the causes of the failure, the prognostic feature was analyzed for each causes of the failure mode. It is suggested that the prognostic feature of the electromagnetic winding could be the change of its resistance. [39] The prognostic feature of the blockage of the core of the valve could be the quantity level of metal scraps in hydraulic oil. Sensors are required to detect the parameters which could indicate the prognostic features.

5.5 Discussion and Conclusion

In this chapter, three typical approaches were discussed in the above sections, each approach could be utilized in different areas. Appropriate prognosis approach was recommended to each component of the system according to the features of these components.

In the case study, the failure mode which is “fails to switch to extension position” was chosen, and then, the causes of this failure were analyzed, the last progress was that the prognostic features of the causes were identified. All the other failure modes could be analyzed by following the same process presented in this case study.

Synchronously, sensors are required to detect the parameters which can indicate the failure progression. However, these sensors might reduce the reliability of the system and the writer did not consider the installation of sensors, consequently, further research is needed to increase the reliability of sensors and the installation of them should be taken into account as well.

6 The DPHM Architecture of Landing Gear Extension and Retraction Control System

In this chapter, firstly, a comprehensive integrated DPHM architecture of landing gear extension/retraction control system was introduced. Secondly, the working process was given. Finally, the relationship between the DPHM architecture of landing gear extension/retraction control system and the aircraft level PHM were presented.

6.1 Framework of Landing Gear Extension and Retraction Control System DPHM

The following figure 6-1 illustrates a typical IVHM architecture including the on-board system which means Operational Maintenance Program (OMP), off-board system and integrated aircraft support system. All of these systems should be integrated in order to have an effective acquisition and communication of the related information of health condition and this information would be collected by the DPHM control management unit.

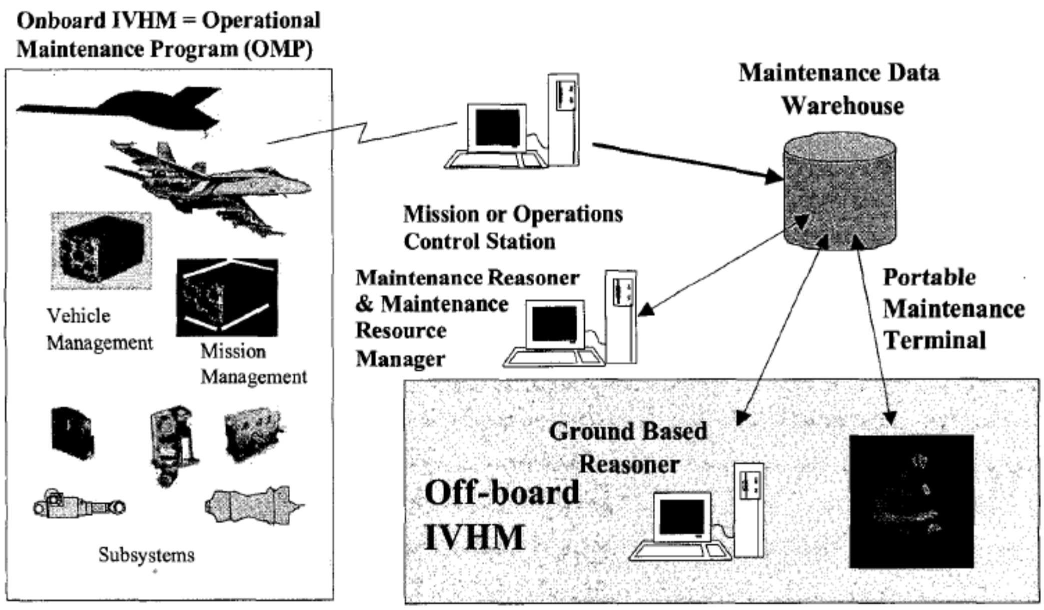


Figure 6-1: On-board and Off-board Elements of IVHM [40]

The DPHM system includes not only the health management technology, but also the integrated maintenance information. The health state information of the system has the capability of noticing the flight crew and maintainer simultaneously. [8]

The IVHM architecture has six layers which are signal processing, health assessment, condition monitoring, prognostics, presentation and decision support. First of all, the signal processing layer is to process the inputs of sensor data and the system control data. The condition monitoring layer has the capability of reporting on the condition of a component or a subsystem. The responsibility of health assessment is to perform the diagnostics and give health information about components or subsystems. The prognostics layer could estimate the remaining useful life (RUL) of a component. The decision support layer could monitor the IVHM system performance and support maintenance management. Finally the presentation layer is connected with the IVHM system users. [40]

As it was introduced above that the DPHM system includes two parts, on-board system and off-board system, and the DPHM of landing gear extension and retraction control system is shown in figure 6-2.

6.1.1 On-board System

The onboard system has the capability to assess the health of components or subsystem in real time. It consists of sensors, landing gear extension and retraction control system elements and avionics devices related to health management. The Diagnosis and Prognosis Processing Module and the signal processing unit could be integrated with the landing gear control and interface unit (LGCIU), and the sensors required for diagnosis and prognosis could be integrated with the system components when they are manufactured as well. Consequently, according to the sensors signal and the system control signal provided by other component without sensors, the on-board system could monitor the system health condition accurately.

The main functions of an on-board system are listed below:

a) System health data acquisition

b) Monitor the landing gear extension and retraction control system status

c) Fault diagnosis

d) Suggest solutions

e) Fault information display and explanation

f) Communicate with aircraft DPHM

6.1.2 Off-board System

The off-board system consists of a ground based reasoner (GBR) and a maintenance data warehouse (MDW) to support the post-processing which has the capability of health prognostic and usage trending. The GBR compare the historical, maintenance and diagnostic/prognostic data with the on-board

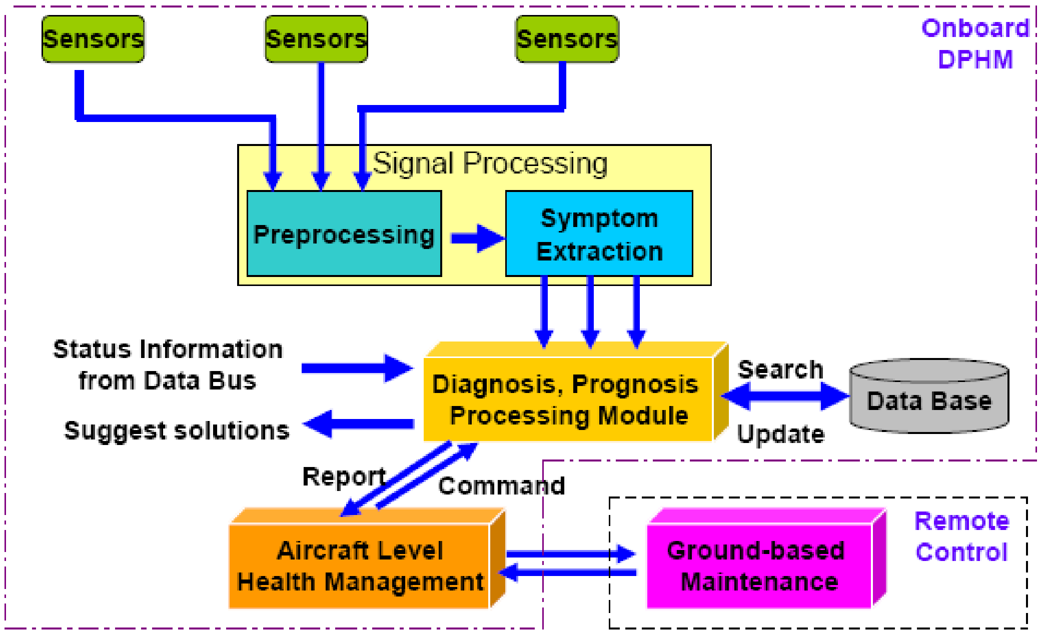


Figure 6-2 DPHM of landing gear extension and retraction control system [6]

system condition data, and then produce diagnostic/prognostic data for the maintenance resource management unit which could guide the maintenance activities. [40]

The main functions of an off-board system are listed below:

a) Communicate with aircraft DPHM

b) System components prognosis

c) Management of maintenance actions

d) Maintenance information management

6.2 Working Process of Landing Gear Extension and Retraction Control System DPHM

According to the DPHM of landing gear extension/retraction control system shown in the figure above, the work flow of it was presented as follows:

a. When the system works, the health status of major components are monitored by the sensors and fault signals are collected;

b. The signals should be processed;

c. The feature of collected signals will be identified;

d. The DPHM decide whether the components is failure or not based on the diagnosis and prognosis techniques;

e. If the component is not failure, the acquired information will be analyzed based on the prognosis techniques and the remaining time to failure of the component could be provided.

f. If the component is failure, the reason and the suggestion will be given. The information will be recorded by DPHM;

g. All of these information will be transmitted to the aircraft DPHM,

h. The information could be sent to ground-based maintenance module to guide the maintainer's activity.

6.3 Relationship with Aircraft DPHM and Benefits

The paragraphs above introduced the DPHM architecture of landing gear extension and retraction control system. However, other systems onboard such as flight control system, fuel system, hydraulic system, EPS, avionics and aircraft structure require health management technologies as well. Consequently, the DPHM should consider the whole aircraft, not a single system. The system DPHM could communicate with the aircraft DPHM by utilizing data bus.

It is clearly that the maintenance activity could be improved a lot because of the utilization of diagnosis and prognosis technology. On one hand, for the application of diagnosis technology, the reasons and solutions of a fault can be identified; as a result, a lot of time can be saved for recovering the failure. On the other hand, for the application of prognosis technology, the remaining useful life of a component could be estimated; consequently, the maintenance activity could be arranged without interrupting the normal flight mission. That is to say the cost could be reduced.

6.4 Conclusions

The landing gear extension and retraction control system DPHM integrate onboard system and off- board system, all the functions and the working process were given to fulfill the requirement of the system health management. The development of DPHM should consider the whole aircraft instead of focusing on a single system.

Owing to the implementation of the diagnosis and prognosis technology, the maintenance activity could be improved a lot; as a result, the maintenance cost could be reduced.

7. Conclusion and Future Work

7.1 Conclusion

The main objective of this thesis was to build a set of diagnosis, prognosis and health management methods which are suitable for the aircraft landing gear extension and retraction control system. The research works were performed as follows:

First of all, this thesis began with the literature review chapter. The footprint of the revolution and the development of the DPHM technology were introduced. Then the successful applications of PHM system were presented as well. The literature review also provided the detailed information of diagnosis approaches and prognosis approaches.

Secondly, based on the research methodology, the landing gear extension/retraction control system of AIRBUS A330 was chosen as a case study. All the following research works in this thesis were dependent on this system. The schematic diagram of the system was given and the operational functions of the whole system were identified.

After introducing the landing gear extension and retraction control system, the FHA, FMEA and FTA for the system were conducted. From the FHA, each of the catastrophic events of the landing gear extension/retraction control system was identified. The FHA is also a starting point of the FMEA and FTA. The detailed results of FHA were shown in the Appendix B. A FMEA for the system was performed after the FHA. In the FMEA, all the failure modes of each component of the system and their effects were determined, and each failure was classified according to the severity classification. The detailed results of FMEA were shown in the Appendix C. Then the FTA was performed to identify the root causes of each top event. The detailed results of FTA were shown in the Appendix D. According to the combination of the results from FHA, FMEA and FTA, all the root causes and their effects were identified, synchronously; all the components which are related to the catastrophic events are listed. Consequently, the crucial components of the system could be identified and the key parameters of the components could be acquired.

According to the results of the system analysis and comparisons of diagnostic approaches, rule-based expert system was chosen for the landing gear extension and retraction control system DPHM. Six basic components are included in a rule based expert system, they are knowledge base, system data base, inference engine, user interface, knowledge base acquisition facility and explanation facility. The architecture of the rule-based expert system, the acquisition of comprehensive domain expert knowledge is in the most important factor, and it could be acquired from three aspects: system operational principle, fault tree analysis and operational experiences of maintainers. It is suggested that this approach is suitable for aircraft landing gear extension/retraction control system to realize the automated failure diagnosis.

In the prognostic research, three typical approaches were discussed in the above sections. Each approach could be utilized in different areas. An appropriate prognosis approach was recommended for each component of the system, according to the features of these components. In the case study, the failure mode which is “fails to switch to extension position” was chosen, and then, the causes of this failure were analyzed, the last progress was that the prognostic features of the causes were identified. All the other failure modes could be analyzed by following the same process presented in this case study.

Finally, a comprehensive integrated DPHM architecture of landing gear extension and retraction control system was developed. The operational process for the system was also expressed.

In conclusion, a complete DPHM system was provided by the research given above for the system. It has the capability to monitor the system status, detect the abnormal signals, diagnose system failures, provide solutions to maintainers and indicate the remaining useful life of a component or the system. It is clear that the maintenance activity could be improved a lot because of the utilization of diagnosis and prognosis technology. In other words, the unscheduled maintenance could be reduced. Consequently, the maintenance activity could be arranged without interrupting the normal flight mission. That is to say the maintenance cost could be reduced. All of the research objectives were achieved.

7.2 Future Work

This thesis mainly focused on the component and system level to utilize the system real-time status monitoring, diagnostics and prognostics. However, the DPHM of the landing gear extension and retraction control system should not be isolated with the aircraft level DPHM. The interface between them shall be considered.

As it was mentioned earlier, various sensors were required for the diagnosis and prognosis research. The writer mainly considered the type of sensors which could be utilized, but the sensors installation which could greatly affect the performance of them was not considered and the sensors reliability is needed to be determined as well.

Because of the lack of component and system data and the internal structure of components, the prognostic research works focused on the qualitative analysis and the prognosis process, not quantitative analysis and algorithm, the failure modes of a component may not be fully understood. Future works are needed after acquiring the component and system data and the internal structure of components.

As it was mentioned earlier, the maintenance cost could be reduced. However, the cost of the system installation and operation such as mass and power requirements is still need to be studied to find the net cost benefit.

References

[1] Kirby Keller, Kevin Swearingen, Jim Sheahan, Mike Bailey, Jon Dunsdon,K.Wojtek Przytula, Malibu and Brett Jordan (2006), "*Aircraft ElectricalPower System Prognostics and Health Management.*" IEEE, pp 12.

[2] Andrew Hess, Leo Fila. (2001), The Joint Strike Fighter (JSF) PHM Concept: Potential Impact on Aging Aircraft Problems, IEEE, paper#403, November 17, 200l.

[3] Industry Canada (2004), Aircraft Systems Diagnostics, Prognostics and Health Management Technology Insight Document (Version 0.2), Canada.

[4] George Vachtsevanos; Frank Lewis; Michael Roemer; Andrew Hess and Biqing Wu (2006), Intelligent Fault Diagnosis and Prognosis for Engineering Systems,aJohn Wiley and Sons, INC.

[5] Stephen B. Johnson. Introduction to System Health Engineering and Management in Aerospace. 1st Integrated Systems Health Engineering and Management Forum. Napa, CA. November 2005

[6] Zhongtian, T,. Lawson, C. and Cranfield University. School of Engineering (2010), Aircraft Electrical Power System Diagnostics, Prognostics and Health Management, MSc Thesis, Cranfield University, Bedford shire, UK.

[7] Ashok N. Srivastava, Robert W. Mah, Claudia Meyer. Integrated Vehicle Health Management "Automated detection, diagnosis, prognosis to enable mitigation of adverse events during flight." (Version 2.01) NASA, Aeronautics Research Mission Directorate Aviation Safety Program, August 14 2008.http://www.aeronautics.nasa.gov/nra_pdf/ivhm_tech_plan_c1.pdf

[8] Liang, N. Lawson, C. and Cranfield University. School of Engineering (2008), Aircraft fuel system prognostics and health management, MSc Thesis, Cranfield University, Bedford shire, UK.

[9] Ann Patterson-Hine, Gordon Aaseng, Gautam Biswas and Sriram Narasimhan

(2005), "A Review of Diagnostic Techniques for ISHM Applications", NASA, USA.

[10]Patton, R., P. Frank, and R. Clark, Fault Diagnosis in Dynamic Systems: Theory and Applications, Prentice Hall, Inc., Hertfordshire, UK, 1989.

[11] Hagop Panossian. Integrated Health Management and Adaptive Control Systems
http://www.engineeringatboeing.com/dataresources/IntegratedHealthManagement AndAdaptiveControlSystems.pdf

[12] W,Zhenhua, LIU Yuanpeng. Applications of Prognostics and Health Management in Aviation Industry. IEEE 978-1-4244-7950-4/111, 2011

[13] Michael J. Roemer, Carl S. Byington, Gregory J. Kacprzynski, G,Vachtsevanos. An Overview of Selected Prognostic Technologies with Reference to an Integrated PHM Architecture 1st Integrated Systems Health Engineering and Management Forum Napa, CA. November 2005

[14] Michael J. Roemer, Carl S. Byington, Gregory J. Kacprzynski, George Vachtsevanos. An Overview of Selected Prognostic Technologies with Application to Engine Health Management ASME Turbo Expo 2006: Power for Land, Sea, and Air, 2006, Barcelona, Spain

[15]Engel, Gilmartin, Bongort & Hess.Prognostics, the Real Issues Involved with Predicting Life Remaining.0-7803-5846-5/00/$10.00.2000 IEEE

[16] Whitaker, N. Lawson, C. and Cranfield University. School of Engineering (2011), The Application of Integrated Vehicle Health Management To an Aircraft Fuel System, Individual Research Project Thesis, Cranfield University, Bedford shire, UK.

[17] Market Outlook 2009, September 2009, www.rolls-royce.com

[18]Ramon Fernando Colmenares Quinero (2009), Techno-Economic and Environmental Risk Assessment of Innovative Propulsion Systems for Short-Range

Civil Aircraft, School of Engineering, Cranfield University

[19]Huping, L (2008). Individual final Report of Group Design Project, Cranfield University. School of Engineering

[20]S. Boggia, K. Rüd. INTERCOOLED RECUPERATED AERO ENGINE. Advanced Project Design, MTU Aero Engines. München, Germany

[21] Jane's aero-engines, Prentice Hall. Issue 21-2007.

[22] Team 3 (2009), Preliminary Design of High Bypass Geared Turbofan Team 3 Technical Report, Cranfield University. School of Engineering

[23] L.R. Jenkinson, et al(1999), Civil Jet Aircraft Design, Butterworth-Heinemann, Oxford U.K

[24]http://www.pw.utc.com/vgn-ext-templating/v/index.jsp?vgnextoid=59ab4d845c37a110VgnVCM100000c45a529fRCRD, August 2008

[25] Society of Automotive Engineers. Guidelines and Methods for conducting the Safety Assessment Process on Civil Airborne Systems and Equipment. SAE ARP 4761, December 1996

[26] A330 flight crew operating manual, http://www.smartcockpit.com/

[27] http://www.airbus.com/aircraftfamilies/passengeraircraft/a330family/

[28] Procedure for Failure Mode, Effects and Criticality Analysis (FMECA). National Aeronautics and Space Administration. 1966. RA–006–013–1A.

[29] Ajith Abraham, Rule-based Expert Systems, Oklahoma State University, Stillwater, OK, USA

[30] M Sasikumar, S Ramani, S Muthu Raman, KSR Anjaneyulu, R Chandrasekar (2007), A Practical Introduction to Rule Based Expert Systems, Narosa Publishing House, New Delhi

[31] Dickey, J., J. Dimmick and M. Moore, “Acoustic measurement of valve leakage rates”, 1 Materials Evaluation, 195-207. Vol. 36, 1978, pp. 67-77.

[32] Germain, J.L., L. Granal, D. Provost and M. Touillez, “Inspection systems for valves monitoring at EDF”, Proceedings of the 10th International Conference on Condition Monitoring and Diagnostic Engineering Management (COMADEM), Sheffield, UK, 1996, pp. 41 1- 420.

[33]C.O.Bizarria, Takashi,Y. Prognostics and Health Monitoring for an Electro-Hydraulic Flight Control Actuator, 978-1-4244-2622-5/09/$25.00 ©2009 IEEE

[34]L.Hernandez, N.Z.Gebraeel. ELECTRONICS PROGNOSTICS--"DRIVING JUST-IN-TIME MAINTENANCE".1-4244-0052-X/06/$20.00 ©2006 IEEE

[35] http://www.bbc.co.uk/news/world-europe-15543209

[36]http://article.wn.com/view/2011/04/14/Air_France_jet_in_emergency_landing/

[37] Byington, C. S., Watson, M., and Edwards, D. 2004c. Dynamic Signal Analysis and Neural Network Modeling for Life Prediction of Flight Control Actuators. Proceedings of the American Helicopter Society 60th Annual Forum. Alexandria, VA: AHS.

[38]Byington, C. S., Watson, M. J., and Edwards, D. 2004b. Data-Driven Neural Network Methodology to Remaining Life Predictions for Aircraft Actuator Components. Proceedings of the IEEE Aerospace Conference. New York: IEEE

[39] Lall, P. Lowe, R. Goebel, K. Use of prognostics in risk-based decision making for BGAs under shock and vibration loads. 978-1-4244-5343-6/10/$26.00 ©2010 IEEE

[40] Keller, K. Wiegand, D. Swearingen, K. Reisig, C. Black, S. Gillis, A. Vandernoot, M. AN ARCHITECTURE TO IMPLEMENT INTEGRATED VEHICLE HEALTH MANAGEMENT SYSTEMS. 0-7 803-7094-5/01/$10.000 2001 IEEE

[41] Klaus Stiffens, et al, Driving the Technological Edge in Airbreathing Propulsion

Appendix A: GDP Report

A.1 GDP Introduction

A1.1 Background

FW-11 is a project cooperated between Aviation Industry Corporation of China (AVIC) and Cranfield University. This group design project is a new conceptual design and the target of it is to develop a flying wing commercial airliner.FW-11, a 200-seat airliner which the range is 7500 nm, mainly focuses on Asia-Pacific region market. As a part of AVIC MSc program, the FW-11 project is constructed by three phases: conceptual design phase, preliminary design phase, and detail design phase. The author was involved in the conceptual design phase which could be divided into three steps: derivation of requirements, design a conventional aircraft as baseline aircraft and design FW-11 comparing with the baseline aircraft.

A.1.2 Main Tasks

The author was in charge of the engine market, engine selection, engine sizing and performance. For the engine selection, the writer will select an existing engine from the market firstly, and then a new concept engine will be considered so that the performance of them can be compared by utilizing the TURBOMATCH.

According to the development procedure of the FW-11, a conventional configuration was developed firstly for comparison, and then the flying wing configuration was considered.

A.2 Engine Market

According to the Rolls-Royce market outlook, it can be seen from the tables below that in the next 20 years 141,000 engines will be demanded for the engine market which worth over $800 billions and the twin-aisle aircraft has the biggest portion in terms of value.

Table A-1 Engine delivery summary 2009~2028 [17]

Engine delivery summary 2009-2028

Sector	Units	Value ($bn)
Business jets	72,409	103
Regional aircraft	14,384	44
Single-aisle aircraft	34,613	250
Twin-aisle aircraft	17,636	381
Freighters	2,140	44
Total	**141,182**	**822**

Table A-2 Aircraft delivery summary 2009~2028 [17]

Aircraft delivery summary 2009-2028

	2009-2018	2019-2028	Total
Very light jets	2,616	3,525	**6,140**
Small business jets	3,490	4,696	**8,187**
Medium business jets	4,045	6,913	**10,958**
Large business jets	3,418	5,787	**9,205**
Business jet total	**13,568**	**20,921**	**34,490**
30-50 seats	399	1,296	**1,695**
70-90 seats	2,563	2,280	**4,843**
Regional aircraft total	**2,962**	**3,576**	**6,538**
110 seats	629	678	**1,307**
130 to 180 seats	6,680	7,746	**14,426**
200 and 250 seats	1,519	1,843	**3,362**
300 and 350 seats	1,184	1,925	**3,109**
400+ seats	371	564	**935**
Freighters	419	378	**797**
Mainline aircraft total	**10,802**	**13,134**	**23,936**
Grand total	**27,332**	**37,631**	**64,964**

Separating the engine market into different range of thrust, the two tables below shows that the thrust over 22000 lb have the biggest value and the most delivery units.

Table A-3 engine delivery value [17]

Engine delivery value ($bn)

Category	2009-2018	2019-2028	Total
Turboprops	3	3	**6**
<3,000lb	4	3	**7**
3,000 – 6,000lb	5	8	**13**
6,000 –10,000lb	17	29	**46**
10,000 – 22,000lb	35	47	**82**
22,000 – 45,000lb	112	131	**243**
45,000 – 75,000lb	80	62	**141**
>75,000lb	98	186	**283**
Total	**354**	**468**	**822**

Table A-4 engine delivery units [17]

Engine delivery units

Category	2009-2018	2019-2028	Total
Turboprops	1,666	1,426	**3,092**
<3,000lb	7,950	8,103	**16,053**
3,000 – 6,000lb	5,234	9,161	**14,395**
6,000 –10,000lb	10,280	17,371	**27,651**
10,000 – 22,000lb	10,633	16,515	**27,148**
22,000 – 45,000lb	15,307	17,760	**33,067**
45,000 – 75,000lb	4,507	3,364	**7,871**
>75,000lb	4,310	7,595	**11,905**
Total	**59,887**	**81,295**	**141,182**

A3 Engine Selection, Sizing and Performance

As the concept of this project was considered to be developed in three stages, a conventional configuration aircraft was developed, then some unconventional concept options were compared, finally the flying wing concept aircraft was built. In terms of the development of the project, appropriate engines should be selected for the firstly.

For the engine selection, the writer will select an existing engine from the market firstly, and then a new concept engine will be considered so that the performance of them can be compared.

From the technology aspect, there are some new engine concepts we should consider which are geared turbofan, open rotor, intercool and recuperated and etc. Each of the new concept engines has advantage and disadvantage and also needs new technology.

Table A-5 pros and cons of engine concepts [18]

Engine concepts	Advantages	Disadvantages
Open Rotor	Low SFC	Noise due to absence of nacelle
	Very high BPR means high propulsive efficiency	Cabin noise
	Lighter engine with lower drag due to the absence of the fan case	Sonic fatigue for aircraft-engine integration
Geared Turbofan	High BPR	Technology needed for cooling system
	higher fan efficiency and lower fan noise	Uncertainty of the weight
Intercool and recuperated aero engine	lower emission and core weight	New components contribute to engine weight and maintenance cost
	Higher efficiency	

On one hand, the performance of these new concept engines was compared; engine models were built by utilizing TURBOMATCH. The models are shown in appendix A1, A2 and A3. It can be seen from the Table 3-6 that the SFC of open rotor engine and Intercool and recuperated aero engine are lower than the geared turbofan engine. On the other hand, there are engine concept might be available for our aircraft, however, according to the EIS of the aircraft is 2020, the EIS of the engine should be before 2020 in order to reduce the risk. Consequently, geared turbofan engines should be our best choice of FW-11.

Table A-6 Simulation results of new concept engines

	Altitude(m)	Flight Mach Number	SFC (mg/Ns)
Open rotor	10680	0.82	14.78769
GTF&ICA	10680	0.82	14.98499
GTF	10680	0.82	15.20291

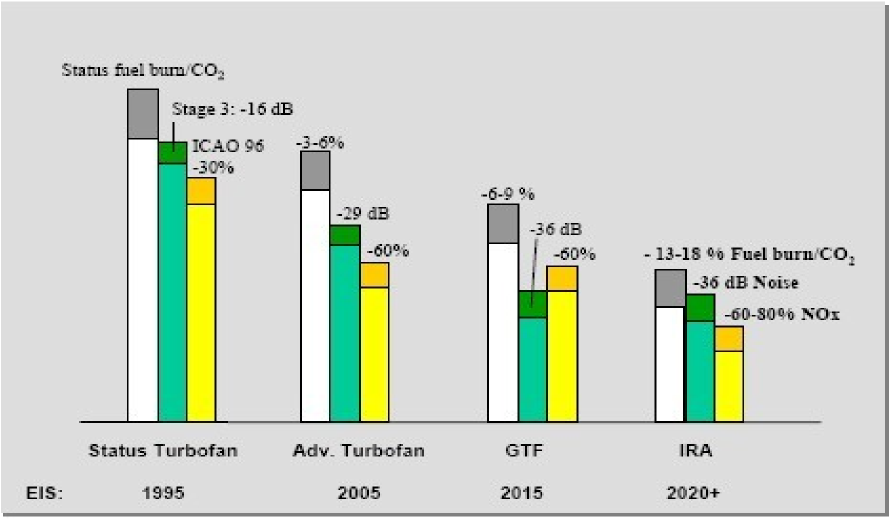


Figure A-1 Emission and EIS of engines [20]

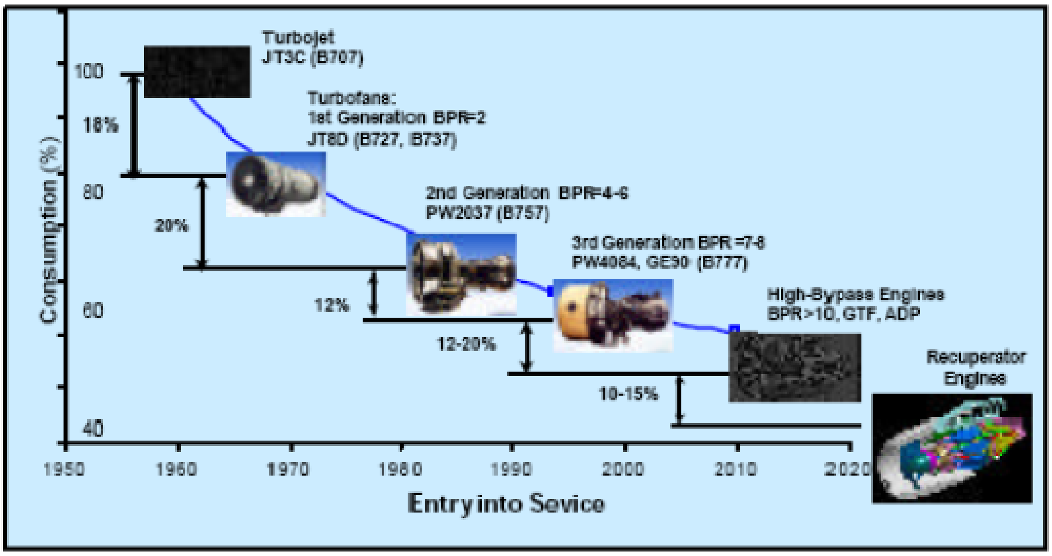


Figure A-2 SFC Reduction by Bypass Ratio [41]

The thrust requirements of aircraft can be calculated by the following equation with considering 10% installation loss. [19]

$$T_{Req} = 1.1 \times W_{TO} \times \left(\frac{T}{W}\right)_{TO}$$

T_{Req} : Thrust requirement

W_{TO} : Take off weight

$\left(\frac{T}{W}\right)_{TO}$: Take off thrust weight ratio

A3.1 Engines for Conventional Configuration Aircraft

As the thrust weight ratio is recommended by the parameter team are 0.295(medium range) and 0.25(long range), and the maximum takeoff mass are 195445kg (medium range) and 188182kg (long range), the thrust requirement could be calculated by the equation shown above. The overall thrust required are 632kN (medium range) and 506kN (long range). Considering the family issue, one type of engine is selected for both medium range and long range baseline engine, which is Trent 700.

In order to provide performance parameters of the engine to the performance team, a model of Trent 700 need to be conducted by utilizing TURBOAMTCH which is a kind of engine simulation software. Main parameters of the engine could be found in JANES' book, such as OPR, FPR, mass flow, SFC, etc. The simulation result is presented in the table 3-4 below.

Table A-7 Simulation result and dimensions of Trent 700 [21]

	Long range	Medium range
MTOW@ISA+10oC, Sea level	188,182kg	195,445kg
Overall thrust required	506kN	632kN
Number of engine	2	
Installation	Under-wing mounted	
Thrust required per engine	253kN	316kN
Baseline engine	Trent 700	
Fan diameter	2.47m	
Length	3.91m	
Dry weight	4,785kg	
SFC@ISA+15oC, Sea level	8.97mg/Ns	
SFC@35000ft, M=0.85	17.01mg/Ns	

As is mentioned above, geared turbofan engine is selected to be mounted on the conventional configuration aircraft. An engine model was built to simulate its performance base on the same thrust provided as Trent 700, and the simulation result is shown in the table 3-5 below. The model was built according to the engine model conducted by AVIC team in Cranfield University. [22]

Table A-8 Simulation result of GTF for conventional configuration aircraft

SFC@ISA+15oC, Sea level	6.72mg/Ns
SFC@35000ft, M=0.85	15.20mg/Ns

A3.2 Engine for FW-11

As the thrust weight ratio is recommended by the parameter team is 0.205, and the maximum takeoff mass is 176469kg, the thrust requirement could be calculated by utilizing the same equation as the conventional one. The thrust required is 196kN per engine.

Because of the existing engines at this thrust level are outdated which means the performance are dissatisfied, the writer chose GTF engine for FW-11 directly. Then the GTF engine could be sized as follow.

According to reference [23], the diameter and mass are scaled by using following equations, respectively.

$$D_F = D_{F,Ref} \times \left(\frac{f_N}{f_{N,Ref}}\right)^{0.5}$$

$$M_F = M_{F,Ref} \times \frac{f_N}{f_{N,Ref}}$$

D_F : Fan diameter

f_N : Net thrust

M_F : Mass

$D_{F,Ref}$ Fan diameter of reference engine

$f_{N,Ref}$: Net thrust of reference engine

$M_{F,Ref}$: Mass of reference engine

Then the diameter and mass could be estimated based on the reference engine which is PW1000 developed by Pratt&Whitney. Parameters of the reference engine are listed below.

Table A-9: The Parameters of Reference Engine [24]

Thrust	
Static Uninstalled Thrust@ISA+15°C, Sea Level	102.436kN
BPR	8
Dimensions	
Fan Diameter	1854.2mm
Weight	
Dry Weight	2451.6

According to the above engine, the parameters of the GTF engine of FW-11 are calculated and the results are shown below.

Table A-10 Simulation result and dimensions of GTF for FW-11

Bypass ratio	11
Fan diameter	2.87m
Length	3.17m
Dry weight	4,702kg
Static uninstalled thrust@ISA+15oC, Sea level	196kN
Uninstalled thrust@ISA+10oC, Sea level, Take off	178kN
Uninstalled thrust@35000ft, M=0.82	56kN
SFC@ISA+15oC, Sea level	6.72mg/Ns
SFC@35000ft, M=0.82	15.20mg/Ns

The TURBOMATCH simulation results of GTF for FW-11 are given in the figures below.

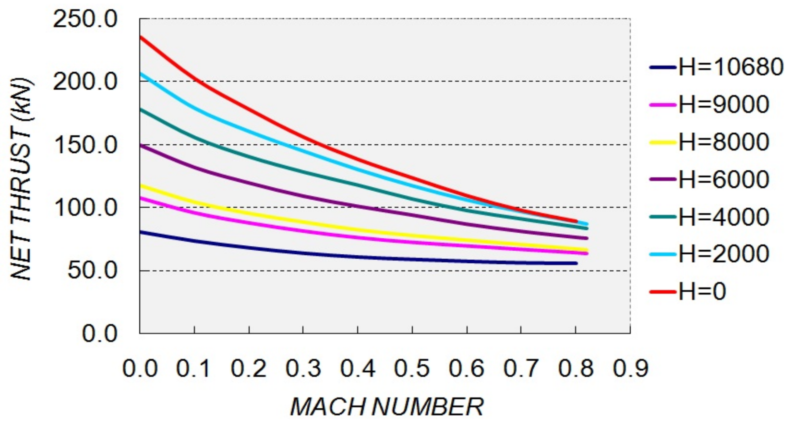


Figure A-3 Thrust Vs Various Altitude and Mach number

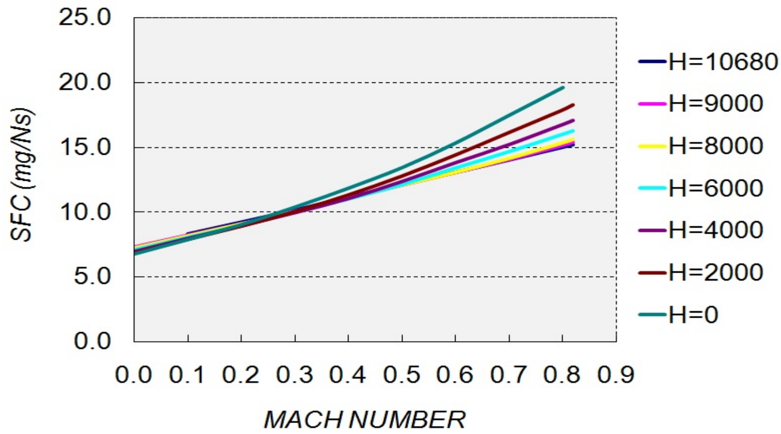


Figure A-4 SFC Vs Various Altitude and Mach number

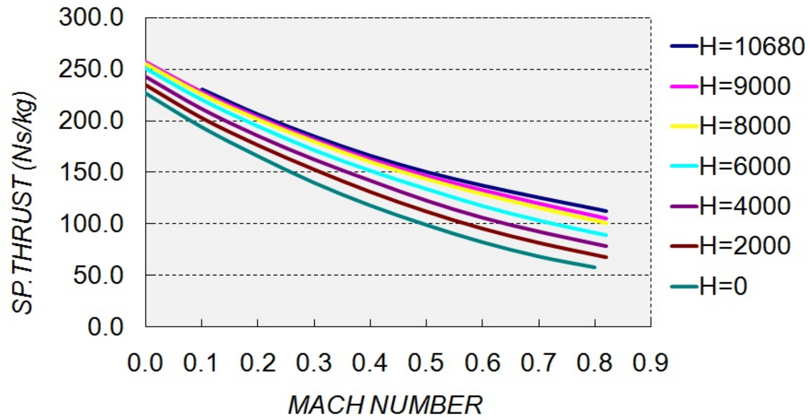


Figure A-5 SP.THRUST Vs Various Altitude and Mach number

These results are given to the performance team in order to validate the thrust provided by the engine can fulfill the thrust requirement at different flight phases, and according to the validation, the thrust level is satisfied.

Appendix A1

The TURBOMATCH model of an open rotor engine is presented as follow.

```
////
OD SI KE VA FP
-1
-1
INTAKE    S1,3       D1-4       R200
INTAKE    S2,25      D5-8       R390
COMPRE    S3,4       D9-15      R210 V9 V10
PREMAS    S4,20,5    D16-19
COMPRE    S5,6       D20-26     R220 V20 V21
PREMAS    S6,21,7    D27-30
ARITHY    D400-404
COMPRE    S7,8       D31-37     R230 V31
PREMAS    S8,22,9    D38-41
PREMAS    S9,23,10   D42-45
BURNER    S10,11     D46-48 R240
MIXEES    S11,22,12
ARITHY    D405-411
TURBIN    S12,13     D49-56,250,57 V50
MIXEES    S13,23,14
MIXEES    S14,21,15
ARITHY    D412-416
TURBIN    S15,16     D58-65,260,66 V59
ARITHY    D450-457
COMPRE    S25,26     D70-76 R270 V70 V71
TURBIN    S16,17     D100,77-83,270,85 V77
DUCTER    S17,18     D86-89
NOZCON    S18,19,1   D90 R290
NOZCON    S26,27,1   D91 R300
```

```
ARITHY   D420-426
ARITHY   D430-436
ARITHY   D440-446
ARITHY   D450-456
OUTPBD   D290,200,300,390,21,32,500,510,520
PERFOR   S1,2,0        D92-95,290,200,240,300,390,0,0,0,0
CODEND
////
! INLET 1
1 10680.0
2 0.0
3 0.8
4 -1.0

! INLET 2
5 10680.0
6 0.0
7 0.8
8 -1.0

! LOW PRESSURE COMPRESSOR
9 0.85
10 -1.0
11 2.449813
12 0.91
13 0.0
14 4.0
15 0.0

! AIR BLEED
```

16 0.00

17 0.0

18 1.0

19 0.0

! HPC1 COMPRESSOR

20 0.85

21 -1.0

22 7.9556

23 0.9

24 1.0

25 5.0

26 0.0

! Sealing Air to LPT

27 0.01

28 0.0

29 1.0

30 0.0

! HPC2 COMPRESSOR

31 0.85

32 -1.0

33 1.847

34 0.9

35 1.0

36 2.0

37 0.0

! Cooling Air to HPT NGV and Blade

38 0.075

39 0.0

40 1.0

41 0.0

! Cooling Air to HPT Blade

42 0.01622

43 0.0

44 1.0

45 0.0

! BURNER

46 0.045

47 0.999

48 -1.0

! TURBINE-HPT

49 0.0

50 -1.0

51 -1.0

52 0.93

53 -1.0

54 2.0

55 5.0

56 -1.0

57 0.0

! TURBINE-LPT

58 0.0

59 -1.0

60 -1.0

61 0.934

62 -1.0

63 1.0

64 5.0

65 -1.0

66 0.0

! COUNTER-ROTATING FAN

70 0.85

71 -1.0

72 1.15

73 0.915

74 1.0

75 1.0

76 0.0

! TURBINE-LPT

100 0.0

77 -1.0

78 -1.0

79 0.934

80 -1.0

81 4.0

82 5.0

83 -1.0

85 0.0

! CORE DUCT

86 0.0

87 0.0

88 0.0

89 1.E6

! CONVERGENT NOZZLE

90 -1.0

! CONVERGENT NOZZLE

91 1.0

! PERFORMANCE

92 -1.0

93 -1.0

94 0.0

95 0.0

! ARITHY

400 5.0

401 -1.0

402 32.0

403 -1.0

404 21.0

! ARITHY

405 1.0

406 -1.0

407 250.0

408 -1.0

409 220.0

410 -1.0

411 230.0

! ARITHY
412 5.0
413 -1.0
414 260.0
415 -1.0
416 210.0

! ARITHY
420 2.0
421 -1.0
422 500.0
423 -1.0
424 290.0
425 -1.0
426 200.0

! ARITHY
430 2.0
431 -1.0
432 510.0
433 -1.0
434 300.0
435 -1.0
436 390.0

! ARITHY
440 4.0
441 -1.0

```
442 520.0
443 -1.0
444 510.0
445 -1.0
446 500.0

! ARITHY
450 3.0
451 -1.0
452 823.0
453 -1.0
454 823.0
455 -1.0
456 457.0
457 1.0
-1
1 2 48.0 ! INLET MASS FLOW
2 2 1200.0 ! BYPASS MASS FLOW
11 6 1400.0 ! TET
-1
1   10680.0
2   0.0
3   0.82
5   10680.0
6   0.0
7   0.82
-1
-1
-3
```

Appendix A2

The TURBOMATCH model of an Intercool and recuperated aero engine is presented as follow.

```
////
OD SI KE VA FP
-1
-1
INTAKE   S1,2       D1-4        R300
COMPRE   S2,3       D5-11       R310    V5    V6
PREMAS   S3,4,22    D12-15      V12
MIXEES   S22,31,23
PREMAS   S23,24,29  D16-19      V16
DUCTER   S29,30     D20-23
HETCOL   S24,25     D24-27
MIXFUL   S25,30,26  D28-30
DUCTER   S26,27     D31-34
NOZCON   S27,28,1   D35         R330
ARITHY              D200-207
COMPRE   S4,5       D36-42      R340    V36
PREMAS   S5,6,31    D43-46
PREMAS   S6,7,32    D215-218
HETHOT   S24,7,8    D47-50
COMPRE   S8,9       D51-57      R350    V51   V52
DUCTER   S9,10      D58-61
PREMAS   S10,11,33  D62-65
PREMAS   S11,12,34  D219-222
HETCOL   S12,13     D66-69
DUCTER   S13,14     D70-73
BURNER   S14,15     D74-76      R370
MIXEES   S15,33,16
```

```
TURBIN    S16-17          D77-84,350,85                    V78
ARITHY                   D208-214
TURBIN    S17,18          D86-93,345,94                    V87
HETHOT    S12,18,19      D95-98
DUCTER    S19,20          D99-102
NOZCON    S20,21,1        D103                 R400
OUTPBD                    D207,209,8
PERFOR    S1,0,0         D104-107,330,300,370,400,0,0,0,0,0
CODEND
////
1 10680.0
2 0.0
3 0.82
4 1.0

5 0.85
6 1.0
7 1.7
8 0.915
9 0.0
10 1.0
11 0.0

12 0.083333           !Wout.1/Win    --- BYPASS SPLITTER
13 0.0
14 1.0
15 0.0

16    0.2
17    0.0
```

18   1.0
19   0.0

20 0.0
21 0.00
22 0.0
23 0.0

24 0.1
25 0.6
26 1.0
27 0.0

28   1.0
29   1.0
30   0.4

31 0.0
32 0.00
33 0.0
34 0.0
35 -1.0

!ARITHY:BOOSTER SPEED=FAN SPEED
200   5.0
201 -1.0
202 37.0
203 -1.0
204   6.0
205 -1.0

206 207.0
207 1.0

36 0.85
37 1.0
38 2.377
39 0.91
40 0.0
41 2.0
42 0.0

43 1.0
44 0.0
45 1.0
46 0.0

215 1.000
216 0.000
217 1.000
218 0.000

47 0.1
48 0.6
49 1.0
50 0.02

51 0.85
52 1.0
53 8.91
54 0.9

55 0.0
56 3.0
57 0.0

58 0.0
59 0.00
60 0.0
61 0.0

62 0.8
63 0.0
64 0.98
65 0.0

219 1.000
220 0.00
221 1.000
222 0.000

66 0.1
67 0.73
68 1.0
69 0.02

70 0.0
71 0.0
72 0.0
73 0.0
74 0.05
75 0.99

76 -1.0

77 0.0
78 0.8
79 0.6
80 0.93
81 -1.0
82 3.0
83 3.0
84 -1.0
85 0.0

!ARITHY: LPTWORK
208 1.0
209 -1.0
210 345.0
211 -1.0
212 310.0
213 -1.0
214 340.0

86 0.0
87 0.8
88 0.6
89 0.934
90 -1.0
91 1.0
92 3.0
93 -1.0
94 0.0

95 0.1

96 0.73

97 1.0

98 0.02

99 0.0

100 0.0

101 0.0

102 0.0

103 -1.0

104 -1.0

105 -1.0

106 0.0

107 0.0

-1

1 2 430.0 ! MASS FLOW

15 6 1630.0 !TET

-1

-3

Appendix A3

The TURBOMATCH model of a GTF aero engine is presented as follow.

```
////
OD SI KE VA FP
-1
-1
INTAKE    S1,2 D1-4 R200
COMPRE    S2,3 D5-11 R210 V5 V6
PREMAS    S3,16,4 D12-15 V12
ARITHY    D90-94
COMPRE    S4,5 D16-22 R230 V16
PREMAS    S5,17,6 D23-26
MIXEES    S16,17,18
DUCTER    S18,19 D27-30 R220
NOZCON    S19,20,1 D31 R290
COMPRE    S6,7 D32-38 R240 V32 V33
PREMAS    S7,21,26 D39-42
ARITHY    D95-99
COMPRE    S26,8 D43-49 R270 V43
PREMAS    S8,22,27 D50-53
PREMAS    S27,23,9 D55-58
BURNER    S9,10 D59-61 R250
MIXEES    S10,22,11
ARITHY    D407-413
TURBIN    S11,12 D62-69,280,88 V63
MIXEES    S12,23,13
MIXEES    S13,21,14
ARITHY    D400-406
TURBIN    S14,15 D70-77,260,89 V71
```

```
DUCTER   S15,24 D78-81
NOZCON   S24,25,1 D82 R300
PERFOR   S1,0,0 D83-86,300,200,250,290,0,0,0,0,0
CODEND
BRICK DATA////

! INLET
1 10680.0
2 0.0
3 0.8
4 -1

! FAN
5 0.85 ! SURGE MARGINE
6 1.0
7 1.45
8 0.915
9 0.0
10 1.0
11 0.0 !

! BYPASS-MAIN
12 0.916667
13 0.0
14 1.0
15 0.0

! BOOSTER
16 0.85
17 1.0
```

18 1.6901

19 0.91

20 1.0

21 1.0

22 0.0

! AIR BLEED

23 0.00

24 0.0

25 1.0

26 0.0

! BYPASS-DUCT

27 0.0

28 0.01

29 0.0

30 1.E6

! FAN NOZZLE

31 -1.0

! HPC1 COMPRESSOR

32 0.85

33 1.0

34 7.9556

35 0.9

36 1.0

37 5.0

38 0.0

! Sealing Air to LPT

39 0.01

40 0.0

41 1.0

42 0.0

! HPC2 COMPRESSOR

43 0.85

44 1.0

45 1.847

46 0.9

47 1.0

48 2.0

49 0.0

! Cooling Air to HPT NGV and HPT Blade

50 0.075 ! Mass Flow RATIO

51 0.0 ! MASS FLOW LOSS

52 1.0

53 0.0

! Cooling Air to HPT Blade

55 0.01622 ! Mass Flow RATIO

56 0.0 ! MASS FLOW LOSS

57 1.0

58 0.0

! BURNER

59 0.045

60 0.999

61 -1.0

! TURBINE-HPT
62 0.0
63 -1.0
64 -1.0
65 0.903
66 -1.0
67 3.0
68 5.0
69 -1.0

! TURBINE-LPT
70 0.0
71 -1.0
72 -1.0
73 0.934
74 -1.0
75 1.0
76 5.0
77 -1.0

! CORE DUCT
78 0.0
79 0.0
80 0.0
81 1.E6

! CONVERGENT NOZZLE
82 -1.0

! PERFORMANCE

83 -1.0

84 -1.0

85 0.0

86 0.0

! Turbine NGV Angle

88 0.0

89 0.0

! ARITHY : BOOSTER SPEED = FAN SPEED

90 5.0

91 -1.0

92 17.0

93 -1.0

94 6.0

! ARITHY : HPC1 Speed = HPC2 SPEED

95 5.0

96 -1.0

97 44.0

98 -1.0

99 33.0

! ARITHY : LPTWORK = BOOSTERWORK + FANWORK

400 1.0

401 -1.0

402 260.0

403 -1.0

404 210.0

405 -1.0

406 230.0

! ARITHY : HPTWORK = HPC1 WORK + HPC2 WORK

407 1.0

408 -1.0

409 280.0

410 -1.0

411 240.0

412 -1.0

413 270.0

-1

1 2 495.0 ! MASS FLOW

10 6 1510.0 ! TET

-1

-3

Appendix B

Table B Landing gear extension/retraction control system FHA summary

Function	**Failure Condition (Hazard Description)**	**Flight Phase**	**Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants**	**Hazard Class**
Control nose landing gear and main landing gear extension/retraction	Loss of nose landing gear extension	Landing	1. The aircraft will lose nose landing gear extension function 2. The work load of flight crew will increased significantly 3. Occupants might be injured	Catastrophic
	Loss of nose landing gear retraction	Take off	1. The aircraft will lose nose landing gear retraction function 2. The work load of flight crew will increased 3. No effect on occupants.	Minor
	Lose of left main landing gear extension	Landing	1. The aircraft will lose left main landing gear extension function 2. The work load of flight crew will increased significantly 3. Occupants might be injured	Catastrophic
	Lose of left main landing gear retraction	Take off	1. The aircraft will lose left main landing gear retraction function 2. The work load of flight crew will increased 3. No effect on occupants.	Minor

Table B Landing gear extension/retraction control system FHA summary

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants	Hazard Class
Control nose landing gear and main landing gear extension/retraction	Lose of right main landing gear extension	Landing	1. The aircraft will lose right main landing gear extension function 2. The work load of flight crew will increased significantly 3. Occupants might be injured	Catastrophic
	Lose of right main landing gear retraction	Take off	1. The aircraft will lose right main landing gear retraction function 2. The work load of flight crew will increased 3. No effect on occupants.	Minor
Control nose landing gear doors and main landing gear doors extension/retraction	Loss of nose landing gear doors extension	Landing	1. If the aircraft lose this function, it will result in the loss of nose landing gear extension function. 2. The work load of flight crew will increased significantly 3. Occupants might be injured	Catastrophic
	Loss of nose landing gear doors retraction	Take off	1. The aircraft will lose nose landing gear doors retraction function 2. The work load of flight crew will increased 3. No effect on occupants.	Minor

Table B Landing gear extension/retraction control system FHA summary (cont.)

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants	Hazard Class
Control nose landing gear doors and main landing gear doors extension/retraction	Loss of left main landing gear doors extension	Landing	1. If the aircraft lose this function, it will result in the loss of left main landing gear doors extension function. 2. The work load of flight crew will increased significantly 3. Occupants might be injured	Catastrophic
	Loss of left main landing gear doors extension	Take off	1.The left main landing gear can not be retracted.	Minor
	Loss of left main landing gear doors retraction	Landing/Take off	1. The aircraft will lose left main landing gear doors retraction function 2. The work load of flight crew will increased 3. No effect on occupants.	Minor
	Loss of right main landing gear doors extension	Landing	1. If the aircraft lose this function, it will result in the loss of right main landing gear doors extension function. 2. The work load of flight crew will increased significantly 3. Occupants might be injured	Catastrophic
	Loss of right main landing gear doors extension	Take off	1 The right main landing gear can not be retracted	Minor

Table B Landing gear extension/retraction control system FHA summary (cont.)

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants	Hazard Class
Control nose landing gear doors and main landing gear doors extension/retraction	Loss of right main landing gear doors retraction	Landing/Take off	1. The aircraft will lose right main landing gear doors retraction function 2. The work load of flight crew will increased 3. No effect on occupants.	Minor
Landing gear position indication and warning	Lose of nose landing gear position indication	Landing/Take off	1. The aircraft will lose nose landing gear position indication function 2. The work load of flight crew will increased 3. No effect on occupants	Minor
	Lose of left main landing gear position indication	Landing/Take off	1. The aircraft will lose left main landing gear position indication function 2. The work load of flight crew will increased 3. No effect on occupants	Minor

Table B Landing gear extension/retraction control system FHA summary (cont.)

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants	Hazard Class
Landing gear position indication and warning	Lose of right main landing gear position indication	Landing/Take off	1. The aircraft will lose right main landing gear position indication function 2. The work load of flight crew will increased 3. No effect on occupants	Minor
	Erroneous nose landing gear retraction position indication without warning	Take off	3. The aircraft will display inaccurate nose landing gear position 4. Crew may be unable to recognize invalid data display 3. No effect on occupants	Minor
	Erroneous nose landing gear extension position indication without warning	Landing	1. The aircraft will display inaccurate nose landing gear position 2. Crew may be unable to recognize invalid data display 3. Occupants might be injured	Catastrophic
	Erroneous left main landing gear retraction position indication without warning	Take off	1. The aircraft will display inaccurate left main landing gear position 2. Crew may be unable to recognize invalid data display 3. No effect on occupants	Minor

Table B Landing gear extension/retraction control system FHA summary (cont.)

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants	Hazard Class
Landing gear position indication and warning	Erroneous left main landing gear extension position indication without warning	Landing	1. The aircraft will display inaccurate left main landing gear position 2. Crew may be unable to recognize invalid data display 3. Occupants might be injured	Catastrophic
	Erroneous right main landing gear retraction position indication without warning	Take off	1. The aircraft will display inaccurate right main landing gear position 2. Crew may be unable to recognize invalid data display 3. No effect on occupants	Minor
	Erroneous right main landing gear extension position indication without warning	Landing	1. The aircraft will display inaccurate right main landing gear position 2. Crew may be unable to recognize invalid data display 3. Occupants might be injured	Catastrophic
	Erroneous nose landing gear retraction position indication with warning	Take off	1. The aircraft will display inaccurate nose landing gear position 2. The work load of flight crew will increased 3. No effect on occupants	Minor

Table B Landing gear extension/retraction control system FHA summary (cont.)

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants	Hazard Class
Landing gear position indication and warning	Erroneous nose landing gear extension position indication with warning	Landing	1. The aircraft will display inaccurate nose landing gear position 2. The work load of flight crew will increased 3. No effect on occupants	Minor
	Erroneous left main landing gear retraction position indication with warning	Take off	1. The aircraft will display inaccurate left main landing gear position 2. The work load of flight crew will increased 3. No effect on occupants	Minor
	Erroneous left main landing gear extension position indication with warning	Landing	1. The aircraft will display inaccurate left main landing gear position 2. The work load of flight crew will increased 3. No effect on occupants	Minor
	Erroneous right main landing gear retraction position indication with warning	Take off	1. The aircraft will display inaccurate right main landing gear position 2. The work load of flight crew will increased 3. No effect on occupants	Minor

Table B Landing gear extension/retraction control system FHA summary (cont.)

Function	Failure Condition (Hazard Description)	Flight Phase	Effect of Failure Condition on 1.Aircraft 2.Crew 3.Occupants	Hazard Class
Landing gear position indication and warning	Erroneous right main landing gear extension position indication with warning	Landing	1. The aircraft will display inaccurate right main landing gear position 2. The work load of flight crew will increased 3. No effect on occupants	Minor
System internal data exchange	Loss of internal data exchange	Landing/Take off	1. signals will not be transmitted between the two LGCIU 2. The work load of flight crew will increased 3. No effect on occupants	Minor
External data exchange	Loss of external data exchange	Landing/Take off	1. signals will not be transmitted to other systems 2. The work load of flight crew will increased 3. No effect on occupants	Minor

Appendix C

Table C Landing Gear Extension/Retraction Control System FMEA Summary

Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
L/G Lever	Fails to switch to up position	Take off	Fails to switch to up position	Loss of the normal landing gear retraction function	Reduce the redundancy of landing gear retraction function	Minor
	Fails to switch to down position	Landing	Fails to switch to down position	Loss of the normal landing gear extension function	Reduce the redundancy of landing gear extension function	Minor
Landing Gear Control and Interface Unit 1(LGCIU1)	Loss of the control of door selector valve	Landing/ Take off	Loss of the control of door selector valve	Loss of the LGCIU1 normal landing gear extension/retraction function	Reduce the redundancy of landing gear extension /retraction function	Minor
	Loss of the control of gear selector valve	Landing/ Take off	Loss of the control of gear selector valve	Loss of the LGCIU1 normal landing gear extension/retraction function	Reduce the redundancy of landing gear extension /retraction function	Minor

Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Landing Gear Control and Interface Unit 1(LGCIU1)	Loss of proximity sensors signal input	Landing/ Take off	Loss of proximity sensors signal input	Loss of the LGCIU1 proximity sensors signal output	Reduce the redundancy of proximity sensors signal input	Minor
	Loss of proximity sensors signal output	Landing/ Take off	Loss of proximity sensors signal output	Loss of the LGCIU1 proximity sensors signal output	Reduce the redundancy of proximity sensors signal output	Minor
	Loss of data from LGCIU2	Landing/ Take off	Loss of data from LGCIU2	Loss of the communication between LGCIU1 and LGCIU2	Reduce the redundancy of landing gear extension /retraction function	Minor
	Loss of data transferred to LGCIU2	Landing/ Take off	Loss of data transferred to LGCIU2	Loss of the communication between LGCIU1 and LGCIU2	Reduce the redundancy of landing gear extension /retraction function	Minor

Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Landing Gear Control and Interface Unit 1(LGCIU1)	Loss of data from L/G lever	Landing/ Take off	Loss of data from L/G lever	Loss of the LGCIU1 normal landing gear extension/retraction function	Reduce the redundancy of landing gear extension /retraction function	Minor
	Erroneous landing gear position data output	Landing/ Take off	Erroneous landing gear position data output	Erroneous landing gear position data output	Reduce the redundancy of landing gear position data output	Minor
Landing Gear Control and Interface Unit 2(LGCIU2)	Loss of the control of door selector valve	Landing/ Take off	Loss of the control of door selector valve	Loss of the LGCIU2 normal landing gear extension/retraction function	Reduce the redundancy of landing gear extension /retraction function	Minor
	Loss of the control of gear selector valve	Landing/ Take off	Loss of the control of gear selector valve	Loss of the LGCIU2 normal landing gear extension/retraction function	Reduce the redundancy of landing gear extension /retraction function	Minor

Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Landing Gear Control and Interface Unit 2(LGCIU2)	Loss of proximity sensors signal input	Landing/ Take off	Loss of proximity sensors signal input	Loss of the LGCIU2 proximity sensors signal output	Reduce the redundancy of proximity sensors signal input	Minor
	Loss of proximity sensors signal output	Landing/ Take off	Loss of proximity sensors signal output	Loss of the LGCIU2 proximity sensors signal output	Reduce the redundancy of proximity sensors signal output	Minor
	Loss of data from LGCIU1	Landing/ Take off	Loss of data from LGCIU1	Loss of the communication between LGCIU1 and LGCIU2	Reduce the redundancy of landing gear extension /retraction function	Minor
	Loss of data transferred to LGCIU1	Landing/ Take off	Loss of data transferred to LGCIU1	Loss of the communication between LGCIU1 and LGCIU2	Reduce the redundancy of landing gear extension /retraction function	Minor

Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Landing Gear Control and Interface Unit 2(LGCIU2)	Loss of data from L/G lever	Landing/ Take off	Loss of data from L/G lever	Loss of the LGCIU2 normal landing gear extension/retraction function	Reduce the redundancy of landing gear extension /retraction function	Minor
	Erroneous landing gear position data output	Landing/ Take off	Erroneous landing gear position data output	Erroneous landing gear position data output	Reduce the redundancy of landing gear position data output	Minor
Door selector valve	Fails to switch to extension position	Landing/ Take off	Fails to switch to extension position	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function	Minor
	Internal leakage	Landing/ Take off	Internal leakage	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function	Minor

Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Door selector valve	Fails to switch to retraction position	Landing/ Take off	Fails to switch to retraction position	Loss of the landing gear door retraction function	Landing gear doors remain open	Minor
	Selector valve always at extension position	Landing/ Take off	Selector valve always at extension position	Loss of the landing gear door retraction function	Landing gear doors remain open	Minor
	Selector valve always at retraction position	Landing/ Take off	Selector valve always at retraction position	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function	Minor
	Loss the control of actuators	Landing/ Take off	Loss the control of actuators	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function	Minor
			Loss the control of actuators	Loss of the normal landing gear door retraction function	Landing gear doors remain open	Minor

Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Gear selector valve	Internal leakage	Landing/ Take off	Internal leakage	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function	Minor
	Fails to switch to extension position	Landing/ Take off	Fails to switch to extension position	Loss of the normal landing gear door extension function	Reduce the redundancy of landing gear extension function	Minor
	Fails to switch to retraction position	Landing/ Take off	Fails to switch to retraction position	Loss of the landing gear retraction function	Landing gears remain at extension position	Minor
	Selector valve always at extension position	Landing/ Take off	Selector valve always at extension position	Loss of the landing gear retraction function	Landing gears remain at extension position	Minor

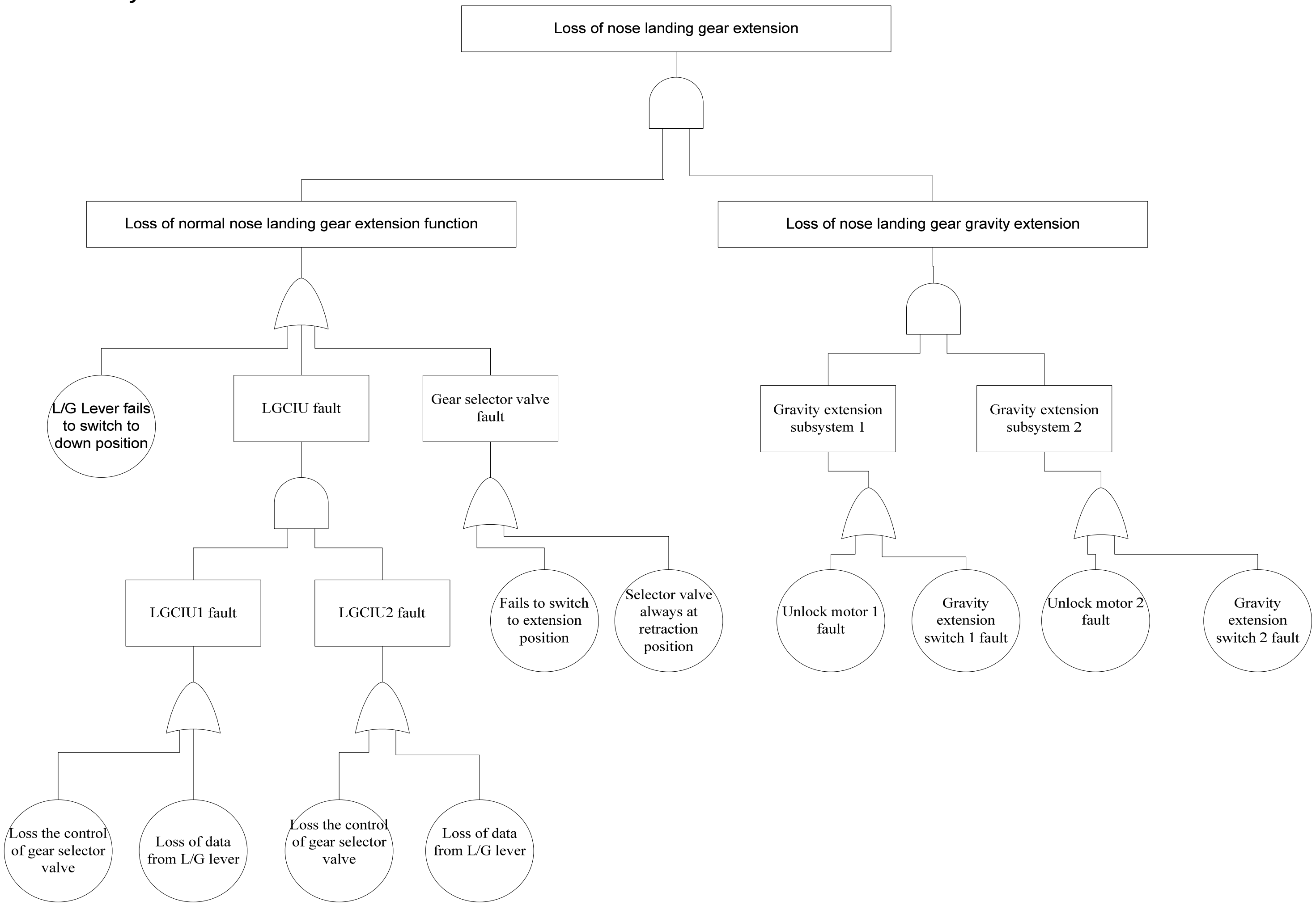
Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

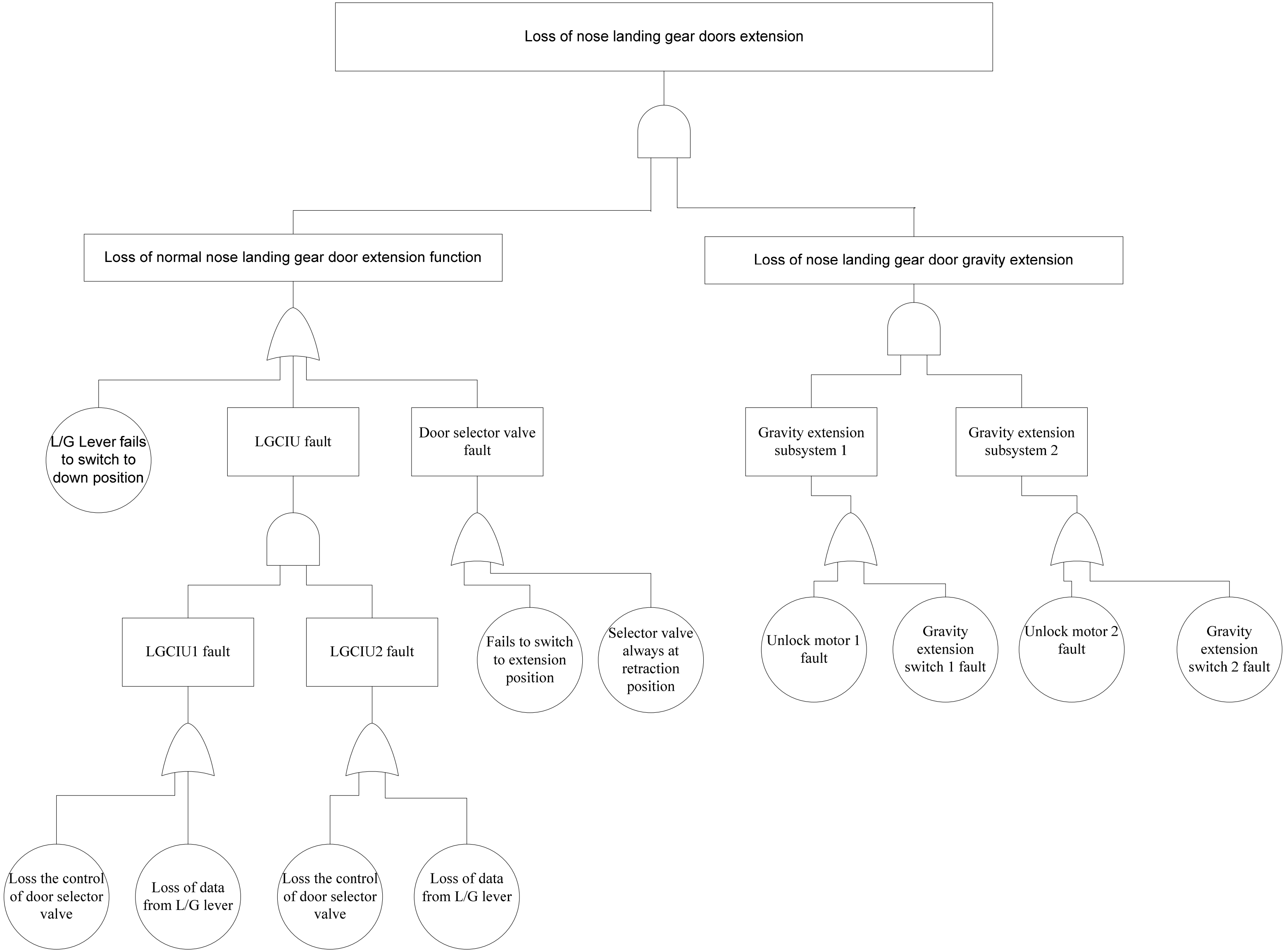
Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Gear selector valve	Selector valve always at retraction position	Landing/ Take off	Selector valve always at retraction position	Loss of the normal landing gear extension function	Reduce the redundancy of landing gear extension function	Minor
	Loss the control of actuators	Landing/ Take off	Loss the control of actuators	Loss of the normal landing gear extension function	Reduce the redundancy of landing gear extension function	Minor
			Loss the control of actuators	Loss of the normal landing gear retraction function	Landing gears remain at extension position	Minor
Proximity sensor	Always indicates proximate position	Landing/ Take off	Always indicates proximate position	Fault indication of landing gear position indication	Reduce the redundancy of landing gear position indication	Minor

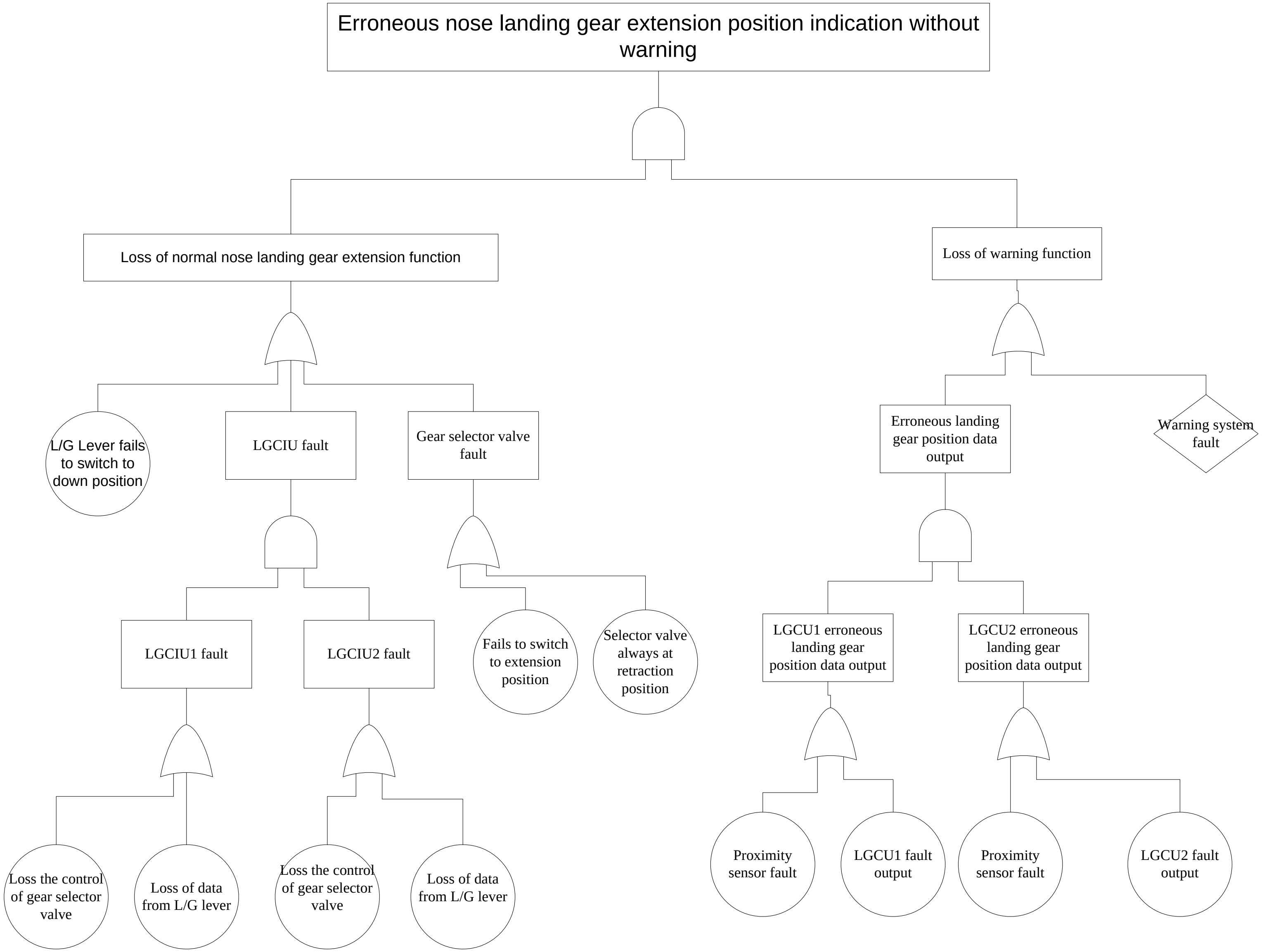
Table C Landing Gear Extension/Retraction Control System FMEA Summary (cont.)

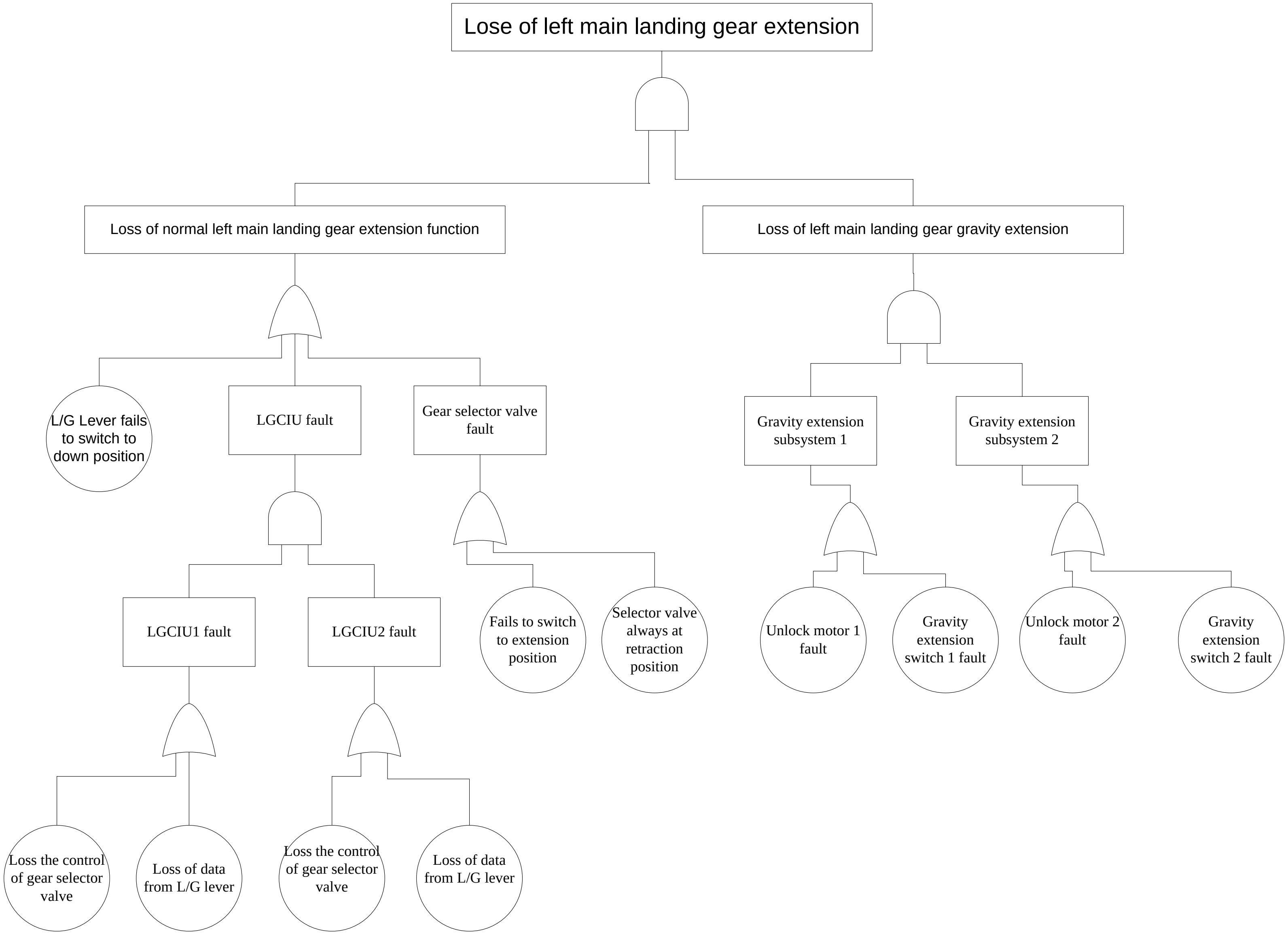
Item	Failure mode	Flight phase	Local Effect	Effect on the system	Effect on aircraft	Severity Level
Proximity sensor	Always indicates removed position	Landing/ Take off	Always indicates removed position	Fault indication of landing gear position indication	Reduce the redundancy of landing gear position indication	Minor
Gravity extension switch	Fails to switch to down position	Landing/ Take off	Fails to switch to down position	Reduce the redundancy of gravity extension function	None	Minor
Gravity extension motor	Open circuit	Landing/ Take off	Open circuit	Motor out of work	Reduce the redundancy of landing gear gravity extension function	Minor
	Short circuit	Landing/ Take off	Short circuit	Loss of gravity extension function	Reduce the redundancy of landing gear extension function	Minor

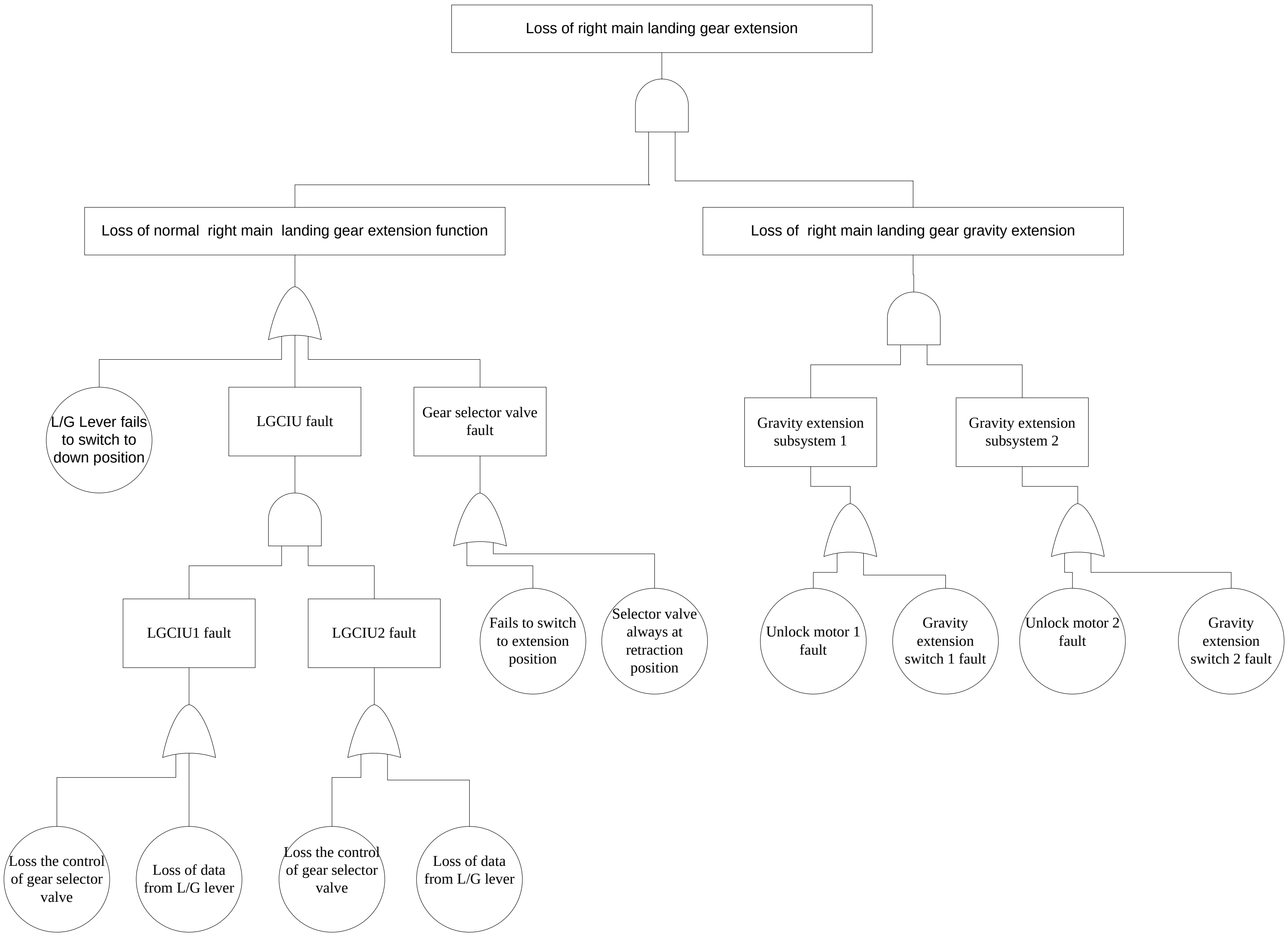
Appendix D: Summary of FTA

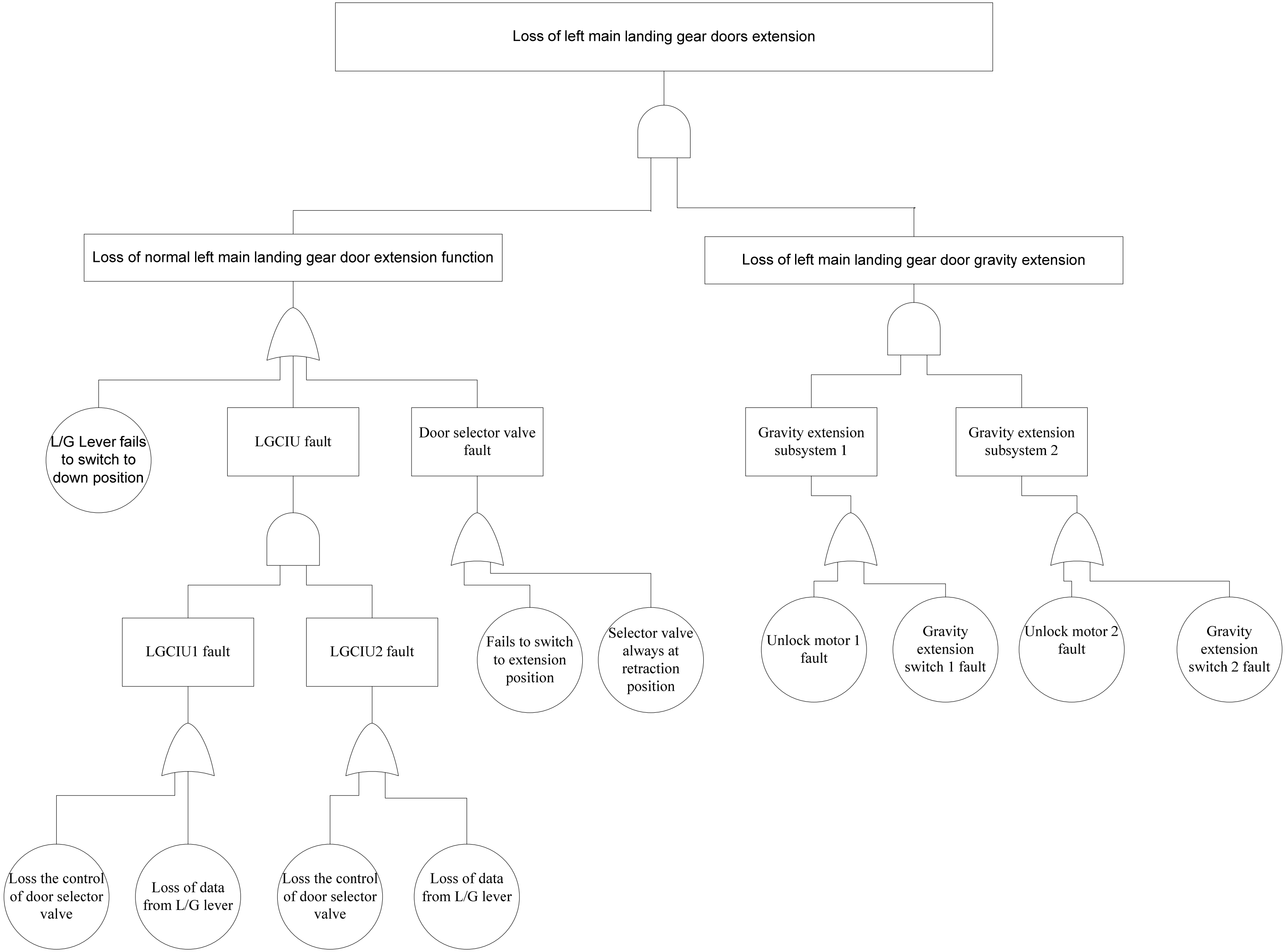


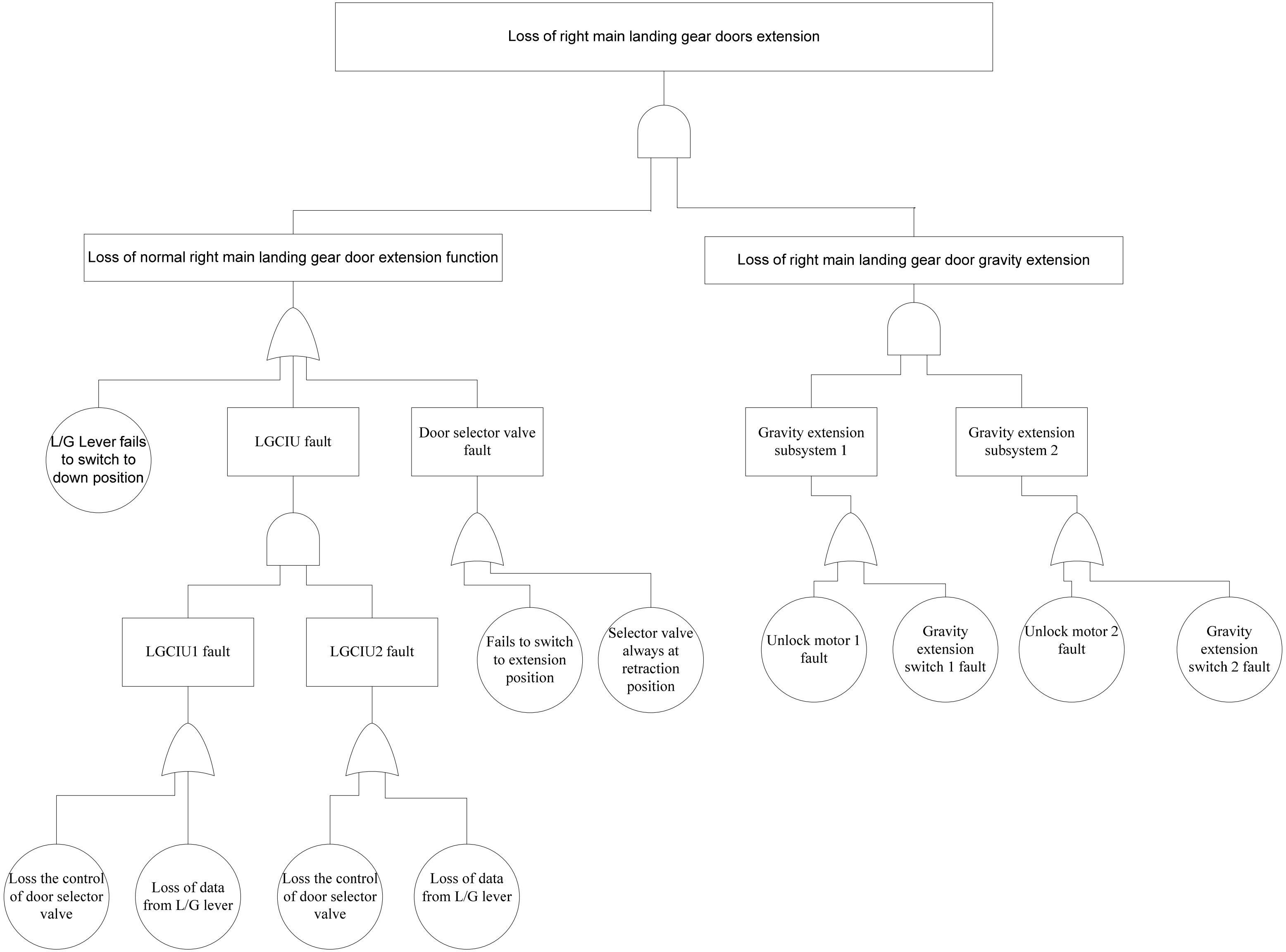

Loss of nose landing gear doors extension
Loss of normal nose landing gear door extension function
Loss of nose landing gear door gravity extension
L/G Lever fails to switch to down position
LGCIU fault
Door selector valve fault
Gravity extension subsystem 1
Gravity extension subsystem 2
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
Unlock motor 1 fault
Gravity extension switch 1 fault
Unlock motor 2 fault
Gravity extension switch 2 fault
Loss the control of door selector valve
Loss of data from L/G lever
Loss the control of door selector valve
Loss of data from L/G lever

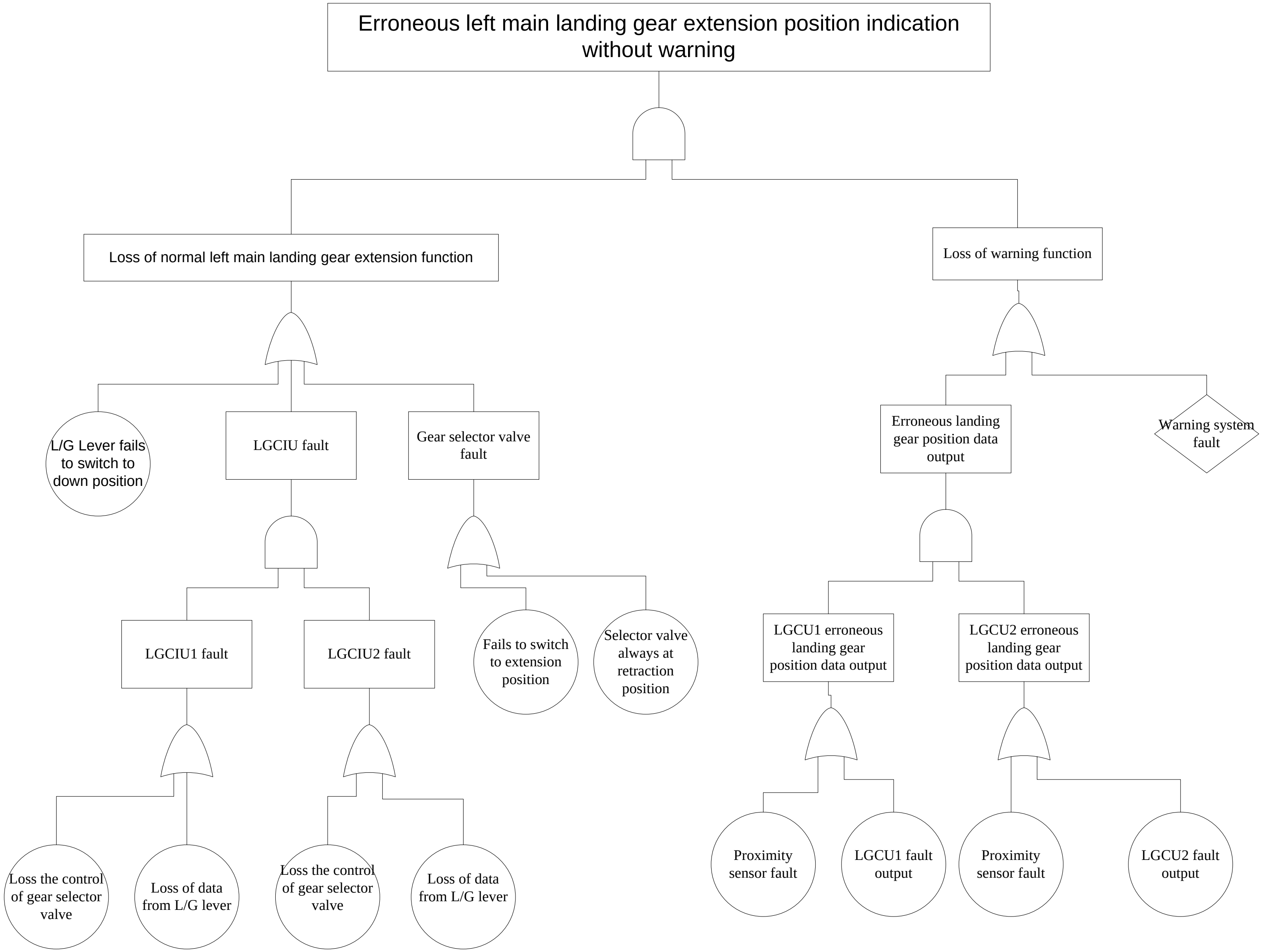

Erroneous nose landing gear extension position indication without warning
Loss of normal nose landing gear extension function
Loss of warning function
L/G Lever fails to switch to down position
LGCIU fault
Gear selector valve fault
Erroneous landing gear position data output
Warning system fault
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
LGCU1 erroneous landing gear position data output
LGCU2 erroneous landing gear position data output
Loss the control of gear selector valve
Loss of data from L/G lever
Loss the control of gear selector valve
Loss of data from L/G lever
Proximity sensor fault
LGCU1 fault output
Proximity sensor fault
LGCU2 fault output


Lose of left main landing gear extension
Loss of normal left main landing gear extension function
Loss of left main landing gear gravity extension
L/G Lever fails to switch to down position
LGCIU fault
Gear selector valve fault
Gravity extension subsystem 1
Gravity extension subsystem 2
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
Unlock motor 1 fault
Gravity extension switch 1 fault
Unlock motor 2 fault
Gravity extension switch 2 fault
Loss the control of gear selector valve
Loss of data from L/G lever
Loss the control of gear selector valve
Loss of data from L/G lever

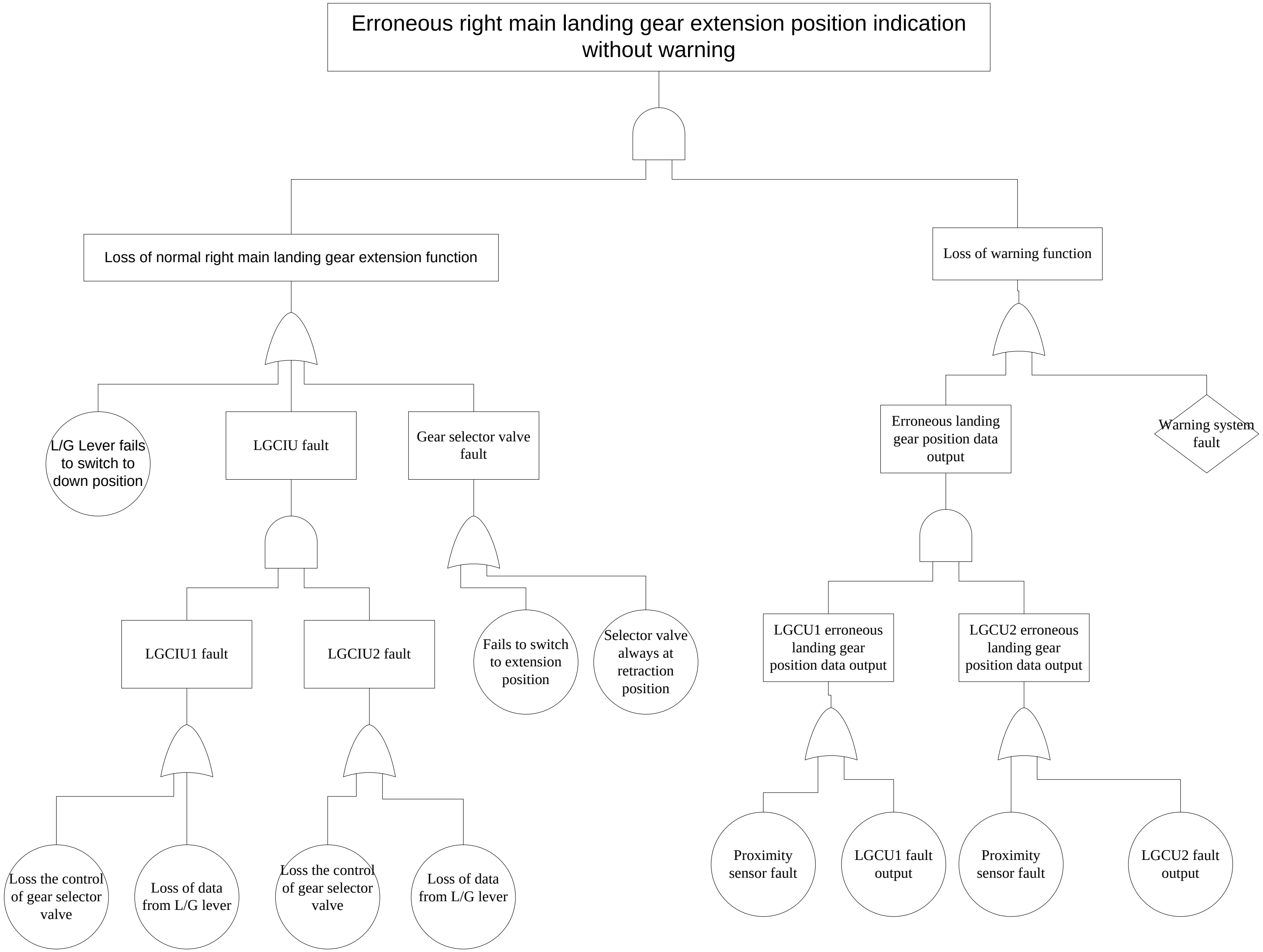

Loss of right main landing gear extension
Loss of normal right main landing gear extension function
Loss of right main landing gear gravity extension
L/G Lever fails to switch to down position
LGCIU fault
Gear selector valve fault
Gravity extension subsystem 1
Gravity extension subsystem 2
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
Unlock motor 1 fault
Gravity extension switch 1 fault
Unlock motor 2 fault
Gravity extension switch 2 fault
Loss the control of gear selector valve
Loss of data from L/G lever
Loss the control of gear selector valve
Loss of data from L/G lever


Loss of left main landing gear doors extension
Loss of normal left main landing gear door extension function
Loss of left main landing gear door gravity extension
L/G Lever fails to switch to down position
LGCIU fault
Door selector valve fault
Gravity extension subsystem 1
Gravity extension subsystem 2
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
Unlock motor 1 fault
Gravity extension switch 1 fault
Unlock motor 2 fault
Gravity extension switch 2 fault
Loss the control of door selector valve
Loss of data from L/G lever
Loss the control of door selector valve
Loss of data from L/G lever


Loss of right main landing gear doors extension
Loss of normal right main landing gear door extension function
Loss of right main landing gear door gravity extension
L/G Lever fails to switch to down position
LGCIU fault
Door selector valve fault
Gravity extension subsystem 1
Gravity extension subsystem 2
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
Unlock motor 1 fault
Gravity extension switch 1 fault
Unlock motor 2 fault
Gravity extension switch 2 fault
Loss the control of door selector valve
Loss of data from L/G lever
Loss the control of door selector valve
Loss of data from L/G lever



Erroneous left main landing gear extension position indication without warning
Loss of normal left main landing gear extension function
Loss of warning function
L/G Lever fails to switch to down position
LGCIU fault
Gear selector valve fault
Erroneous landing gear position data output
Warning system fault
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
LGCU1 erroneous landing gear position data output
LGCU2 erroneous landing gear position data output
Loss the control of gear selector valve
Loss of data from L/G lever
Loss the control of gear selector valve
Loss of data from L/G lever
Proximity sensor fault
LGCU1 fault output
Proximity sensor fault
LGCU2 fault output


Erroneous right main landing gear extension position indication without warning
Loss of normal right main landing gear extension function
Loss of warning function
L/G Lever fails to switch to down position
LGCIU fault
Gear selector valve fault
Erroneous landing gear position data output
Warning system fault
LGCIU1 fault
LGCIU2 fault
Fails to switch to extension position
Selector valve always at retraction position
LGCU1 erroneous landing gear position data output
LGCU2 erroneous landing gear position data output
Loss the control of gear selector valve
Loss of data from L/G lever
Loss the control of gear selector valve
Loss of data from L/G lever
Proximity sensor fault
LGCU1 fault output
Proximity sensor fault
LGCU2 fault output