

# Rapid Prototyping of Small Robots

Greg Reshko  
Carnegie Mellon University  
Pittsburgh, PA, USA  
reshko@ri.cmu.edu

Matthew T. Mason  
Carnegie Mellon University  
Pittsburgh, PA, USA  
matt.mason@ri.cmu.edu

Illah R. Nourbakhsh  
Carnegie Mellon University  
Pittsburgh, PA, USA  
illah@ri.cmu.edu

## 1. Introduction

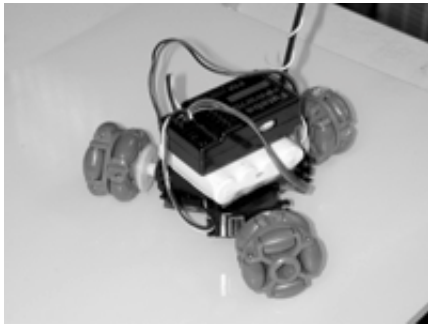


Figure 1

This paper describes our work on high quality rapid prototyping. The focus is on techniques that produce prototypes of desired quality and yet do not take long to build. We present necessary information about methods of control, power, sensors, batteries, electronics, and more. We outline materials, methods, and tools. We also explain how to use servomotors, Lego, and electronics to achieve satisfying results.

Figure 1 shows an example of the kind of project. With the right tools and materials, and with parts on hand, the omni wheel telerobot took less than half an hour from conception to completion. The Appendices provides detailed information, including the steps to construct the Palm Pilot Robot Kit.

### 1.1 Why prototype?

We have noticed that some designers tend to prototype very quickly [1]. Sometimes you can learn something important in a few minutes from a prototype that might have taken weeks or months otherwise. Mechanical design seems to require iteration, so, the faster you can iterate, especially at the beginning of a project, the better.

### 1.2 Levels of prototyping

Prototyping ranges from an idea to a complete product. The quality and the level of detail of a prototype should depend on its purpose. For example, Figure 1 shows the first prototype of the Palm Pilot Robot [5], which is nothing more than three servos taped to a receiver. This simple model is sufficient to fulfill its purpose of demonstrating holonomic motion of the base. Later we built a more complex prototype with sensors to show that the robot can follow walls.

## 2. Control

We examined and tested three types of control of prototypes: human powered prototypes, remote control, and computer control.



Figure 2

### 2.1 Human powered prototypes

One of the most common goals of prototyping is to demonstrate a concept or an idea. Usually complexity of a prototype varies with the complexity of an idea. Relatively simple or predictable prototypes do not need motors and batteries – they can be powered and controlled by humans instead. An example of a human-powered prototype is a regular four-wheel LEGO vehicle in Figure 2. There is no need to attach motors and remote-control equipment to demonstrate that it can move back and forth. On the contrary, it is impossible to demonstrate wheel traction simply by turning the wheels. Therefore, prototypes in which human

intervention affects the results require a remote or computer control system.

### **2.2 Remote control**

Human remote control is useful when precise or unusual methods of control are required. It is also the simplest way to control a prototype without actually physically interfering with it.

For example, the fastest way to determine what happens to a robot that rapidly accelerates and then decelerates is to use a remote control system. A simple and easy to use remote control system for model airplanes will suffice to demonstrate whether such robot will immediately come to a stop or skid for a certain distance. Such control system has four channels and provides good range, reliable communication, and up to four proportional controls, which allow smooth adjustment of speed or angular position of servos.

An example is Three-Wheel Mobipulator robot. Human remote control provides an easy method of control of the steered wheel and the brake at the same time, while not requiring any programming or additional electronics.

### **2.3 Computer control**

When a robot requires precise and complex operations or is involved in an application that requires sensors or computer feedback to take actions, the computer control becomes the right choice. An example of such control is a simple autonomous prototype with encoders on its wheels driving in a straight path.

Companies develop a variety of boards with different capabilities that can control servo and stepper motors by means of serial or parallel communication with a computer. Some boards just translate commands from a computer to PWM signals, whereas others are programmable.

Pontech's SV203 board is a good example of a relatively simple and inexpensive computer control system. It uses serial communication to talk to a computer and can run by itself. However, it is very slow and simplistic compared to a desktop computer. Most boards have very limited number of functions and the amount of memory. Although the board by itself can be sufficient for a number of applications, the two alternatives are to use a tether and connect a robot to a reasonably powerful computer, or to use a more complex board such as 68HC11 chip or BASIC stamp.

Another advantage of computer control over the previous two methods is the ability to use sensors. Most control boards have already built-in analog and digital inputs and can connect to a variety of sensors.

## **3. Power**

Size, shape, and voltage of batteries depend on its application. For small-scale prototypes, we use 6V or 4.5V Nickel-Metal Hydride (NiMH) battery. It is fully rechargeable and can provide steady voltage for a relatively long time. These batteries can be used for servomotors and electronics, because they provide high current. A small regular 9V or 6V NiMH with a voltage regulator can be used to power electronics, since it does not require high current.

Tethered models can be powered externally, since they already require wires for communication. External power supply has an advantage of providing stable high-current output without a need to recharge.

## **4. Sensors**

When controlling a robot by a computer, or when it is an autonomous system, sensors become an integral part of prototyping.

### **4.1. Digital and analog sensors**

There are two types of sensors: digital and analog. Digital sensors, such as micro-switches or pushbuttons, are easy to implement by interfacing them directly to the electronics.

- **Micro switches** or push buttons are small switches that are useful when physical confirmation of a contact is required, such as in obstacle detection.

Analog sensors provide a range of output values, but usually require an analog-to-digital converter to convert their values into a binary number, which a computer can understand. Analog sensors can also be converted to binary sensors by using a voltage divider, which usually requires one additional resistor connected to the ground.

Analog sensors [2] include the following:

- **Photoresistors** are variable resistors that change their resistance due to the intensity of visible light. Phototransistors are similar, but provide greater sensitivity. Photodiodes have even greater sensitivity and respond rapidly to changes in illumination.
- **Infrared** sensors are used as proximity and reflectivity sensors and are almost unaffected by visible light.
- **Pyroelectric** sensors respond to very small temperature changes, because its crystal induces a charge when it is heated.
- **Bend sensors** have conductive ink between two electrodes to give a variable resistance, depending upon the degree of bending. Total resistance changes by a factor of about 3 to 5 as the bend sensor goes from straight to maximum bend.
- **Force-sensing resistors** are also based on conductive ink technology. They are very sensitive, and their resistance is changed by several orders of magnitude as force is applied.
- **Rubbery ruler** is a unique tube-like sensor that measures change in its length. Inside the tube has two wires, and when it stretches, the distance between the wires increases and the capacitance decreases.
- **Microphones** provide a way to add sound detection ability to a robot, although it usually requires additional electronics.
- **Piezoelectric film** sensors detect vibrations, changes in applied force, and changes in temperature and far-infrared radiation.
- **Sonar** sensors measure distance to an object.
- **Tilt** sensors have a drop of electrolytic fluid between its electrodes. The amount of conduction between the center electrode and each of the outer electrodes is determined by the degree to which the outer electrode is immersed in the electrolytic fluid.
- **Shaft Encoders** are important for precise control of motors and can be implemented using IR or light sensors.
- **Proprioceptive** sensors measure the internal state of the robot, such as battery-level sensing, stall current sensing, etc.

### 4.2. Infrared Rangefinders

Sharp GP2D12 infrared triangulation sensors (distributed by Acroname, Inc.) are very accurate rangefinders. These devices use linear position sensitive devices (PSD) and their measurements are accurate to approximately 1cm [Appendix A]. Sensors return their readings as variable voltage, ranging from 0 to 5 volts. Analog-to-digital converter is used to convert this analog value to digital reading ranging from 0 to 255. The sensor's manual includes a graph of sensor's value versus distance. Distance is approximated by using a power regression:

$$d(s) = 2141.7 * s^{-1.07886}$$

where  $d$  is distance in cm and  $s$  is 8-bit sensor's value from 0 to 255.

IR sensors require significant amount of power. When using small boards, such as SV203, the sensors should be connected to unregulated 6V, instead of regulated 5V. Outputs of these sensors are connected to boards' analog input pins.

## 5. Components

### 5.1 Fasteners

The most common type of fasteners in small-scale prototyping are little nuts and bolts. They come in variety of types and sizes. In our prototypes, we use 4-40" and 6-32" hexagonal head bolts and nuts, since they are appropriate for small-scale models. Usually, we use regular steel nuts, however plastic lock nuts and nylon insert nuts are useful for variable tightening of a bolt.

### 5.2 Materials

#### Aluminum:

We found aluminum to be one of the best prototyping materials. It is lightweight and can be easily machined. A specific advantage of aluminum is its pliability. It can be bent at virtually any angle, although it depends on its thickness. 1/4" plates can be bent up to 90°, whereas thin plates can be bent all the way to 180°. Aluminum can also be drilled, tapped, or cut more easily than other materials, such as steel.

**Acrylic plastic:**

Acrylic plastic is also an interesting material. It can be cut and filed to provide almost perfect edge. It is also easy to drill and tap. One of its advantages is that two pieces can be connected together in any fashion by using acetone or other solvent-welder. A solvent bond is similar to a weld, so it is extremely durable. Furthermore, unlike other glues, solvent securely connects two materials in very short time.

**Polycarbonate plastic:**

Like acrylic, this plastic is easily machined. It can be cut, milled, and drilled. However, it is quite difficult to tap, because the material can be compressed. Its unique advantage is that it can be bent without heating, for example, using a brake. Most plastics either break during even minor bending or require to be heated. Another interesting property of polycarbonate plastic is its strength – a ½” thick sheet is bullet proof.

**5.3 Lego**

Lego by itself is a great kit for prototyping. Complex parts, such as gear trains, arms, and steering mechanisms can be implemented quickly and easily using Lego parts for construction [3].

**5.3.2 Lego structures**

Sometimes it is faster to use Lego than to manufacture similar parts using usual materials. A good example is Lego wheels. Manufacturing a wheel is not an easy task and usually requires some time, whereas Lego wheels come in many shapes and sizes, such as a smooth-surfaced pulley or a large traction-wheel.

**5.3.2 Lego Wheels**

Small wheels and pulleys can be glued to servos with a heat-melt glue, whereas big Lego traction-wheels can be securely attached to CS60 servos, because servo’s connector fits nicely between wheel’s plastic and rubber.

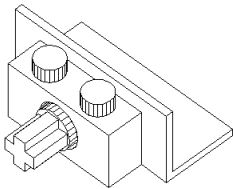


Figure 3

An easy way to attach free spinning wheels to a prototype is to connect small Lego wheels to a 2x1 Lego beam with a hole in the middle by a Lego connector peg. The Lego beam is then glued to a structure, for example, an aluminum angle in Figure 3.

Larger wheels require two 4x1 or larger beams and a Lego axle that goes through the beams and the wheel.

**5.4 Double-sided Foam Tape and Variable-rigidity attachment**

Sometimes it is useful when servos are not rigidly attached to a structure, but are rather flexible. For example, it is definitely a plus for a four-wheel vehicle, since it ensures that all wheels are going to be on the ground at the same time. (It is difficult to achieve the same result with a rigid attachment, since it is almost impossible to make four perfectly leveled supports for servos).

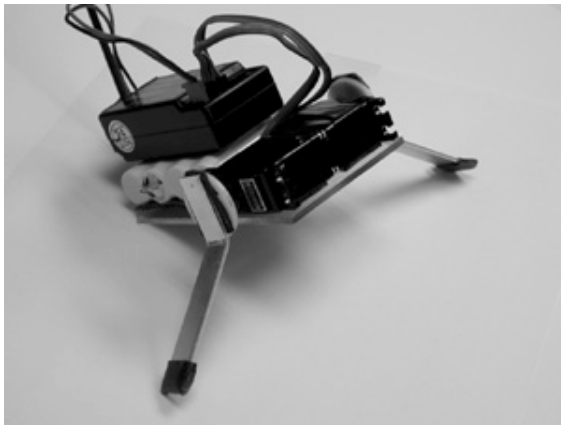


Figure 4

One of the fastest, but also secure ways to do that is to attach servos to the base using a double-sided sticky tape. Such tape is usually quite thick, which allows servos to have some flexibility. Structures that are more flexible require a few more layers of tape.

By varying area covered with tape and tape’s thickness, it is possible to get any degree of flexibility of a connection – from very rigid (such as one layer of tape covering the whole servo) to very flexible. In Figure 4 all servos, a receiver, and a battery pack are connected by double-sided tape to a rectangular piece of plastic. Furthermore, the tape is strong enough to hold aluminum legs attached securely to

plastic servo connectors.

### 5.5 Velcro

A simple and yet secure way to attach a receiver or a battery to a robot is to use Velcro. A small 1"x1" piece on a robot and at the bottom of a battery or a receiver will securely hold it in place. Velcro's advantage is that it can be detached – this is not the case with other adhesives.

## 6. Servomotors

Servomotors can be used very efficiently for prototyping as primary drive motors, because of their mounting design, built-in gear reduction, and simple remote control. Lightweight and compact receiver-battery pack is also useful at relatively small models (ex. when a model is just twice the size of a receiver). Furthermore, servos can provide both types of actuation: angular position and velocity control. Angular position control means that servo's input controls its position, whereas velocity control affects servo's velocity.

### 6.1 Modular assembly and servo case as structural element

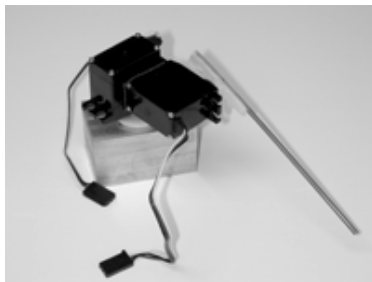


Figure 5

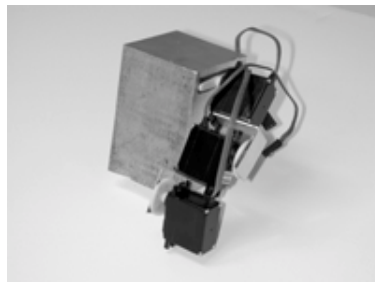


Figure 6

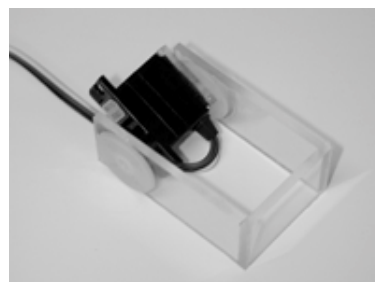


Figure 7

When a prototype is relatively small, servos take a lot of space. Instead of using servos purely as rotary actuators, it is more efficient to use their cases as structures of a robot.

A simple spherical actuator in Figure 5 can be made by taping one servo to another. By using only three aluminum angles and a tape, it is possible to make a three joint leg (Figure 6). Three servos provide not only three actuators, but also three links. Because, servos have very high torque-to-weight ratio, they make up very efficient legs. Such leg can lift a body that is much heavier than the leg itself.

To increase durability, C-shape aluminum piece can be used instead of an angle. This C-shape connector attaches to servo's white plastic connector on one side and to simple (connector/bolt) bearing on another side. An alternative to aluminum and double-sided tape is acrylic plastic and solvent-welder (Figure 7). Connections will be more reliable than those of aluminum and tape, since servo's connector and servo's case itself are made from plastic, and therefore are easily glued.

By using such modules (servo with C-shape connector), it is possible to connect several servos together in a linkage, using the same design for each link. This reduces the amount of time required for assembly.

### 6.2 Converting servo's servo-drive to continuous-rotation

Usual procedure is to replace servo's potentiometer with two resistors of equal value, and then remove any hardware that prevents servo's gears to rotate freely (small plastic parts on gears, parts of case in some servos). The two resistors should have the same total resistance as the original potentiometer.



Figure 8

When the potentiometer is large enough to be attached by some kind of a connector to a gear, which is the case in most servos, then the modification procedure is different and is much simpler, since it does not require any extra parts. First, the top part of a potentiometer should be cut off by a saw or shears (Figure 8). Then, by turning the remaining part of potentiometer, it should be set to center position (servomotor is stopped). To ensure that the remaining part of the potentiometer will stay in this position, it should be glued to servo's case (just a drop of glue around the potentiometer's cut-off part). After the potentiometer is glued to the case, the servo can be reassembled.

After these modifications the servo controls its velocity instead of angular position.

However, servomotors are not designed for speed-control and therefore their speed is not directly proportional to the 8-bit value (0...255) sent to the board. The graph below shows a relation between sent values and actual speed of Cirrus CS30 servomotor:

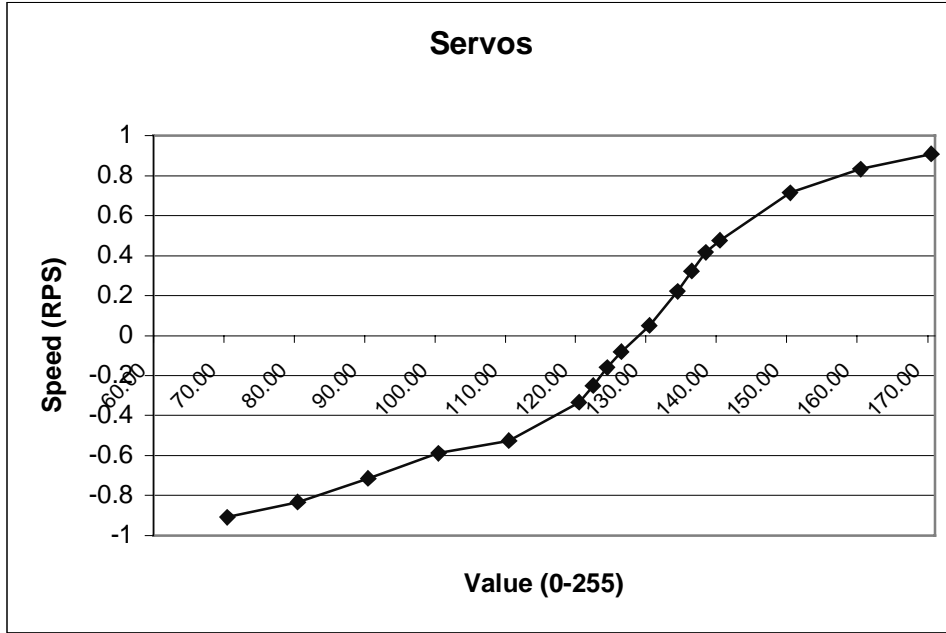


Figure 9

The curve through the points on the graph in Figure 9 is approximated to a reasonable degree by a cubic regression

$$s(v) = 39.81*v^3 - 12.61*v^2 + 22.12*v + 128.42$$

where  $s$  is 'servo value' from 0 to 255 and  $v$  is servo's velocity in revolution per second.

### 6.3 Pre-modified servomotors

The methods described above are successful for modifying any servo. However, a company named MrRobot™ sells a number of already modified servos (Appendix C).

These servos rotate smoothly, because additional lubrication is added to servos' gears. No further modifications are needed, and the modified servos are inexpensive.

### 6.4 Attaching a servo to a structure

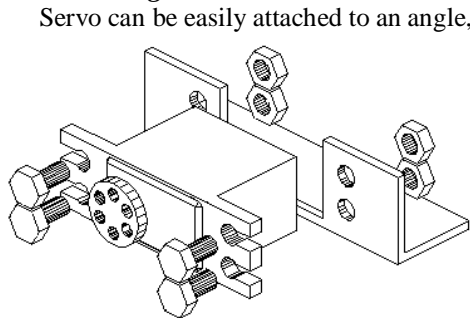


Figure 10

Servo can be easily attached to an angle, by milling (punching or cutting out) a slot, drilling four holes, and attaching the servo using four bolts (Figure 10). The slot should be as wide as servo's base. Holes should be the same diameter as the mounting holes on a servo. This attachment will be extremely secure, because the servo is connected to an angle by four bolts and has the other surface of an angle as an additional horizontal support. Plastic on servos acts as a lock-washer, preventing bolts from loosening.

This servo-angle assembly can be attached virtually to any surface using only two bolts.

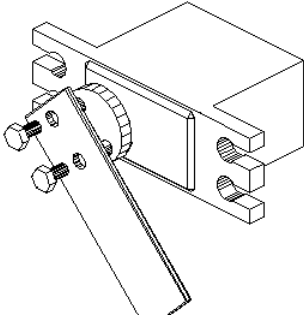


Figure 11

**6.5 Attaching a structure to a servo**

Large wheels or any structure that requires high torque can be attached to a servo by using a large plastic connector (usually provided with a servo), drilling in it appropriate number of holes, and then bolting the connector to the structure (Figure 11).

A small wheel can be attached to a servo with a heat-melt glue. However, it is important not to glue the screw that goes through the connector to the servo. Otherwise, it will be impossible to use the servo for any other purpose. Using these techniques, it is possible to assemble such mechanisms as a steered drive wheel or a four-bar linkage in a very short time.

**6.6 Dual-side drive for a servo**

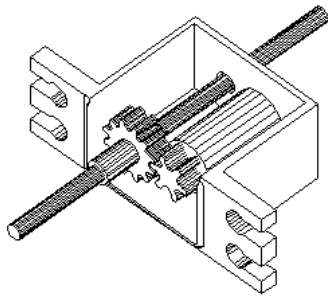


Figure 12

Sometimes it is necessary to use one servomotor to rotate two parts located on its both sides, for example when using one servomotor to drive two wheels.

The first step is to place servo's circuit board outside servo's case by desoldering the board and connecting it by wires to the motor. Then the gear is drilled using a drill-bit, which is slightly smaller than the axle. Using the same drill bit, drill a hole in the opposite side of a servo as shown in Figure 12. After axle is inserted into the desired position, it should be glued to the gear on both sides using epoxy, super glue, or similar adhesive.

**6.7 One channel control for two continuous-rotation servos**

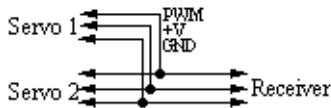


Figure 13

When servo is converted from a regular servo-drive mode to continuous rotation, its potentiometer is replaced with two resistors of equal value. However, if one servo is offset forward (for example, 8KΩ and 10KΩ resistors) and the other is offset backward (10KΩ and 8KΩ), and both servos are connected in parallel to the same power and PWM outputs of a receiver, as noted in Figure 13, the following behavior is observed:

| Position of control on transmitter | Left Servo     | Right servo    | Total effect |
|------------------------------------|----------------|----------------|--------------|
| Neutral                            | Forward        | Forward        | Forward      |
| Forward                            | Faster forward | Reverse        | Right turn   |
| Backward                           | Reverse        | Faster forward | Left turn    |

This way of controlling two servos using only one channel is useful when continuous forward motion with left/right turning is required. This technique also doubles the maximum number of servos controlled by a receiver.

**6.8 Direct computer control of servos**

Servomotors' speed and direction of rotation depends on the PWM signal. Usually this signal is generated by hardware, however it is also possible to control servomotors directly from software.

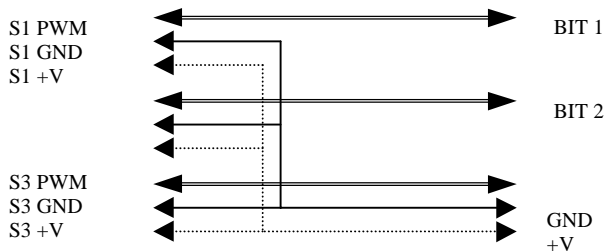


Figure 14

Computer's parallel port provides at least eight binary outputs (high/low), which can be used for control of hardware [4]. Therefore, at least eight servos can be connected directly to a computer as shown in Figure 14. Each bit represents a servo. A servo is controlled by writing 1 or 0 to its bit using

appropriate timing. For example, for CS30 servomotor, 1ms HIGH followed by 4ms LOW drives servomotor forward and 4ms HIGH / 1ms LOW drives it backward. All servos can be controlled simultaneously. The following C++ function drives two servos forward and two backward:

```
// DATA is LPT1 data port (usually 0x0378)
// outportb() outputs value to port
void Drive()
{
  while (no_interrupt)
  {
    // 0011: bits 1 and 2 - HIGH, bits 4 and 8 - LOW
    outportb(DATA, 0x03); // bits 1 and 2 (1+2=3)
    delay(1);           // 1ms delay
    // 1100: bits 1 and 2 - LOW, bits 4 and 8 - HIGH
    outportb(DATA, 0x0C); // bits 4 and 8 (4+8=C)
    delay(4);           // 4ms delay
  }
}
```

Although this method requires a ribbon of cables, since each servo needs a separate PWM input, it eliminates the need for any additional hardware.

Power cables of small servomotors connect directly to one or several HIGH pins of a parallel port, whereas ground wires connect directly to GND pins. This eliminates a battery, which might be unnecessary for a small robot.

### 6.9 Servo controller boards

Although, direct computer connection to servos provides a simple and inexpensive way to control them, other alternatives are usually more preferable.

Servo controller boards, such as Pontech's SV203 board, are often used to control servomotors and read inputs. SV203 board can simultaneously control up to eight servos and has five analog-to-digital inputs. Short strings are used for communication between the board and a computer. For example, "M128" – moves a selected servo to position 128.

Sampling of sensors is also easy. A computer sends a request to sample a desired sensor, and then receives a value of the sensor followed by ASCII character 13.

This provides a simple user-friendly interface. Another advantage of such boards is their small size and stand-alone ability. For example, SV203B is 2" x 1" board, which can control sensors and motors without being connected to a computer.

## 7. Machining

We have found that the two most useful machines that are needed are a mill and a band saw. Brakes, shears, presses, and others are definitely useful, but are not required.

- **Mill** is probably the most versatile machine and very useful. It can smoothen edges after a band saw and perform various high-quality vertical-milling operations. Using a mill-chuck can also work as a high-precision drill eliminating a need for a drill press.
- **Drill press** is used to drill straight or tapered holes. Drill bits produce straight holes, whereas countersinks make holes tapered. Countersinks can also deburr holes after drilling.
- **Band saw** is required to cut materials.
- **Brake and shear** are useful for good quality bending and breaking of sheet metal. When a shear cuts a material, it usually has a very even smooth edge.
- **Lathe** is used for manufacturing of round cylinder-based parts.
- **Taps** are used to make threads in holes (for bolts) when use of nuts presents a problem or is not required (for example, attaching something to a large aluminum block). For our purposes, 4-40 tap and No.43 drill bit are used for 4-40 bolts and 6-32 tap and No.36 drill bit for 6-32 bolts.



## **8. Electronics**

Electronics is one of the main components of most robots, and therefore is an integral part of prototyping. Refer to Jones & Flynn [2] and Horowitz & Hill [6] for additional information.

### **8.1 Circuit boards**

Bread boarding is probably most useful for initial testing and debugging, since it is inexpensive, and components and connections can be easily rearranged. However, the component density is very low, and the resulting board is usually several times bigger than a printed circuit board (PCB). In addition, capacitance between rows can seriously affect high-frequency circuits.

Other prototyping boards include wire-wrap, Scotchflex and Speedwire. Wire wrap uses special pins and wires, which are curled around these pins. Both, Scotchflex and Speedwire, use sockets and plug strips to connect components. Printed circuit boards and multi-layer boards are rarely used for prototyping, but are great for the final production of the circuit.

### **8.2 Connectors**

Connectors are widely used in electronics. Probably the most common type of connectors are terminal plug strips and terminal sockets. When there are many wires, several terminal strips are glued together to form one wide connector.

It is also useful to key all connectors. Keying is a way of making sure that you cannot put the connector backwards. An example will be to have one additional terminal or to cut off an unused one.

Other connectors, such as DB25 or DB9, are usually used for specific connections such as a printer port on a computer, but can also be used with the same efficiency on a robot.

## **9. Conclusion and results**

Using parts obtained from manufacturers listed in Appendix C, we constructed many prototypes to prove that various techniques described in this text can be directly applied to create a working robot. Small robots shown in Appendix B demonstrate various concepts of rapid prototyping.

Although an important step in building a robot is creativity and problem solving, many concepts of this paper can help amateur as well as professional robot developers.

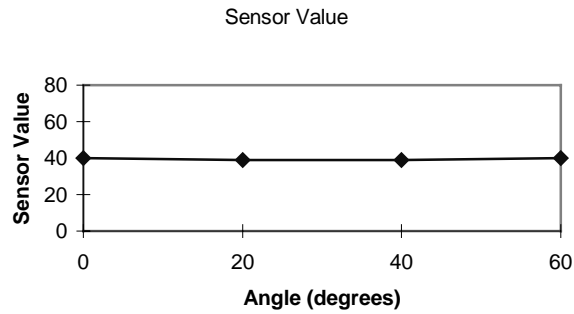
**Appendix A**

**Test of Sharp GP2D12 Infrared Rangefinder (using AnalogDevices 16bit A/D converter)**

Illumination angle test:

Varied angle between a cardboard and line of sight of a sensor. All measurements were taken at 40cm distance from the range finder.

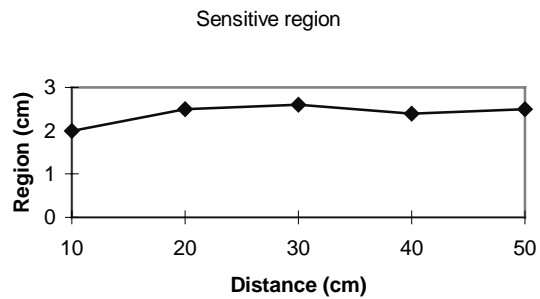
| Angle | Sensor Value |
|-------|--------------|
| 0     | 40           |
| 20    | 39           |
| 40    | 39           |
| 60    | 40           |



Cone-shape test:

Sensitive region measured at variable distance.

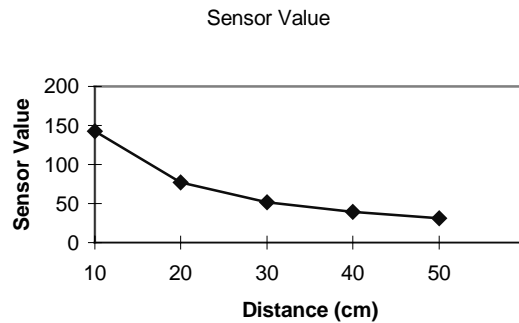
| Distance | Sensitive region |
|----------|------------------|
| 10       | 2.0              |
| 20       | 2.5              |
| 30       | 2.6              |
| 40       | 2.4              |
| 50       | 2.5              |



Sensor value test:

Values of a rangefinder were measured at various distances.

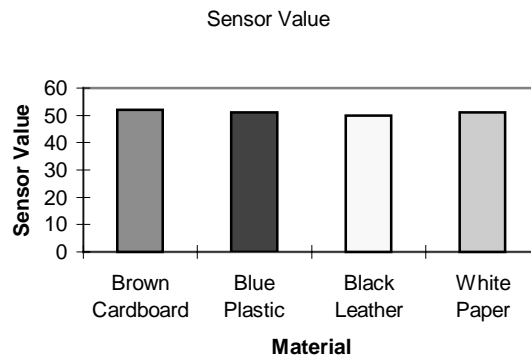
| Distance | Sensor Value |
|----------|--------------|
| 10       | 143          |
| 20       | 77           |
| 30       | 52           |
| 40       | 39           |
| 50       | 31           |



Material-sensitivity test:

Several materials were used to measure sensor's value at 30cm distance.

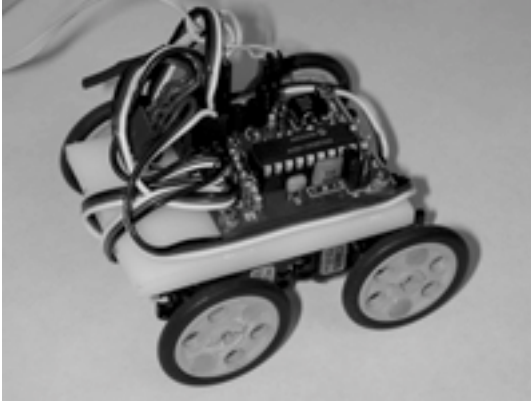
| Material        | Sensor Value |
|-----------------|--------------|
| Brown Cardboard | 52           |
| Blue Plastic    | 51           |
| Black Leather   | 50           |
| White Paper     | 51           |



## Appendix B

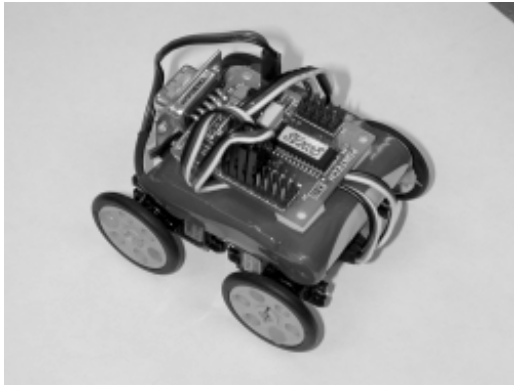
Examples of working prototypes:

### ❖ Mobipulator 3:



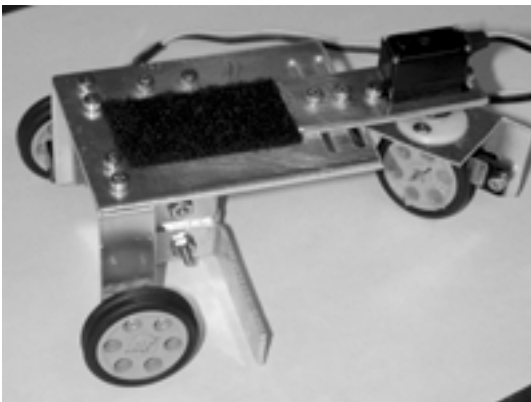
- Four servos are transformed to continuous-rotation.
- Servos are attached to the base using foam tape.
- Small wheels are attached to the servos.
- The robot is computer controlled.
- The robot has one infrared sensor.
- External power supply is used as a power source.
- All servos are controlled by a small board, which connects to a computer.

### ❖ Mobipulator 4:



- Mobipulator 4 includes most of the features of its previous version.
- The robot uses Pontech's SV203B/C board and is fully autonomous.

### ❖ Three Wheel Mobipulator:



- Two servos (front drive and steering) are transformed to continuous-rotation.
- Servos are attached to structures.
- Small wheel is attached to the front driving servo.
- A brake is attached to the third unmodified servo.
- Velcro is used to attach a receiver.
- There are two free spinning Lego wheels.
- The robot has its own battery and a receiver.

## Appendix C

### Manufacturer Contact Information list:

The list below contains several companies whose products were used for techniques of rapid prototyping.

#### Infrared rangefinders:

Acroname, Inc.  
P.O. Box 1894  
Nederland, CO 80466-1894  
Voice: 303-258-3161  
Fax: 303-247-1892  
Website: <http://www.acroname.com/>

#### Various hardware, tools, and raw materials:

McMaster-Carr Supply Company  
P.O. 94930  
Cleveland, OH 44101-4930  
Voice: (330) 995-5500  
Fax: (330) 995-9600  
Website: <http://www.mcmaster.com/>

#### Already modified servo motors:

Mr Robot™  
8822 Trevillian Road  
Richmond, VA 23235  
Voice: 1-888-MR-ROBOT  
Website: <http://www.mrrobot.com/>

#### SV200 Servomotor and Stepper motor controllers:

Pontech, Inc.  
719 Monroe Way  
Placentia, CA 92870  
Voice: 714-985-9286  
Fax: 714-985-9288  
Website: <http://www.pontech.com/>

#### R/C equipment and electronics (transmitters, receivers, batteries, etc.):

TowerHobbies  
PO Box 9078  
Champaign, IL 61824-9078  
Voice: (800) 637-6050  
Website: <http://www.towerhobbies.com/>

**Appendix D****Required Parts for the Palm Pilot Robot Kit**

| Qty | Part   | Manufacturer             | Cost    |
|-----|--|--------------------------|---------|
| 1   | 256 ¾ x 1½ Polyethylene foam tape strips (Part #75785T87)        | McMaster-Carr            | \$8.50  |
| 3   | 4cm diameter omni-directional wheels                             | American Roller Products | \$15    |
| 3   | MS492MH continuous rotation servos using the "Mekatronix" method | MrRobot                  | \$56    |
| 3   | Sharp GP2D12 Infrared Rangefinders                               | Acroname Inc.            | \$40    |
| 1   | SV203 Board  | Pontech                  | \$59.99 |
| 1   | Palm Pilot's Hot Sync cable (Part #10104U)                       | Palm Computing           | \$19.99 |
| 1   | 6.0V 2000mAh Nickel-Metal Hydride battery (Part #LC1922)         | TowerHobbies             | \$31.99 |
| 1   | Clear Cast Acrylic Disk 6" Dia x 1/8" Thk (Part # 8581K26)       | McMaster-Carr            | \$2.96  |
| 1   | SuperGlue  | Hardware store           | \$5     |

Note: The above parts list does not include the Palm Pilot itself.

## Appendix E

### Step-by-step instructions for building Palm Pilot Robot

1. Obtain a list of required parts.
2. Align the white connector so it is well centered in relation to the omni-wheel. Glue the connectors to omni-wheels by using a super glue or a similar adhesive.



3. Connect servo-connectors with glued omni-wheels to servos. Using a narrow phillips screwdriver, which fits inside the omniwheel, tighten the screw that holds servo's plastic connector in place.



4. Put the double-sided foam tape on top of all 3 servos.



5. Attach servomotors to the base by using double-sided sticky tape.



## Rapid Prototyping of Small Robots

- Using double-sided foam tape attach the battery to the base. Note: if you have a battery that is too big or just does not fit under the robot, you can put it on top of the robot.

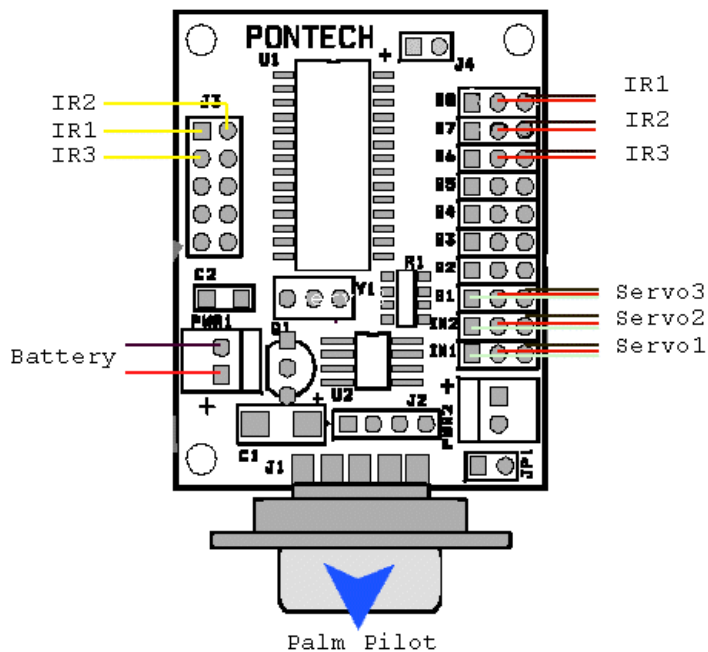


- Place IR sensors between servos and attach them to the base using the same foam tape. Place them as deep inside the base as possible, but make sure that they are placed at an equal distance from the edge of the base in front of them.

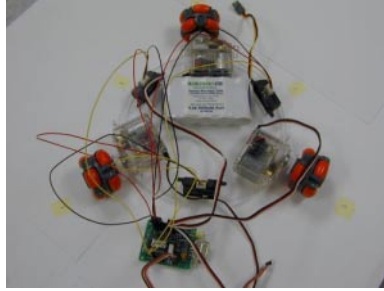
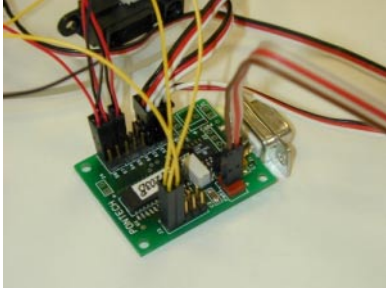


- Refer to the diagram found in Serial Servo Controller's handbook and connect all wires from servomotors and sensors to SSC board. All servos should have Futaba type of connectors. Number servos clockwise and connect wires to SV203 board in that order. Number all IR sensors, so that the number of the sensor is the same as the number of the servo opposite from it. Connect wires from IR sensors to SV203 board using the diagram below:

PPR: SV203 diagram



## Rapid Prototyping of Small Robots



9.

10. Cut Palm's HotSync cable approximately 8 inches from Palm's connector. Connect cable's wires to male DB9 connector as follows:

Red wire - pin 5

Black wire - pin 3

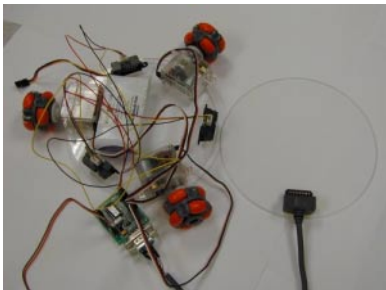
Brown wire - pin 2



11. Using the foam tape attach HotSync cable's palm connector to the disc. The connector should be placed near the edge.



12. Attach DB9 connector to SV203 board.



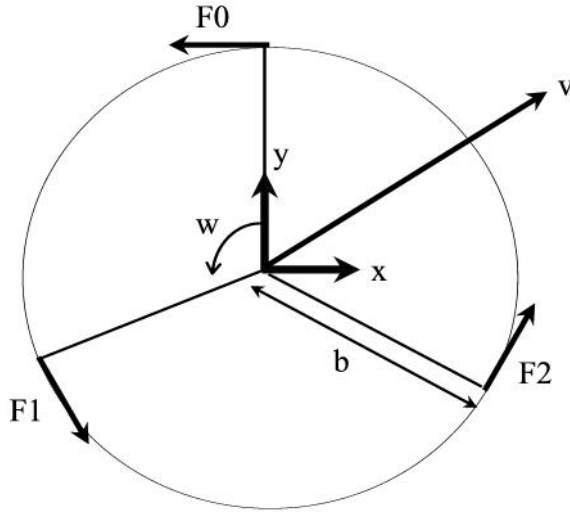
13. Test the robot by running a sample program.



**Appendix F**

Control of motors based on a given direction vector  $V$  and angular speed  $\omega$

To make the base move in a given direction the following work was necessary to write a function `Vector_Drive(V,  $\omega$ )` which drives the robot in a direction specified by a given vector  $V$ , while rotating the robot at an angular speed  $\omega$ .



- $r$  – wheel radius
- $F_0, F_1, F_2$  – unit direction vectors
- $v$  – velocity in body frame
- $\omega$  – angular velocity
- $b$  – wheel baseline
- $v_0, v_1, v_2$  – wheel linear velocities
- $\omega_0, \omega_1, \omega_2$  – wheel angular velocities
- $n$  – wheel number
- $p_n$  – velocity of the body at a given wheel  $n$
- $F_0 = [-1, 0]$
- $F_1 = [1/2, -\sqrt{3}/2]$
- $F_2 = [\sqrt{3}/2, 1/2]$

Finding body velocity from wheel velocity:

Each wheel constrains the velocity in a particular direction at the specified point. At each wheel, the velocity depends on  $v$  and  $\omega$ , and is the sum of the velocity due to rotation (expressed in the body frame) and the motion of the body frame in the world:

$$p_n = v + (b \cdot \omega) \cdot F_n$$

$p_n \cdot F_n =$  wheel velocity, therefore

$$\text{wheel velocity} = v \cdot F_n + b \cdot \omega \text{ and } r \cdot \omega_n = v \cdot F_n + b \cdot \omega.$$

Thus:

$$\omega_0 = (v \cdot F_0 + b \cdot \omega) / r$$

$$\omega_1 = (v \cdot F_1 + b \cdot \omega) / r$$

$$\omega_2 = (v \cdot F_2 + b \cdot \omega) / r$$

References

- [1] Inaba, M. *International Symposium on Robotics Research 1993*. Video Proceedings, 1993.
- [2] Jones, J., Flynn, A., Seiger, B. *Mobile robots: Inspiration to implementation*. A K Peters, Ltd. Natick, Massachusetts. 1998.
- [3] *UWF Lego Robots*. [Online] Available <http://www.coginst.uwf.edu/lego/>, May 5, 2000.
- [4] Anderson, Peter H. "Use of a PC Printer Port for Control and Data Acquisition". *Journal for Engineering Technology*, 1996.
- [5] Reshko, G., Mason M., Nourbakhsh, I., Zeglin, G. "Palm Pilot Robot project". [Online] Available <http://www.cs.cmu.edu/~pprk/>, May 5, 2000.
- [6] Horowitz, P., Hill, W. *The Art of Electronics* 2nd Edition. Cambridge University Press, 1989.