7 Motors

7.1 Variety Abounds

A few years ago, a computer was the largest and most expensive component of a robot, while motors and batteries consumed only small percentages of the budget. These days, while motors and batteries have changed little, the relationship has flipped. Microelectronics have shrunk in size and cost so drastically that, for the types of mobile robots we describe in this book, the motors and gears will typically be the most costly items.

An electric motor converts electrical energy to mechanical energy. Motors come in all manner of shapes and sizes. There are electromagnetic direct current (DC) motors and electromagnetic alternating current (AC) motors and a number of variations of each. AC motors are typically used for large machinery (such as machine tools, washers, dryers, and the like) and are powered from an AC power line. You might run across AC motors with titles such as single-phase, split-phase, capacitor start, permanent split-capacitor, shaded-pole and three-phase motors. AC motors are seldom used in mobile robots because a mobile robot's power supply is typically a DC battery.

We will focus on DC motors in this book. DC motors are commonly used for smaller jobs and will suit our purposes well. They also appear in a large variety of shapes and sizes: permanent magnet iron core, permanent magnet ironless rotor, permanent magnet brushless, wound field series connected, wound field shunt connected, wound field compound connected, variable reluctance stepper, permanent magnet stepper, and hybrid stepper motors.

For a robot's needs, a DC motor usually runs at too high a speed and too low a torque. In order to swap these characteristics, a DC motor must be geared down. Connecting the shaft of a motor to a geartrain causes the output shaft from the geartrain to rotate much more slowly and to deliver significantly more torque than the input shaft. A geartrain can be assembled discretely and attached to the motor shaft, or a DC motor can be purchased with the geartrain already prepackaged inside the motor housing.

These compact motors are termed *DC gearhead motors* and will be most useful in putting together a small robot. DC gearhead motors are normally based on permanent magnet ironless rotor motors in order to be as lightweight as possible. They can also be purchased with position encoders integrally connected. Figure 7.1 illustrates two conventional DC gearhead motors.

Most DC motors have two electrical terminals. Applying a voltage across these two terminals will cause the motor to spin in one direction, while a reverse polarity voltage will cause the motor to spin in the other direction. The polarity of the voltage determines motor direction, while the amplitude of the voltage determines motor speed.

However, some DC motors, such as stepper motors, have more than two electrical terminals, often up to six or eight. Signals are applied to these wires, which energize different coils inside the motor sequentially. The rotor is subsequently attracted to each portion and "stepped around" in a continuous fashion. Thus, the timing of these signals determines the motor speed, the phase between the signals determines the motor direction, and the number of commands determines the motor position.

Another type of DC motor with more than two electrical terminals is an assembly known as a *servo motor*. Although the term *servo motor* is used in a variety of contexts, what we are talking about here

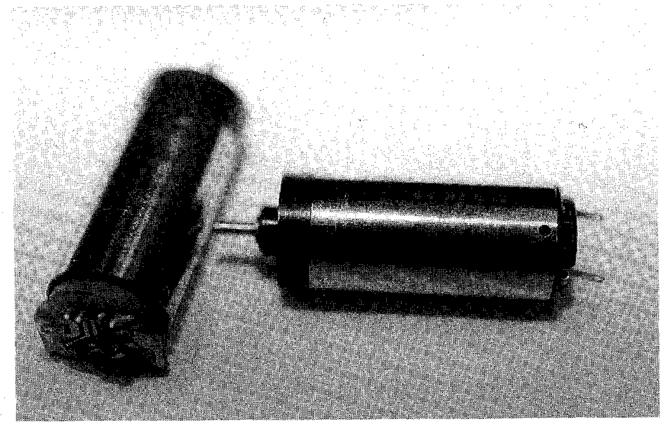


Figure 7.1. These DC gearhead motors manufactured by Escap are permanent magnet ironless rotor models with 54:1 and 27:1 geartrain ratios. The motor on the left has an attached printed circuit board, which interfaces to a position encoder encapsulated in the motor housing.

is the three-wire DC servo motor that is often used for a control surface on a model airplane or for a steering motor on a radio-controlled car. This type of assembly incorporates a DC motor, a geartrain, limit stops beyond which the shaft cannot turn, a potentiometer for position feedback, and an integrated circuit for position control. Of the three wires protruding from the motor casing, one is for power, one is for ground, and one is a control input where a pulse-width signals to what position the motor should servo. When we speak about a motor servoing to a position, we mean that an electrical circuit directs the motor to rotate to the commanded position and keeps it there. If you try to grab the motor shaft while the servo loop is running, and forcibly rotate the shaft to a different position, the electrical circuit will read the angle of the potentiometer, realize that the shaft is no longer at its commanded position, and increase the current to the motor. This will increase the torque the motor puts out and the motor will push back against the torque you are applying with your hand. The servo motor will continue to do this until the shaft has rotated back to its commanded position. A servo motor then is an assembly which consists of a DC gearhead motor,

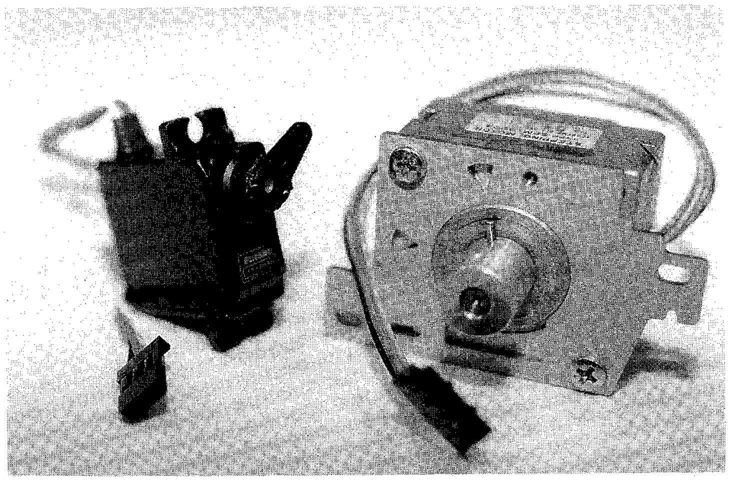


Figure 7.2. Shown on the left is a Futaba servo motor and on the right, a stepper motor. Note the three-wire lead on the servo motor and the six wires protruding from the stepper motor.

a position sensor on the shaft, and an integrated circuit for control, all packaged into the casing of the servo motor.

The flaps and control surfaces on model airplanes do not have to rotate continuously, so limit stops are added to these motors and a single-turn potentiometer then suffices to provide position information back to the integrated circuit that controls the motor position. Servo motors can be extremely compact and easy to control, and because they are mass produced for the toy industry, they are often cheaper than other DC gearhead motors. Although they rotate less than 360 degrees and hence are not suitable for wheeled robot propulsion, these model airplane servo motors often find their way into robot grippers, arms, and legs. Figure 7.2 shows both a servo motor and a stepper motor.

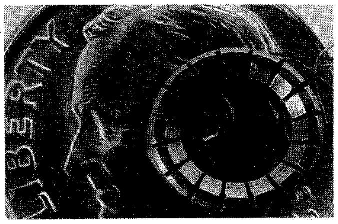
If you want to skip ahead to building Rug Warrior's locomotion system, we will tell you right now that our choice was to take Royal Titan Maxi Servos, available from Tower Hobbies, strip out the controller chips and potentiometers and remove the limit stops, and use these motors as continuously revolvable DC gearhead motors to

drive Rug Warrior's wheels. This is the cheapest, simplest solution we could find for this book's example robot.

DC motors are also characterized another way: as either brush-type or brushless motors. These designations refer to the manner of commutation used that converts direct current from the battery into the alternating current required to generate motor action. If the DC current is commutated mechanically with brushes, the commutator segments at the ends of the rotating rotor coil physically slide against the stationary brushes that are connected to the motor's terminals on the outside of the case. If the DC current is converted into AC current in the rotor electronically, with position sensors and a microprocessor controller, then no brushes are needed. Brush-type motors are more common and cheaper. Brushless DC motors have an advantage over brush-type motors in that friction is reduced, leading to longer life and finer control for the motor. Also, brushless motors can produce less radio frequency interference. The trade-off is that brushless DC motors require more extensive control circuitry in order to do the commutation electronically.

In addition to electromagnetic DC and AC motors, there are a few other types of motors that are not electromagnetic. Piezoelectric ultrasonic motors, which can be found in autofocus lenses in some Japanese cameras, work on the principle of mechanical bending of a piezoelectric ceramic, using frictional coupling to a rotor. The Japanese have also introduced these motors into headrest actuators in new luxury cars, paper pushing mechanisms in copiers, and in tinier versions in wristwatches for use as silent (vibrating) alarms. Ultrasonic motors, in contrast to conventional electromagnetic motors, spin at lower speeds and with higher torques, alleviating the need for geardown. This means they can be compact and lightweight, but the frictional coupling between rotor and stator results in problems of wear. A small piezoelectric ultrasonic motor is shown in Figure 7.3.

Also, in research labs around the world, *electrostatic* motors are being micromachined out of silicon in dimensions on the scale of a human hair. Electrostatic motors work on the principle of charge attraction, where a force is created as two charged plates slide past each other. At small scales, electrostatic forces can be relatively strong, but for large motors, electromagnetic forces are more effec-



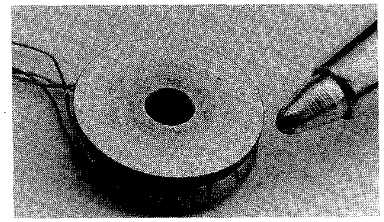


Figure 7.3. This 8 millimeter (mm) diameter piezoelectric ultrasonic motor, built at the MIT Mobile Robot Lab, is composed of two pieces: the stator and the rotor. The *stator*, shown on the left, is a steel ring with piezoceramics bonded onto the bottom that causes a wave to travel around the ring. The top piece, the *rotor*, is made of brass and, when pressed against the stator, is dragged along and spins. The stator with a rotor on top is illustrated on the right.

tive. Although micromotors have not reached the stage of practical use, they are intriguing.

Shape memory alloys can also be used for robot actuation. A shape memory metal such as Nitinol changes shape reversibly on being heated and cooled. Mondo-tronics, Inc., sells a small, six-legged robot (shown in Figure 7.4) that is actuated by these materials. When the wire is heated by passing current through it, the wire changes shape and shrinks, causing a leg to lift. When the wire is cooled (i.e., when no current is passing through it) the wire changes back to its original longer shape and the leg goes back down. The wires are attached to the legs in such a way that, while three legs lift the others push backward. Alternating this pattern between the two sets of three legs causes the robot to propel itself forward. Plans and instructions for building a similar microrobot called *Stiquito* are available to the public. If you have access to the Internet, you may acquire this information via anonymous FTP. Connect to site cs.indiana.edu, and look in the pub directory.

Even more esoteric is a new class of actuators that are starting to a ppear in research laboratories around the world. These are cotton-like fibers that act similarly to artificial muscles. With the alternating addition of acidic and basic solutions, these actuators can shrink and expand up to 1,000 times their original volume with strength and speed equal to those of human muscle. While still a lab-

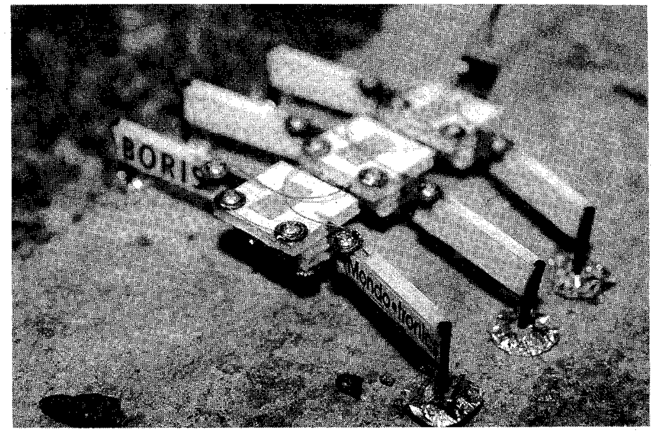


Figure 7.4. This 10 centimeter (cm) robot from Mondo-tronics weighs 50 grams (g) and is actuated by shape memory wires which are wrapped around various screws mounted on the legs and body. Passing 200 milliamperes (mA) of current through a sequence of wires causes alternating legs to lift up and move forward.

oratory curiosity, these polymer gels may prove to be the technology of the future.

7.2 How a DC Motor Works

For the project at hand, let us focus on how permanent magnet DC gearhead motors work. Understanding the mechanism behind the production of torque is helpful when trying to read a motor specification sheet for choosing the correct-sized motor. Such understanding will be helpful again later, when designing the power electronics for controlling the motor from a microprocessor.

Electromagnetic forces in DC motors come about when current-carrying conductors are placed in magnetic fields, as illustrated in Figure 7.5. Magnetic fields can be generated by permanent magnets. Flux lines across an air gap flow from one magnet's north pole to another magnet's south pole. The Lorentz force law states that current-carrying conductors placed in magnetic fields create forces. The force, F, created is perpendicular to both the direction of the

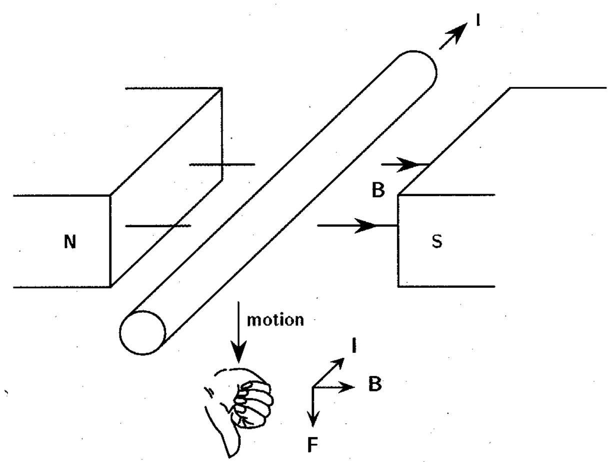


Figure 7.5. A magnetic flux field, B, is set up by the permanent magnets in the direction from north pole to south pole. A current-carrying conductor placed in such a field experiences a force acting on it. The resultant force is directed downward.

current, I, and the direction of the flux field, B. The direction of F is determined by the right-hand rule, where the fingers curl from the direction of the current toward the direction of the flux field and the thumb points in the direction in which the resultant force is created. In the case of Figure 7.5, the force produced is in the downward direction.

Rotary motion requires a loop of wire. Figure 7.6(a) shows a loop of wire mounted on an axis of rotation and situated in the flux field set up by the permanent magnets. Figure 7.6(b) illustrates the resulting forces. Because forces are created in a direction perpendicular to both the current's direction and the magnetic field's direction, current going into the loop along the top generates, according to the right-hand rule, a force acting downward. Current coming out along the bottom portion of the loop creates a force acting upward. The force disparity, acting at a distance from the center of rotation, causes the loop to experience a torque. The loop will rotate until a force disparity no longer exists. That point would be reached when the plane of the loop is vertical and the forces on the top and bottom

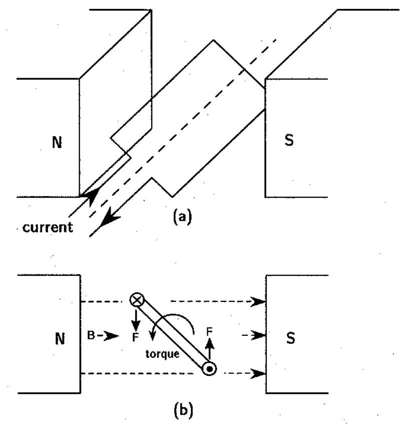


Figure 7.6. (a) This loop of wire has current flowing into the page on the left side and out of the page on the right. (b) The resulting oppositely directed forces, acting at a distance from the center of rotation, cause the loop to rotate until it is vertical.

portions of the loop would both act through the center of rotation, resulting in zero torque.

Continuous rotary motion can be achieved by reversing the direction of the current just as this point is about to be reached. The process of deriving this necessary alternating current from a DC battery is called *commutation*. Mechanical commutation requires a set of brushes that allow the ends of the loop of wire to slip across the contacts of the battery. The commutator setup is shown in Figure 7.7.

A disassembled DC gearhead motor is shown in Figure 7.8. A large number of loops of wire are usually incorporated in order to increase the torque of the motor. These loops are wrapped around an armature that can contain an iron core for increased flux or be ironless for lighter weight. Two half cylindrically shaped permanent magnets are housed along the inside of a steel casing, which provides a flux return path. The wound armature is fitted between the magnets, leaving a small air gap. As the current through the armature alternates, a force is created, causing the armature and the shaft to rotate.

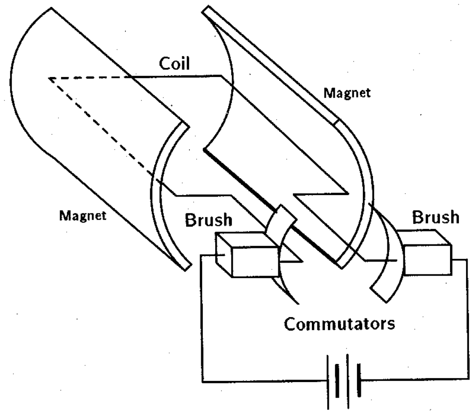


Figure 7.7. A commutation system using brushes is one way to make a DC motor. The commutator segments are attached to the loop of wire and rotate with it, while the brushes remain stationary as the commutator segments slide past.

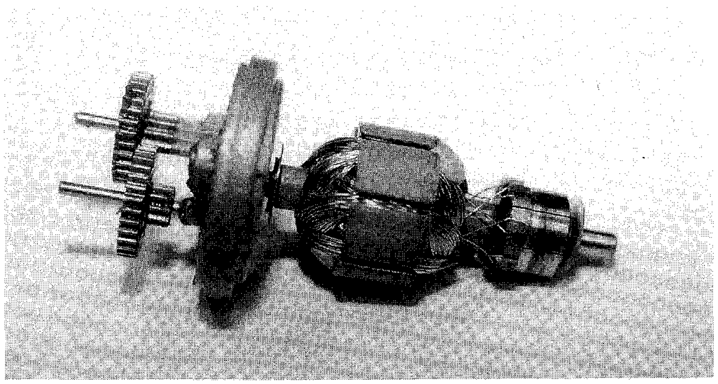


Figure 7.8. A permanent magnet DC gearhead motor shown here has been removed from its housing. Windings of the armature around a central core with ends connected to commutator segments can be seen at the right, while the geartrain is mounted on the shaft at the left. A cylindrical housing (not shown) fits around the armature and holds two permanent magnets along its inner shell.

7.3 Sizing a DC Motor

Selecting an appropriate motor for your robot involves both understanding the loads that the robot will impose on the motor and the performance that the motor can deliver, as detailed in the manufacturer's data sheets. Some manufacturers present the pertinent characteristics in the form of a graph, while others list the specifications in table format. Sometimes, if the motor is obtained from a surplus dealer or extracted from a toy, it is not possible to obtain data sheets, in which case simple experiments can be performed to measure the pertinent characteristics. Whatever the case may be, it is useful to have a clear understanding of the motor language and to brush up on the conversions between various units of measurement.

7.3.1 Torque, Speed, Power, and Energy

Torque is the angular force that a motor can deliver at a certain distance from the shaft. For instance, 5 oz.-in. of torque means that, at a distance of 1 inch away from the shaft of a motor, the motor is strong enough to pull up a weight of 5 ounces through a pulley (see Figure 7.9). In metric units, motor torques are often specified in Newton-meters (Nm). (When you try to imagine how much force a Newton is, think of the weight of an apple. A force of 1 Newton is about equal to the force that gravity exerts on one apple's mass.) Alternatively, metric units for torque can also be found specified in terms of *gram-force-centimeters* (gf-cm), where a gram-force is meant to signify the force that gravity exerts on 1 gram of mass. We will stick to metric units in this book, but some conversions to keep handy are:

$$1\,\text{N}=1\,\frac{\text{kg-m}}{\text{sec}^2}=0.225\,\text{lb}$$

$$1\,\text{kg}=2.21\,\text{lb (mass)} \qquad \text{and} \qquad 1\,\text{in}=2.54\,\text{cm}$$

Also, when we begin to talk about electrical power being converted to mechanical power in a motor, it is useful to keep straight the relationships involving *power* (in watts) and *energy* (in joules). *Power* is the rate at which you are using up *energy*. The relationship between power and energy is expressed as:

$$1\,\text{Watt}{=}1\,\frac{\text{Joule}}{\text{sec}}$$

Figure 7.9 illustrates the electrical to mechanical power conversion of a DC motor. The electrical power supplied to the motor, P_e, equals the voltage, V, across the motor's terminals times the current, I, through the motor. The current, measured in units of amperes, is the amount of charge, in coulombs, passing through any cross-section of a conductor per second:

$$P_e = VI$$

$$1\,\text{Ampere} = 1\,\frac{\text{Coulomb}}{\text{sec}}$$

$$1\,\text{Watt} = 1\,\text{Volt}\cdot\text{Ampere} = 1\,\text{Volt}\cdot\frac{\text{Coulomb}}{\text{sec}}$$

Mechanical power, P_m, equals the torque, T, output by the shaft times its angular speed, ω, where the torque is taken in Newton-meters and the angular speed is measured in units of radians per second:

$$P_m = T\omega$$

$$\frac{2\pi\,\text{rad}}{\text{sec}} = 1\,\frac{\text{rev}}{\text{sec}}$$

$$1\,\text{Watt} = 1\,\frac{\text{Nm}}{\text{sec}}$$

Since power is energy per unit time, this tells us that one joule of energy can be expressed in two ways: either as 1 Newton-meter or as 1 coulomb-volt:

$$1\,\text{J}{=}1\,\text{Nm} \qquad \text{and} \qquad 1\,\text{J}{=}1\,\text{CV}$$

This is just reaffirming the fact that energy is energy, whether it comes from a mechanical origin or an electrical origin. A motor is just a transducer transforming energy from one form to another.

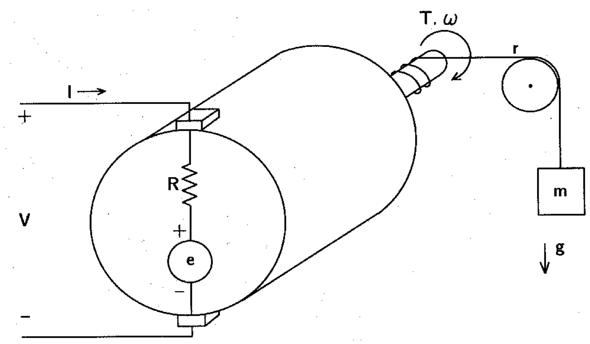


Figure 7.9. A simple model of a DC motor is an equivalent circuit that models the motor windings as having a resistance, R, and generating (when running) a back-emf voltage, e. The electrical power input to the motor is the product $P_e = VI$, and the mechanical power output is the product of torque and rotational speed, $P_m = T\omega$.

7.3.2 A Motor Model

These relationships, describing the conversion of electrical power to mechanical power in a permanent magnet DC motor, can be clearly seen by the equivalent circuit model shown in Figure 7.9. The mechanical output power (due to losses from friction, windage, heating in the coils, and so on) will be some fraction of the electrical input power. This percentage is given as the efficiency, η, where:

$$P_m = \eta P_e$$

The rotor coil that we saw in Figure 7.6 is essentially an inductor with a resistance R. When the rotor is turning, the commutator segments sliding past the brushes create an alternating current in the armature windings. A changing current, $\frac{di}{dt}$, through an inductor induces a voltage across it:

$$v = L\frac{di}{dt}$$

where L is the proportionality constant called the inductance. As the motor turns, this voltage is induced and opposes the applied driving voltage. The faster the motor turns, the more often the current switches direction, and so the larger the induced voltage becomes. Since this voltage opposes the applied drive voltage, as it increases, it tends to limit the current through the resistance, R. As the current falls, less flux is created around the conductor and the torque also falls. In summary, as the speed goes up, the torque goes down.

The rotating motor then can simply be modeled by the induced voltage, e, called the *back-emf* (*emf* stands for electromotive force) and the winding resistance, R. The applied voltage is related to the back-emf and the current through the motor by:

$$V = IR + e$$

Note that, when the motor is not rotating, e is 0 V and the current through the motor is just equal to the applied drive voltage divided by the resistance. This is the current required to start the motor from zero speed, called the *starting current* or *stall current*, I_S:

$$I_S = \frac{V}{R}$$

When the rotor is rotating, e increases proportionally with the speed of the armature:

$$e = k_e \omega$$

where k_e is called the back-emf constant. The applied voltage is then related to the current and the armature speed by:

$$V = IR + k_e \omega$$

The negative feedback provided by the back-emf causes the motor to settle to a steady-state operating point of speed and torque, as determined by the load and the applied voltage. The torque that the motor produces is dependent on the flux field around the loop of the conductor, and that flux is controlled only by the current. The torque increases linearly with current with a proportionality constant k_t, known as the *torque constant*:

$$T = k_t I$$

Solving for I and plugging it into the equation above, we get:

$$V = \frac{TR}{k_t} + k_e \omega$$

It turns out that k_t is actually equal to k_e. We can see this from the fact that the mechanical power output by the shaft will be the electrical power input, minus the I^2R losses due to heating in the resistor:

$$P_m = P_e - I^2R$$

$$T\omega = VI - I^2R$$

Plugging in for T and V,

$$k_t I \omega = (IR + k_e \omega)I - I^2R$$

gives

$$k_t = k_e = k$$

The applied voltage is then related to the torque and speed by the constant k:

$$V = \frac{TR}{k} + k\omega$$

Rearranging, we find that the speed-torque relationship is linear with a negative slope:

$$\omega = -\frac{R}{k^2}T + \frac{V}{k}$$

These relationships can be more clearly seen when plotted along with the motor performance curves.

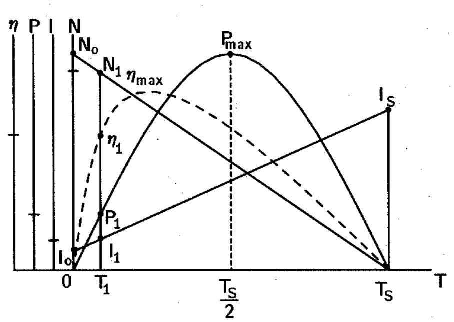


Figure 7.10. For a given voltage, a DC motor has the typical drooping characteristics of speed, N, decreasing linearly torque, T. As the current, I, is increased, the torque is increased, also linearly. Power output, P, is the product of torque and speed and has a quadratic characteristic. Maximum efficiency, η_{max}, occurs at a lower torque than the maximum power output torque.

7.3.3 Speed-Torque Curves

The speed and torque characteristics for a DC motor depend on a variety of parameters that have to do with the geometry of the motor, the materials involved, the number of windings, and the voltage at which the motor is driven. Typically, a manufacturer provides a data sheet showing the pertinent characteristics. These are usually illustrated in a speed-torque graph for a given applied drive voltage. Efficiency, current, and power output are often plotted along with speed on the vertical axis against torque on the horizontal axis, as shown in Figure 7.10.

We can see in Figure 7.10 that the speed-torque curve is linear, with a negative slope as we derived, and has a y-intercept dependent upon the applied voltage. Also, the current increases linearly with torque and is independent of applied voltage, as we showed earlier. The power curve has a negative quadratic form which is understood by remembering that:

$$P_m = T\omega$$

and plugging in our equation for ω:

$$P_m = -(\frac{R}{k^2})T^2 + \frac{V}{k}T$$

where we see the negative quadratic dependence of power on torque.

You will find it useful to check a few points of interest on a motor data sheet in choosing the most appropriate motor for your robot. The *no-load speed*, marked N_o in Figure 7.10, is the speed, at a given voltage, at which the torque is 0. (N usually refers to the angular speed in units of rpm. Remember to convert to $\frac{\text{rads}}{\text{sec}}$ when plugging into these equations for ω.) This is the speed of the motor with nothing attached to the shaft. That is, the no-load speed, the value of ω for $T = 0$, is just

$$\omega_{max} = \frac{V}{k}$$

The current in this no-load condition, I_o, is called the *no-load current* and is that required to overcome motor friction and windage.

At the other end of the scale, the torque that the motor can deliver just as it stalls and can no longer rotate is known as the *stall torque*, T_s. The current at this condition, I_S, is the stall current. Since the motor is not moving when stalled, the back-emf is 0 and the maximum current, I_S, is just the applied voltage divided by the coil resistance, as mentioned earlier. Torque being proportional to I, the maximum torque is:

$$T_S = \frac{kV}{R}$$

At any given point of operation of torque and speed, the mechanical power output is the product of the two. The torque at which the maximum power occurs can be found by taking the derivative of the power with respect to the torque, setting the result equal to 0, and solving for T:

$$\frac{dP_m}{dT} = 0 = -\frac{2RT}{k^2} + \frac{V}{k}$$

$$T = \frac{kV}{2R}$$

or

$$T = \frac{1}{2}T_{max}$$

Thus, the point of maximum power output is attained at half the stall torque. The corresponding speed at this operating point is then found to be:

$$\omega = -\frac{R}{k^2}\frac{kV}{2R} + \frac{V}{k} = \frac{V}{2k}$$

or

$$\omega = \frac{1}{2}\omega_{max}$$

The maximum power then is simply:

$$P_m = \frac{1}{4}\omega_{max}T_{max}$$

The ratio of mechanical power output to electrical power input is the *efficiency*, η. Note that maximum efficiency cannot be achieved at maximum power output. In fact, the point of maximum efficiency, where you would like to drive your motor, is a low-torque, high-speed operating point. Consequently, we typically select an oversized motor so that it can run at an efficient operating point while supplying enough torque.

It turns out that the maximum efficiency, for reasons we will not go into here, can be calculated from the measurements of the no-load current, I_o, and the stall current, I_S:

$$\eta_{max} = (1 - \sqrt{\frac{I_o}{I_S}})^2$$

This can be useful for characterizing a motor for which you do not have data sheets.

The data shown in Figure 7.10 are for one given value of applied voltage. If the motor is run at a lower voltage, the speed-torque line shifts downward as shown in Figure 7.11(a). As the voltage is decreased, the speed and the torque are both decreased. Changing the voltage changes the speed of the motor. Another way to change the speed without having such an adverse effect on the torque (in fact, a method that has an advantageous effect on the torque) is to use a geardown. As shown in Figure 7.11(b), gearing down the motor by, say, a factor of 2, cuts the no-load speed in half while doubling the stall torque. Thus, power is maintained constant through

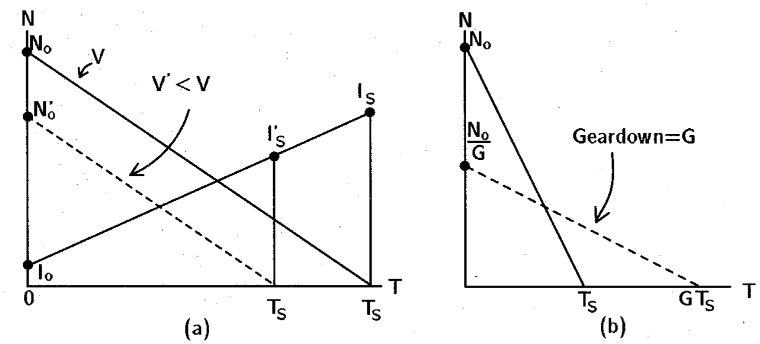


Figure 7.11. (a) Running the motor at a lower voltage causes it to slow down for all values of torque output. (b) Gearing down the motor reduces the speed by the gear ratio, G, and increases the torque by the same factor, G.

a lossless (frictionless) geartrain. Typically though, there are losses both through the motor and again through the geartrain. Good motors these days might have efficiencies of 90% or better, but cheap toy motors (like the ones we will use in the Rug Warrior prototype) might be only 50% efficient, or less. Adding these losses to those through the geartrain and then taking into account the losses between wheels and the ground (from friction, slippage, etc.) results in a system that is not very efficient. For Rug Warrior, most of the energy from its battery pack goes into the propulsion system. Powering Rug Warrior's computers and sensors will be practically insignificant in comparison.

7.4 Gears

Geartrains and transmission systems come in a variety of forms, such as spur gears, planetary gears, rack-and-pinion systems, worm gears, lead screws and belt-and-pulley drives. Figure 7.12 illustrates a number of these mechanisms. High-quality geartrains are usually metal, but plastic gears are often found in toys.

The DC gearhead motor shown earlier in Figure 7.8 had a *spur gear* set on the output shaft. Spur gears are the most common forms of gears found in DC gearhead motors. A schematic of a two-level

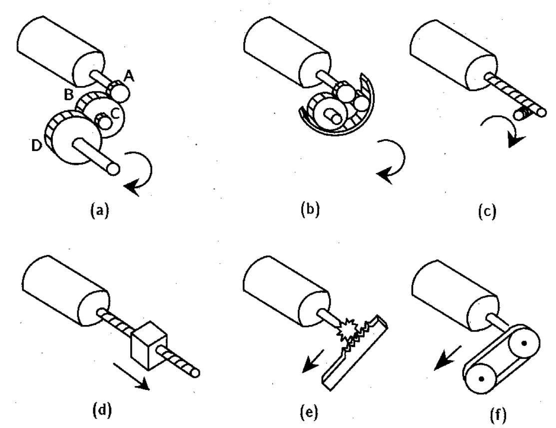


Figure 7.12. (a) Spur gears mesh pairs of gears with different numbers of teeth to achieve speed reduction. (b) Planetary gears have several gears meshed in an outer ring for large reduction. (c) Worm gears produce rotary motion at right angles to the shaft. (d) A lead screw and nut can create linear motion as can (e) rack-and-pinion systems and (f) belt-and-pulley drives.

spur geartrain is shown in Figure 7.12(a). The small gear, mounted directly on the motor shaft, is called a *pinion* and has to rotate many times to turn the gear it is meshed to once. Thus, even though the pinion may spin very quickly, the gear it is attached to spins very slowly. If A, B, C, and D denote the number of teeth on each corresponding gear in the figure, then the speed of the output shaft is related to the speed of the input shaft by:

$$\omega_{out} = \frac{A}{B}\frac{C}{D}\omega_{in}$$

where the final speed has been decreased by the geardown ratio.

Planetary gears are similar to spur gears but are less common in low-end gearhead motors and are slightly more expensive. The difference between planetary gears and spur gears is that planetary gears, as shown in Figure 7.12(b), fit a number of gears concentrically inside a toothed ring. This configuration produces greater efficiency and higher output torques in a smaller package. Planetary geartrains are sometimes found in portable battery-powered screwdrivers and drills.

Worm gears are another means for achieving large geardown in a small space. Worm gears, shown in Figure 7.12(c), instead of having teeth, are threaded and match to a lead screw attached to the shaft of the motor. In this way, the output motion is turned to right angles from the motor shaft.

For linear motion, a *lead screw and threaded nut* can be used. Figure 7.12(d) illustrates how the motor shaft turns the lead screw and a threaded nut moves linearly down the shaft, depending on the number of threads per inch on the lead screw. Lead screws can give very large geardown but are not very efficient.

Rack-and-pinion systems, Figure 7.12(e), also turn rotary motion into linear motion. In this case, a small pinion gear on the motor shaft rotates against a straight length of rack having matching teeth, propelling the rack linearly back and forth.

Another linear motion mechanism is the belt-and-pulley system, shown in Figure 7.12(f). This is the mechanism used to drive a tank-treaded vehicle, such as we will describe later for Rug Warrior II.

7.5 Motor Data Sheets

While it is possible to buy a plain DC motor and attach any number of gear-reduction mechanisms for propelling your robot, we will focus on DC gearhead motors here for Rug Warrior (typically with spur gears) because it makes life easier when geartrain and motor are packaged together. There is no need to find a machine shop and spend time making gearboxes.

Picking an appropriate motor involves understanding a manufacturer's data sheets. A data sheet is usually given for the motor alone, and then another data sheet is supplied for the type of gearbox (with an assortment of reduction ratios) that will fit that motor. The gearbox specification can place constraints on the motor, such as for maximum allowable input speed or maximum deliverable output torque.

Actual data sheets for the small Escap motors (shown in Figure 7.1 of this chapter) are given in Figure 7.13 and Figure 7.14. The data are given here in tabular form instead of graph form, but the reader can reconstruct the graphs that were discussed earlier, (as

D.C. motor
escap® 16 M 11

Standard types available from stock			-210	-208	-207	-205
Measuring voltage		V	6	7.5	9	15
No-load speed		rpm	8400	7800	8300	8200
Stall torque		mNm	3	2.5	2.3	2.4
		oz-in	0.42	0.35	0.33	0.34
Power output		W	0.7	0.5	0.5	0.5
Av. no-load current		mA	7	5	4	2.5
Typical starting voltage		V	0.06	0.1	0.1	0.2
Max. continuous current		A	0.4	0.28	0.24	0.14
Max. recommended speed		rpm	12000	12000	12000	12000
Max. angular acceleration		10^3 rad/s²	96	114	120	102
Back-EMF constant		V/1000 rpm	0.7	0.94	1.1	1.8
Rotor inductance		mH	0.5	0.8	1	3
Motor regulation R/k^2		10^3/Nms	300	330	380	350
Terminal resistance		ohm	13.4	27	39.5	105
Torque constant		mNm/A	6.7	9	10.2	17
		oz-in/A	0.949	1.28	1.44	2.41
Rotor inertia		kgm² · 10^{-7}	0.7	0.56	0.5	0.6
Mechanical time constant		ms	20	18	19	21
Thermal time constant	rotor	s	6	5	4	4
	stator	s	380	380	380	380
Thermal resistance	rotor-body	°C/W	10	10	10	10
	body-ambient	°C/W	35	35	35	35

Figure 7.13. The Escap model 16M11-210 DC motor is a 6 volt (V) motor with a no-load speed of 8,400 revolutions per minute (rpm) and a stall torque of 3 milli-Newton-meters (mNm). (By courtesy Portescap, Inc.)

illustrated in Figure 7.10), since the major features, such as no-load speed, stall current and stall torque are given in these tables. The torque constant given in the table can be used to find the slope of the I-T curve, and the back-emf constant can be used to determine the slope of the ω-T curve. (Note that, if these constants are converted to the same units, they are equal.)

For instance, Figure 7.13 describes the performance of the motor by itself without a gearhead. Four models of this motor are available, each with a different winding and therefore intended to be run at a different voltage. The voltage for which the specifications are given is called the *measuring voltage* or sometimes the *rated voltage*. Thus, the 16M11-210 motor, when run at 6 V, will have a no-load speed of 8,400 rpm, a stall torque of 3×10^{-3} Nm, and a maximum possible output power of 0.7 W.

If the 16M11 motor is purchased with an attached gearhead, the part number for the gearmotor is M1616M11; its specifications, as shown in Figure 7.14, recommend that the -210 winding version be run at 5 V so that the no-load speed of the motor stays within the

D.C. gearmotor
escap® M 1616 M 11

Standard types available from stock		M 1616 M 11					
Max. recom. dynamic output torque	mNm (oz-in)	50 (7.1) at 20 rpm					
	mNm (oz-in)	30 (4.2) at 150 rpm					
Max. recom. static output torque	mNm (oz-in)	250 (35.4)					
Max. recommended input speed	rpm	7500					
Available reduction ratios		9	27	54	243	486	2190
				81		729	
Average efficiency		0.8	0.7	0.65	0.6	0.55	0.5
Nr. of geartrains / direction of rotation		2/=	3/≠	4/=	5/≠	6/=	7/≠
Length L	mm	37.1	38.6	40.1	41.6	43.1	44.6
Mass	g	28	29	29	30	31	32
Motor specifications		**-210**			**-207**		
Measuring voltage[1)]	V	5			8		
No-load speed	rpm	7000			7200		
Stall torque	mNm (oz-in)	2.5 (0.354)			2.1 (0.297)		
Terminal resistance	ohm	13.4			39.5		
Torque constant	mNm/A (oz-in/A)	6.7 (0.949)			10.2 (1.44)		
Other motor characteristics	see page	17			17		
Gearmotor specifications							
Av. no-load current	mA	10			8		
Typical starting voltage	V	0.1			0.3		
Mechanical time constant	ms	21			19		

Figure 7.14. The Escap model M1616M11-210 gearhead motor should be driven at 5 V (instead of 6 V) in order to keep the no-load speed of the motor within the maximum allowable input speed of the gearbox. (By courtesy of Portescap, Inc.)

allowable input speed of the gearbox. The gearmotor with the 54:1 reduction will weigh 29 g, be 40 mm long, be 16 mm in diameter, and have an efficiency of 65%. The no-load speed will be:

$$N_o = \frac{7000\,\text{rpm}}{54} = 130\,\text{rpm}$$

and the stall torque will be:

$$T_S = (54)(2.5\,\text{mNm})(0.65) = 88\,\text{mNm}$$

Earlier, we showed that the maximum possible output power was:

$$P_{m,max} = \tfrac{1}{4}\omega_{max}T_{max}$$

We can calculate this maximum power by converting the no-load speed and the stall torque to the appropriate units. If we want to know how many radians per second are equal to 130 revolutions per minute, the easiest way to keep all the conversions straight is to set up the question this way:

$$?\frac{\text{rads}}{\text{sec}} = 130\frac{\text{rev}}{\text{min}}$$

Since multiplying the righthand side by 1 does not change the equality, we can multiply 130 rpm by identity relationships, converting revolutions to radians and minutes to seconds in such a way that the old units cancel out:

$$?\frac{\text{rads}}{\text{sec}} = 130\,\frac{\text{rev}}{\text{min}} \cdot \frac{2\pi\,\text{rads}}{\text{rev}} \cdot \frac{1\text{ min}}{60\,\text{sec}} = 13.6\frac{\text{rads}}{\text{sec}}$$

This gives:

$$P_{m,max} = \tfrac{1}{4}T_{max}\omega_{max} = \tfrac{1}{4}(88 \times 10^{-3}\,\text{Nm})(13.6\tfrac{\text{rads}}{\text{sec}}){=}0.3\,\text{W}$$

Escap motors are fairly high quality, and like many DC gearhead motors, can cost over $100 each. Escap (actually, Portescap is the name of the company) sells old-inventory motors (catalog motors but ones that have sat on the shelves for too long to be sold as new) for a fraction of their original cost. Although the selection is limited, this source can be useful for hobbyists. Maxon, Micro Mo, Pittman, Inland, Globe, Canon, Copal, and Namiki are a few of the other numerous manufacturers that sell DC motors and have readily available catalogs with specification sheets. Surplus dealers often buy out remains of original equipment manufacturers' (OEMs) unused motors and sell them at significantly reduced costs. Dealers such as Burden's Surplus Center, Herbach and Rademán, America's Hobby Center, Edmund Scientific, Sheldon's Hobbies, Stock Drive Products, and Tower Hobbies sell wide assortments of smaller, cheaper DC gearhead motors.

Most of the low-cost permanent magnet DC motors, such as those found in toys, are made by one company–Mabuchi. Mabuchi produces over 3 million motors a day and sells them in lots of 5,000 or more. They make strictly stand-alone motors, not gearhead motors, but sell them to OEM manufacturers who then incorporate motors into toys, model airplanes, and the like. Typically, a toy manufacturer will use the molding of the toy itself to be the gearbox for the plastic geartrain they add to the motor so it is not always convenient to extract the motor and build it into your robot.

Model airplane servo motors, on the other hand, are very modular and convenient for this purpose. While most model airplane

servos continue to be high-priced, mass production of the most common models has led to lower prices for servo motors. Futaba, Royal Products Corporation and Airtronics are a few of the manufacturers of these servo motors. Catalogs from hobby stores, such as Tower Hobbies and Sheldon's Hobbies, list a wide range of models. Higher-quality servos with metal gears and ball bearings are available, also.

Servo motor data sheets (which are typically printed on the backs of the packages) look different from the data sheets for DC gearhead motors. Servo motors usually run from a 5 V supply. For instance, for the Royal Titan Maxi Servo, the specifications are described this way:

Royal Titan Maxi Servo

Weight	3.7 oz.
Output Torque	112 oz.-in.
Current Drain	8 mA
Transit Time	$\frac{0.22\text{sec}}{60^\circ}$

A *transit time* (in $\frac{\text{sec}}{\text{deg}}$) is given instead of a no-load speed (in rpm) because the integrated circuit servos the motor to a specified position and it never spins all the way around. However, if the servo is stripped down to being just a DC gearhead motor (potentiometer, limit stops, and integrated circuit removed), this transit time is equivalent to the no-load speed. The output torque listed above is simply the stall torque. Converting to proper units to find power output:

$$?\frac{\text{rads}}{\text{sec}} = \frac{60^\circ}{0.22\text{sec}} \cdot \frac{2\pi\,\text{rads}}{360^\circ} = 4.8\frac{\text{rads}}{\text{sec}} = 46\,\text{rpm}$$

$$?\text{Nm} = 112\,\text{oz.-in.} \cdot \frac{\text{lb.}}{16\,\text{oz.}} \cdot \frac{1\,N}{0.225\,1\,\text{lb.}} \cdot \frac{2.54\,\text{cm}}{1\,\text{in.}} \cdot \frac{1\,\text{m}}{100\,\text{cm}} = 0.79\,\text{Nm}$$

The maximum possible power then is:

$$P_{m,max} = \tfrac{1}{4}T_{max}\omega_{max} = \tfrac{1}{4}(0.79\,\text{Nm})(4.8\tfrac{\text{rads}}{\text{sec}}) = 0.95\,\text{W}$$

which is 3.2 times as large as the earlier Escap motor — but then, this is a larger motor. To compare weights, we convert to grams:

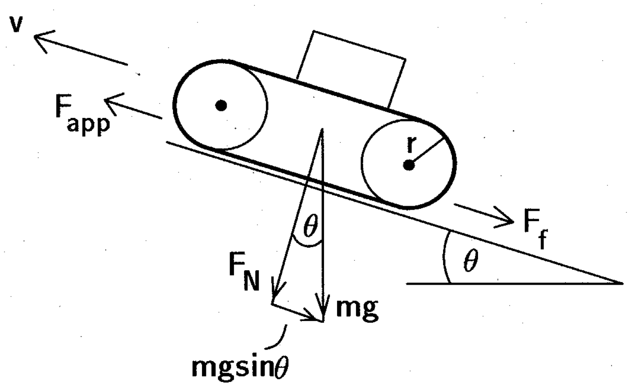


Figure 7.15. This free-body diagram of a tracked-drive Rug Warrior illustrates the forces acting on the vehicle as it climbs a hill. Use of this diagram helps to determine the maximum torques that the robot's motors will be required to deliver.

$$?g=3.7\,\text{oz.}\cdot\frac{28\,\text{g}}{1\,\text{oz.}}=104\,\text{g}$$

The Royal Titan servo motor then is about 3.6 times heavier than the 29 g Escap DC gearhead motor discussed previously. It turns out, however, that the Royal Titan with the potentiometer and circuit board removed, leaving essentially a comparable DC gearhead motor, weighs only 78 g. This seems to make sense, as the Royal Titan gears are plastic and the Escap gears are metal.

7.6 Motors for Rug Warrior

7.6.1 A Vehicle Model

In order to get a rough idea of how much power the motors for Rug Warrior must be able to deliver, we can sketch the scenario illustrated in Figure 7.15. Assume that Rug Warrior uses a differential drive mechanism (two motors) and needs to climb a ramp of angle θ at constant velocity, v. The free-body diagram makes explicit the forces acting on the vehicle.

Because the vehicle moves at constant velocity, there must be no net force on the car. That is, since:

$$F = ma$$

and the acceleration, a, is 0 (the car moves at constant velocity), the net force F must be 0. This means that the applied force, F_{app}, from the wheels acting in the direction up the hill must balance the forces down the hill resisting that force. These resisting forces are the friction force and the force that is the component of the vehicle's weight acting in the direction down the hill. Thus:

$$F_{app} = F_f + F_W$$

where F_f is equal to the coefficient of friction, μ, times the normal force, F_N:

$$F_f = \mu F_N = \mu mg\cos\theta$$

and F_W is $mg\sin\theta$ (where mg, mass times the acceleration due to gravity, is just the weight of the robot). This leaves:

$$F_{app} = \mu mg\cos\theta + mg\sin\theta$$

The power required from the motors is the product of the force that needs to be applied by the wheels times the velocity, v, the robot travels up the hill:

$$P_m = F_{app}v$$

where each motor must supply half that power, as Rug Warrior has two motors.

The torque and speed requirements of each motor can be calculated from:

$$\frac{P}{2} = T\omega \quad \text{and} \quad \omega = \frac{v}{r}$$

where r is the radius of the wheel.

The range and the running time of the robot are dependent upon the battery pack, since power is the rate of energy usage. If the battery has E joules of energy, then the battery lifetime, t, will be:

$$t = \frac{E}{P}$$

The range of distance, D, the robot can travel will be: constrained by

$$D = vt$$

Typically, battery capacity is not given in joules but in units of ampere-hours. To find the energy contained in a battery pack, we must multiply the capacity rating in ampere-hours by the nominal voltage rating of the battery. (Recall that 1 joule equals 1 coulomb-volt and 1 ampere equals 1 coulomb per second.) For instance, suppose a 3 V battery has a 1,300 milli-ampere-hours (mAh) capacity. How many joules does it contain?

$$?\mathrm{J} = 3\,\mathrm{V} \cdot 1300 \times 10^{-3}\,\mathrm{Ah} \cdot \frac{\frac{\mathrm{C}}{\mathrm{sec}}}{\mathrm{A}} \cdot \frac{3600\mathrm{sec}}{\mathrm{h}} = 14,040\,\mathrm{CV} = 14,040\,\mathrm{J}$$

7.6.2 Selecting a Motor

The model we just described for Rug Warrior is hardly realistic. We certainly do not expect that our robot will be climbing up a ramp forever. Rather, because reality is so complicated (e.g., uneven terrain, stop-and-go crises, unknown coefficients of friction, accidents with chair legs, etc.), we use this model simply to attempt to size the peak power requirements.

Let's say that our goal is for Rug Warrior to weigh under 1.5 pounds, which is roughly 650 g. Furthermore, assume that we would like our robot to climb a 30 degree grade at a steady half foot per second, which is $\frac{0.15\,\mathrm{m}}{\mathrm{sec}}$. We will use two motors and a tank-drive locomotion system. Picking a value for μ is a way of trying to account for slippage and friction from the treads and the like. It is not clear what this coefficient of friction will be, but we can make some assumption and pad our result by oversizing the motors at the end. Let's pick μ to be 0.3. The power required then is:

$$P_m = F_{app}v = mg(\mu \cos\theta + \sin\theta)v$$

$$P_m = (0.65\,\mathrm{kg} \cdot 9.8\frac{\mathrm{m}}{\mathrm{sec}^2})(0.3\cos 30^o + \sin 30^o)(0.15\frac{\mathrm{m}}{\mathrm{sec}}) = 0.73\,\mathrm{W}$$

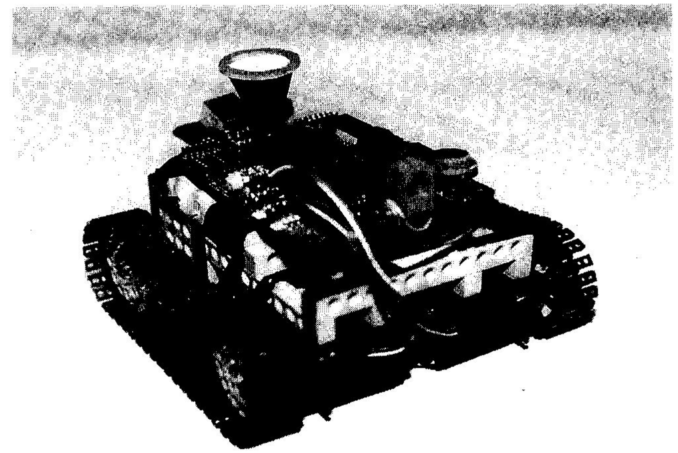


Figure 7.16. The easiest way to build a Rug Warrior is to start with model airplane servo motors; add LEGO parts for bearings, axles, and treads; and then place the batteries, electronics, and sensors on top.

We want to oversize our motors quite a bit, both because there are so many unknowns and because the maximum efficiency point is at a much lower torque than the maximum power point. If we multiply our power requirement by a whopping factor of 3, that would give:

$$P_m = 2.1\,\mathrm{W} \qquad \text{or} \qquad \frac{P_m}{2} \simeq 1\,\mathrm{W}$$

7.6.3 Converting Servo Motors

What we have chosen, as we mentioned earlier, is to use model airplane servo motors. We recommend these motors for the Rug Warrior project of this book because they are fairly inexpensive and easy enough to modify. Although servo motors are not as cheap as toy motors, the fact that they come with gearboxes already built in means that we need not bother with machining a custom gearbox.

Figure 7.16 illustrates the tank-tread version of Rug Warrior that we built using two Royal Titan Maxi Servos, which cost $25 each, LEGO gears for wheels, LEGO tracks for tank treads, and LEGO axles and blocks for bearings and chassis. The PC board on top is

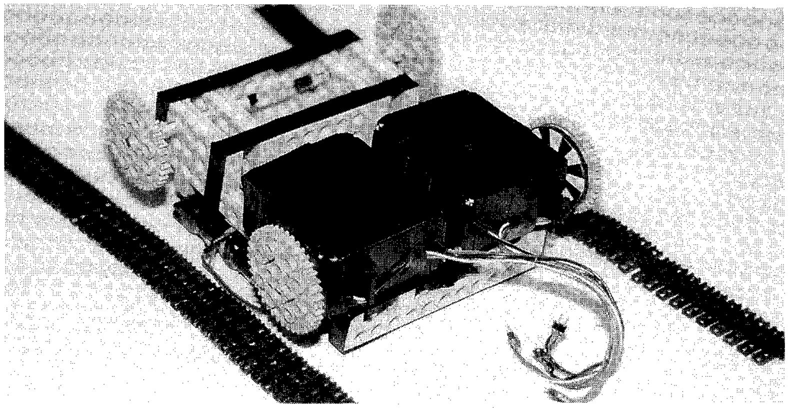


Figure 7.17. The underside of Rug Warrior contains two servo motors taped to the chassis, and LEGO gears mounted on the motor shafts for wheels. LEGO tracks are then used to make tank treads.

3.4"×4.5" and contains an MC68HC11A0, with the 10 sensors and the accompanying control electronics.

The tank drive is made up of two motors, connected to the back wheels in a differential fashion. The front wheels are passive, each having its own axle and bearing. The tank treads are wrapped around from back wheels to front wheels, so the robot can pivot in place.

Figure 7.17 is a view of Rug Warrior from the underside. The two black boxes are the servos. Attached to each is a LEGO gear for a wheel. The gear acts to mesh easily with tracks also supplied by LEGO. It is possible to build a sturdier and lighter-weight chassis, perhaps something made from aluminum sheet metal using a sheet metal bender and a punch for forming sides and placing holes. Real ball bearings and ground shafts could be used for the front wheels (obtainable from suppliers such as Berg, Small Parts Inc., etc.), but it turns out that ball bearings can cost as much as the MC68HC11A0 computer chip! Instead, we elected to use the LEGO building system, not just for gears and tracks but to continue with it for front wheel axles and bearings, as the axles that come with LEGO are made from hard plastic and spin nicely in the holes in the LEGO

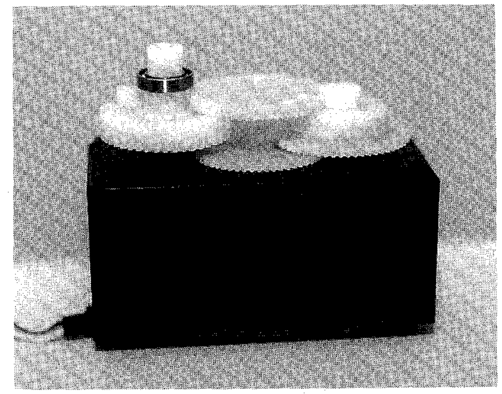


Figure 7.18. Some servo motors are easier to convert to continuous rotation than others. The gearhead of a Royal Titan Maxi Servo is shown here. The leftmost gear is above the potentiometer, and the ball bearing ring is mounted on its top for support of the output shaft. A plastic limit stop is molded onto the gear just below and to the left of the ball bearing.

bricks that we use for the chassis. We used double-sticky tape or black electrical tape to hold the chassis together.

To build this propulsion system for Rug Warrior, first modify the servos so that they can spin all the way around. Figure 7.18 shows the gearhead portion of the Maxi Servo; it has four stages of reduction for a 143:1 geardown. The motor shaft is at the right, the potentiometer shaft is at the left (the motor and potentiometer are below, inside the case), and the third shaft is in the middle. The output power is taken off at the potentiometer shaft. A plastic nib, molded onto the gear there, prevents the shaft from turning multiple revolutions. Above that nib is a metal ring, which is the ball bearing that supports the load.

Next, cut that plastic nib off. A pair of dikes (i.e., diagonal wire cutters) will work fine for the job. Then take that gear off and remove a plastic inset from its underside, which the potentiometer shaft's flat is held against. Not all servo motors have this feature of the removable inset. Some have the inset molded into the gear and have the gear turn directly on the potentiometer's shaft, which means it is not possible to easily make it continuously revolvable.

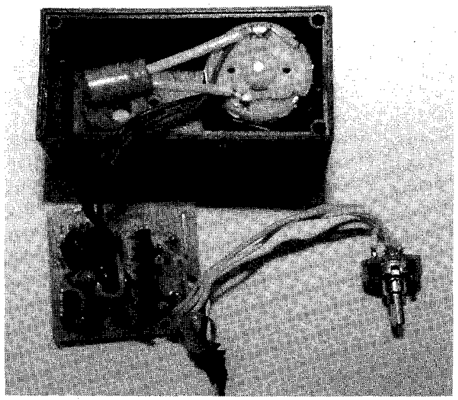


Figure 7.19. A bottom view of the servo in the previous picture shows a Mabuchi motor is in the righthand portion of the casing. The lefthand portion holds the potentiometer and a small circuit board containing an integrated circuit for servo control.

The Royal Titan servos have the removable inset and also have the gear resting on a bushing around the pot's shaft, which means you can actually remove the potentiometer completely. This brings us to the next step; removing the potentiometer.

Figure 7.19 is a view from the underside of the servo motor, with the cover removed and the potentiometer and servo circuit pulled out. Clip the wires for your motor, removing the circuit board. Take out the potentiometer by removing the screw holding it in place. Note the motor on the right. It is a Mabuchi motor and comes equipped with a capacitor across its leads and two resistors to ground to suppress noise spikes from the motor. Desolder the remains of the wires from the servo circuit, and solder on two new wires to the two terminals of the motor. Replace the cover over the gears, making sure the shafts sit properly in their holes. Try hooking a power supply or a battery pack up to two motor leads. The motor should spin continuously. Reversing the polarity of the applied voltage should reverse the direction of spin.

Adding wheels to a servo motor is convenient because servo motors come with an assortment of attachments (plates, levers, star-shaped mounting brackets, etc.) that are designed to fit snuggly

onto the output shaft. Figure 7.20 illustrates a servo motor with the lever attachment. A simple way to mount the LEGO gear is to use the circular plate attachment (instead of the lever attachment), which is roughly the same size as the gear; sand off any small ridges on the plate and/or the gear and glue them together.

It may seem odd to actually throw away a few components from a servo motor and still wind up with the lowest-cost route to a DC gearhead motor. Such are the benefits of mass markets. We will use a MC68HC11A0 and some power electronics (in a form known as an H-bridge) to drive the motors for steering Rug Warrior's treads. However, first let us digress a moment to explain how and where an unmodified servo motor would normally be used.

7.6.4 Unmodified Servo Motors

Typically, a radio-controlled model airplane servo motor is used to adjust a control surface on a wing of a model airplane to a certain position. The integrated circuit and potentiometer are used to implement a closed-loop position control system. The radio sends what is known as a *pulse-code modulated signal* to a receiver on the model plane. As stated earlier, of the three wires emanating from the servo motor, one is for power, one is for ground, and one is connected to this pulse-code modulated signal. Figure 7.20 illustrates the protocol for commanding the servo to a given position.

Basically, a servo motor expects a train of pulses of varying widths. These pulses are repeated at a given period, typically set to 20 ms. The width of the pulse is the code that signifies to what position the shaft should turn. The center position is usually attained with 1.3 ms wide pulses, while pulse widths varying from 0.7 milliseconds (ms) to 1.7 ms will command positions all the way to the right and all the way to the left, respectively.

These position servo motors can be very useful for robot accessories (such as fingers, grippers, legs, and squirt guns) where the range of motion does not require continuous revolution. For continuous motion, we described how to modify the servo and reduce it to a simple DC gearhead motor by throwing away the control circuit and power electronics that come with it and adding our own. However, there is a way to use these motors as continuous revolution DC

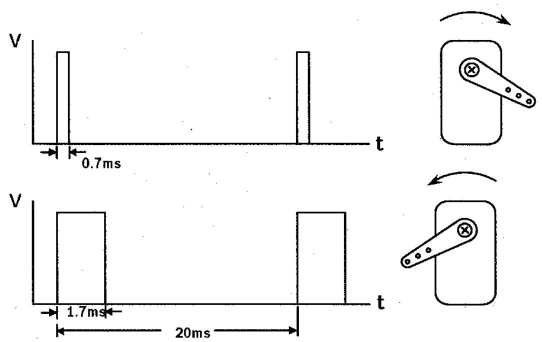


Figure 7.20. An unmodified servo is a three-wire device that takes power, ground, and a pulse-code modulated signal, such as the one shown above. Wider or thinner pulses tell the servo to move to a designated position, either clockwise or counterclockwise from center.

gearhead motors without having to add our own H-bridges and control electronics. The trick is to remove the inset in the plastic gear as before, which affixes itself to the flat of the potentiometer's shaft, but do not actually remove the potentiometer. Set the potentiometer to its central position. Now the gears will turn continuously but the potentiometer will never move. With this configuration, if we send the motor a pulse-code modulated signal to move all the way to the right, the motor will try to comply, never get any feedback, and never stop. Similarly, a pulse-code modulated signal to move to a position to the left will cause continuous rotation all the way to the left. This is an elegant trick (hack, to use the proper term) but we do not pursue it any further for Rug Warrior, because we want to explain how to attack the more common problem of driving a regular DC motor in general, and how to implement a servo loop.

7.7 Interfacing Motors

A microprocessor cannot drive a motor directly, since it cannot supply enough current. Instead, there must be some interface circuitry so that the motor power is supplied from another power source and

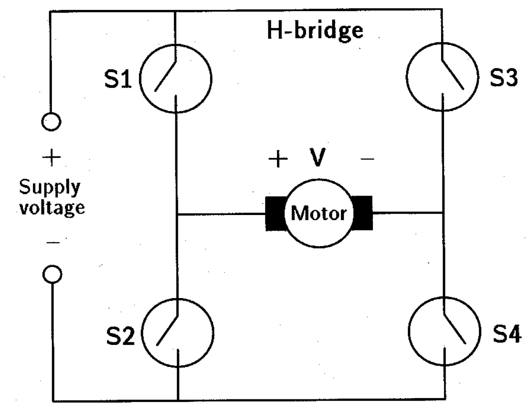


Figure 7.21. A circuit topology known as an H-bridge is used to control a motor. Four switches are controlled by a microprocessor and determine the direction in which current is allowed to pass through the motor. Changing the direction of the current changes the direction of the motor rotation.

only the control signals derive from the microprocessor. This interface circuitry can be implemented in a variety of technologies, such as relays, bipolar transistors, power MOSFETs (metal oxide semiconductor field effect transistors), and motor-driver integrated circuits. In all technologies, however, the basic topology of the circuit is usually the same. This circuit is known as an *H-bridge* and merely consists of four switches connected in the topology of an H, where the motor terminals form the crossbar of the H, as shown in Figure 7.21. You can imagine the abstraction of each switch as being implemented by either relays or transistors, where the power is supplied by the battery and the control signals by the microprocessor.

7.7.1 H-Bridges

In an H-bridge, the switches are opened and closed in a manner so as to put a voltage of one polarity across the motor for current to flow through it in one direction (setting up magnetic fields and causing it to turn) or a voltage of the opposite polarity, causing current to flow through the motor in the opposite direction for reverse rotation.

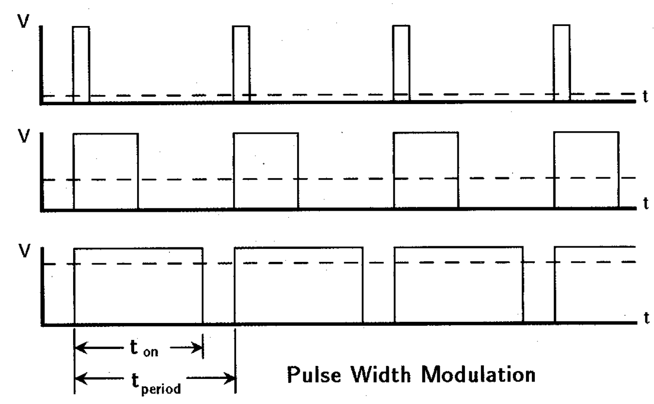


Figure 7.22. Pulse-width modulation of the voltage, by turning switches in the H-bridges on and off for various lengths of time, creates a different average voltage across the motor. Solid lines represent voltages applied when the switches are closed. Dotted lines represent the resulting average voltage applied across the motor.

For example, if switches S1 and S4 in Figure 7.21 are closed while switches S2 and S3 are open, current will flow from left to right in the motor. When switches S2 and S3 are closed and switches S1 and S4 are open, current will flow from right to left, reversing the motor. If the terminals are floating, the motor will freewheel, and if the terminals are shorted, the motor will brake.

To control the speed of the motor, the switches are opened and closed at different rates in order to apply different average voltages across the motor. This technique, called *pulse-width modulation*, is illustrated in Figure 7.22, where V is the voltage across the motor and t is time. For instance, if switches S1 and S4 are used for pulse-width modulation while switches S2 and S3 are left open, the voltage across the motor (as defined in Figure 7.21) will be equal to and of the same polarity as the supply voltage when S1 and S4 are closed and 0 V when they are open. The speed of a DC motor can be adjusted by changing the pulse-width ratio:

$$\text{Pulse-Width Ratio} = \frac{t_{on}}{t_{period}}.$$

of the voltage applied across its terminals.

Note that what we are describing here is different from pulse-code modulation for servo motors, discussed earlier. There, some "intelligence" was added so that the pulse width was a code signifying to what *position* the servo should move. Here, we are merely using varying pulse widths to create different average voltages across the motor to change its *speed*.

We mentioned before that the abstractions of switches in Figure 7.21 can be implemented in a number of ways. Relays can be used to turn motors on and off and reverse their directions as we saw in the TuteBot example, but relays are seldom used in pulse-width modulation speed controllers because they typically cannot switch quickly enough. Relays also tend to wear out. Solid-state switches, such as power bipolar transistors and power MOSFETs, are more convenient for pulse-width modulation schemes, and we will concentrate on these implementations here.

It is possible to design your own solid-state H-bridge controller, but there are also a number of single-chip solutions on the market. We chose one of these for Rug Warrior, and the anxious reader can skip ahead to the section on motor-driver power integrated circuits (see Section 7.7.4). However, if your particular project has requirements not available in a commercial H-bridge chip or if you are simply curious, the following sections give a bit of background on what is inside a motor-driver integrated circuit.

7.7.2 Switching Inductive Loads

Whether using solid-state switches or relays, problems arise when switching inductive loads such as motors, as illustrated in Figure 7.23. We know that the voltage induced across an inductor is proportional to the rate of change of current through it:

$$v = L\frac{di}{dt}$$

If the current through an inductor has reached a steady state and is not changing, the voltage across it is 0 V and the inductor behaves like a straight piece of wire. Figure 7.23(a) shows what happens if that steady-state current is upset by the opening of a switch. Namely, the current cannot instantaneously go to 0 A so a voltage, $v = L\frac{di}{dt}$, is induced in a direction opposing the flow of

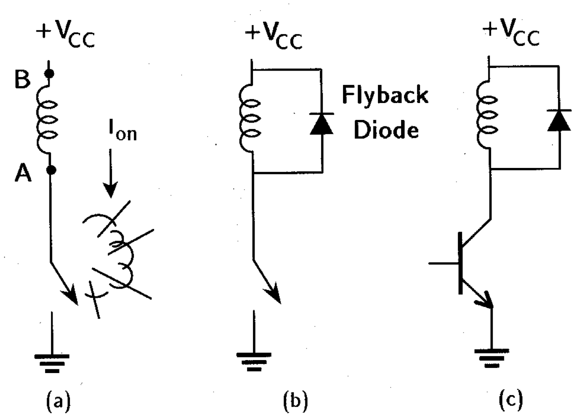


Figure 7.23. (a) The steady-state current through an inductor, I_{on}, cannot immediately go to 0 A when the switch is opened. The changing current induces a voltage across the inductor, making the potential at A greater than at B, causing the switch or relay to arc over. (b) Flyback diodes protect switches from blowing up. (c) Transistor switches must be protected in the same manner.

current. That is, the point marked A will be at a potential positive with respect to point B (which is at V_{cc}). Although the current does not change instantaneously when the switch is opened, it does change very quickly, and the faster the rate of change, the larger the induced voltage spike. Depending on the size of the inductor, the magnitude of the current, and how quickly the switch is opened, these voltage spikes can temporarily reach several hundred volts or more, enough to cause the switch to arc over and blow up.

The solution to this problem is to put what is known as a *flyback diode* in the reverse direction across the inductive load (Figure 7.23[b]) so that the voltage spike will forward bias the diode, creating a return path for the current. In this way, the power will "fly back" to the power supply.

Solid-state switches are just as susceptible to voltage spike destruction as mechanical switches, which is why transistor circuits switching inductive loads are usually shown with appropriate flyback diodes, as illustrated in Figure 7.23(c).

7.7.3 Power Electronics

As we discuss controlling motors from a microprocessor and the power electronics needed for the interface, we will talk about transistors used as switches. In Chapter 5 on sensors, we saw transistors, or collections of transistors in the form of op-amps, used as linear amplifiers to add gain to a circuit for amplifying small signals from sensors into larger signals understood by a microprocessor. The microphone circuit and the sonar circuit were examples. In addition to transistors used as linear amplifiers, we have also seen transistors used in another way: as CMOS (complementary metal oxide semiconductor) logic-gate switches. All the circuitry making up the internals of the 6811, its associated RAM and various discrete NAND gates and inverters, are simply composed of low-power, n-channel and p-channel MOSFET transistors used as switches. MOSFETs are similar to bipolar junction transistors in some sense, yet different in many ways. We will give some comparisons and contrasts between MOSFETs and transistors in a moment.

First, however, transistors can be classified another way, either as signal-level devices or as power devices. Transistors used for linear amplification of sensor signals or for logical manipulation of bits are concerned with processing information and are generally low-power devices. Power transistors, on the other hand, are capable of handling larger currents and voltages. They might be used as linear amplifiers in output stages of high-fidelity audio systems to drive speakers or they might be used as switches in H-bridges to pulse-width modulate motors requiring large currents. Power devices are typically larger than signal-level devices, as they require more silicon area for higher current-handling capability and larger packages for heat dissipation.

Semiconductors and Charge Carriers

Solid-state switches and power electronics are semiconductor devices. What is a *semiconductor* exactly, and why is silicon the material of choice for the semiconductor industry?

In a normal *conductor*, for instance, a metal such as aluminum, free electrons act as charge carriers and move in a direction toward a