19

WORKING WITH STEPPER MOTORS

In past chapters we've looked at powering robots using everyday continuous DC motors. DC motors are cheap, deliver a lot of torque for their size, and are easily adaptable to a variety of robot designs. By their nature, however, the common DC motor is rather imprecise. Without a servo feedback mechanism or tachometer, there's no telling how fast a DC motor is turning. Furthermore, it's difficult to command the motor to turn a specific number of revolutions, let alone a fraction of a revolution. Yet this is exactly the kind of precision robotics work, particularly arm designs, often requires.

Enter the stepper motor. Stepper motors are, in effect, DC motors with a twist. Instead of being powered by a continuous flow of current, as with regular DC motors, they are driven by pulses of electricity. Each pulse drives the shaft of the motor a little bit. The more pulses that are fed to the motor, the more the shaft turns. As such, stepper motors are inherently "digital" devices, a fact that will come in handy when you want to control your robot by computer. By the way, there are AC stepper motors as well, but they aren't really suitable for robotics work and so won't be discussed here.

Stepper motors aren't as easy to use as standard DC motors, however, and they're both harder to get and more expensive. But for the applications that require them, stepper motors can solve a lot of problems with a minimum of fuss. Let's take a closer look at steppers and learn how to apply them to your robot designs.

Inside a Stepper Motor

There are several designs of stepper motors. For the time being, we'll concentrate on the most popular variety, the four-phase unipolar stepper, like the one in Fig. 19.1. A unipolar stepper motor is really two motors sandwiched together, as shown in Fig. 19.2. Each motor is composed of two windings. Wires connect to each of the four windings of the motor pair, so there are eight wires coming from the motor. The commons from the windings are often ganged together, which reduces the wire count to five or six instead of eight (see Fig. 19.3).

WAVE STEP SEQUENCE

In operation, the common wires of a unipolar stepper are attached to the positive (sometimes the negative) side of the power supply. Each winding is then energized in turn by grounding it to the power supply for a short time. The motor shaft turns a fraction of a revolution each time a winding is energized. For the shaft to turn properly, the windings must be energized in sequence. For example, energize wires 1, 2, 3, and 4 in sequence and the motor turns clockwise. Reverse the sequence, and the motor turns the other way.

FOUR-STEP SEQUENCE

The wave step sequence is the basic actuation technique of unipolar stepper motors. Another, and far better, approach actuates two windings at once in an on-on/off-off four-step sequence, as shown in Fig. 19.4. This enhanced actuation sequence increases the driving power of the motor and provides greater shaft rotation precision.

There are other varieties of stepper motors, and they are actuated in different ways. One you may encounter is bipolar. It has four wires and is pulsed by reversing the polarity of the power supply for each of the four steps. We will discuss the actuation technique for these motors later in this chapter.

Design Considerations of Stepper Motors

Stepping motors differ in their design characteristics over continuous DC motors. The following section discusses the most important design specifications for stepper motors.

STEPPER PHASING

A unipolar stepper requires that a sequence of four pulses be applied to its various windings for it to rotate properly. By their nature, all stepper motors are at least two-phase. Many are four-phase; some are six-phase. Usually, but not always, the more phases in a motor, the more accurate it is.
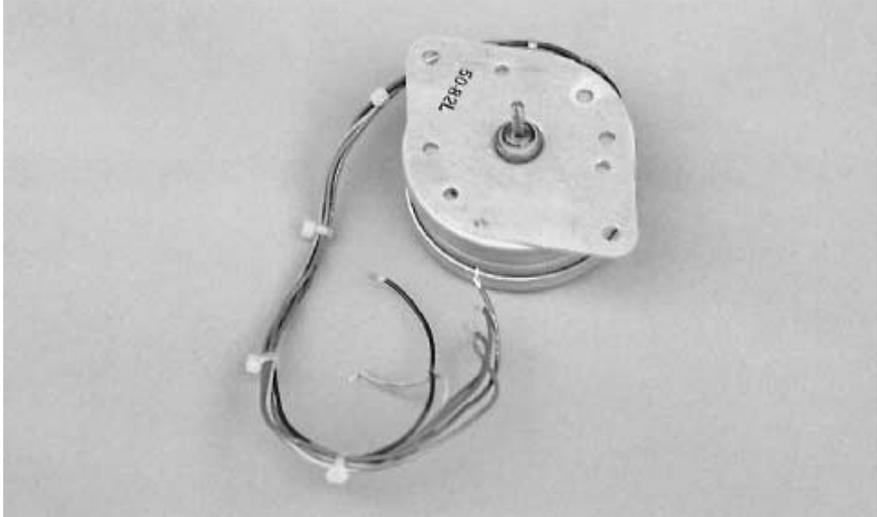
FIGURE 19.1   A typical unipolar stepper motor.
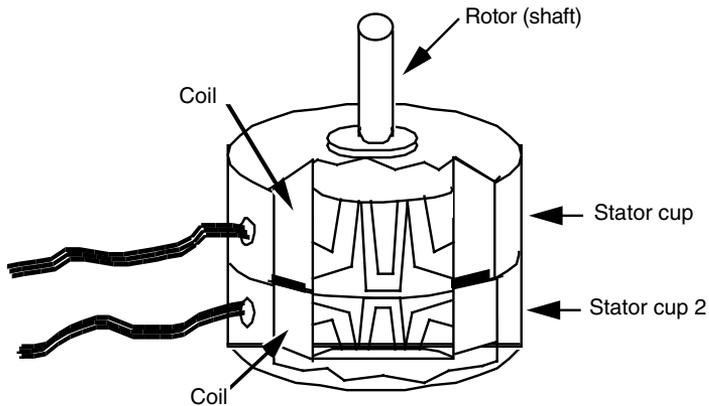

FIGURE 19.2   Inside a unipolar stepper motor. Note the two sets of coils and stators. The unipolar stepper is really two motors sandwiched together.

STEP ANGLE

Stepper motors vary in the amount of rotation of the shaft each time a winding is energized. The amount or rotation is called the *step angle* and can vary from as small as 0.9° (1.8° is more common) to 90°. The step angle determines the number of steps per revolution. A stepper with a 1.8° step angle, for example, must be pulsed 200 times for the shaft to turn one complete revolution. A stepper with a 7.5° step angle must be pulsed 48 times for one revolution, and so on.
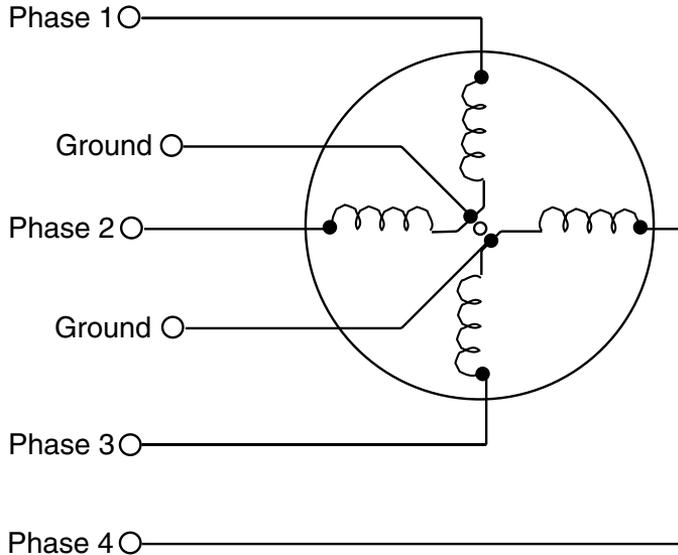
Phase 1 ○──────────────┐

Ground ○──────────┐

Phase 2 ○──────

Ground ○──────────┘

Phase 3 ○──────────────┘

Phase 4 ○──────────────────

FIGURE 19.3 **The wiring diagram of the unipolar stepper. The common connections can be separate or combined.**

STEP	PHASE 1	PHASE 2	PHASE 3	PHASE 4
1	ON	OFF	ON	OFF
2	OFF	ON	ON	OFF
3	OFF	ON	OFF	ON
4	ON	OFF	OFF	ON

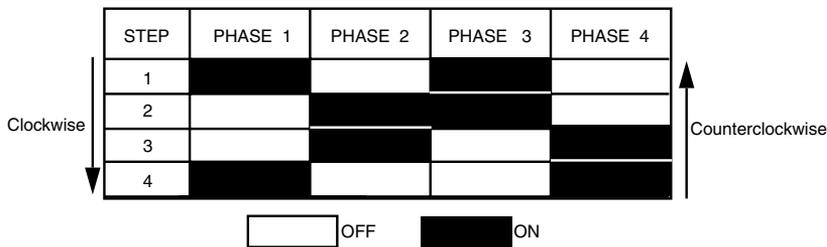Clockwise ↓   Counterclockwise ↑

☐ OFF   ■ ON

FIGURE 19.4 **The enhanced on-on/off-off four-step sequence of a unipolar stepper motor.**

PULSE RATE

Obviously, the smaller the step angle is, the more accurate the motor. But the number of pulses stepper motors can accept per second has an upper limit. Heavy-duty steppers usually have a maximum pulse rate (or step rate) of 200 or 300 steps per second, so they have an effective top speed of one to three revolutions per second (60 to 180 rpm). Some smaller steppers can accept a thousand or more pulses per second, but they don't usually provide very much torque and aren't suitable as driving or steering motors.

Note that stepper motors can't be motivated to run at their top speeds immediately from a dead stop. Applying too many pulses right off the bat simply causes the motor to freeze up. To achieve top speeds, you must gradually accelerate the motor. The acceleration can

be quite swift in human terms. The speed can be one-third for the first few milliseconds, two thirds for the next few milliseconds, then full blast after that.

RUNNING TORQUE

Steppers can't deliver as much running torque as standard DC motors of the same size and weight. A typical 12-volt, medium-sized stepper motor may have a running torque of only 25 oz-in. The same 12-volt, medium-sized standard DC motor may have a running torque that is three or four times more.

However, steppers are at their best when they are turning slowly. With the typical stepper, the slower the motor revolves, the higher the torque. The reverse is usually true of continuous DC motors. Fig. 19.5 shows a graph of the running torque of a medium-duty, unipolar 12-volt stepper. This unit has a top running speed of 550 pulses per second. Since the motor has a step angle of 1.8°, that results in a top speed of 2.75 revolutions per second (165 rpm).

BRAKING EFFECT

Actuating one of the windings in a stepper motor advances the shaft. If you continue to apply current to the winding the motor won't turn any more. In fact, the shaft will be locked, as if you've applied brakes. As a result of this interesting locking effect, you never need to add a braking circuit to a stepper motor because it has its own brakes built in.

The amount of braking power a stepper motor has is expressed as *holding torque*. Small stepper motors have a holding torque of a few oz-in. Larger, heavier-duty models have holding torque exceeding 400 oz-in.

VOLTAGE, CURRENT RATINGS

Like DC motors, stepper motors vary in their voltage and current ratings. Steppers for 5-, 6-, and 12-volt operation are not uncommon. But unlike DC motors, if you use a higher voltage than specified for a stepper motor you don't gain faster operation, but more running
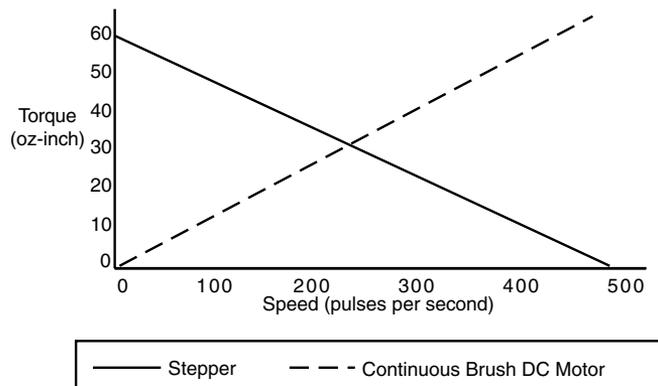

FIGURE 19.5 With a stepper motor, torque increases as the speed of the motor is reduced.

and holding torque. Overpowering a stepper by more than 80 to 100 percent above the rated voltage may eventually burn up the motor.

The current rating of a stepper is expressed in amps (or milliamps) per phase. The power supply driving the motor needs to deliver at least as much as the per-phase specification, preferably more if the motor is driving a heavy load. The four-step actuation sequence powers two phases at a time, which means the power supply must deliver at least twice as much current as the per-phase specification. If, for example, the current per phase is 0.25 amps, the power requirement at any one time is 0.50 amps.

Controlling a Stepper Motor

Steppers have been around for a long time. In the old days, stepper motors were actuated by a mechanical switch, a solenoid-driven device that pulsed each of the windings of the motor in the proper sequence. Now, stepper motors are invariably controlled by electronic means. Basic actuation can be accomplished via computer control by pulsing each of the four windings in turn. The computer can't directly power the motor, so transistors must be added to each winding, as shown in Fig. 19.6.

USING A STEPPER MOTOR CONTROLLER CHIP

In the absence of direct computer control, the easiest way to provide the proper sequence of actuation pulses is to use a custom stepper motor chip, such as the Allegro Microsystems
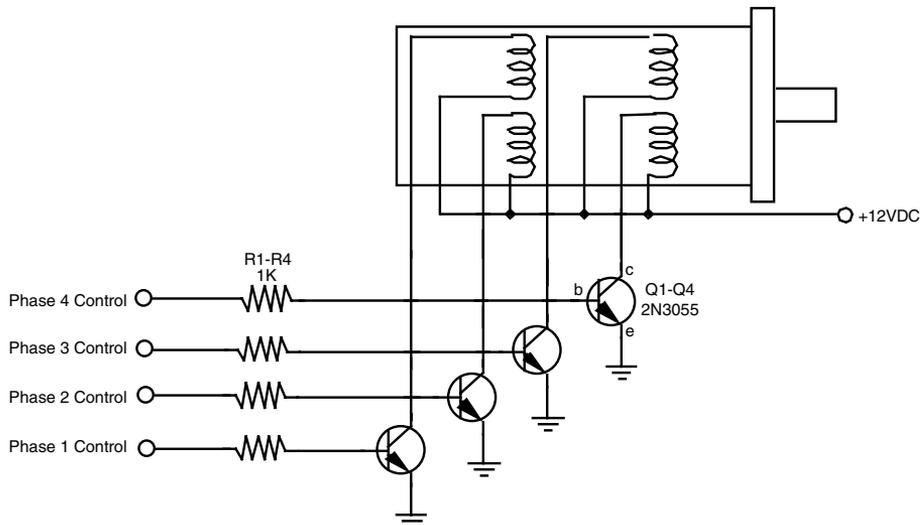

FIGURE 19.6 The basic hookup connection to drive a stepper motor from a computer or other electronic interface. The phasing sequence is provided by software or other means through a port following a four-bit binary sequence: 1010, 0110, 0101, 1001 (reverse the sequence to reverse the motor).

UCN5804. This chip is designed expressly for use with the common unipolar stepper motor and provides a four-step actuation sequence. Stepper motor translator chips tend to be modestly priced, at about $5 to $10, depending on their features and where you buy them.

Figure 19.7 (refer to the parts list in Table 19.1) shows a typical schematic of the UCN5804. Heavier duty motors (more than about 1A per phase) can be driven by adding power transistors to the four outputs of the chips, as shown in the manufacturer's application notes. Note the Direction pin. Pulling this pin high or low reverses the rotation of the motor.

Using logic gates to control stepper motors

Another approach to operating unipolar stepper motors is to use discrete gates and clock ICs. You can assemble a stepper motor translator circuit using just two IC packages. The circuit can be constructed using TTL or CMOS chips.

The TTL version is shown in Fig. 19.8 (refer to the parts list in Table 19.2). Four Exclusive OR gates from a single 7486 IC provide the steering logic. You set the direction by pulling pin 12 HIGH or LOW. The stepping actuation is controlled by a 7476, which contains two JK flip-flops. The Q and 'Q outputs of the flip-flops control the phasing of the motor. Stepping is accomplished by triggering the clock inputs of both flip-flops.

The 7476 can't directly power a stepper motor. You must use power transistors or MOSFETs to drive the windings of the motor. See the section titled "Translator Enhancements" for a complete power driving schematic as well as other options you can add to this circuit.

The CMOS version, shown in Fig. 19.9 (refer to the parts list in Table 19.3), is identical to the TTL version, except that a 4070 chip is used for the Exclusive OR gates and a 4027 is used for the flip-flops. The pinouts are slightly different, so follow the correct schematic for the type of chips you use. Note that another CMOS Exclusive OR package, the 4030, is also available. Don't use this chip; it behaved erratically in this, as well as other pulsed, circuits.

In both the TTL and CMOS circuits, the stepper motor itself can be operated from a supply voltage that is wholly different than the voltage supplied to the ICs.

TRANSLATOR ENHANCEMENTS

Four NPN power transistors, four resistors, and a handful of diodes are all the translator circuits described in the last section need to provide driving power. (You can also use this scheme to increase the driving power of the UCN5804, detailed earlier). The schematic for the circuit is shown in Fig. 19.10 (refer to the parts list in Table 19.4). Note that you can substitute the bipolar transistors and resistors with power MOSFETs. See Chapter 17, "Choosing the Right Motor for the Job," for more information on using power MOSFETs.

You can use just about any NPN power transistor that will handle the motor. The TIP31 is a good choice for applications that require up to one amp of current. Use the 2N3055 for heavier-duty motors. Mount the drive transistors on a suitable heat sink.

You must insert a bias resistor in series between the outputs of the translation circuit and the base of the transistors. Values between about 1K and 3K should work with most motors and most transistors. Experiment until you find the value that works without causing the flip-flop chips to overheat. You can also apply Ohm's law, figuring in the current draw of the motor and the gain of the transistor, to accurately find the correct value of the resistor. If this is new to you, see Appendix A, "Further Reading," for a list of books on electronic design and theory.
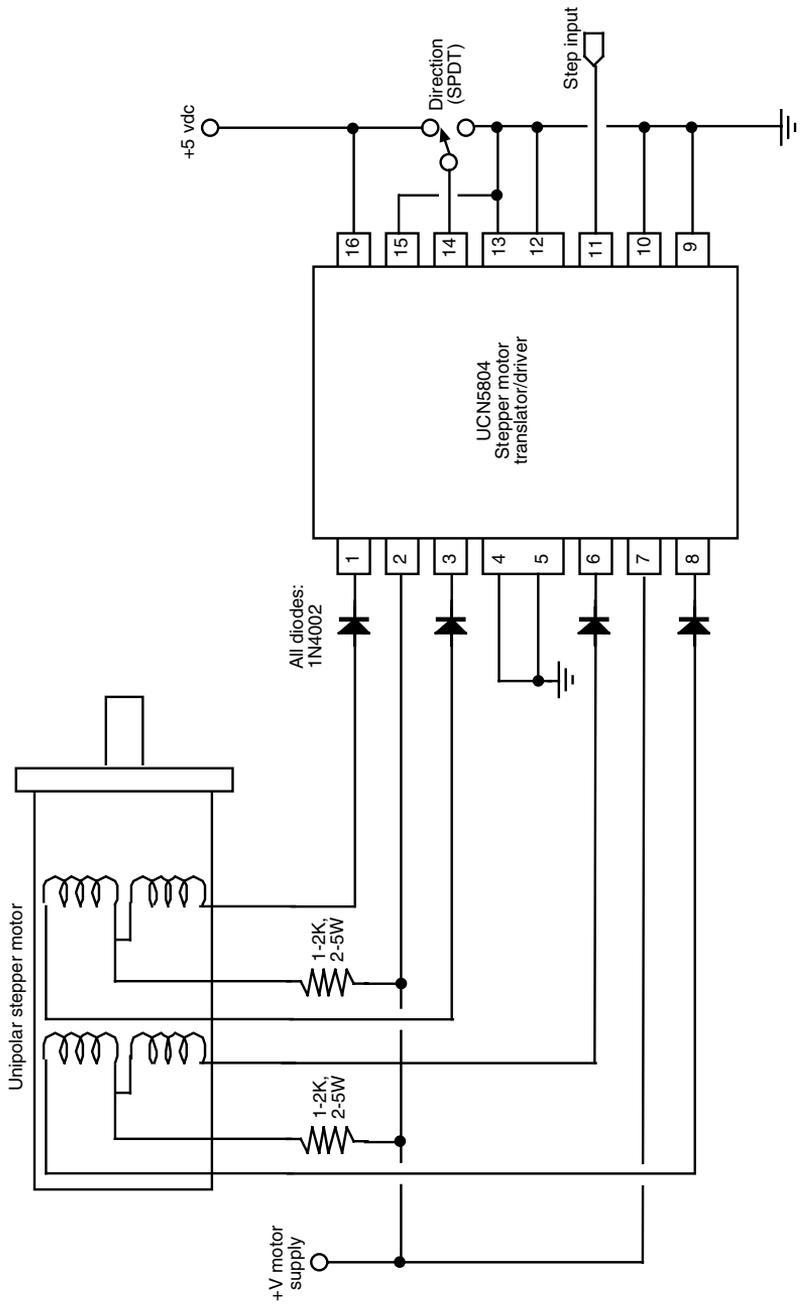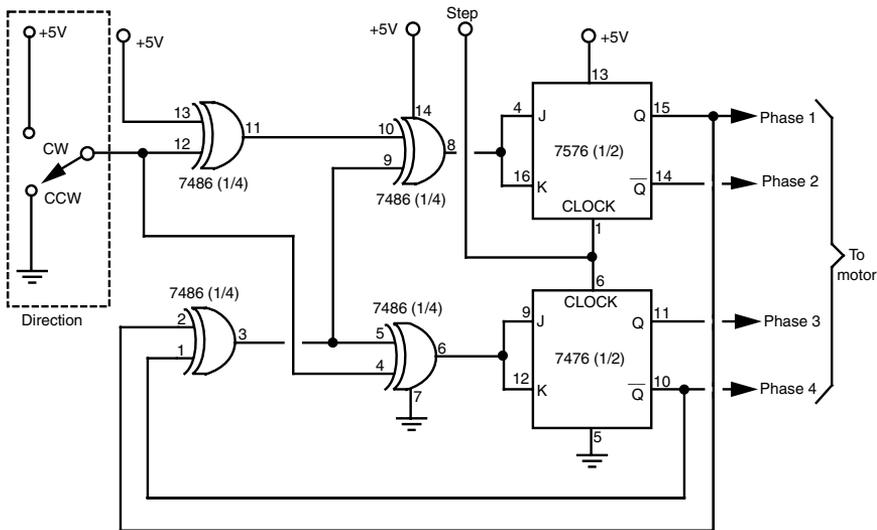
FIGURE 19.7 The basic wiring diagram for the UCN5804.

TABLE 19.1 PARTS LIST FOR UCN5804 STEPPER MOTOR TRANSLATOR/DRIVER.	
IC1	Allegro UCN5804 Stepper Motor Translator IC
R1, R2	1–2K resistor, 2–5 watts
D1–D4	1N4002 diode
M1	Unipolar stepper motor
Misc	SPDT switch, heat sinks for UCN5804 (as needed)

FIGURE 19.8 **Using a pair of commonly available TTL ICs to construct your own stepper motor translator circuit.**

TABLE 19.2 PARTS LIST FOR TTL STEPPER MOTOR TRANSLATOR	
IC1	7486 Quad Exclusive OR Gate IC
U2	7476 Dual "JK" flip-flop IC

It is sometimes helpful to see a visual representation of the stepping sequence. Adding an LED and current-limiting resistor in parallel with the outputs provides just such a visual indication. See Fig. 19.11 for a wiring diagram (refer to the parts list in Table 19.5). Note the special wiring to the flip-flop outputs. This provides a better visual indication of the stepping action than hooking up the LEDs in the same order as the motor phases.

Figure 19.12 shows two stepper motor translator boards. The small board controls up to two stepper motors and is designed using TTL chips. The LED option is used to provide a
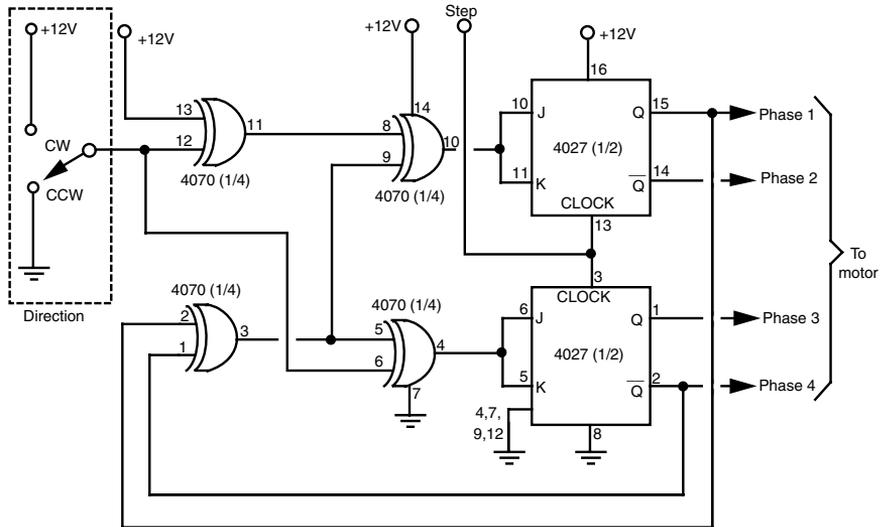
FIGURE 19.9   Using a pair of commonly available CMOS ICs to construct your own stepper motor translator circuit.

TABLE 19.3 PARTS LIST FOR CMOS STEPPER MOTOR TRANSLATOR.	
IC1	4070 Quad Exclusive OR Gate IC
IC2	4027 Dual "JK" flip-flop IC

visual reference of the step sequence. The large board uses CMOS chips and can accommodate up to four motors. The boards were wire-wrapped; the driving transistors are placed on a separate board and heat sink.

TRIGGERING THE TRANSLATOR CIRCUITS

You need a square wave generator to provide the triggering pulses for the motors. You can use the 555 timer wired as an astable multivibrator, or make use of a control line in your computer or microcontroller. When using the 555, remember to add the 0.1 ∝F capacitor across the power pins of the chip. The 555 puts a lot of noise into the power supply, and this noise regularly disturbs the counting logic in the Exclusive OR and flip-flop chips. If you are getting erratic results from your circuit, this is probably the cause.

USING BIPOLAR STEPPER MOTORS

As detailed earlier in the chapter, unipolar stepper motors contain four coils in which two of the coils are joined to make a center tap. This center tap is the "common"
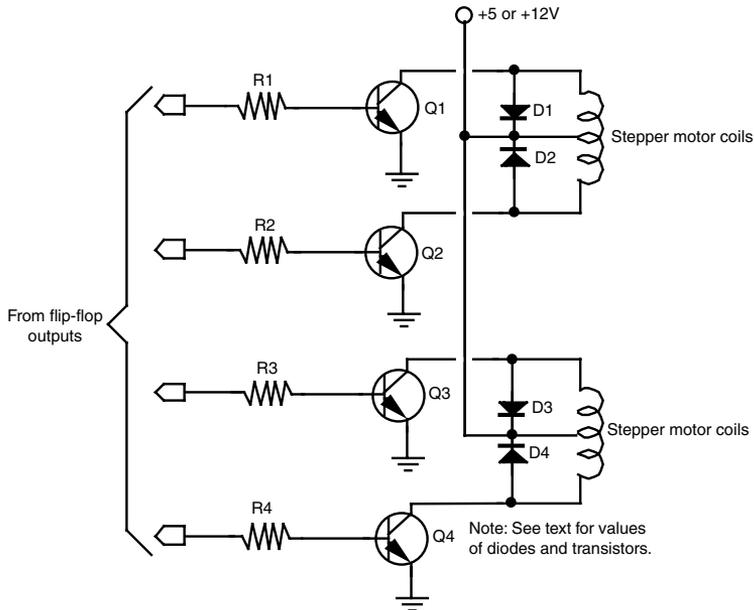
FIGURE 19.10 **Add four transistors and resistors to provide a power output stage for the TTL or CMOS stepper motor translator circuits.**

TABLE 19.4 PARTS LIST FOR STEPPER MOTOR DRIVER.

Q1–Q4	Under 1 amp draw per phase: TIP32 NPN transistor
	1 to 3 amp draw per phase: TIP120 NPN Darlington transistor
R1–R4	1K resistor, 1 watt
D1–D4	1N4004 diode
Misc	Heat sinks for transistors

connection for the motor. Bipolar stepper motors contain two coils, do not use a common connection, and are generally less expensive because they are easier to manufacture. A bipolar stepper motor has four external connection points. An old method for operating a bipolar stepper motor was to use relays to reverse the polarity of a DC voltage to two coils. This caused the motor to inch forward or backward, depending on the phasing sequence.

Today, the more common method for operating a bipolar stepper motor is to use a specialty stepper motor translator, such as the SGS-Thompson L297D (the L297D can also be used to drive unipolar stepper motors). To add more current driving capacity to the L297D you can add a dual H-bridge driver, such as the L298N, which is available from
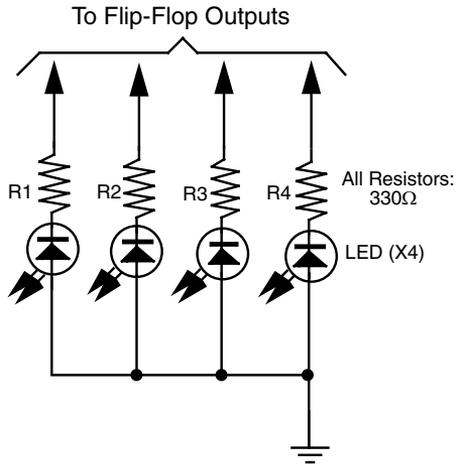
To Flip-Flop Outputs

R1   R2   R3   R4   All Resistors:
330Ω

LED (X4)

FIGURE 19.11 Add four LEDs and resistors to provide a visual indication of the stepping action.

TABLE 19.5   PARTS LIST FOR UCN5804 STEPPER MOTOR TRANSLATOR/DRIVER.

R1–R4	300-ohm resistor
LED1–4	Light-emitting diode

All resistors have 5 or 10 percent tolerance, 1/4-watt.

the same company. The truth table for the typical driving sequence of a bipolar stepper motor is shown in Fig. 19.13 .

BUYING AND TESTING A STEPPER MOTOR

Spend some time with a stepper motor and you'll invariably come to admire its design and be able to think up all sorts of ways to make it work for you in your robot designs. But to use a stepper, you have to get one. That in itself is not always easy. Then after you have obtained it and taken it home, there's the question of figuring out where all the wires go! Let's take each problem one at a time.

SOURCES FOR STEPPER MOTORS

Despite their many advantages, stepper motors aren't nearly as common as the trusty DC motor, so they are harder to find. And when you do find them, they're expensive when new. The surplus market is by far the best source for stepper motors for hobby robotics. See Appendix B, "Sources," for a list of selected mail order surplus companies that regularly carry a variety of stepper motors. They carry most of the "name brand" steppers: Thompson-Airpax, Molon, Haydon, and Superior Electric. The cost of surplus steppers is often a quarter or fifth of the original list price.

The disadvantage of buying surplus is that you don't always get a hookup diagram or adequate specifications. Purchasing surplus stepper motors is largely a hit-or-miss
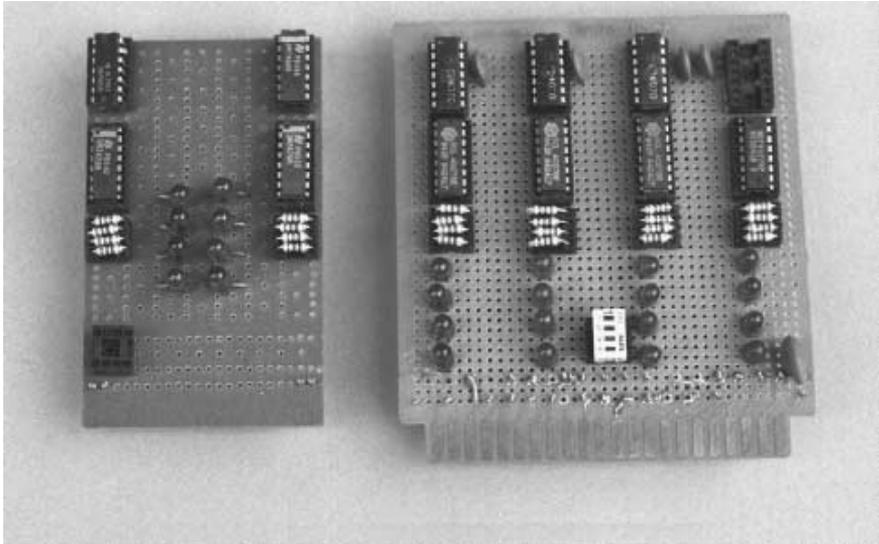
FIGURE 19.12   Two finished stepper motor translator boards, with indicator LEDs. The board on the left controls two stepper motors; the board on the right controls four stepper motors.

affair, but most outlets let you return the goods if they aren't what you need. If you like the motor, yet it still lacks a hookup diagram, read the following section on how to decode the wiring.

WIRING DIAGRAM

The internal wiring diagram of both a bipolar and unipolar stepper motor is shown in Fig. 19.14. The wiring in a bipolar stepper is actually easy to decode. You use a volt-ohm meter to do the job right. You can be fairly sure the motor is two-phase if it has only four wires leading to it. You can identify the phases by connecting the leads of the meter to each wire and noting the resistance. Wire pairs that give an open reading (infinite ohms) represent two different coils (phases). You can readily identify mating phases when there is a small resistance through the wire pair.

Unipolar steppers behave the same, but with a slight twist. Let's say, for argument's sake, that the motor has eight wires leading to it. Each winding, then, has a pair of wires. Connect your meter to each wire in turn to identify the mating pairs. As illustrated in Fig. 19.15, no reading (infinite ohms) signifies that the wires do not lead to the same winding; a reading indicates a winding.

If the motor has six wires, then four of the leads go to one side of the windings. The other two are commons and connect to the other side of the windings (see Fig. 19.16). Decoding this wiring scheme takes some patience, but it can be done. First, separate all those wires where you get an open reading. At the end of your test, there should be two three-wire sets that provide some reading among each of the leads.
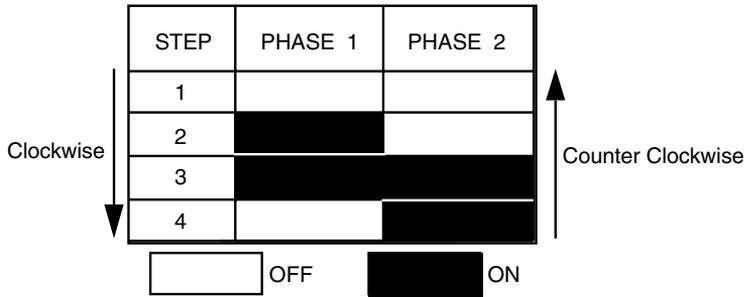
STEP	PHASE 1	PHASE 2
1		
2	■	
3	■	■
4		■

Clockwise ↓   Counter Clockwise ↑

☐ OFF   ■ ON

FIGURE 19.13   The phasing sequence for a bipolar stepper motor.

Phase 1   Phase 2
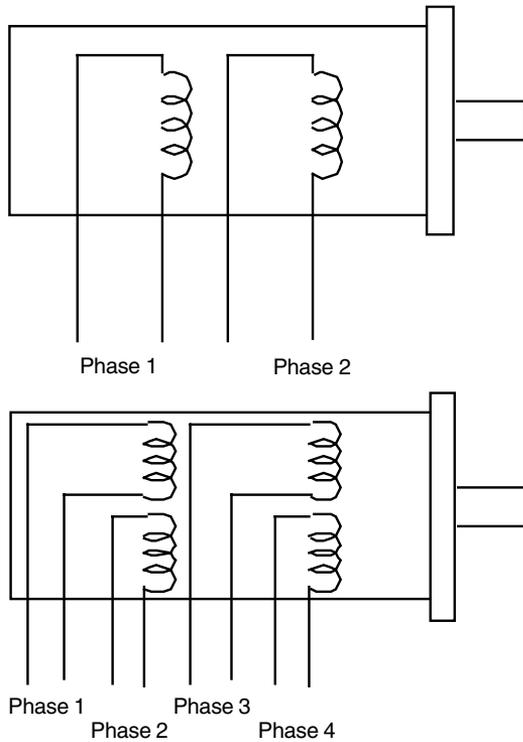
Phase 1   Phase 3
     Phase 2   Phase 4

FIGURE 19.14   Pictorial diagrams of the coils
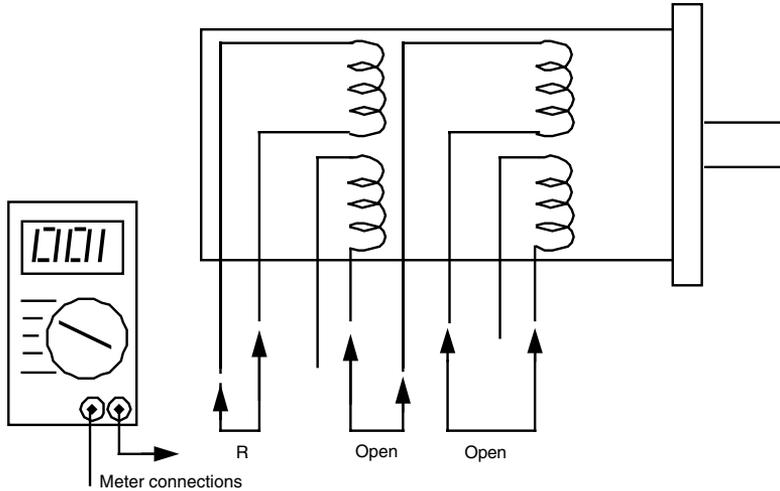in a bipolar and unipolar step-
per motor.

FIGURE 19.15 Connection points and possible readings on an 8-wire unipolar stepper motor.
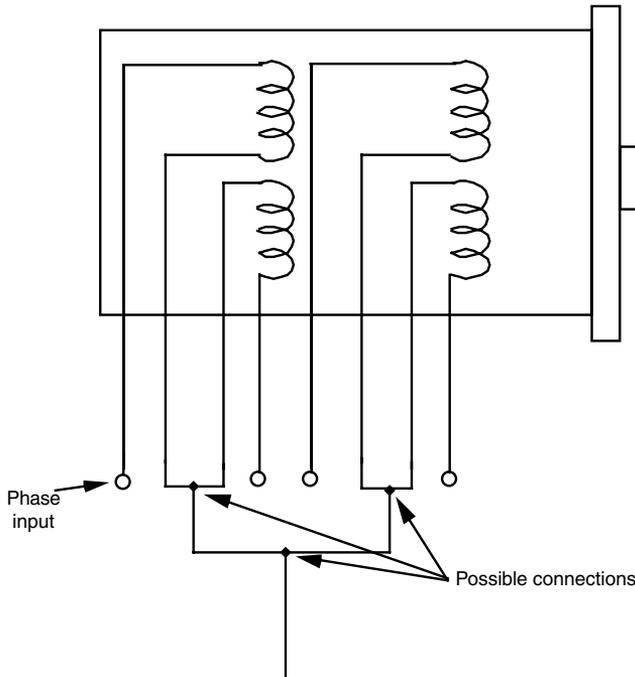

FIGURE 19.16 Common connections may reduce the wire count of the stepper motor to five or six, instead of eight.

Locate the common wire by following these steps. Take a measurement of each combination of the wires and note the results. You should end up with three measurements: wires 1 and 2, wires 2 and 3, and wires 1 and 3. The meter readings will be the same for two of the sets. For the third set, the resistance should be roughly doubled. These two wires are the main windings. The remaining wire is the common.

Decoding a five-wire motor is the most straightforward procedure. Measure each wire combination, noting the results of each. When you test the leads to one winding, the result will be a specified resistance (let's call it "R"). When you test the leads to two of the windings, the resistance will be double the value of "R," as shown in Fig. 19.17. Isolate this common wire with further testing and you've successfully decoded the wiring.
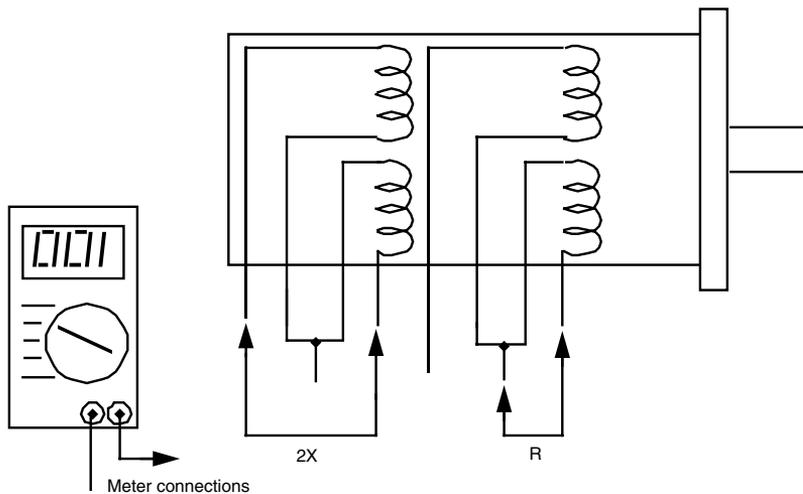

FIGURE 19.17 Connection points and possible readings on a 5- or 6-wire unipolar stepper motor.

From Here

To learn more about…	Read
Driving a robot	Chapter 16, "Robot Locomotion Principles"
Selecting a motor for your robot	Chapter 17, "Choosing the Right Motor for the Job"
Connecting motors to computers, microcontrollers, and other electronic circuitry	Chapter 29, "Interfacing with Computers and Microcontrollers"