22

BUILD A HEAVY-DUTY SIX-LEGGED WALKING ROBOT

Let's be honest with each other. Do you like challenges? Do you like being faced with problems that demand decisive action on your part? Do you like spending many long hours tinkering in the garage or workshop? Do you like the idea of building the ultimate robot, one that will amaze you and your friends? If the answer is yes to all these questions, then maybe you're ready to build the Walkerbot, which we will describe in depth in this chapter.

This strange and unique contraption walks on six legs and turns corners with an ease and grace that belies its rather simple design. The basic Walkerbot frame and running gear can be used to make other types of robots as well. In Chapter 23, "Advanced Locomotion Systems," you'll see how to convert the Walkerbot to tracked or wheeled drive. The conversion is simple and straightforward. In fact, you can switch back and forth between drive systems.

The Walkerbot design described in this chapter is for the basic frame, motor, battery system, running gear, and legs. You can embellish the robot with additional components, such as arms, a head, computer control, you name it. The frame is oversized (in fact, it's too large to fit through some inside doors!), and there's plenty of room to add new subsystems. The only requirement is that that weight doesn't exceed the driving capacity of the motors and batteries and that the legs and axles don't bend. The prototype Walkerbot weighs about 50 pounds. It moves along swiftly and no structural problems have yet occurred. Another 10 or 15 pounds could be added without worry.

Frame

The completed Walkerbot frame measures 18 inches wide by 24 inches long by 12 inches deep. Construction is all aluminum, using a combination of 41/64-inch-by-1/2-inch-by-1/16-inch channel stock and 1-inch-by-1-inch-by-1/16-inch angle stock.

Build the bottom of the frame by cutting two 18-inch lengths of channel stock and two 24-inch lengths of channel stock, as shown in Fig. 22.1 (refer to the parts list in Table 22.1). Miter the ends. Attach the four pieces using 1 1/2-inch-by-3/8-inch flat angle irons and secure them with 3-by-1/2-inch bolts and nuts. For added strength, use four bolts on each corner.

In the prototype Walkerbot, I replaced many of the nuts and bolts with aluminum pop rivets in order to reduce the weight. Until the entire frame is assembled, however, use the bolts as temporary fasteners. Then, when the frame is assembled, square it up and replace the bolts and nuts with rivets one at a time. Construct the top of the frame in the same manner.

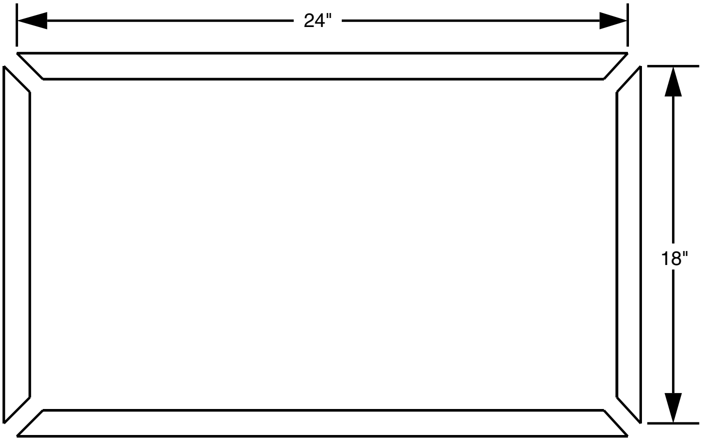

FIGURE 22.1 **Cutting diagram for the frame of the Walkerbot (two sets).**

TABLE 22-1 PARTS LIST FOR WALKERBOT FRAME.

4	24-inch lengths 41/64-inch-by-1/2-inch-by-1/16-inch aluminum channel stock
4	18-inch lengths 41/64-inch-by-1/2-inch-by-1/16-inch aluminum channel stock
4	12-inch lengths 1-inch-by-1-inch-by-1/16-inch aluminum angle stock
8	1 1/2-inch-by-3/8-inch flat angle iron
4	24-inch lengths 1-inch-by-1-inch-by-1/16-inch aluminum angle stock
2	17 5/8-inch lengths 1-inch-by-1-inch-by-1/16-inch aluminum angle stock
Misc	8/32 stove bolts, nuts, tooth lock washers, as needed

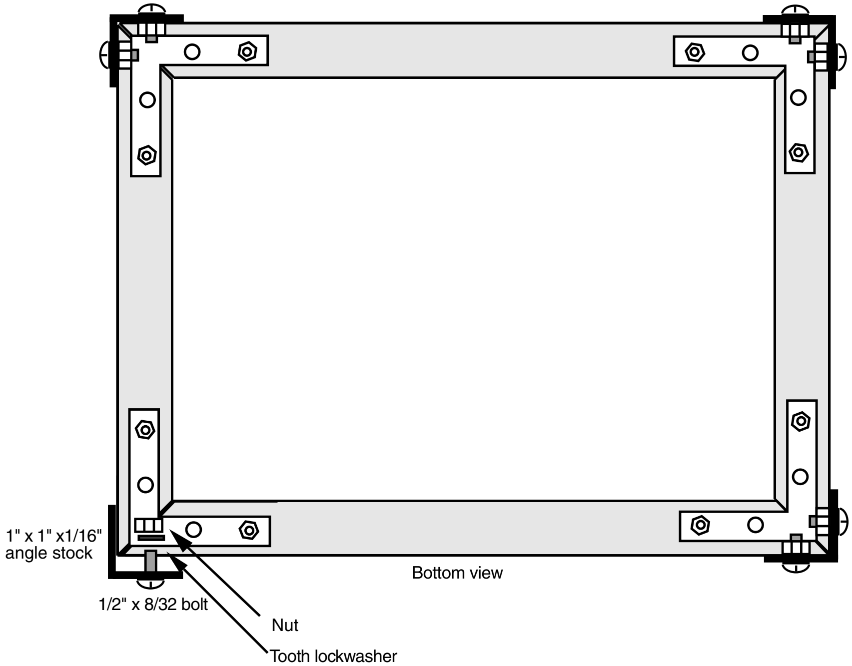

FIGURE 22.2 **Hardware detail for securing the angle stock to the top and bottom frame pieces.**

Connect the two halves with four 12-inch lengths of angle stock, as shown in Fig. 22.2. Secure the angle stock to the frame pieces by drilling holes at the corners. Use 8/32 by 1/2-inch bolts and nuts initially; exchange for pop rivets after the frame is complete. The finished frame should look like the one diagrammed in Fig. 22.3.

Complete the basic frame by adding the running gear mounting rails. Cut four 24-inch lengths of 1-inch-by-1-inch-by-1/16-inch angle stock and two 17 5/8-inch lengths of the same angle stock. Drill 1/4-inch holes in four long pieces as shown in Fig. 22.4. The spacing between the sets of holes is important. If the spacing is incorrect, the U-bolts won't fit properly.

Refer to Fig. 22.5. When the holes are drilled, mount two of the long lengths of angle stock as shown. The holes should point up, with the side of the angle stock flush against the frame of the robot. Mount the two short lengths on the ends. Tuck the short lengths immediately under the two long pieces of angle stock you just secured. Use 8/32 by 1/2-inch bolts and nuts to secure the pieces together. Dimensions, drilling, and placement are critical with these components. Put the remaining two long lengths of drilled angle stock aside for the time being.

Legs

You're now ready to construct and attach the legs. This is probably the hardest part of the project, so take you time and measure everything twice to assure accuracy. Cut six 14-inch

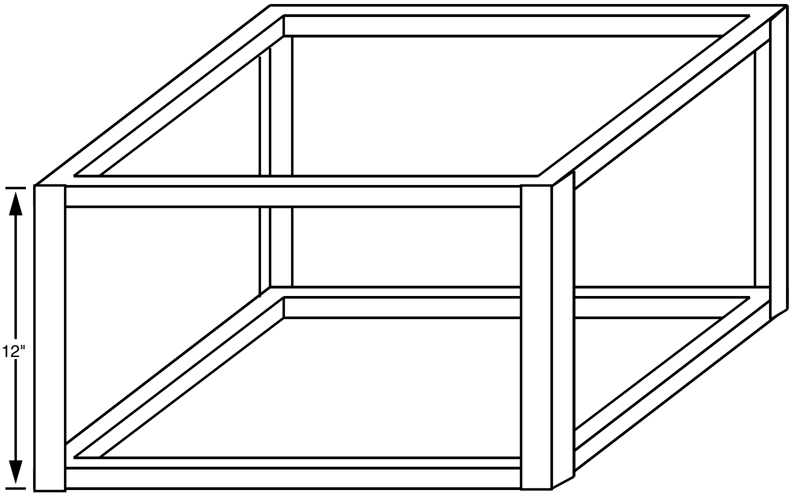

FIGURE 22.3 How the Walkerbot frame should look so far.

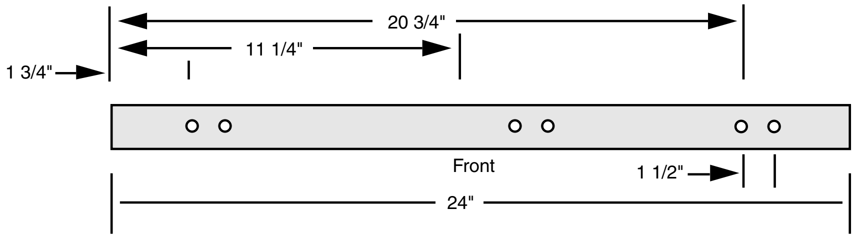

FIGURE 22.4 Cutting and drilling guide for the motor mount rails (four).

lengths of 57/64-inch-by-9/16-inch-by-1/16-inch aluminum channel stock. Do not miter the ends. Drill a hole with a #19 bit 1/2 inch from one end (the "top"); drill a 1/4-inch hole 4 3/4 inches from the top (see Fig. 22.6; refer to the parts list in Table 22.2). Make sure the holes are in the center of the channel stock.

With a 1/4-inch bit, drill out the center of six 4 5/8-inch-diameter circular electric receptacle plate covers. The plate cover should have a notched hole near the outside, which is used to secure it to the receptacle box. If the cover doesn't have the hole, drill one with a 1/4-inch bit 3/8 inch from the outside edge. The finished plate cover becomes a cam for operating the up and down movement of the legs.

Assemble four legs as follows: Attach the 14-inch-long leg piece to the cam using a 1/2-inch length of 1/2 Schedule 40 PVC pipe and hardware, as shown in Fig. 22.7. Be sure the ends of the pipe are filed clean and that the cut is as square as possible. The bolt should be tightened against the cam but should freely rotate within the leg hole.

Assemble the remaining two legs in a similar fashion, but use a 2-inch length of PVC pipe and a 3-inch stove bolt. These two legs will be placed in the center of the robot and

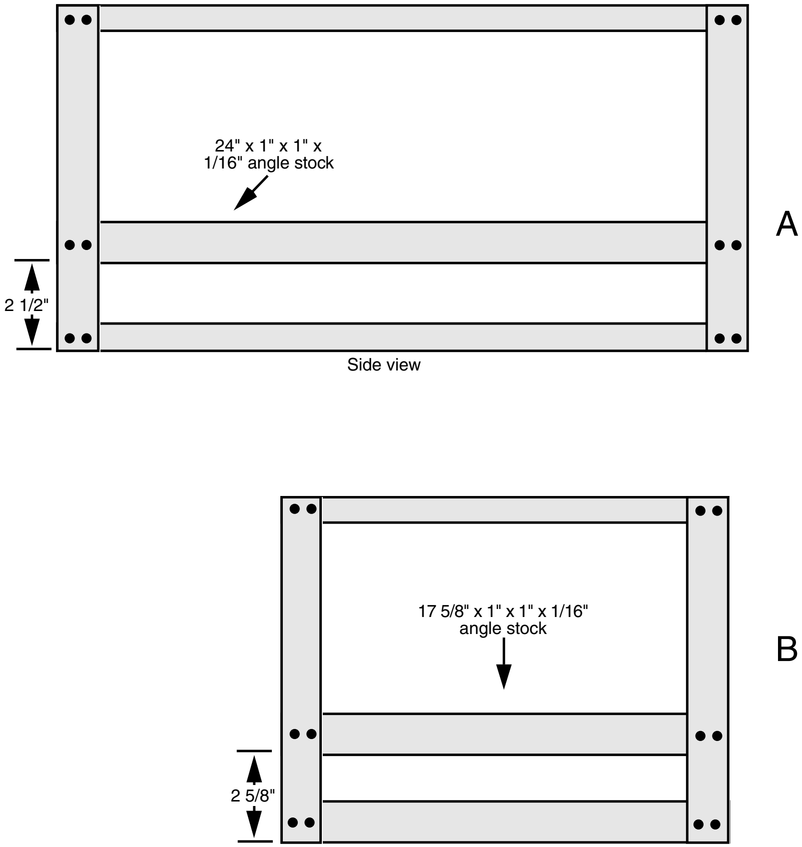

FIGURE 22.5 **The motor mount rails secured to the robot.** ***a*****. The long rail mounts 2 1/2 inches from the bottom of the frame (the holes drilled earlier point up);** ***b*****. The short end crosspiece rail mounts 2 5/8 inches from the bottom of the frame.**

will stick out from the others. This allows the legs to cross one another without interfering with the gait of the robot. The "bearings" used in the prototype were 1/2-inch-diameter closet door rollers.

Now refer to Fig. 22.8. Thread a 5-inch-by-1/4-inch 20 carriage bolt through the center of the cam, using the hardware shown. Next, install the wheel bearings to the shafts, 1-inch from the cam. The 1 1/4-inch-diameter bearings are the kind commonly used in lawn mowers and are readily available. The bearings used in the prototype had 1/2-inch hubs. A 1/2-inch-to-1/4-inch reducing bushing was used to make the bearings compatible with the diameter of the shaft.

Install 3 1/2-inch-diameter 30 tooth #25 chain sprocket (another size will also do, as long as all the leg mechanism sprockets in the robot are the same size). Like the bearings,

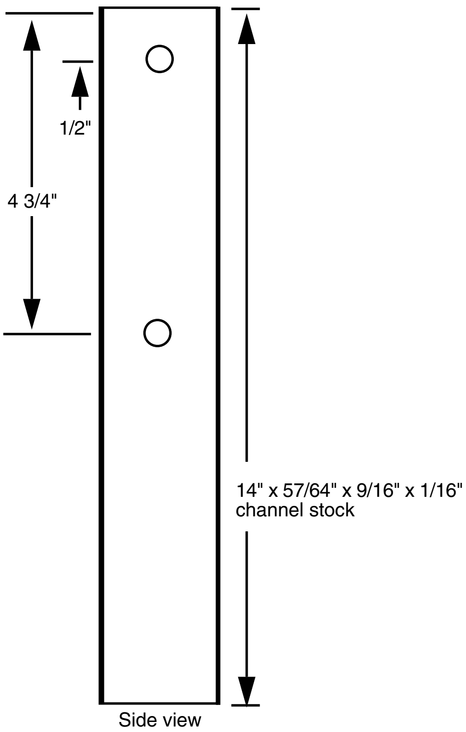

FIGURE 22.6 Cutting and drilling guide for the six legs.

TABLE 22.2 PARTS LIST FOR WALKERBOT LEGS

6	14-inch lengths 57/64-inch-by-9/16-inch-by-1/16-inch aluminum channel stock
6	6-inch lengths 41/64-inch-by-1/2-inch-by-1/16-inch aluminum channel stock
6	Roller bearings
6	Steel electrical covers (4 5/8-inch diameter)
6	5-inch hex-head carriage bolt
6	2-inch-by-3/8-inch flat mending iron
6	1 1/4-inch 45° "Ell" Schedule 40 PCV pipe fitting
Misc	10/24 and 8/32 stove bolts, nuts, tooth lock washers, locking nuts, flat washers, as needed. 1/2-inch Schedule 40 PVC cut to length (see text)

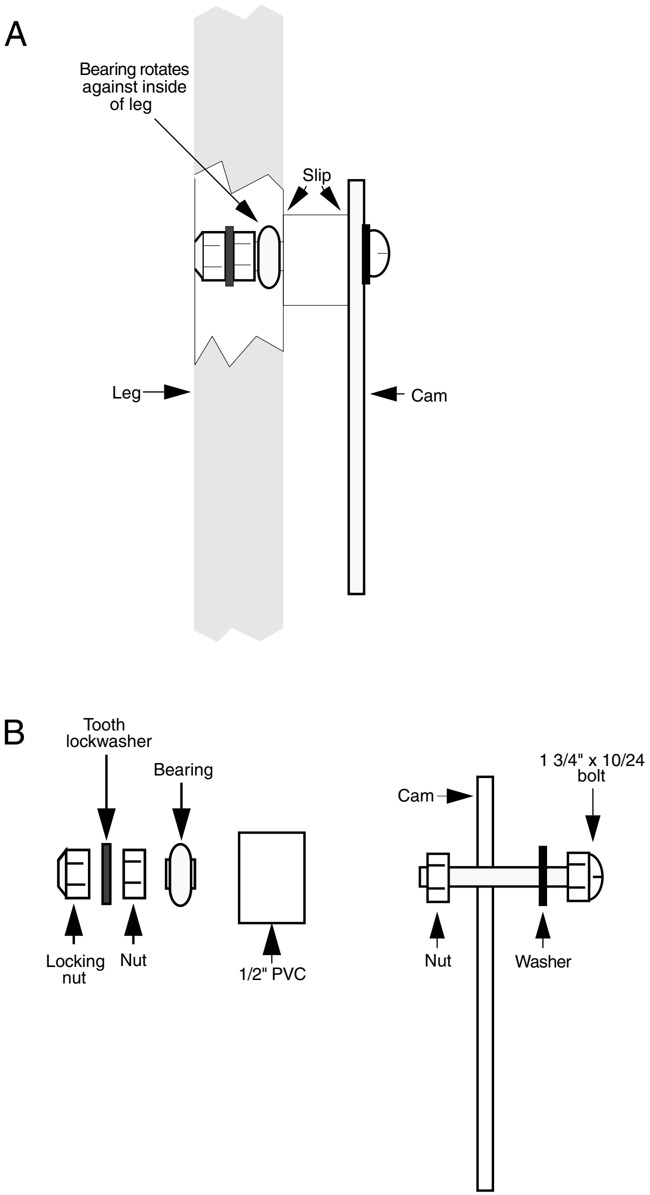

FIGURE 22.7 **Hardware detail for the leg cam. *a*. Complete cam and leg; *b.* Exploded view. Note that two of the legs use a 2-inch piece of PVC and a 3-inch bolt.**

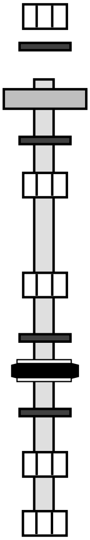

FIGURE 22.8 **Hardware detail of the leg shafts.**

a reducing bushing was used to make the 1/2-inch I.D. hubs of the sprockets fit on the shaft. The exact positioning of the sprockets on the shaft is not important at this time, but follow the spacing diagram shown in Fig. 22.9 as a guide. You'll have to "fine-tune" the sprockets on the shaft as a final alignment procedure anyway.

Once all the legs are complete, install them on the robot using U-bolts. The 1 1/2-inch-wide-by-2 1/2-inch-long-by-1/4-inch 20 thread U-bolts fit over the bearings perfectly. Secure the U-bolts using the 1/4-inch 20 nuts supplied.

Refer to Fig. 22.10 for the next step. Cut six 6-inch lengths of 41/64-inch-by-1/2-inch-by-1/16-inch aluminum channel stock. With a #19 bit, drill holes 3/8 inch from the top and bottom of the rail. With a nibbler tool, cut a 3 1/2-inch slot in the center of each rail. The slot should start 1/2 inch from one end.

Alternatively, you can use a router, motorized rasp, or other tool to cut the slot. In any case, make sure the slot is perfectly straight. Once cut, polish the edges with a piece of 300 grit wet-dry Emory paper, used wet. Use your fingers to find any rough edges. There can be none. This is a difficult task to do properly, and you may want to take this portion to a sheet metal shop and have them do it for you (it'll save you an hour or two of blister-producing nibbling!). An alternative method, which requires no slot cutting, is shown in Fig. 22.11. Be sure to mount the double rails exactly parallel to one another.

Mount the rails using 8/32 by 2-inch bolts and 8/32 nuts. Make sure the rails are directly above the shaft of each leg or the legs may not operate properly. You'll have to drill through both walls of the channel in the top of the frame.

The rails serve to keep the legs aligned for the up-and-down pistonlike stroke of the legs. Attach the legs to the rails using 3/8-inch-by-1 1/2-inch bolts. Use nuts and locking nuts fasteners as shown in Fig. 22.12. This finished leg mechanism should look like the one depicted in Fig. 22.13. Use grease or light oil to lubricate the slot. Be sure that there

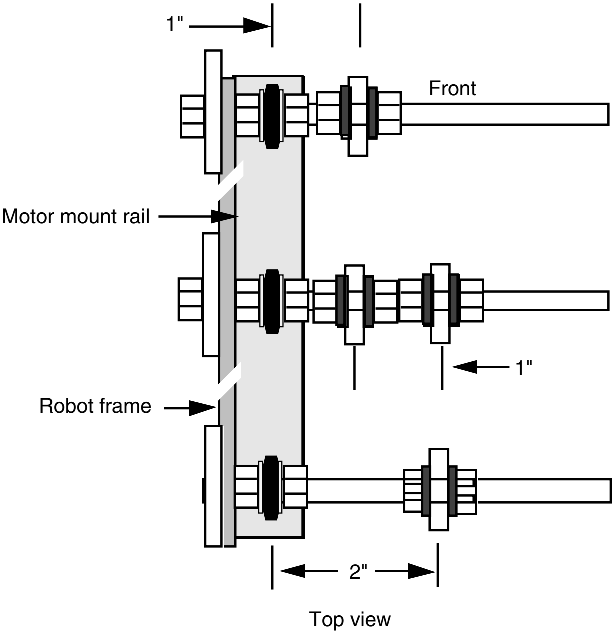

FIGURE 22.9 The leg shafts attached to the motor mount rails (left side shown only).

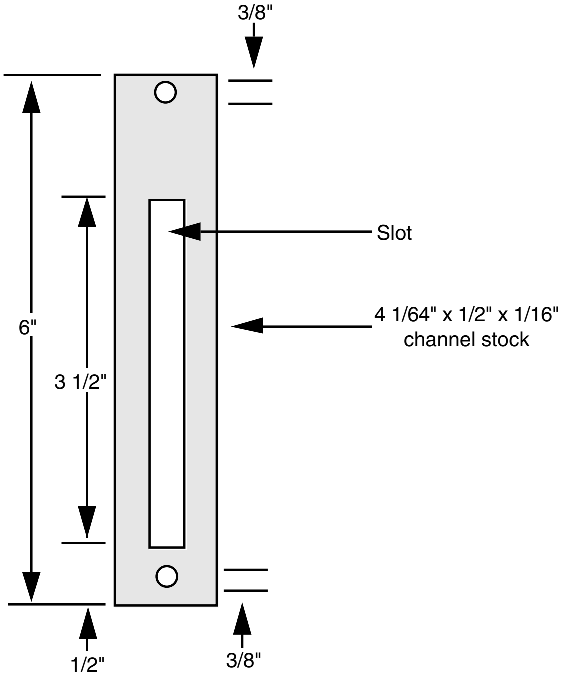

FIGURE 22.10 Cutting and drilling guide for the cam sliders (six required).

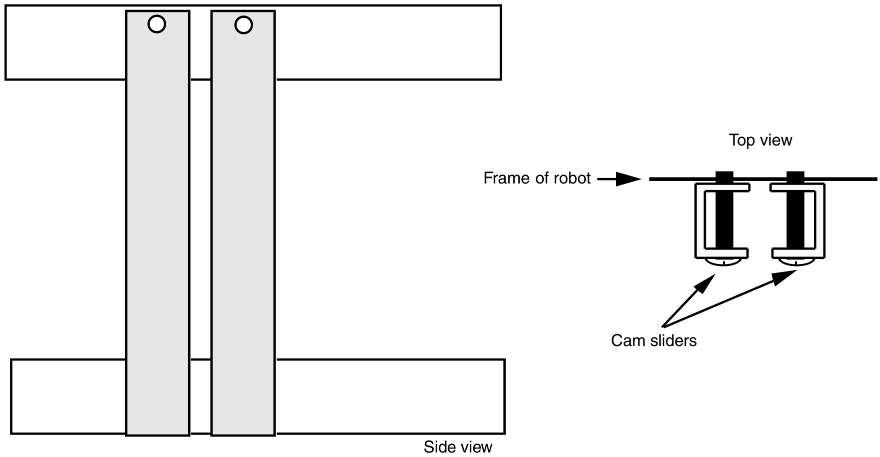

FIGURE 22.11 An alternative approach to the slotted cam sliders.

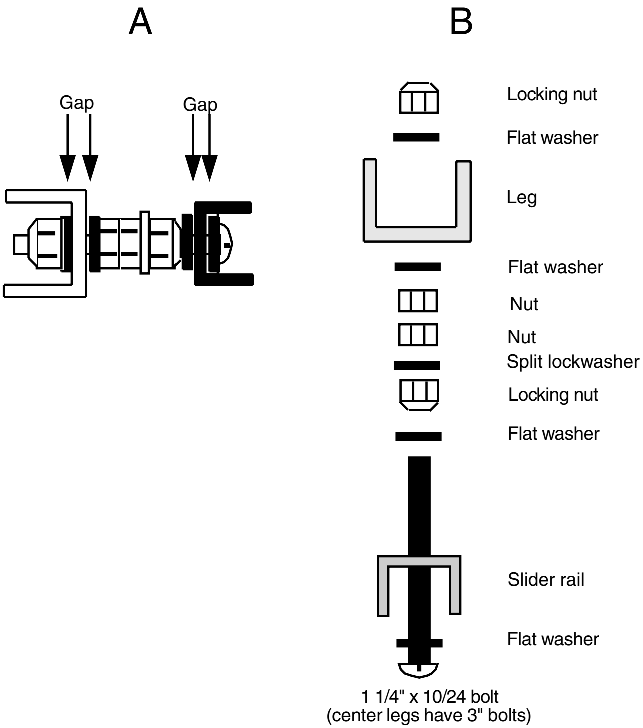

FIGURE 22.12 Cam slider hardware detail. *a.* Complete assembly; *b.* Exploded view. Note that the center legs have 2-inch bolts.

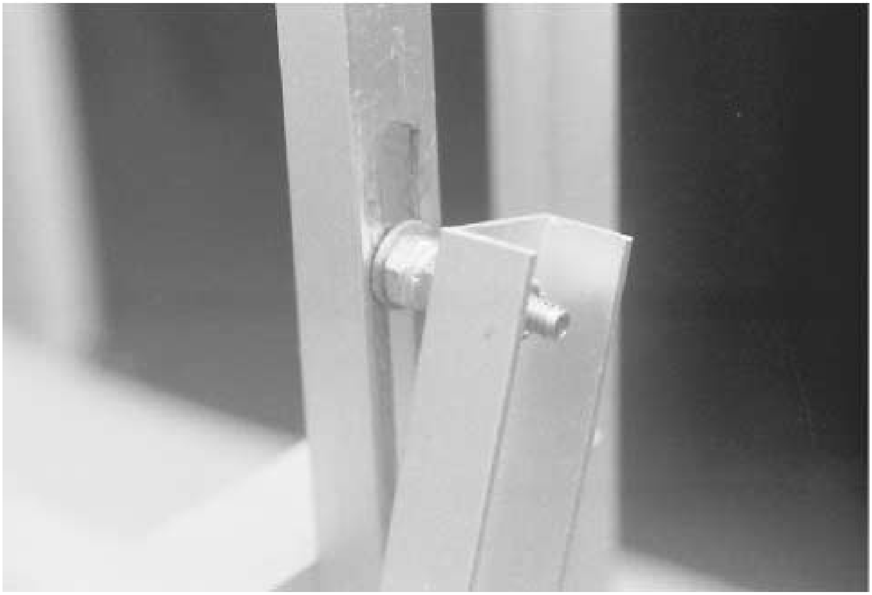

FIGURE 22.13 **The slider cam and hardware. The slot must be smooth and free of burrs, or the leg will snag.**

is sufficient play between the slot and the bolt stem. The play cannot be excessive, however, or the leg may bind as the bolt moves up and down inside the slot. Adjust the sliding bolt on all six legs for proper clearance.

Drill small pilot holes in the side of six 45° 1 1/4-inch PVC pipe elbows. These serve as the feet of the legs. Paint the feet at the point if you wish. Using #10 wood screws, attach a 2-inch-by-3/8-inch flat mending iron to each of the elbow feet. Drill 1/4-inch holes 1 1/4 inches from the bottom of the leg. Secure the feet onto the legs using 1/2-inch-by-1/4-inch 20 machine bolts, nuts, and lock washers. Apply a 3-inch length of rubber weather strip to the bottom of each foot for better traction. The leg should look like the one in Fig. 22.14. The legs should look like the one in Fig. 22.15. A close-up of the cam mechanism is shown in Fig. 22.16.

Motors

The motors used in the prototype Walkerbot were surplus finds originally intended as the driving motors in a child's motorized bike or go-cart. The motors have a fairly high torque at 12 volts DC and a speed of about 600 rpm. A one-step reduction gear was added to bring the speed down to about 230 rpm. The output speed is further reduced to about 138 rpm by using a drive sprocket. For a walking machine, that's about right, although it could stand to be a bit slower. Electronic speed reduction can be used to slow the motor output down to about 100

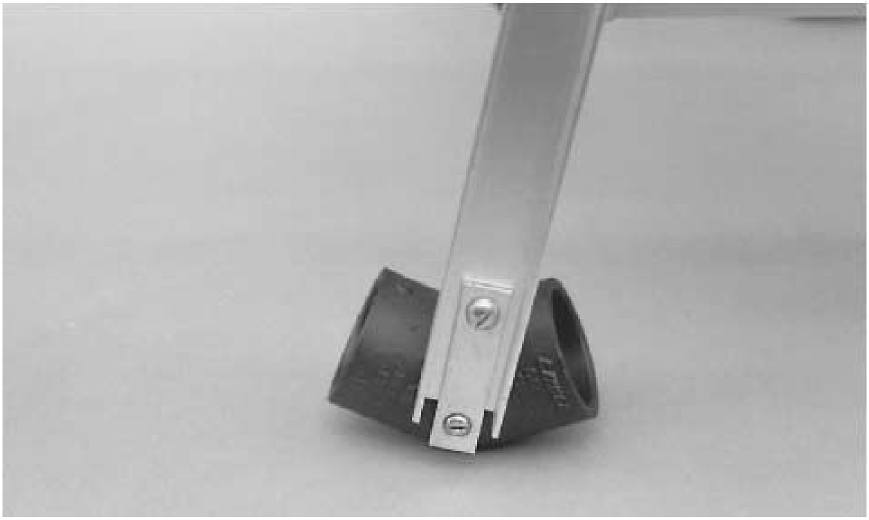

FIGURE 22.14 PVC plumbing fittings used as feet. The feet use a flat mending iron. Add pads or rubber to the bottom of the feet as desired.

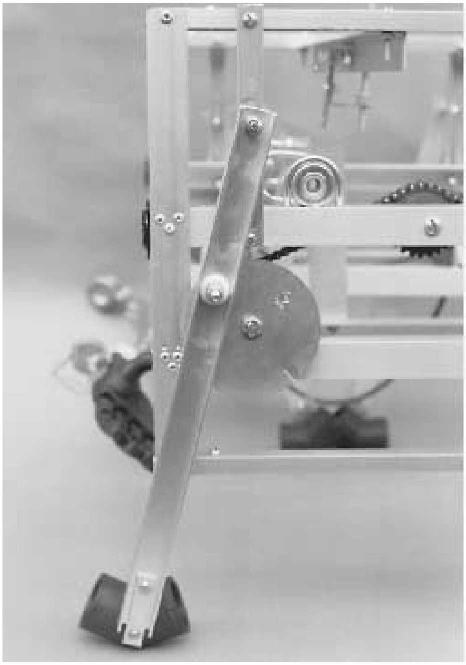

FIGURE 22.15 One of six legs, completed (shown already attached to the robot).

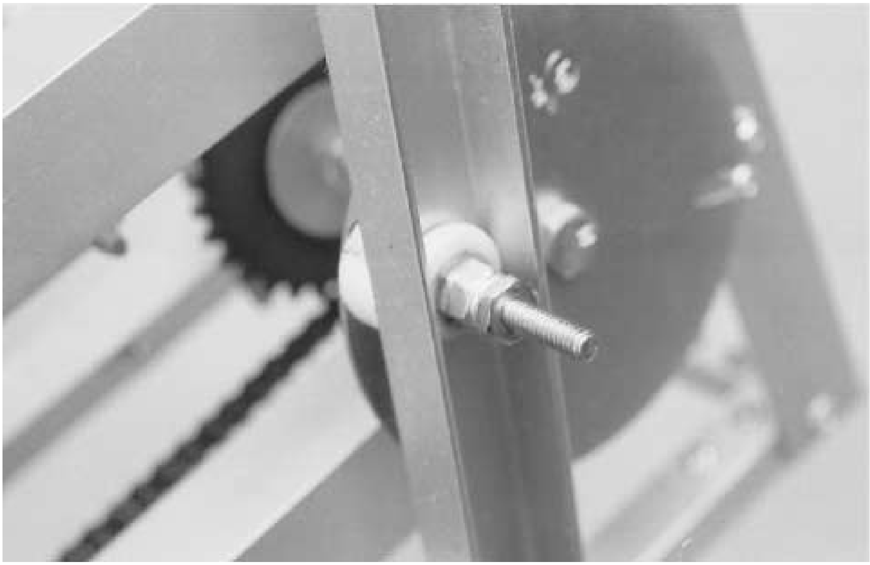

FIGURE 22.16 **A close-up detail of the leg cam.**

rpm. You can use other motors and other driving techniques as long as the motors have a (pre-reduced) torque of at least 6 lb-ft. and a speed that can be reduced to 140 rpm or so.

Mount the motors inside two 6 1/2-inch-by-1 1/2-inch mending plate Ts. Drill a large hole, if necessary, for the shaft of the motor to stick through, as shown in Fig. 22.17 (refer to the parts list in Table 22.3). The motors used in the prototype came with a 12-pitch 12-tooth nylon gear. The gear was not removed for assembly, so the hole had to be large enough for it to pass through. The 30-tooth 12-pitch metal gear and 18-tooth 1/4-inch chain sprocket were also sandwiched between the mending plates.

The 1/4-inch shaft of the driven gear and sprocket is free running. You can install a bearing on each plate, if you wish, or have the shaft freely rotate in oversize holes. The sprocket and gear have 1/2-inch I.D. hubs, so reducing bushings were used. The sprocket and gear are held in place with compression. Don't forget the split washers. They provide the necessary compression to keep things from working loose.

Before attaching the two mending plates together, thread a 28 1/2-inch length of #25 roller chain over the sprocket. The exact length can be one or two links off; you can correct for any variance later on. Assemble the two plates using 8/32 by 3-inch bolts and 8/32 nuts and lock washers. Separate the plates using 2-inch spacers.

Attach the two 17 7/8-inch lengths of angle bracket on the robot, as shown in Fig. 22.18. The stock mounts directly under the two end pieces. Use 1/2-inch-by-8/32 bolts and nuts to secure the crosspieces in place. Secure the leg shafts using 1 1/4-inch bearings and U-bolts.

Mount the motor to the newly added inner mounting rails using 3-inch-by-1/2-inch mending plate Ts. Fasten the plates onto the motor mount, as shown in Fig. 22.19, with

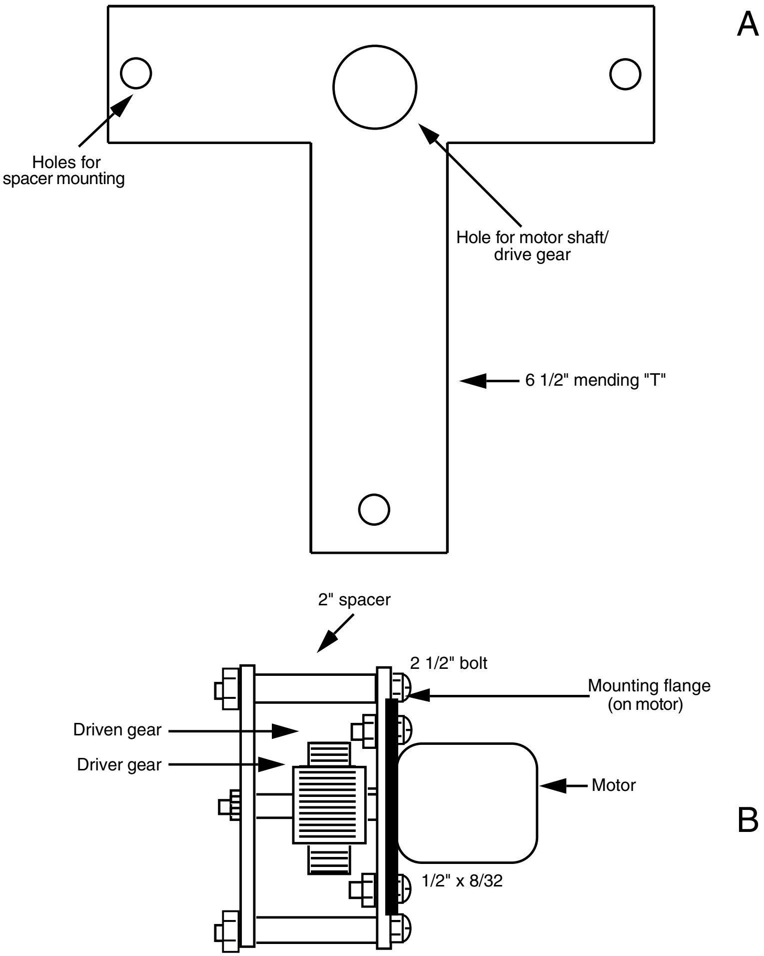

FIGURE 22.17 **Motor mount details.** *a*. **Drilling guide for the mending T;** *b*. **The motor and drive gear-sprocket mounted with two mending Ts.**

8/32 by 1/2-inch bolts and nuts. Position the shaft of the motor approximately 7 inches from the back of the robot (you can make any end of the shaft the back; it doesn't matter). Thread the roller chain over the center sprocket and the end sprocket. Position the motor until the roller chain is taut. Mark holes and drill. Secure the motor and mount to the frame using 8/32 by 1/2-inch bolts and nuts. Repeat the process for the opposite motor. The final assembly should look like Fig. 22.20.

Thread a 28 1/2-inch length of #25 roller chain around sprockets of the center and front legs. Attach an idler sprocket 7 1/2 inches from the front of the robot in line with the leg mounts. Use a diameter as close to 2 inches as possible for the idler; otherwise, you may

TABLE 22-3 PARTS LIST FOR WALKERBOT MOUNT-DRIVE SYSTEM	
4	6 1/2-inch galvanized mending plate T
4	3-inch galvanized mending plate T
2	Heavy-duty gear-reduction DC motors
12	3 1/2-inch-diameter 30-tooth #15 chain sprocket
4	28 1/2-inch-length #25 roller chain
12	2 1/2-inch-by-1 1/2-inch-by-1/4-inch 20 U-bolts, with nuts and tooth lock washers
12	1 1/2-inch O.D. 1/4-inch-to-1/2-inch ID bearing
Misc	Reducing bushings (see text)

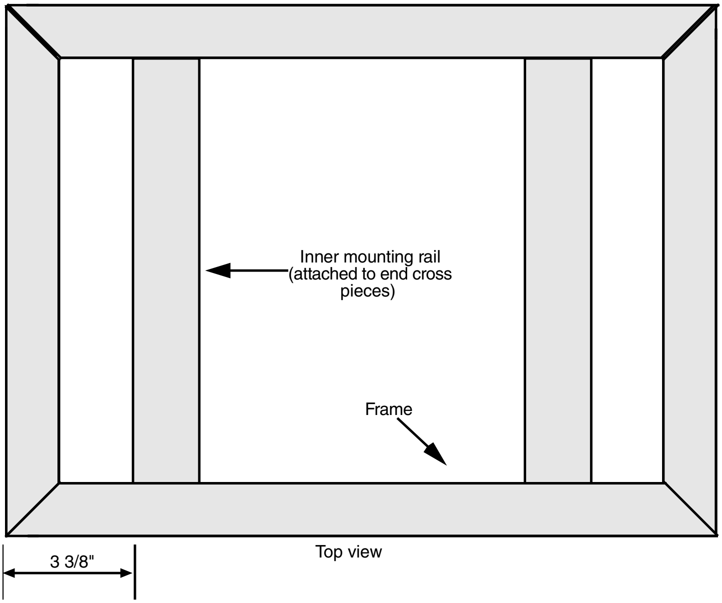

FIGURE 22.18 **Mounting location of the inner rails.**

need to shorten or lengthen the roller chain. Thread the roller chain around the sprocket, and find a position along the rail until the roller chain is taut (but not overly tight). Make a mark using the center of the sprocket as a guide and drill a 1/4-inch hole in the rail. Attach the sprocket to the robot. Figs. 22.21 through 22.23 show the motor mount, idler sprocket, and roller chain locations.

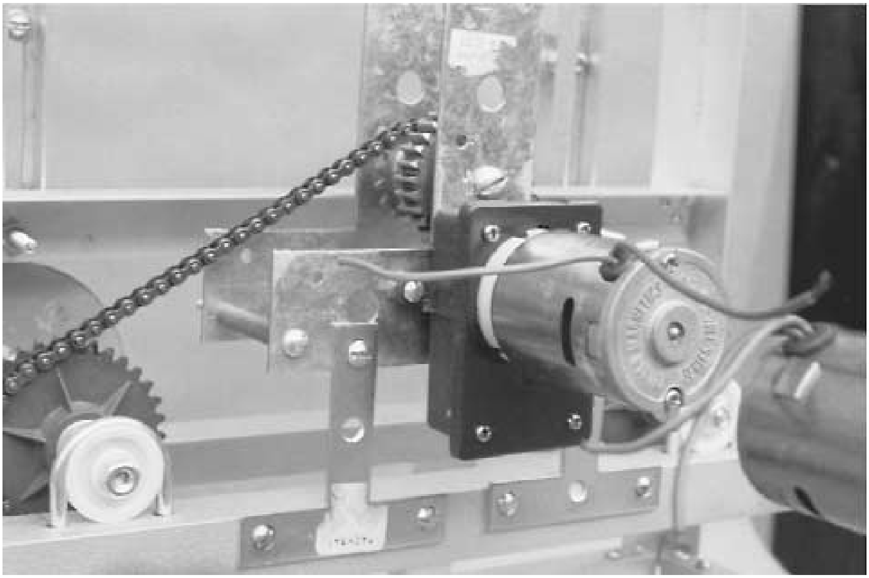

FIGURE 22.19 One of the drive motors mounted on the robot using smaller galvanized mending Ts.

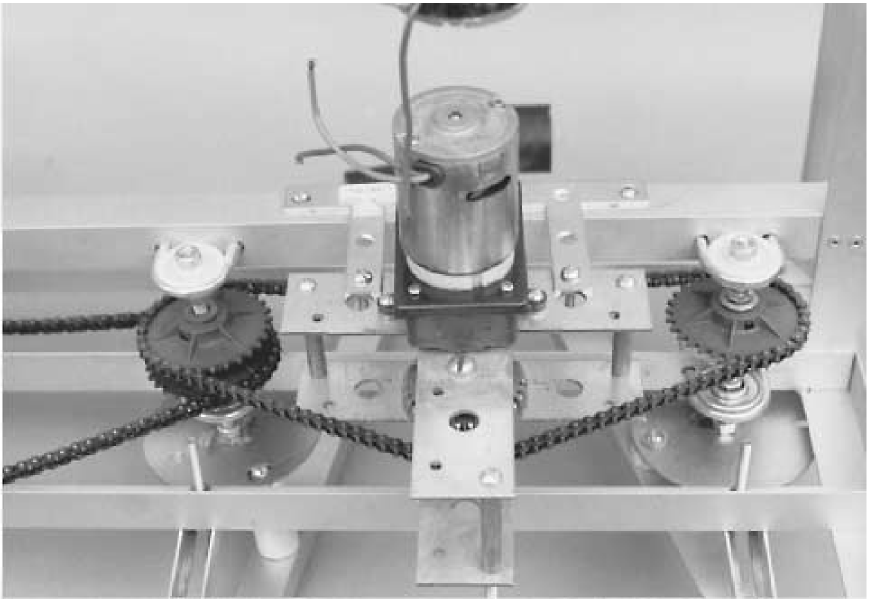

FIGURE 22.20 Drive motor attached to the Walkerbot, with drive chain joining the motor to the leg shafts.

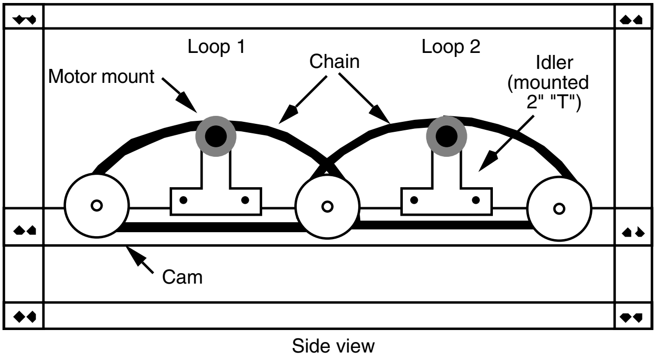

FIGURE 22.21 **Mounting locations for idler sprocket.**

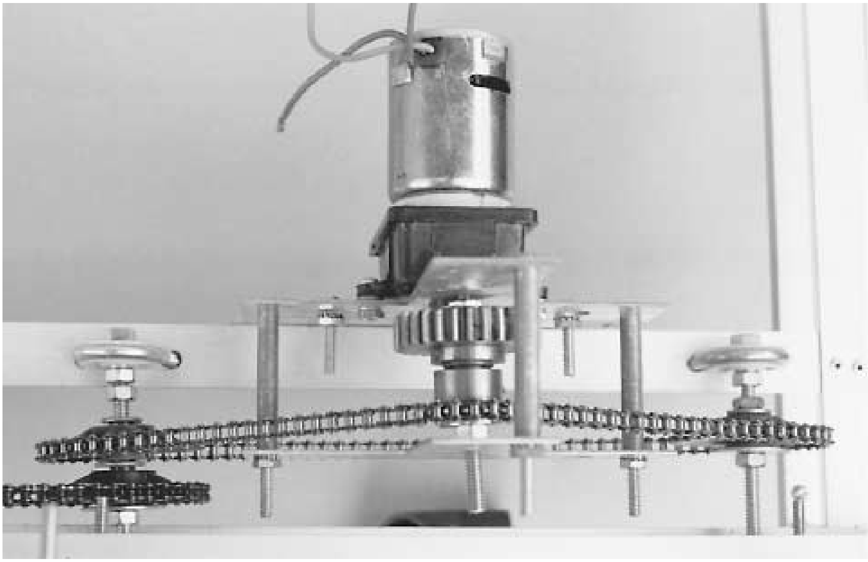

FIGURE 22.22 **A view of the mounted motor, with chain drive.**

Batteries

The Walkerbot is not a lightweight robot, and its walking design requires at least 30 percent more power than a wheeled robot. The batteries for the Walkerbot are not trivial. You have a number of alternatives. One workable approach is to use two 6-volt motorcycle batteries, each rated at about 30 ampere-hours (AH). The two batteries together equal a slimmed-down version of a car battery in size and weight.

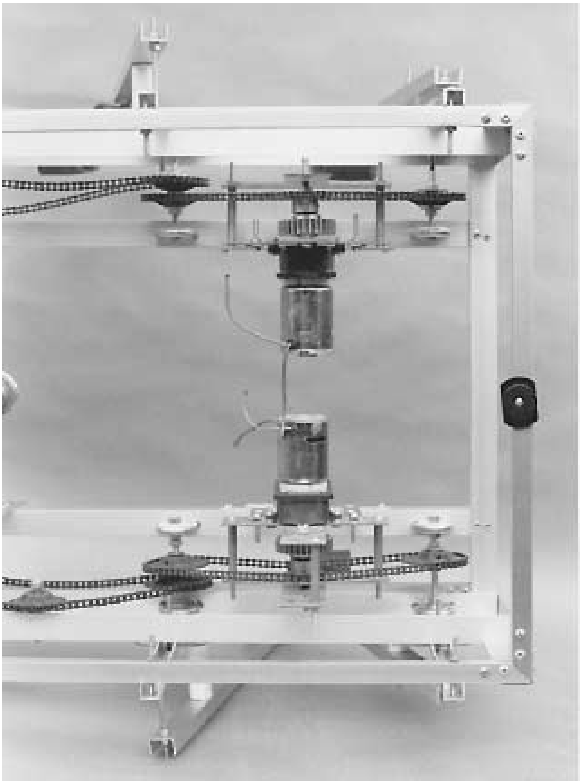

FIGURE 22.23 **Left and right motors attached to the robot.**

You can also use a 12-volt motorcycle or dune buggy battery, rated at more than 20 AH. The prototype Walkerbot used 12-AH 6-volt gel cell batteries. The amp-hour capacity is a bit on the low side, considering the two-amp draw from each motor, and the planned heavy use of electronics and support circuits. In tests, the 12-AH batteries provided about two hours of use before requiring a recharge.

There is plenty of room to mount the batteries. A good spot is slightly behind the center legs. By offsetting the batteries a bit in relation to the drive motors, you restore the center of gravity to the center of the robot. Of course, other components you add to the robot can throw the center of gravity off. Add one or two articulated arms to the robot, and the weight suddenly shifts toward the front. For flexibility, why not mount the batteries on a sliding rail, which will allow you to shift their position forward or back depending on the other weight you add to the Walkerbot.

The complete Walkerbot, minus the batteries, is shown in Fig. 22.24. Some additional hardware and holes are apparent on this version. Pay no attention to them. These were either my mistakes (!), or were made for components removed for the illustration.

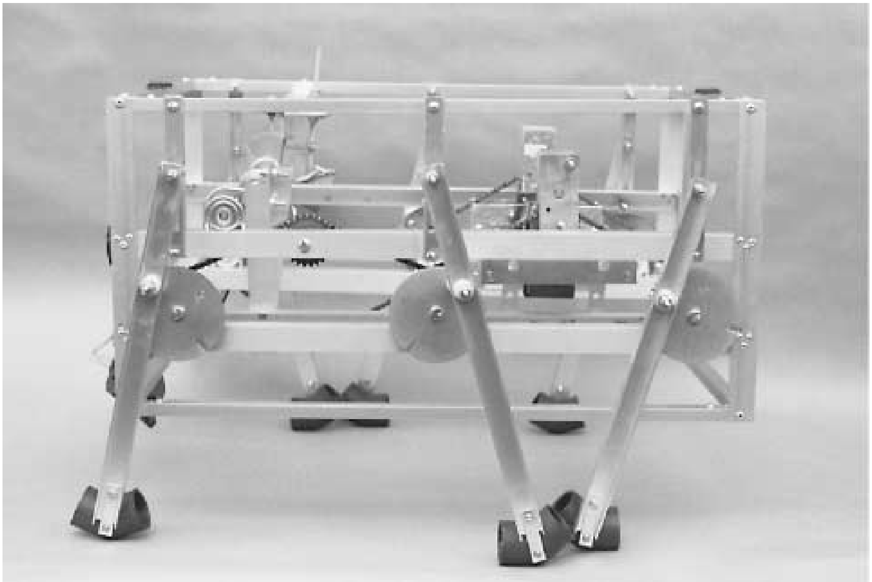

FIGURE 22.24 **The completed Walkerbot.**

Testing and Alignment

You can test the operation of the Walkerbot by temporarily installing a wired control box. The box consists of two DPDT switches wired to control the forward and backward motion of the two legs. See Chapter 8, "Robots of Plastic," for more details and a wiring diagram.

But before you test the Walkerbot, you need to align its legs. The legs on each side should be positioned so that either the center leg touches the ground or the front and back leg touch the ground. When the two sets of legs are working in tandem, the walking gait should be as shown in Fig. 22.25. This gait is the same as an insect's and provides a great deal of stability. To turn, one set of legs stops (or reverses) while the other set continues. During this time, the "tripod" arrangement of the gait will be lost, but the robot will still be supported by at least three legs.

An easy way to align the legs is to loosen the chain sprockets (so you can move the legs independently) and position the middle leg all the way forward and the front and back legs all the way back. Retighten the sprockets, and look out for misalignment of the roller chain and sprockets. If a chain bends to mesh with a sprocket, it is likely to pop off when the robot is in motion.

During testing, be on the lookout for things that rub, squeak, and work loose. Keep your wrench handy and adjust gaps and tighten bolts as necessary. Add a dab of oil to those parts that seem to be binding. You may find that a sprocket or gear doesn't stay tightened on a shaft. Look for ways to better secure the component to the shaft, such as by using a setscrew or another split lock washer. It may take several hours of "tuning up" to get the robot working at top efficiency.

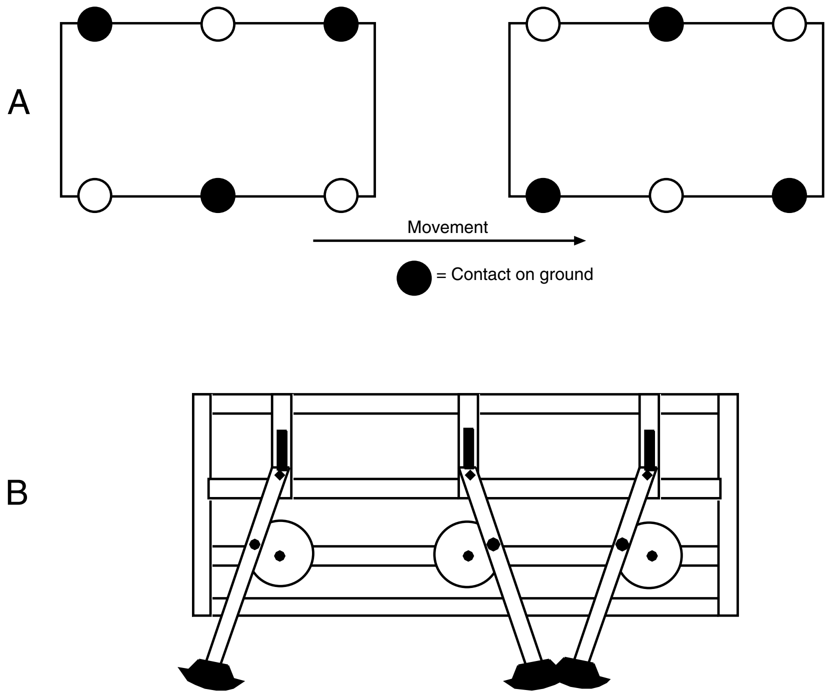

FIGURE 22.25 **The walking gait.** ***a*****. The alternating tripod walking style of the Walkerbot, shared with thousands of crawling insects;** ***b*****. The positioning of the legs for proper walking (front and back legs in synchrony; middle leg 180 degrees out of sync). The middle leg doesn't hit either the front or back leg because it is further from the body of the robot.**

Once the robot is aligned, run it through its paces by having it walk over level ground, step over small rocks and ditches, and navigate tight corners. Keep an eye on your watch to see how long the batteries provide power. You may need to upgrade the batteries if they cannot provide more than an hour of fun and games.

The Walkerbot is ideally suited for expansion. Fig. 22.26 shows an arm attached to the front side of the robot. You can add a second arm on the other side for more complete dexterity. Attach a dome on the top of the robot, and you've added a "head" on which you can attach a video camera, ultrasonic "ears" and "eyes," and lots more. Additional panels can be added to the front and back ends; attach them using hook-and-loop (such as Velcro) strips. That way, you can easily remove the panels should you need quick access to the inside of the robot.

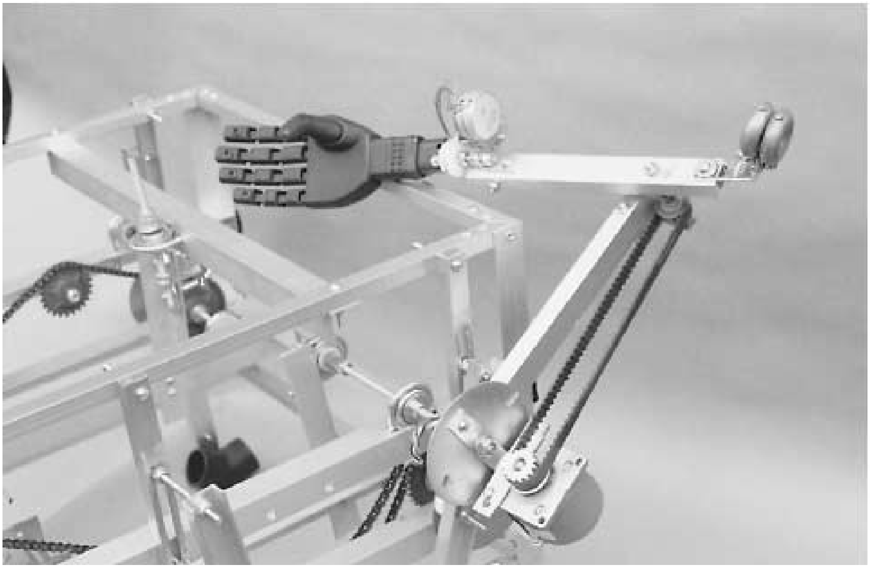

FIGURE 22.26 An arm attached to the front side of the Walkerbot.

From Here

To learn more about…	*Read*
Working with metal	Chapter 10, "Building a Metal Platform"
Robot locomotion styles, including wheels, treads, and legs	Chapter 16, "Robot Locomotion Principles"
Using DC motors	Chapter 18, "Working with DC Motors"
Additional locomotion systems based on the Walkerbot frame	Chapter 23, "Advanced Locomotion Systems"
Constructing an arm for the Walkerbot	Chapter 25, "Build a Revolute Coordinate Arm"