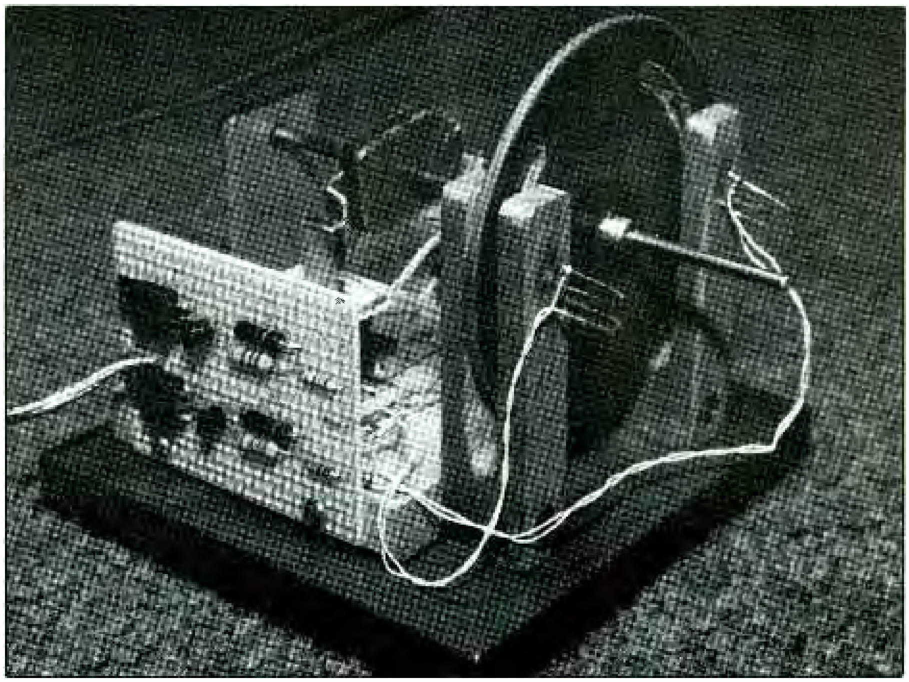
Brushless dc Motor

This build-it-yourself motor uses infrared switching for science-fair and other demonstrations

By Robert F. Tschannen



A conventional dc motor uses a commutator to switch current in its armature coils in a timed sequence. This arrangement permits attraction and/or repulsion of armature poles with respect to field poles. The result is rotary—or "motor"—action of a shaft. In contrast, the motor to be described does *not* have a commutator or brushes. Instead, it uses a slotted disc that alternately passes and interrupts an invisible infrared beam that impinges on infrared phototransistors to produce switching signals. These signals are amplified and used to switch currents through a pair of motor field coils, producing much the same results normally obtained with a commutator and brushes.

We will describe here how to build this novel brushless dc motor, using readily available electronic components and a number of mechanical elements you can easily fabricate at home with very basic woodworking tools and only modest shop skills. The amount of torque delivered by this motor is very small, making the project fairly impractical to use as a driver for any but the smallest of loads. However, your motor will make an excellent science-fair project and can be used for other demonstrations.

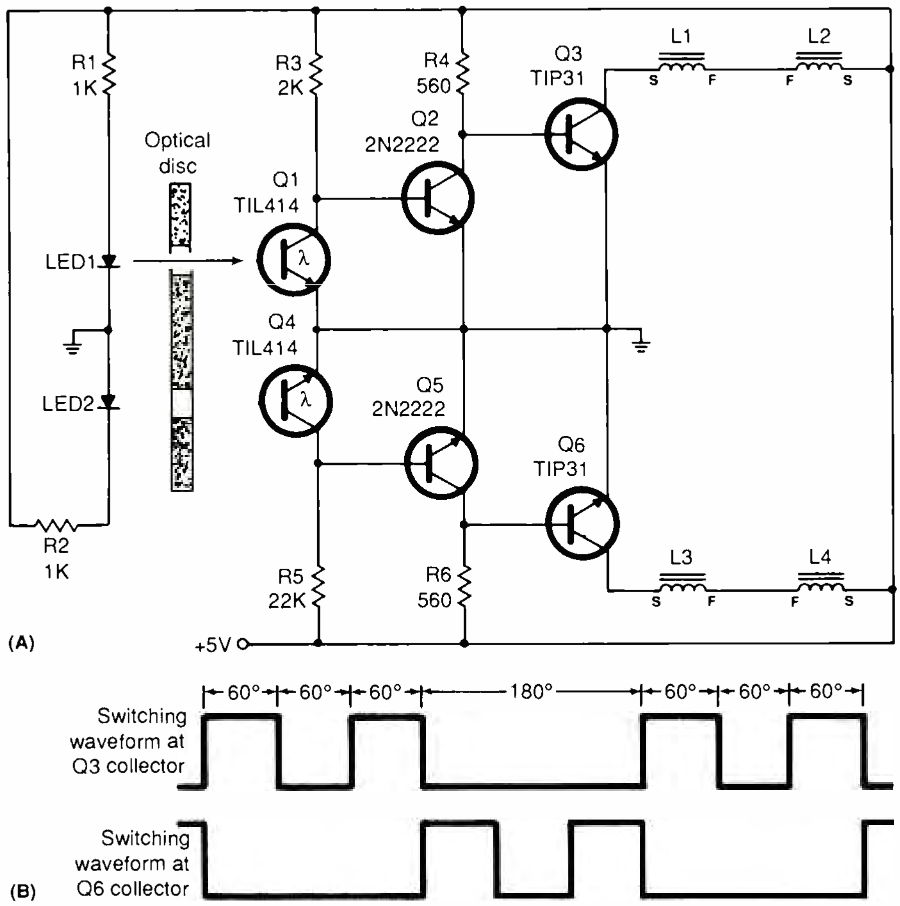
How It Works

The motor's armature has two poles made up of a pair of pole pieces cemented to the flat faces of a ceramic magnet. The armature and a slotted disc mount on a shaft that turns as a common assembly. With this arrangement, it is essential that the slot positions in the disc be properly timed with respect to the armature poles so that switching occurs at precise intervals.

The motor's field coil, or stator, is somewhat unusual in that each pole piece is wound with a pair of coils that are connected in a manner that the field can be reversed when called for by switching circuitry.

Figure 1(A) is the schematic diagram of the electronic circuitry that performs the switching and powering of the motor's field coils. Infrared-emitting diodes *LED1* and *LED2* are continuously powered from a 5-volt dc source through current-limiting resistors *R1* and *R2*. The infrared energy from these IR emitters is allowed to pass through to the respective infrared phototransistors on the other side of the optical disc, depending on the positions of the slots in the latter. Phototransistors *Q1* and *Q4* are the receptors in this circuit.

On start-up, power from the +5-volt dc source flows through the infrared-emitting circuit at the left. IR energy from *LED1* and *LED2* focuses toward the disc. If we assume that the discs slots are positioned so that the IR energy is able to fall on the active surface of *Q1* but not *Q4*, *Q1* will turn on while *Q2* will be held in cutoff. Thus, when *Q1* conducts, it causes the driver/power-amplifier



PARTS LIST

LED1,LED2—SEP8703-1 infrared-emitting diode (Radio Shack Cat. No. 276-143)

Q1,Q4—TIL-414 phototransistor (Radio Shack Cat. No. 276-145)

Q2,Q5—2N2222 or similar silicon npn switching transistor

Q3,Q6—TIP31 or similar silicon npn power transistor

R1,R2—1,000-ohm, ½-watt, 10% tolerance resistor

R3,R5—22,000-ohm, ½-watt, 10% tolerance resistor

R4,R6—560-ohm, ½-watt, 10% tolerance resistor

Misc.—No. 28 or 30 enameled wire; perforated board; 1" rectangular ceramic magnet (Radio Shack Cat. No. 64-1875 or similar); lumber for base and sub-base plates and yokes (see text); steel, brass or aluminum stock for bearings; mild steel for field-coil and pole pieces; Bakelite, phenolic board, sheet aluminum or heavy poster board for optical disc (see text); perforated board or heavy poster board for optional bobbin guides; plastic electrical tape; super glue; woodscrews (see text); hookup wire; solder; etc.

Fig. 1. Schematic diagram of motor's electronics in (A) shows orientation of optical disc with reference to IR-emitter LEDs and receptor phototransistors. Detail (B) illustrates switching waveforms at collectors of power transistors resulting from pattern produced by slots in optical disc.

circuit composed of *Q2* and *Q3* to turn on. With *Q3* conducting, current from the 5-volt dc source passes through field coils *L1* and *L2*.

When current flows through *L1* and *L2*, electromagnetic action attracts the rotor's pole piece, resulting in the rotor making a partial turn. Because the optical disc is physically fixed to the same shaft shared by the rotor assembly, any rotation also causes the switching signal sequence to change as well. Consequently, as the shaft turns and changes the switching pattern, *Q1* will cease conducting as IR energy from *LED1* is cut off from its active surface by an opaque portion of the optical disc intervening between the two.

In operation, the shaft will turn enough for the optical disc's slot to appear between *LED2* and *Q4*. The result is that IR energy will activate the other set of field coils. The sequence of events is the same for the driver/power-amplifier *Q5/Q6* circuit and field coils *L3* and *L4*.

The switching waveforms for the circuit, taken at the collectors of *Q3* and *Q6* are also shown in Fig. 1(B). Note that, on turn-on, the optical disc causes a pair of square-wave pulses, each 60 degrees in duration and separated by a 60-degree interval to be generated by phototransistor *Q1*. During this period, no IR energy reaches *Q4* and, thus, this section of the circuit is held in cutoff.

Next comes a 180-degree interval during which no pulses occur in the *Q1/Q2/Q3* circuit. During this off period, the the lower half of the circuit is activated in the exact same manner as the upper half was during its off period.

The above sequence of events will repeat for as long as power is applied to the circuit. The optical disc will pass or interrupt the IR-energy beams to *Q1* and *Q4* in the sequence described by the switching waveform sequence in Fig. 1(B) so that first one and then the other leg of the circuit is active at any given moment.

Construction

As illustrated in the lead photo, you build the motor on a wooden base, adding an optional sub-base for

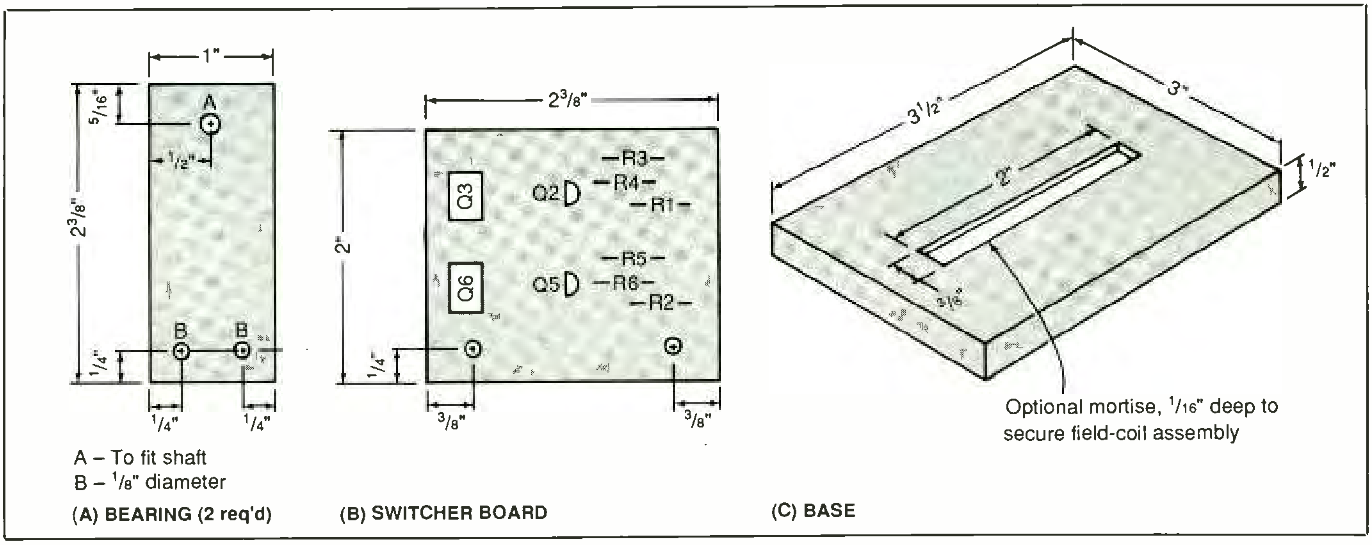


Fig. 2. Fabrication details for bearings (A), circuit-board assembly (B) and base plate (C).

handling convenience. Simple bearings secured to the wood base with woodscrews support the armature assembly.

All switching transistors and associated components are best mounted and wired together on a small piece of perforated board. This circuit-board assembly, in turn, should be secured to the wood base with small round-head woodscrews.

Wooden yokes are used for mounting phototransistors *Q1* and *Q4* and infrared emitters *LED1* and *LED2* directly in line with each other. The yokes must be fabricated so that they straddle the optical disc on each side of the motor's drive shaft and with the source and destination holes exactly aligned with the slots in the optical disc when it is finally mounted in place.

Referring first to Fig. 2(A), fabricate the two motor bearings as shown. Use 16-gauge or so steel, brass or aluminum stock for the bearings. Drill hole A just large enough to fit the shaft chosen for the motor. The shaft can be a *straight* 5-inch length of metal clothes hanger or brass or drill rod. It should not exceed 3/32 inch in diameter. Hence, the A holes drilled in the bearings should be just the slightest bit larger than 3/32 inch to allow the shaft to rotate freely in them. Use a 1/8-inch bit to drill the holes labeled B.

Next, trim the perforated board on which the various driver and power transistors and their associated resistors are to be mounted and wired together to the dimensions shown in Fig. 2(B). Then drill 1/8-inch holes through the board as indicated at the lower-left and lower-right for mounting purposes.

For the base, you need 1/2-inch or so thick wood. This can be either pine lumber, particle board or plywood. After cutting the board to size, you can route a mortise on its top to accommodate the field-coil assembly, as detailed in Fig. 2(C). The mortise should be only about 1/16 inch deep and should be completely flat bottomed. The best way to make this is with a power router, squaring up the corners with a wood chisel. If you do not have a router, simply disregard the mortise.

If you decide to use the optional sub-base, use the same thickness material used for the base itself, cutting it to 4 1/2 inch square.

A flat thin piece of opaque material like Bakelite, phenolic board, sheet aluminum or even heavy poster board can be used to make the optical disc. The material used should be about 1/16 inch thick. This is the most difficult item to fabricate. This is easiest to do with a power bandsaw or jig saw, which is essential if you are using aluminum for the optical wheel's material. With no access to these tools, you would be better off using easier-to-machine Bakelite, phenolic or poster board.

Whichever material you do use, start with a 4-inch square to allow sufficient excess for trimming. Locate the center of this square by drawing diagonal lines to opposite corners. Then, using a compass, scribe or draw a 3-inch-diameter circle on the material, centered at the point where the diagonal lines cross. Next, measure 7/16 in from the circumference of the circle and scribe or draw another concentric circle, referring to Fig. 3(A) for details.

Place a straight edge along one of the previously struck diagonal lines and strike lines that cross the inner circle against the straight edge. Then use a 30/60/90-degree triangle or a protractor to strike lines across the inner circle at 60 degrees from the just-drawn cross lines on the inner

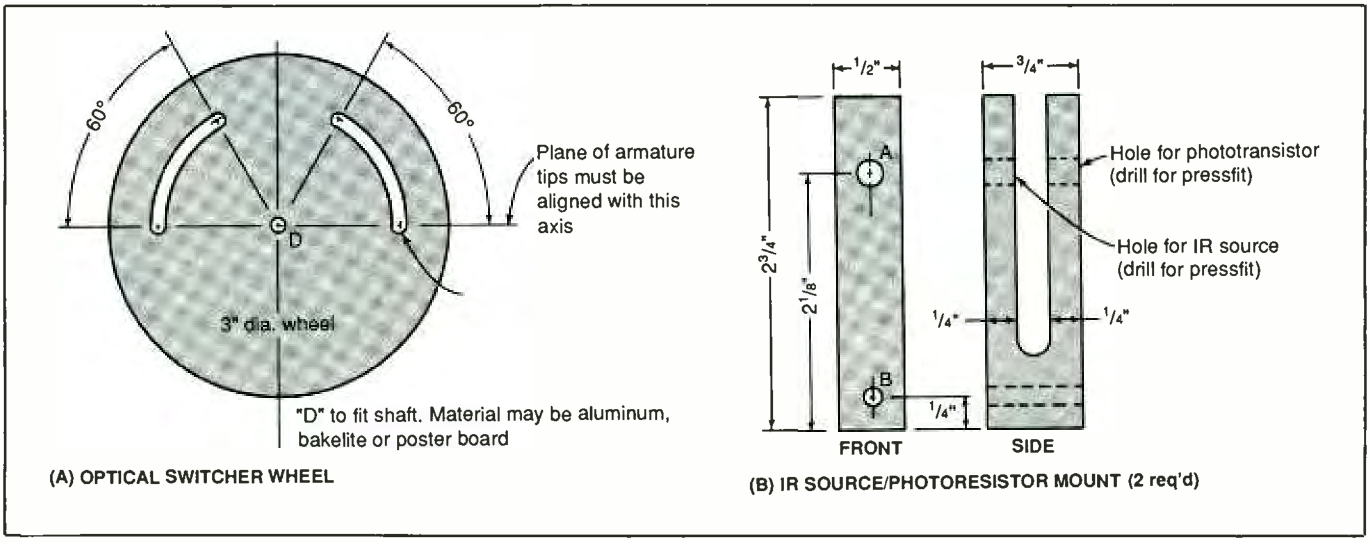


Fig. 3. Fabrication details for optical wheel (A) and IR source/receptor yoke mounts (B).

circle. The four cross points thus indicated are where 1/8-inch-diameter holes must be drilled to start and end the slots in the optical disc. Drill these holes now. Then drill a hole in the center of the disc, sizing it for a press fit of the motor's shaft.

If you have access to a bandsaw, cut the disc out of the square. If not, use a coping saw to do the cutting of nonmetallic material. Then cut the slot. If the material being used is nonmetallic, you can use the coping saw or a jigsaw to cut the slots. You may even be able to use a jigsaw—*not* a coping saw—to cut the slots in aluminum if the material is very soft. Otherwise, drill a series of interconnecting holes and clean out unwanted material with a small round or curved file.

Referring to Fig. 3(B), fabricate the yokes from strips of 3/4 × 1/2-inch pieces of clear pine. After cutting them both to a length of 2 3/4 inches, mark the locations for the holes to be drilled. For holes A, make center-point marks on both sides of the wood pieces since you may have to drill different-size holes through both arms of the yokes to accommodate LED and phototransistor cases that are different diameters. Holes B should be 1/4-inch in diameter and should go clear through both pieces.

With the yoke pieces laid 3/4-inch-wide face up, strike a line down the center of each and measure 3/4 inch up from the ends through which the B holes have been drilled and strike a cross line. Drill a 1/4-inch hole clear through both pieces of wood at the crossed lines.

If you have access to a bandsaw or jig saw, cut 1/4-inch-wide slots whose rounded bottoms are the 1/4-inch holes just drilled. Smooth the sides of the slots with a fine wood file or sandpaper. Temporarily slide a 1/4-inch-thick piece of wood or Masonite into the yoke slots and drill holes A in both yokes. If the selected IR LEDs and phototransistors have cases with different diameters, size these holes accordingly to provide press fits. In this case, make sure that when you drill the hole on either side that you do not go clear through the central wood or Masonite. Remove the wood or Masonite pieces from the slots and discard them.

For the field-coil piece, you need a 4 3/4 by 5/16-inch piece of 1/16- or 3/32-inch-thick mild steel. As illustrated in Fig. 4, drill two 1/8-inch holes, each 2 inches from the ends and centered in the strip, to permit mounting. Then bend the steel strip into a U shape with 1 1/2-inch legs.

You may want to fit onto the legs of the pole piece bobbin guides, as shown in the right illustration in Fig. 4. These optional guides can be fabricated from pieces of perforated board, Bakelite, phenolic board or heavy poster board measuring 3/4 × 5/8 × 1/16 inch. After cutting a 5/16 × 1/16 or 3/32-inch slot down the center of each guide. Punch or drill a small (1/16-inch or so) hole through each guide. Then slip one guide onto each leg of the field-coil piece. Then wrap a layer or two of plastic electrician's tape around the center of each leg to provide insulation, making the insulated areas 5/8 inch wide.

Push the bobbin guides up against the tape and secure in place with plastic cement. Slide the remaining two guides onto the legs as shown and cement these in place. Set the field-coil piece aside until the cement sets.

Meanwhile, prepare the pole pieces, as detailed in Fig. 5. For this, you must fabricate two paddle-shaped pieces of 1/32-inch-thick mild steel as shown in detail (A). Once you have cut to size the steel pieces, drill a

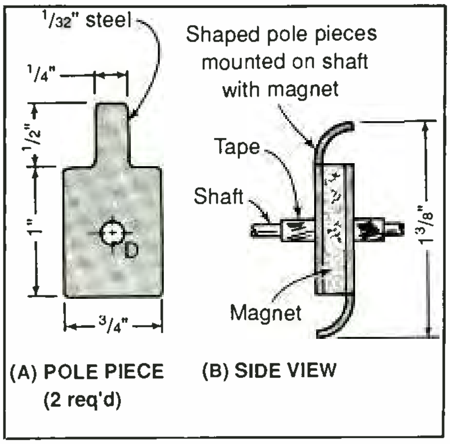


Fig. 4. Machining details for pole pieces (A) and "sandwich" made up of two pole pieces and a magnet.

hole the same size as that in the ceramic magnet chosen. Then bend the narrow tabs on both pieces in a smooth quarter-round arc as in detail (B). Use a drop or two of super glue to cement the steel pieces to opposite faces of the ceramic magnet, orienting the tabs so that they are at opposite ends of the magnet.

Cut to length four 24-foot No. 28 or 30 enameled (so-called "magnet") wires. Attach adhesive tags with the legends L1S and L1F to the start and finish of one wire, L2S and L2F for the start and finish of the second wire, L3S and L3F for the third wire, and L4S and L4F for the fourth wire. (The "S" and "F" in all cases refer to the start and finish ends, while the "L1" through "L4" refer to the individual field windings.)

Holding the L1S and L3S ends together and leaving a 4- to 5-inch starting "tail," wind both wires in parallel with each other around one leg of the field-coil piece. Continue winding until all but a 4- or 5-inch end tail is left. In the same manner, wind the other two wires onto the other leg, beginning with the ends labeled L2S and L4S and ending with the ends labeled L2F and L4F. It is extremely important that you wind both pairs of wires onto the pole piece legs in the *same* direction. Otherwise, the motor will not operate but will simply hum as it consumes power from the dc source. Make the windings neat and even.

Depending on pole material thickness, each 27-foot length of wire should result in about 260 turns. If you have incorporated the bobbin guides, pass each start (labeled S) wire in turn through the small holes in the upper guides, reattaching its label immediately as it is passed through the hole. Do the same with the finish (labeled F) ends, passing each through the small holes in the lower bobbin guides.

You have now fabricated all the mechanical elements that make up the brushless dc motor. Now go back over them, checking them against the various figures to ascertain that each has been fabricated as specified. If so, smooth all cut edges and drilled hole edges to remove burrs and/or splinters. Lightly sand all wood members and, if desired, paint or seal them with clear or tinted urethane.

When everything is dry, use glue and ¾-inch flat-head woodscrews to secure the base plate in the center of the sub-base plate (if you are using it). Then use ½-inch woodscrews to mount the field-coil assembly on the base plate, positioning it squarely in the mortise if you cut this. Then use ½-inch woodscrews to mount a bearing piece centered at one end of the base plate (see lead photo). Slide onto one end of the shaft a friction-fit plastic bushing and position it about ½ inch from that end. If you cannot locate such a bushing, wrap a few layers of ½-inch-wide electrical tape around the shaft flush with the end. Pass the other end of the shaft through the hole in the bearing.

Next, slide onto the shaft the magnetic pole-piece assembly. It will be a loose fit, which will be taken care of later. Slide the other bearing onto the shaft and secure it in place, centered against the opposite end of the base plate, with ½-inch woodscrews (see Fig. 7). Once again, slide onto the free end of the shaft a press-fit plastic bushing or wrap a few turns of electrical tape around the shaft. When you are done with this, there should be just about 1/16 inch of play when you gently move the shaft back and forth.

Follow up with the optical disc. Remember that this is a press-fit operation; so be careful to avoid bending the motor's shaft as you press it into place.

Now mount the yokes in their respective locations to either side of the optical disc, with the LED holes facing away from the field-coil assembly. Carefully align the emitter/receptor holes of each with the slots in the disc, turning the motor's shaft as needed to bring the slots into alignment. Use a 1¼-inch woodscrew to

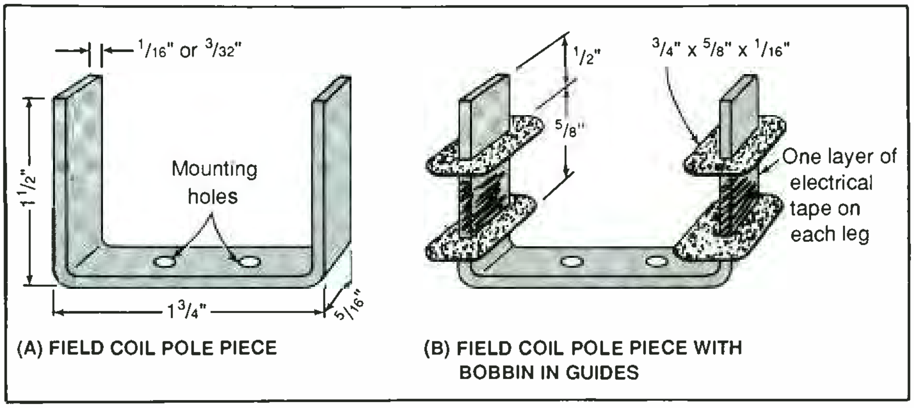


Fig. 5. Machining details for field-coil piece (A) and optional bobbin guides (B).

secure each yoke in place against the base plate.

Now align the shaft elements with the field-coil and yoke assemblies. The armature assembly must be centered over the field-coil assembly. To accomplish this, determine where on the motor's shaft this assembly must be located. Then wrap as many layers of tape over this location as needed to provide a relatively tight fit when the magnet assembly is pushed into place. It is not necessary—or desirable—to make the fit too tight because you will be cementing the magnet assembly into place. Be careful to avoid bending or distorting the shaft as you work.

Return to the optical disc. First, adjust the position of the disc on the motor's shaft so that the former sits centered in the slots in the yokes and is squared with the shaft. Rotate the shaft to make certain that no part of the disc touches the arms of the yoke. Use super glue or quick-set epoxy cement to secure the optical disc in place on the shaft, with square-cut bushings as shown in the lead photo, if you have them.

As you rotate the shaft, check for bearing binding. If you note binding, you may have to disassemble the motor to enlarge the holes in the bearings. Also check the clearance between the tabs on the magnetic pole piece and field-coil assembly. The two should not touch. Ideally, there should be about a 1/16-inch separation between the two assemblies at their closest. If everything appears to be okay, place a drop of light machine oil or grease on each bearing to reduce friction.

Rotate the armature assembly on the motor shaft so that the tabs align equally with the bottoms of the slots in the optical disc. Do not glue this assembly in place just yet.

Now that the mechanical elements are assembled, install transistors *Q2*, *Q3*, *Q5* and *Q6* on the perforated board. Follow up with resistors *R3* through *R6*. Use appropriate soldering or Wire Wrap hardware and include posts for soldering the +5-volt and ground cable into the circuit. Then, referring back to Fig. 1, wire together these components.

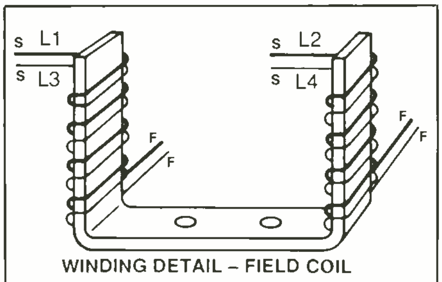


Fig. 6. Winding details for field coils on pole piece. Both coil pairs must be wound in the same direction. Designations "S" and "F" refer to start and finish ends, respectively, of individual coil windings.

Power for the IR emitter circuit should be made from the circuit-board assembly. Therefore, mount *R1* and *R2* on this board. Install a wire that will connect from *R1* to the anode lead of *LED1* and another wire that will connect from *R2* to the cathode lead of *LED2*. Also, include two more wires from the board's ground bus to connect to the cathode lead of *LED1* and the anode lead of *LED2*. Mount the circuit assembly against the wood base with woodscrews, as shown in the lead photo.

Referring to the lead photo, plug the domed cases of IR emitters *LED1* and *LED2* into their respective yoke holes. Do the same with phototransistors *Q1* and *Q4*. Then locate the two ground leads coming from the circuit-board assembly and connect and solder them to the cathode lead of *LED1* and the anode lead of *LED2*. Locate the wire connected to *R1* and solder its free end to the anode lead of *LED1*. Similarly solder the wire connected to *R2* to the cathode lead of *LED2*. Insulate the connections with plastic tubing or electrical tape. Then connect and solder the dc power cord (it should be color-coded red for +5 volts and black for ground or be a length of zip

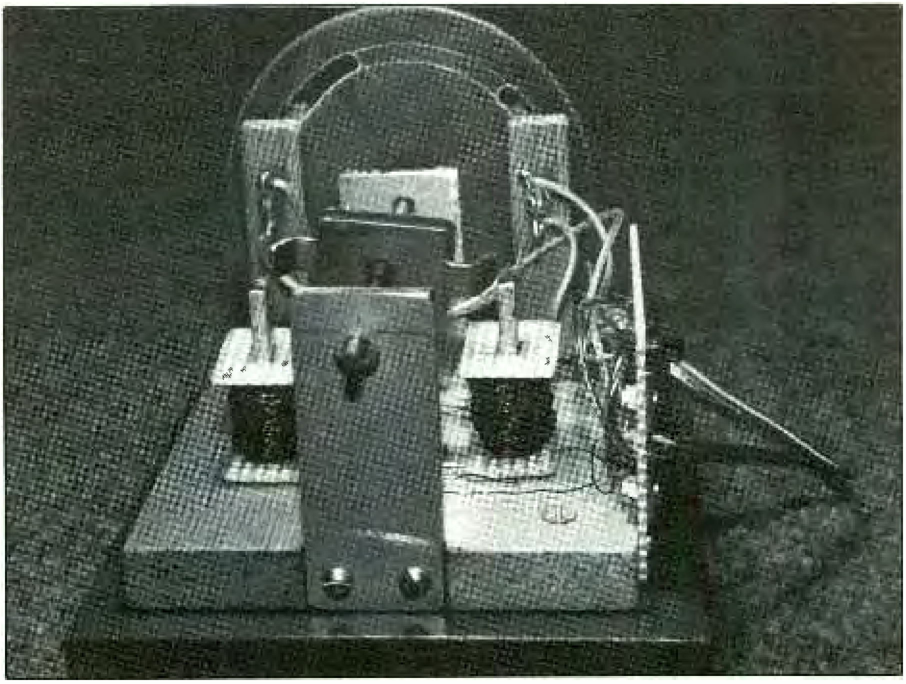


Fig. 7. View of motor from rear shows orientation of pole-piece assembly with respect to optical disc's slots and bushing on end of motor shaft.

cord with one readily identifiable conductor) to the power buses.

Finish up wiring by routing the leads from the field-coil assembly to the appropriate points in the circuit. Determine how long the lead labeled L1S should be to connect to the collector of *Q3* and trim it to that length. Carefully scrape away about 3/8 inch of the insulating enamel coating and connect and solder this lead to *Q3*'s collector. Do the same with the lead labeled L3S, connecting and soldering it to the collector of *Q6*.

Next, trim the leads labeled L1F and L2F, scrape away the enamel, twist the two together and solder. Do the same with the leads labeled L3F and L4F. Repeat with the leads labeled L2S and L4S. Insulate all three connections with electrical tape.

Checkout & Use

Connect the motor to a 4.5- to 6-volt dc source, making certain that the connections are properly polarized. To get things started, turn by hand the shaft in either direction. The motor should take over and come up to speed in a few seconds. If it does not operate as it should, disconnect power and carefully readjust the angular position of the magnetic pole piece assembly with respect to the field-coil assembly while holding the shaft stationary until it does. Once you have the motor operating properly, super glue the pole piece into place.

Should the motor fail to operate altogether, power down and check for shaft binding. If this is not the problem, recheck all wiring against Fig. 1. Make certain that the IR LEDs and phototransistors are properly polarized and that connections to the leads of the driver and power transistor are correct. Also double check polarization of the power-source leads. This is a fairly simple circuit; so troubleshooting should not be too difficult.

You will find that it is best to operate the motor under subdued lighting conditions, unless you provide a light shield for the infrared emitter/receptor arrangement.

Power for the motor can be any 4.5- to 6-volt dc source, including heavy-duty battery, though an ac-operated bench supply should be used if you plan on operating the motor for any extended period of time. You can adjust the motor's operating speed by varying the supply voltage. For demonstration purposes, you can also shine the beam of a small flashlight on the area of the IR source or phototransistors to reduce the speed. **ME**