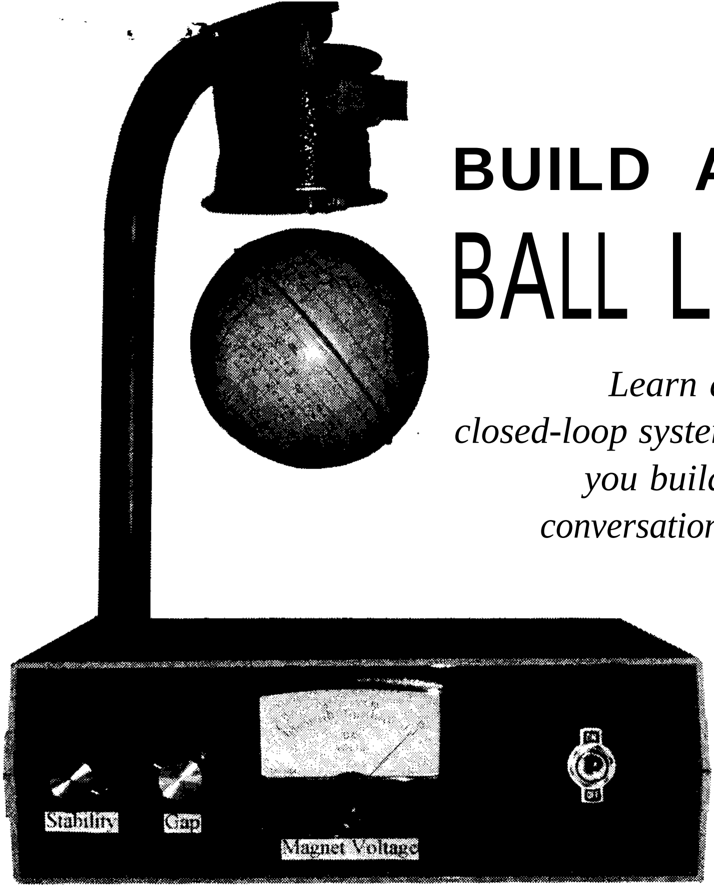


BUILD A MAGNETIC BALL LEVITATOR

Learn all about closed-loop systems while you build a great conversation piece.

BY JAMES CICON

Your approach takes you closer to the planet, A red star shines in the distance. As you watch the Earth floating in space, you think that you can almost see it turning on its axis. With a mind of its own, your finger reaches out to flick the sphere into motion.

With a shock, the infinite depths of the universe collapse down to the confines of your work room as you snap back to reality. The red star is actually the LED on a nearby power supply. Maybe you were daydreaming, but the globe of the earth still floats on top of your workbench. What a conversation piece!

What kind of device are we talking about here? What could make a mini earth float in mid air? The Magnetic Ball Levitator described in this article, that's what. It's an educational project that will teach you all about closed-loop control systems as you build it. Forget complicated math or diagrams-we'll deal with the systems in a hands-on kind of way.

You might have read articles or even books on closed-loop controllers in the past, but if you're like most, you've found that those theory-only discussions do little more than frustrate the reader, To learn about concepts like instability and feedback, you're best off actually experiencing them at work. So read on

Some other great reasons to build the Levitator are that it is cheap to build and does not contain any hard-to-find parts. You probably already have on hand most of the parts that you need to build it. And even if you don't, you should be able to get a trimmed-down unit up and running for between $10 and $20. To do that you would need to skip the fancy case, eliminate the magnet voltage meter, and run the Levitator with a bench top power supply.

Control-System Basics. Control systems are all around us, and even within us. Our blood sugar level is regulated by an internal control system, as is our body temperature. Examples of external control systems include an airplane's autopilot, and even temperature-control circuits of some soldering irons,

While control systems come in many forms, they are all made up of smaller building blocks with functions that are common between all systems. For example, most control systems have a "plant" that has some output to be controlled. An actuator is used to control the output of the plant.

A common control system is the heating system in your home. The plant is the room, the output is the room temperature, and the actuator is the furnace. Many control systems also have an output sensor that determines how well the operation of the plant is maintained, compared to some reference or command input. In our room example the output sensor is the thermostat, and the reference is the setting of the thermostat.

The signal from the output sensor is used to turn on the actuator to affect the plants output if some error exists between the plants output and the reference. That is called feedback-an output signal is fed back via a sensor of some sort, to the actuator to change the output. A control system with feedback is also called a closed-loop control system. In our example, the wire going from your thermostat to your heater is half of the loop. The heated air that comes out of the basement through ventilation ducts and back to the thermostat is the other half of the closed loop.

As mentioned earlier, an error signal is used to turn on the actuator. It is important to understand that the actuator is only activated if the error signal is not zero. For example, say that your thermostat is set at 68° F and your home's temperature is also 68°, but outside it is 35" and windy. Is your heater on? No, there is no error between the room temperature and the thermostat setting, so the furnace is off.

Open or Closed Systems? Lers stick to the example of home heating to do a little comparison between open- and closed-loop systems, The simplest type of heater (see Fig. 1) has a power-level switch (usually with off, low medium, and high settings) and a heating element. An electrical signal flows from the power control to the heater, and the heated air flows from

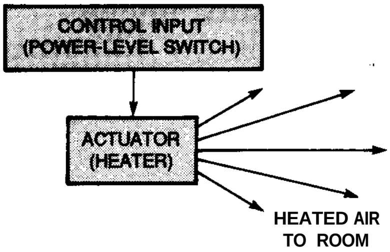


Fig. 1. Here's an example of a simple, open-loop control system. No signal comes back telling the system how well the room is being heated.

the heater to the room. No signal comes back telling the system how well the room is being heated. For that reason, it is called an open-loop control system because the signals in the system only flow in one direction.

The disadvantage of an open-loop system is that you constantly have to adjustthe power control to maintain a comfortable temperature in the room. On cool days the power should be on low on realty cold days it should be on high. The necessary setting will vary **from** the morning to the evening. However, if you install an output sensor, you can determine when the room's temperature is too high or too low and adjust the power to the heater accordingly. Such a closed-loop system is shown in Fig. 2.

The output sensor and error detector shown in Fig. 2 are housed in the thermostat that is used to regulate the heater's output. That thermostat fills the roles of the sensor, error detector, and control input in the system. In many such thermostats, a lever sticking out of the thermostat moves over a temperature scale, while its axis is attached to the center of a spiraled bimetallic strip. The other end of the bimetallic strip is attached to a mercury-level switch.

When the switch is level, the mercury in it lies in the center of the switch and doesn't close any of the switch's contacts. When the switch tips in one direction a heater contact is closed; when it tips in the other direction a cooling contact is closed. If the room temperature heats up, the metal strip rotates in the cooling direction, tips the mercury switch accordingly, and turns off the heater. When the room cools down, the metal strip rotates in the other direction, tilting the mercury switch, and turns the heater on. The lever can turn the coil initially to one side or the other, causing the coil to have to turn further back or further forward to keep the switch level. Thus the room's temperature will have to be hotter or colder to level out the mercury switch.

That type of control system is sometimes called a "bang-bang" controller because the actuator is either fully on or fully off (that results in a rattle or "bang" of a furnace). It works well as long as you do not need very precise control, say an accuracy of ±a few degrees, but can have problems if used for more accurate control. That's because the slightest disturbance to the thermostat will cause it to turn the heater on or off, as the case might be.

To avoid such instability, you need to design hysterisis into the controller. In other words, when the room gets hot, the heater shouldn't turn off until the temperature is a few degrees hotter than the thermostat setting. Likewise, when the room is cool, the heater shouldn'tturn back on until the room is a few degrees cooler than the setting on the thermostat. That keeps random disturbances, like drafts caused by opening a door, from affecting the system.

So, as you can see, there are cases where a much better system than a bang-bang controller is needed. That is where Proportional-Integral-Derivative (PID) controllers come into the picture.

Basics of PID. Figure 3 shows a block diagram of a closed-loop heating system that contains a PID controller. Notice that a PID controller contains all of the basic building blocks contained in an open-loop controller and also the components contained in a bang-bang controller, However, another block called a compensator is added. The compensator itself contains three new "blocks" of amplifiers labeled P (Proportional), I (Integral), and D (Derivative], and an adder to combine the three outputs.

The P block is an op-amp that you would use to boost the gain of an audio signal; the I and D blocks are also amplifiers, In a PID controller, the P block is probably the most important part. The I and D parts are there to fix up problems that can occur in particularly unstable systems. Therefore,

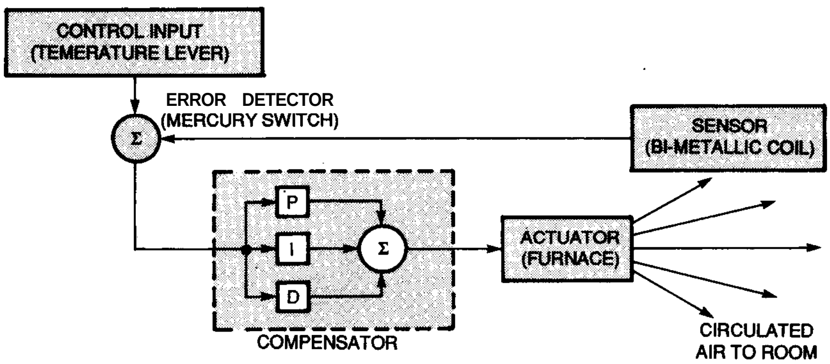


Fig. 3. This closed-loop heating system contains a PID controller. When a PID controller operates, the sensor measures the error in the plant's output and adjusts the actuator to activate proportionally to the error. That results in a smooth response.

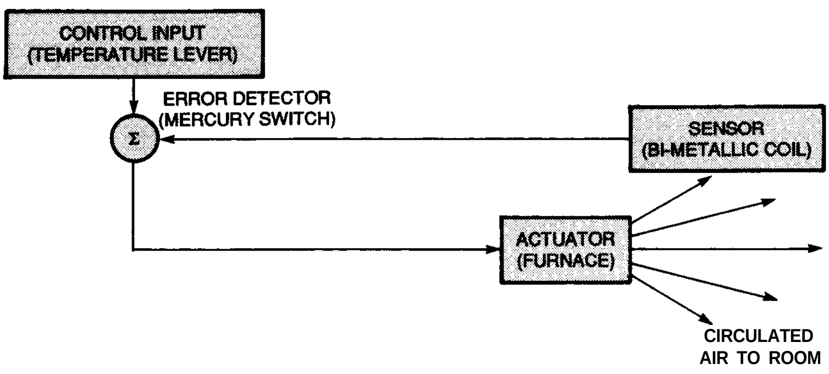


Fig. 2. With the addition of an error detector and an output sensor, a control system becomes a closed-loop type. The system shown here can determine when the room's temperature is too high or too low and adjust the power to the heater accordingly.

in many situations you can eliminate the I or D part (or even both) and the PID controller will work fine.

When a PID controller operates, the sensor measures the error in the plant's output and adjusts the actuator to activate proportionally to the error. That will achieve a smooth response and prevent a system from operating just like a bang-bang controller,

To see how all the basics we looked at can be applied, and to deal with how the I and D parts of a PID controller work let's now move on to the Levitator itself.

Circuit Description. The schematic for the Levitator is shown in Fig. 4. Transformer T1 steps down the voltage from an AC outlet to 25-volts AC, which is then full-wave rectified by BR1. Capacitor C3 provides filtering. An unregulated 30-volts DC is provided from C3 for the high current draw that the actuator section of the circuit requires (more on that section in a moment). An LM7812 regulator, ICl, provides a regulated l2-volts DC for use by the rest of the circuit. Switch S1 is the power switch.

The output sensor of the circuit works as follows: An infrared LED, LED1, shines IR light onto the top of the globe that will be levitated. That IR light reflects off of the top of the globe back up to Q2, an IR phototransistor, Both LED1 and Q2 are mounted on the bottom of electromagnet L1, so the closer the globe is to the bottom of the magnet, the more light is reflected, and the more current flows through Q2. In other words, the amount of current that flows in Q2 is proportional to the amount of light shining on its base. Resistor R4 sets the brightness of LED1.

The reference or control input is set by potentiometer R6 and resistor R8; that fixed resistor sets a minimum resistance value for the reference circuit. If R8 was not present and the wiper of R6 were turned to its lowest setting, a short circuit would exist from the emitter of Q2 to ground (which could damage Q2). Current from Q2 is directed through R6. That current is proportional to the gap between the magnet and the globe under it. You can set the desired gap distance by adjusting R6.

One section of an LM324 quad op-amp, IC2-a, is used as an error-detector. If R6 is set high, a given gap will result in a higher error voltage being generated by the error detector than if R6 were set low.

The compensator of the circuit consists of IC2-b, Rl, R2, C4, R3, and R5. That compensator actually has two inputs, which both have the error signal from IC2-a applied equally to them. One input is through R2, the stability-adjustment potentiometer; the Input coming in via R2 is the proportional [P) input to the compensator, The other input comes in through C4. That input is the derivative (D) input for the compensator. The compensator does not have an integral (I) input, Resistor Rl is a feedback resistor for IC2-b, and R3 and R5 bias the op-amp to operate on a single 12-volt supply.

The magnet assembly is made up of coil L1 and thermal-fuse F1. Because F1 is supposed to stop current flow when the magnet overheats, the fuse should be wired as part of coil L1 (more on that later). Both the magnet assembly and its supporting circuitry (C1, D1, M1, Q1, and R7) make up the actuator. The input to the actuator is the error signal from the gate of Q1, an IRF510 MOSFET transistor, and the output is the magnetic field from the magnet assembly.

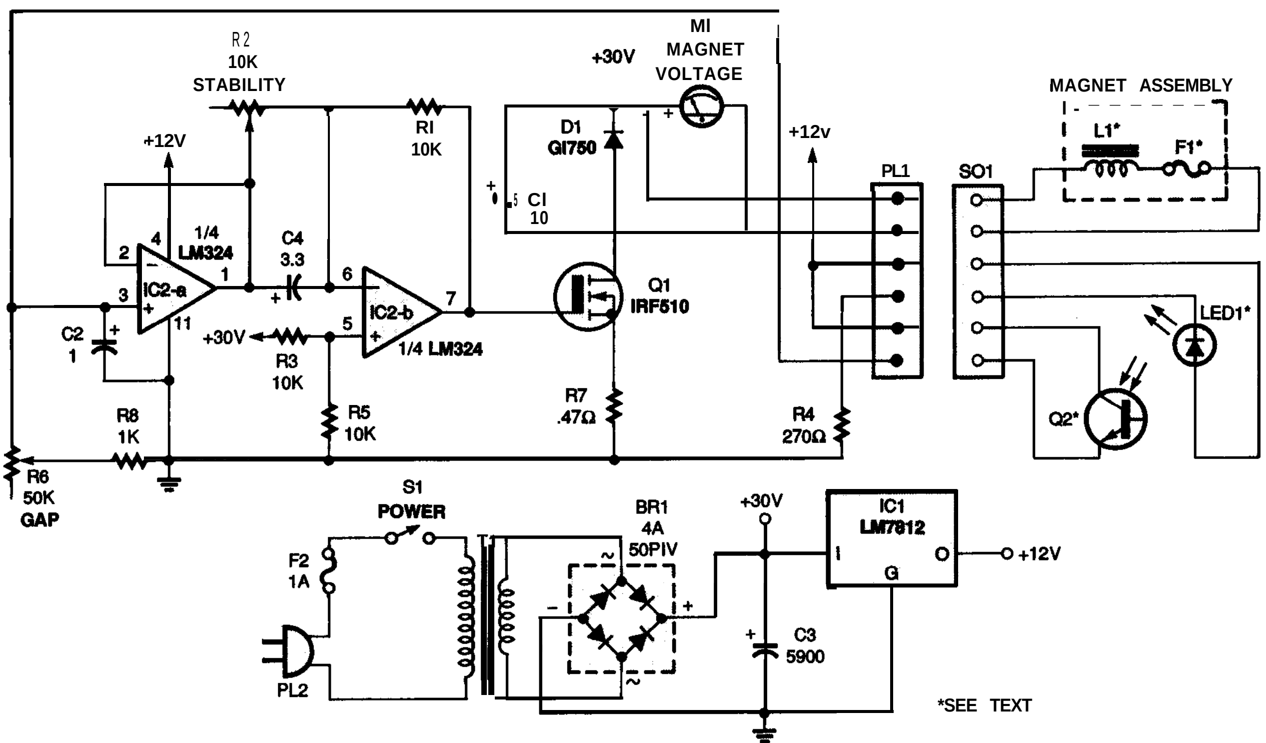


Fig. 4. Here's the schematic for the Magnetic Ball Levitator. The magnet assembly is made up of coil L1 and thermal-fuse F1; note that although those two components are shown in series next to each other, the fuse is actually wound in series as part of coil L1.

Capacitor Cl filters "noise," and diode D1 protects Q1 from large voltage spikes that can occur across the' magnet assembly when the unit is turned off quickly. Meter MI provides an indication of how much voltage is present in the magnet.

The magnet assembly, transistor Q1, and resistor R7 are configured as a power amplifier with a gain of about 20. Transistor Q1 is configured as a common-source amplifier, meaning that the input signal is applied to its gate, and the output signal is taken off of its drain. The impedance of the drain circuit is the magnet resistance, or about 10 ohms, and the impedance of the source circuit is equal to the value of R7, 0.47 ohms.

To see how all the circuit components work together, look at Fig. 5, a block diagram of the Magnetic Ball Levitator. That's essentially the same type of diagram that was used in the earlier discussion of closed-loop systems.

Let's begin with the unit turned on and the ball suspended beneath the magnet a little closer than it should be. When the ball moves too close, more current flows in Q2, and the voltage across R6 increases. The error signal out of IC2-a then goes positive and couples to IC2-b through R2. Op-amp IC2-b amplifies and inverts the signal applying it to the gate of Q1. That negative signal is inverted and amplified, causing voltage on the drain of Q1 to go positive. As a result, less current flows in the magnet windings, which means less magnetic force is applied to the ball.

As the ball drops away from the magnet, the reverse occurs. Less current flows through Q2, which will result in more current flowing through the magnet, The compensator of the circuit keeps that back and forth motion of the ball stable so that it appears to be floating. Remember, potentiometer R2 can be used to adjust the level of that stability

Construction. The author's prototype for the Levitator was built on two perforated boards and mounted in a case measuring 7½ x 10 x 3½ inches. One board contains all the high-power components.

To begin assembly of the high-power component board, mount capacitors Cl and C4 and resistor R7. Then go on to install diode D1 and bridge-rectifier BR1. Position the board near the back of the case.

Mount the rest of the capacitors and fixed resistors on the other board. Next install ICI and IC2 on that board, using an IC socket for IC2. Position the board near the front of the case.

Now its time to add the off-board components. Drill holes in the front of the project case to accommodate potentiometers R2 and R6, and install them. Go on to make holes for M1 and S1, and mount those parts as well.

Next drill a hole on the back panel and mount fuse F2. Also drill holes for the heat sink specified in the parts list. Transistor Q1 mounts on that heat sink. Although the heat sink might seem a little large for Q1, it is necessary because the unit controls up to 2 amps of current at up to 36 volts. That results in a lot of power to dissipate.

Drill another hole in the rear of the case to pass through a power cord. Connect that cord to transformer T1 and mount the latter near the back of the case. You can then complete all the in-case wiring.

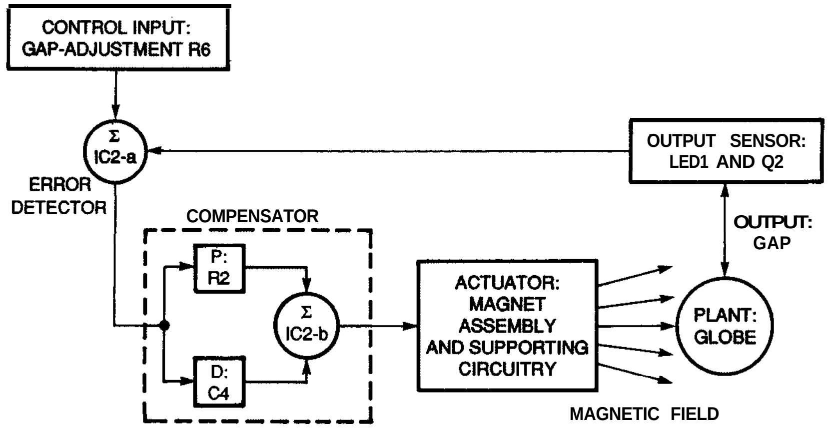


Fig. 5. This block diagram shows how the sections of the Levitator work together to resemble the models of closed-loop systems examined in Figs. 2 and 3.

PARTS LIST FOR THE MAGNETIC BALL LEVITATOR

SEMICONDUCTORS

ICl-LM7812 l2-volt regulator, integrated circuit
IC2-LM324 quad op-amp, integrated circuit
Q1-IRF510 MOSFET transistor
Q2-NPN phototransistor (Radio Shack 276-145 or equivalent}
LEDl-Infrared light-emitting diode (Radio Shack 276-142 or equivalent)
BRl-Full-wave bridge rectifier, 4-ampere, 50-PIV
Dl-GI750 silicon rectifier diode (can be substituted by any 4-ampere, 50-volt unit)

RESISTORS

(All fixed resistors are %-watt, 5% units, except where otherwise noted)
Rl, R3, R5--1O,OOO-ohm
R2-10,000-ohm potentiometer
R4-270-ohm
R6--50,000-ohm potentiometer
R7-0.47-ohm, 5-watt, 10%
RS-1OOO-ohm

CAPACITORS

Cl--10-µF 50-WVDC, electrolytic
C2-1µF, 5O-WVDC, electrolytic
C3-5900-µF 30-WVDC, electrolytic
C4--3.3µF, 5O-WVDC, electrolytic

ADDITIONAL PARTS AND MATERIALS

L1--Magnet coil (see text)
Tl-117-VAC to 25-VAC, 2-ampere power transformer Ml-DC voltmeter, 0- to 15-volt range
Fl-Thermal-protector fuse (Radio Shack 270-1322 or equivalent)
F2-l-ampere fuse
PL1--6-connector power plug
PL2-2-termina1 AC plug
SOl--6-connector power socket
Sl-SPST switch
Perforated board, project enclosure, metal globe, SIP socket, 2 orange-juice-can lids, heat sink measuring 3 X 4 X 1½ inches (JDR Microdevices HS192OOOB or equivalent), ½-inch-diameter PVC tubing, 1-inch-diamter PVC coupling, 2-inch-long l0-24 bolt, magnet-core nail (12-inches long by 3/4-inch diameter), metal epoxy, magnet pin (3/4-inch length of coat-hanger wire), washer, 520 feet of 22-gauge magnet wire, power cord, wire, solder, hardware, etc.

Next, drill holes on the back of the case to mount a l-inch-diameter PVC coupling. That coupling will be used to support the magnet arm made of %-inch PVC pipe. When placed into that coupling, the magnet-arm can then freely turn and be easily removed again Such a design provides a convenient way to lay the arm down flat on the side of the unit for storage purposes.

To make the magnet arm, you will need to bend a piece of PVC tubing to create an L shape. Cut a 3-foot-length section of the material to work with. Heat the middle 9 inches of the tube gradually and evenly; you can use a gas-range burner, a butane torch, or a heat gun to do that. After the 9-inch section you are heating starts to get rubbery, carefully bend the tube around a large coffee can (a 39-ounce can has a 6-inch diameter, which is perfect) to make a 90° angle. If you try to bend the tube with out using a form, the tube will deform and collapse.

After the tube cools, cut it so that the long part of the L-shaped tube is 12-inches long and the short part is 6-inches long. Drill a %-inch hole in the underside of the short end of the mount, about ½ an inch back from its end. The screw that is used to hang the magnet from the mount will pass through that hole.

Now you can put together the magnet assembly; refer to Fig. 5 as you do so. The core of the magnet is a Ye-inch-thick, 12-inch-long nail (perhaps it should more appropriately be called a spike). Drill a G-inch-wide hole ½ an inch into the head of the nail. Next cut the head off of a 2-inch-long IO-24 bolt. Fill the hole in the nail with metal epoxy and drop the cut-off end of the bolt into the hole. When the epoxy hardens, you will have a solid mount with which to hang the magnet assembly from the magnet arm.

Drill %-inch holes through the center of 2 orange-juice-can lids, and use a hand file to remove any burrs, which otherwise could short out the windings of the magnet if left in place. Slide the lids onto the nail, and separate them by a distance of 2 inches, as shown in Fig. 6. Then put on a washer, and mark where a pin hole should be made on the nail to support the bottom lid. Use a 7/64-inch drill to make that hole. Cut off a 3/4-inch length of

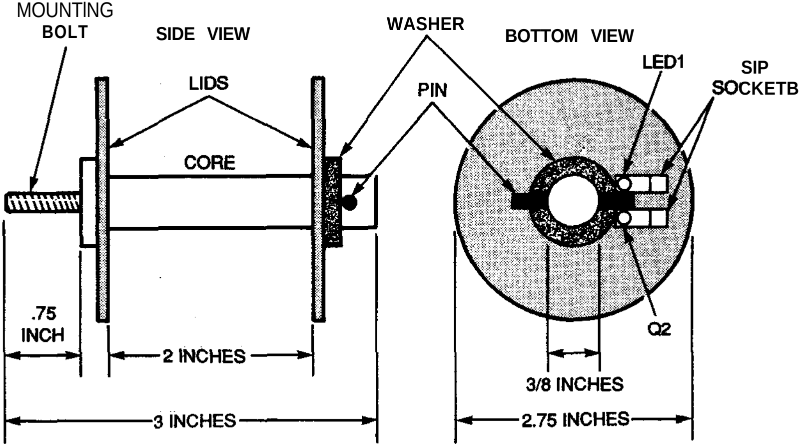
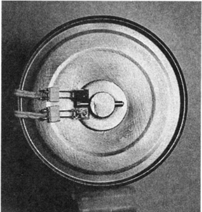


Fig. 6. When building your magnet assembly, use this diagram as a guide.

coat hanger to use for the pin, and insert it.

To make the magnet, you will have to wind 520 feet of 22-gauge magnet wire onto the nail core. There is an easy way to do that: Close the chuck of a hand drill around the point of the nail. Loop the free end of the wire around the core a few times to lock it in place, then set the drill to low and wind the rest of the wire onto the bobbin. After the wire is wound onto the bobbin, use a hacksaw to cut the 12-inch-long nail down to the approximate size shown in Fig. 6. With a hand file, remove any burrs or rough spots from the end of the core.

Then next step is to mount LED1 and Q2 next to each other on the magnet assembly, using two sections of an SIP socket. Position LED1 and Q2 so that the pin at the bottom of the magnet assembly is between them. When you've done that, glue the SIP socket to the bottom can lid (you might have



This bottom view of the magnet shows the placement of the infrared LED and phototransistor to rough up the lid with a wire brush or some fine-grit sandpaper first).

When the glue dries, give LED1 and Q2 a gentle twist so that they are pointing towards each other slightly, That allows the reflected light to bounce from LED1 to the globe to Q2 more efficiently. If you don't bend them like that, the sensor might only have a very short range.

Unwind a couple of turns from the magnet coil and cut the wire. Then solder thermal-fuse F1 in series with the magnet winding, and rewind the few turns you unwound. The fuse is now part of the coil.

Connect a 6-contact power socket (SO1) to the leads of LED1, Q2, and the magnet, Connect a matching 6-contact plug (PL1) to 3-foot lengths of wire, feed the other ends of the wire through the magnet arm, and make the proper connections to the circuit (using the schematic in Fig. 4 as a guide).

Insert the mounting bolt of the magnet assembly into the hole drilled in the short end of the arm, and place a nut over the bolt with a pair of needle-nose pliers. Holding the nut still, turn the magnet assembly to screw the nut onto the mounting bolt. Connect PL1 and SO1 together, insert the arm into its coupling, and your Levitator is ready to use.

Adjustment and Use. Turn on the unit and place the small metal globe under the magnet. If you bring it too close to the magnet, the globe will enter the sensors blind spot. As a result, the globe will stick to the magnet. Should that happen, just remove the globe and find a good distance until the globe "levitates." Adjust the distance of the gap with potentiometer R6 and note how the floating globe moves up and down.

You might notice the globe is bouncing insanely. Adjust potentiometer R2 to correct such an instability.

If you use the Levitator in a bright room, the sensor might become overloaded. That will result in the Levitator occasionally dropping the globe. To correct that problem, simply dim some of the room lights.

Once you have the unit working, you might feel the suspended globe vibrating very rapidly and almost buzzing. That is actually a 60-Hz power hum caused by the room lights. The intensity of an incandescent light is notconstant and carries a 60-Hz component, which the sensor picks up. Such a vibration should not affect stability, but can be annoying. To totally eliminate the problem, operate the Levitator in a room with only natural light.

That should just about do it. Go ahead and experiment with the unit, maybe trying different-sized metal globes. And don't forget to show the Levitator off to your friends, they will be impressed and think that you are a genius. If you have any problems getting your system to be stable, or any other problems at all, feel free to contact the author via e-mail at 75104.3104@compuserve.com. ■