levitator

In view of the current interest in magnetic levitation for applications such as hovertrains (see Elektor 22 p. 2-08) it was felt that a magnetic levitator would make an interesting laboratory demonstration for students. The practical difficulties of cryogenic engineering and the fate of the brass monkey led to the abandonment of the superconducting approach at an early stage of development, and the system finally decided upon was controlled ferromagnetic attraction. The system provides an amusing demonstration and an interesting introduction to feedback control systems.

In order to levitate an object it is necessary to balance gravitational attraction with an equal and opposite force. Anyone who has ever played with permanent magnets will know that it is possible to lift a ferromagnetic object with a magnet.

Controlled levitation, however, is a different matter. For the object to float in a stable position it is necessary for the gravitational force to be balanced precisely by the attractive force of the magnet. Since the force between the magnet and the object varies as the inverse square of the distance between them it is fairly easy to see what will happen. If the object is initially placed in such a position that the magnetic attraction is weaker than the gravitational attraction then the object will tend to fall away from the magnet. As it does so the magnetic force will become weaker, so the object will fall even further, and the magnetic force will become weaker still. If, on the other hand, the object is placed so that the magnetic force is stronger than the gravitational force the object will be attracted upwards. The magnetic force will become even stronger, so the object will be attracted to the magnet even more, until it finally contacts the magnet. Only if the magnetic and gravitational forces are exactly balanced will the object remain in position, and even then any slight disturbance will send it either up or down. In other words, the system is unstable.

To make the system stable a positional feedback control system is required, which adjusts the strength of the magnet according to the position of the object. If the object moves close to the magnet then the field strength of the

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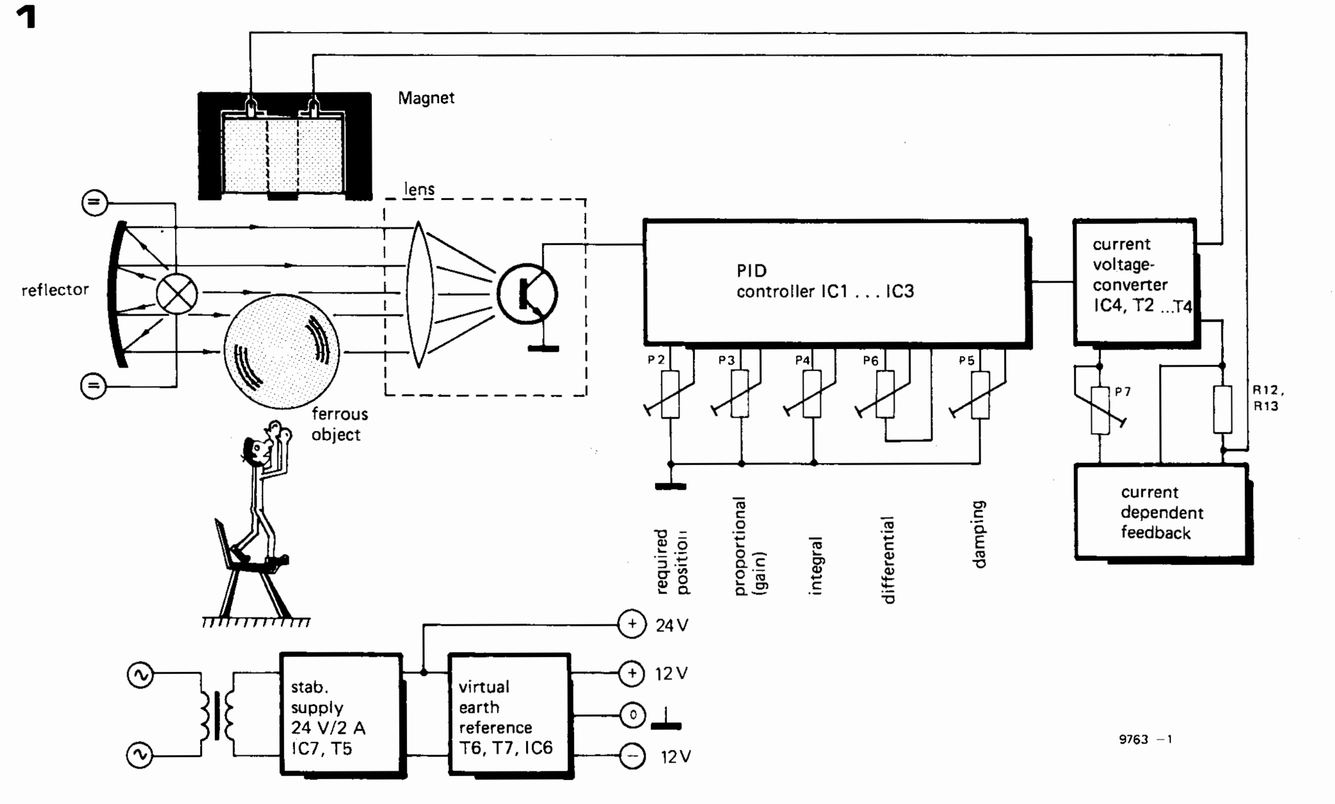

magnet is reduced. If the object tends to fall away from the magnet then the field strength of the magnet is increased. The object will thus assume an equilibrium position where the magnetic and gravitational forces are exactly balanced. If the object is displaced from this position by some external force then it will return automatically, i.e. the system will be stable.

System block diagram

Obviously the two prime requirements of the system are a magnet whose field strength can be varied, and some means of sensing the position of the object. The first criterion is fulfilled by an electromagnet or solenoid, whose field strength can be altered by varying the current passing through the coil. Since there must be no physical contact with the object the second criterion is probably best met by a photoelectric system. The object moves across a beam of light which is focussed onto a phototransistor. As it moves closer to the magnet it obscures more and more of the light. The phototransistor current thus varies in sympathy with the position of the object.

A block diagram of the system is given in figure 1, and illustrates the general setup of the electromagnet and optical system. Without going into the finer points of the electronics at this stage, suffice it to say that if the object tends to fall then the amount of light falling on the phototransistor will increase and the phototransistor current will increase. This will cause a corresponding increase in the electromagnet current and the attractive force will increase, thus pulling the object upwards. If the

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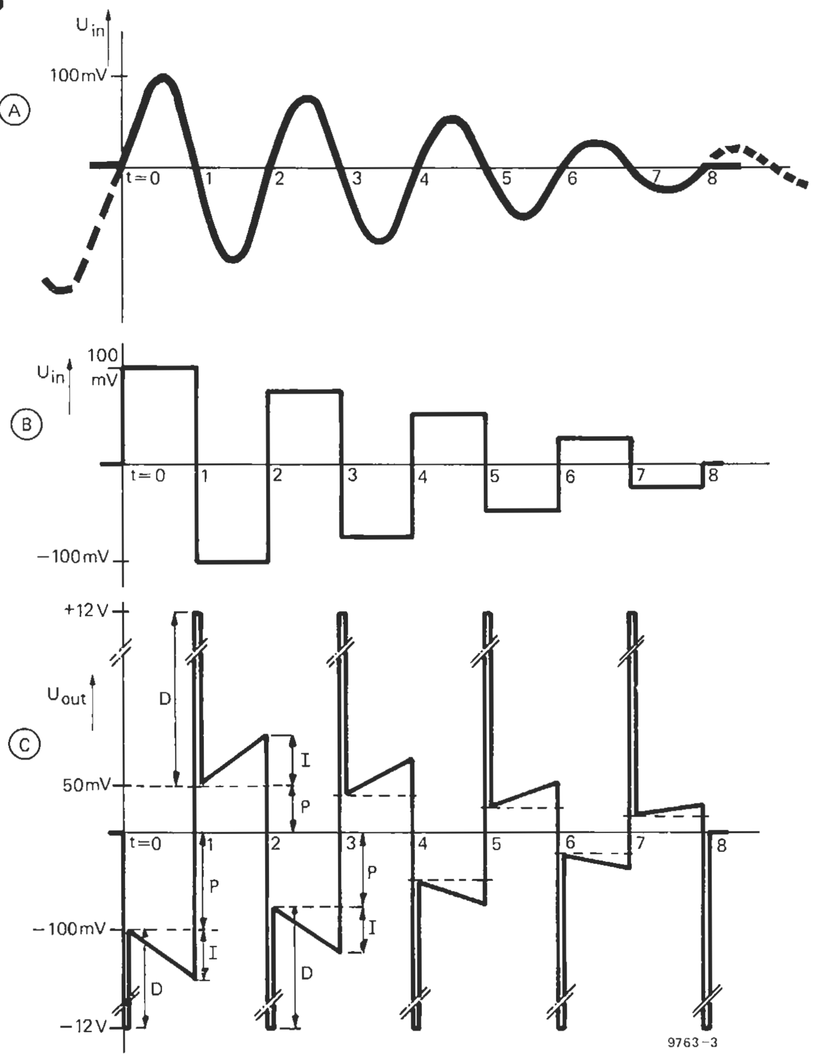

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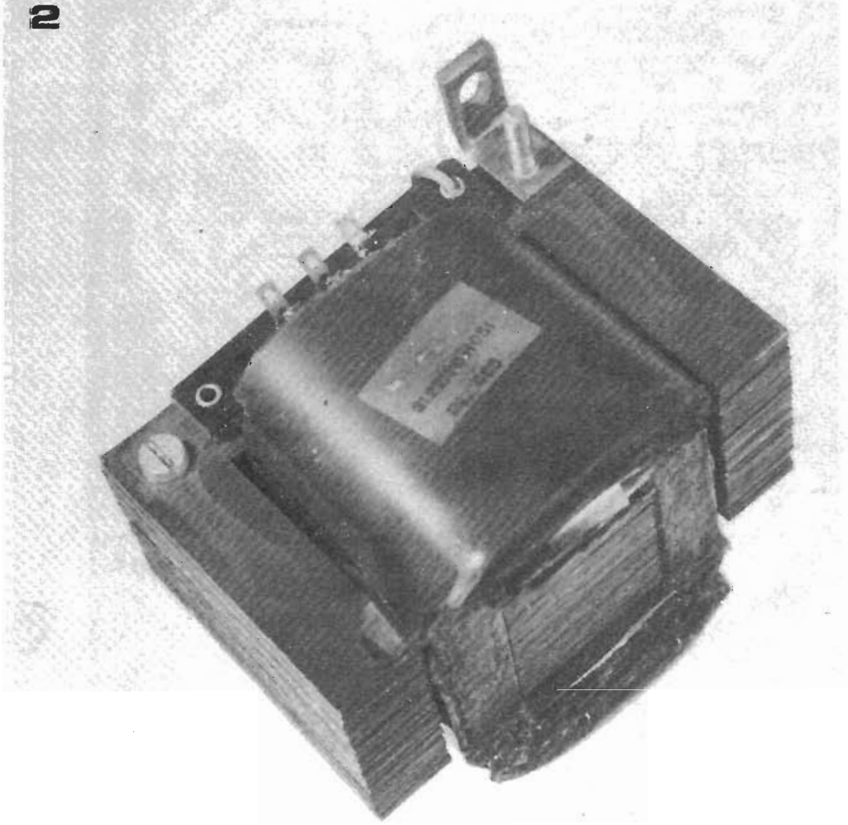
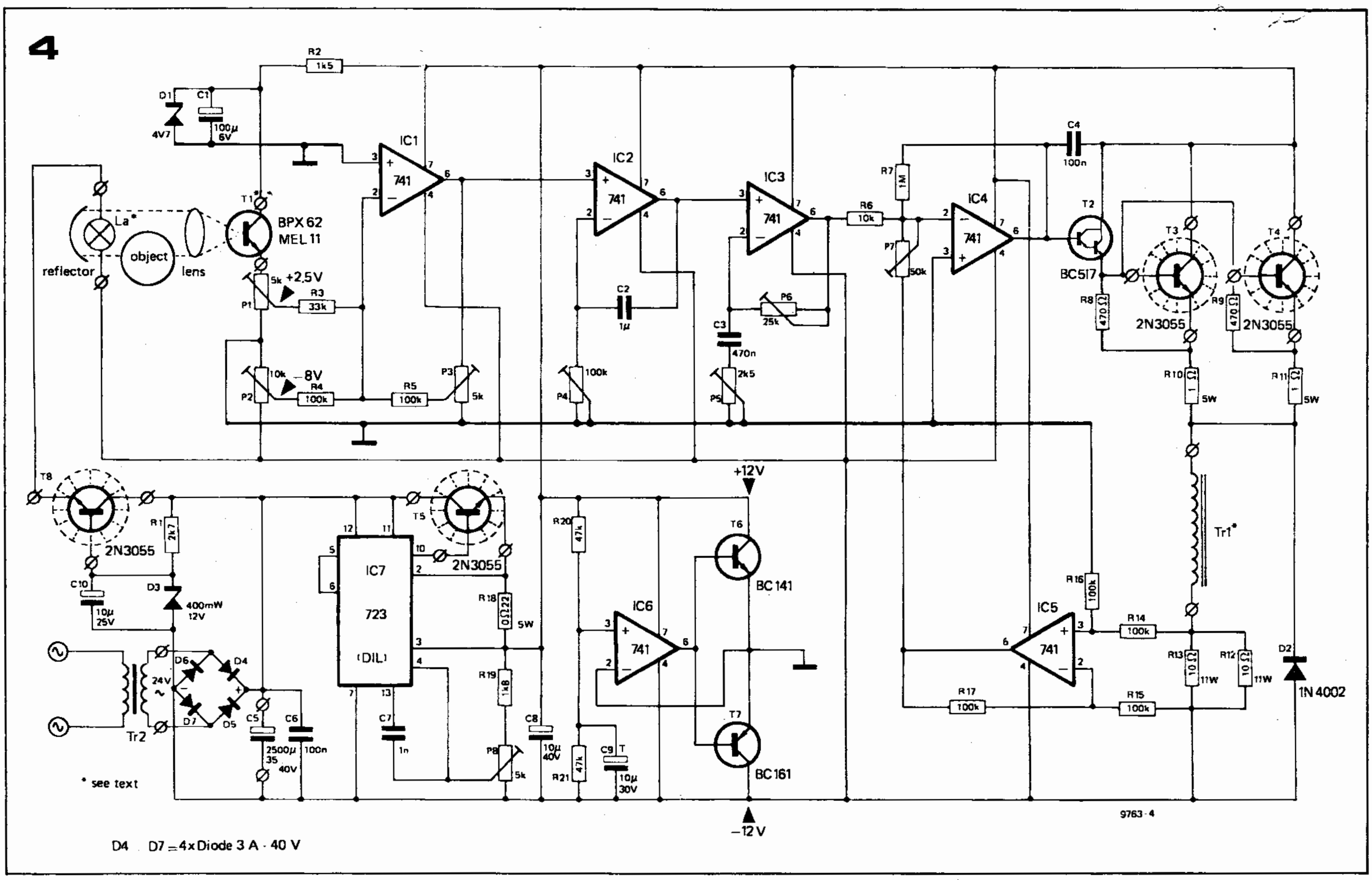


Figure 1. Block diagram of electromagnetic levitator using a three-term positional feedback controller.

Figure 2. Modified mains transformer used as an electromagnet.

Figure 3. Simplified waveforms showing how the object returns to the rest position after a displacement.



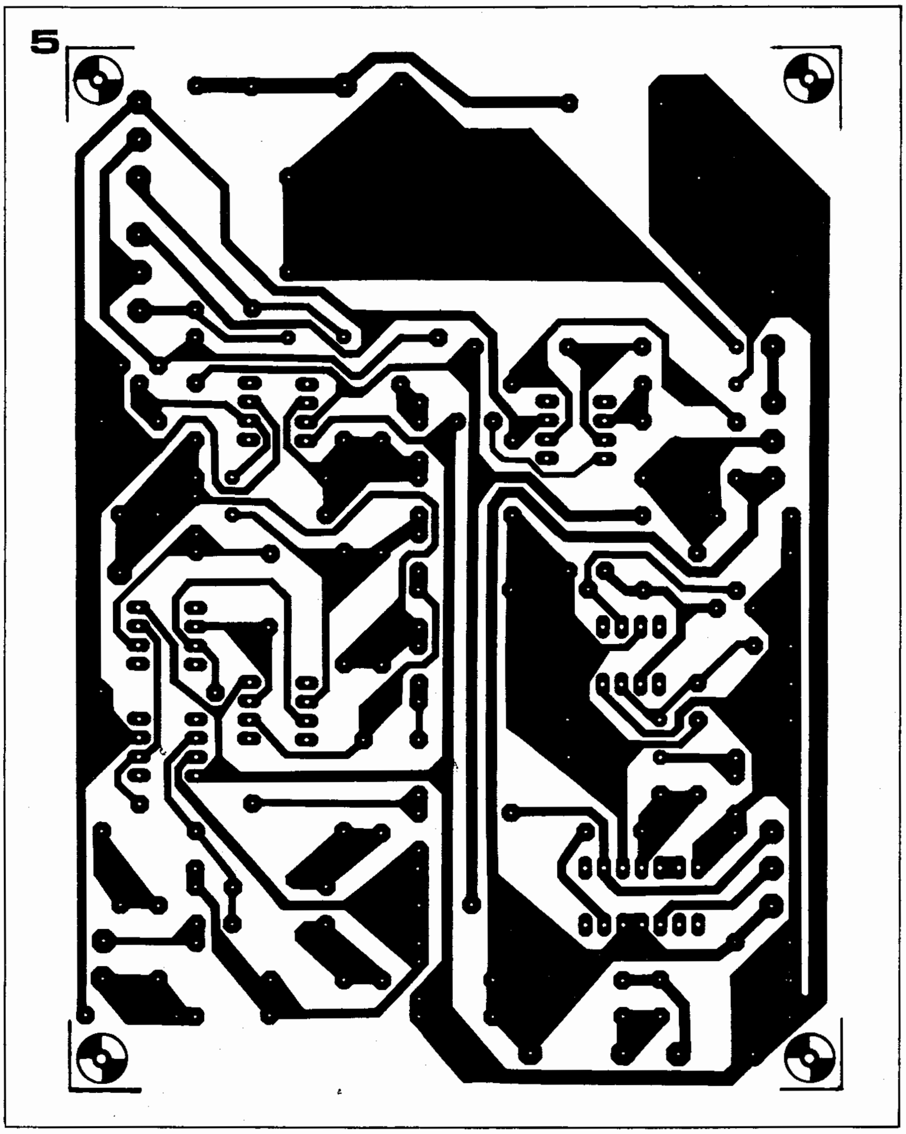


Figure 4. Complete circuit of the levitator.

Figure 5. Printed circuit board and component layout of the levitator. (EPS 9763)

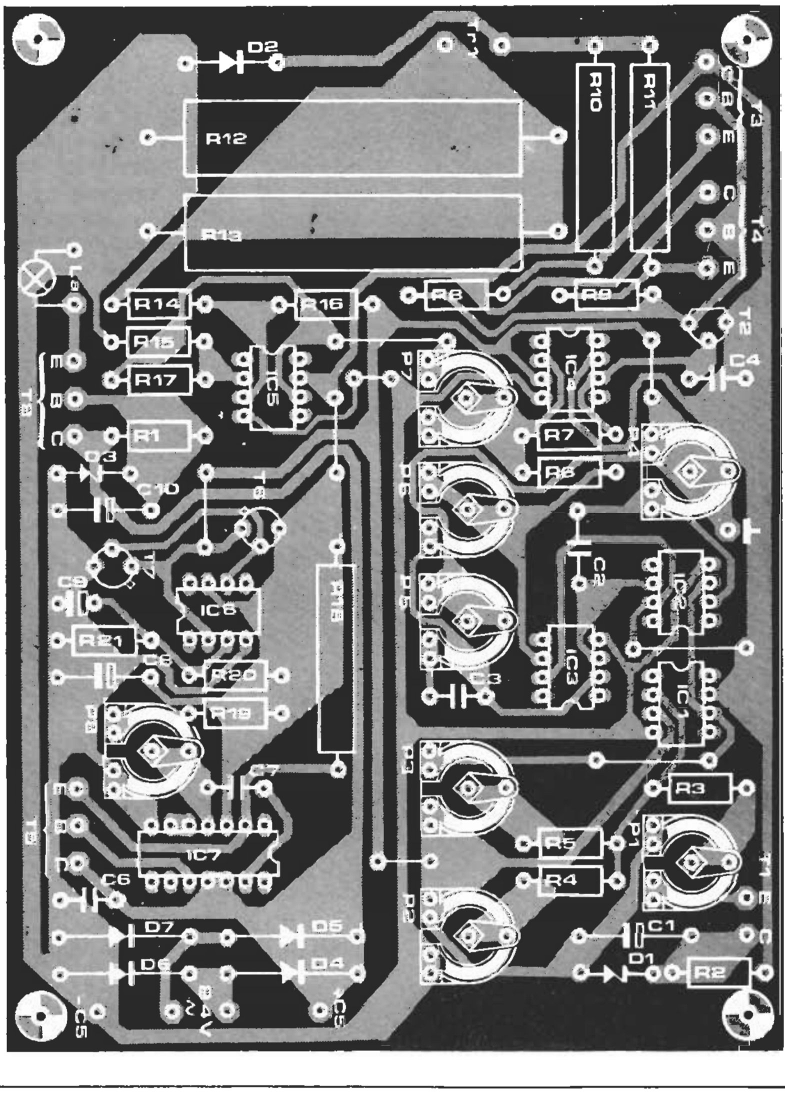
Parts list.

Resistors:
R1 = 2k7
R2 = 1k5
R3 = 33 k
R4,R5,R14,R15,
R16,R17 = 100 k
R6 = 10 k
R7 = 1 M
R8,R9 = 470 Ω
R10,R11 = 1 Ω/5 watt
R12,R13 = 10 Ω/11 watt
R18 = 0Ω22/5 watt
R19 = 1k8
R20,R21 = 47 k
P1,P3,P8 = 5 k (4k7) trimmer
P2 = 10 k trimmer
P4 = 100 k trimmer
P5 = 2k5 (2k2) trimmer
P6 = 25 k (22 k) trimmer
P7 = 50 k (47 k) trimmer

Capacitors:
C1 = 100 µ/6 V
C2 = 1 µ
C3 = 470 n
C4,C6 = 100 n
C5 = 2500 µ/35-40 V
C7 = 1 n
C8 = 10 µ/40 V
C9 = 10 µ/30 V, tantalum
C10 = 10 µ/25 V

Semiconductors:
T1 = BPY 61, BPY 62, BPX 62, MEL 11 or equivalent
T2 = BC 517
T3,T4,T5,T8 = 2N3055
T6 = BC 141
T7 = BC 161
D1 = 4V7/400 mW, zener
D2 = 1N4002
D3 = 12 V/400 mW, zener
D4 . . . D7 = Si-diode 3 A/40 V
IC1 . . . IC6 = 741
IC7 = 723

Miscellaneous:
LA = 12 V/1 W bulb mounted in reflector (torch)
Convex lens of approx 100 mm focal length
Tr1 = rebuilt mains transformer (see text)
Tr2 = mains transformer 24 V/3 A secondary



object tends to rise the reverse occurs. The light falling on the phototransistor decreases, hence so does the attractive force.

Mechanical details

Before proceeding with the circuit description it may be worth while further to discuss the mechanical details of the electromagnet and optical system.

1. The object must obviously be made of ferromagnetic material, e.g. iron, nickel, cobalt or a combination of these such as ferrous steel (not stainless steel).
2. The object should be fairly light in weight so that it can float at a reasonable distance from the solenoid without the need for an excessively strong solenoid.
3. The object should have a cross-sectional area sufficient completely to obscure the light beam.

Hollow containers such as shoe polish or tobacco tins meet these requirements admirably.

4. The light source in the prototype was simply a cheap torch with a reflector diameter of about 40 mm. The bulb was removed and replaced by a 12 V/1 W (or greater wattage) bulb, which is powered from the system's mains power supply. The light sensor can be made from a cheap 50 mm magnifier, as available from most large stationers, and a piece of PVC drainpipe to suit the diameter of the lens. The phototransistor is placed at the principle focus of the lens. To find the approximate focal length of the lens focus the image of a distant light source such as the sun to a spot on a piece of paper, then measure the distance between the paper and the lens. Alternatively a commercial light source/sensor could be used, but it must be fitted with a phototransistor, not an LDR.
5. The electromagnet can be made from a mains transformer which must have 'E' and 'I' laminations, and should have a secondary rating of about 60 V/2 A. The laminations are taken apart and the 'I' stack are discarded. The 'E' laminations are then reassembled so that they all face in the same direction, as shown in figure 2. The secondary of the transformer now becomes the coil of the electromagnet.

Alternatively, the solenoid can be purpose-made using ferrite 'E' cores with a winding of 1,500 turns of 0.2 mm enamelled copper wire. Depending on the core size used levitation distances of several centimetres can be obtained with such a purpose-built solenoid.

Control system

The positional feedback control system is a three-term, proportional plus integral plus differential control system, shown as the central block in figure 1. The controller is provided with five potentiometers that control respectively the desired position of the object, system gain (proportional term), integral term, differential term and damping. The system compares the desired pos-

ition of the object, represented by the slider voltage of P2, with the actual position information from the phototransistor and produces an error voltage to drive the solenoid. As the field strength of the solenoid is current dependent a voltage-current converter at the controller output converts the controller output voltage into a proportional current.
Although it is beyond the scope of this article to attempt a detailed mathematical analysis of a three-term feedback control system the general principles are fairly simple to grasp.

Proportional term

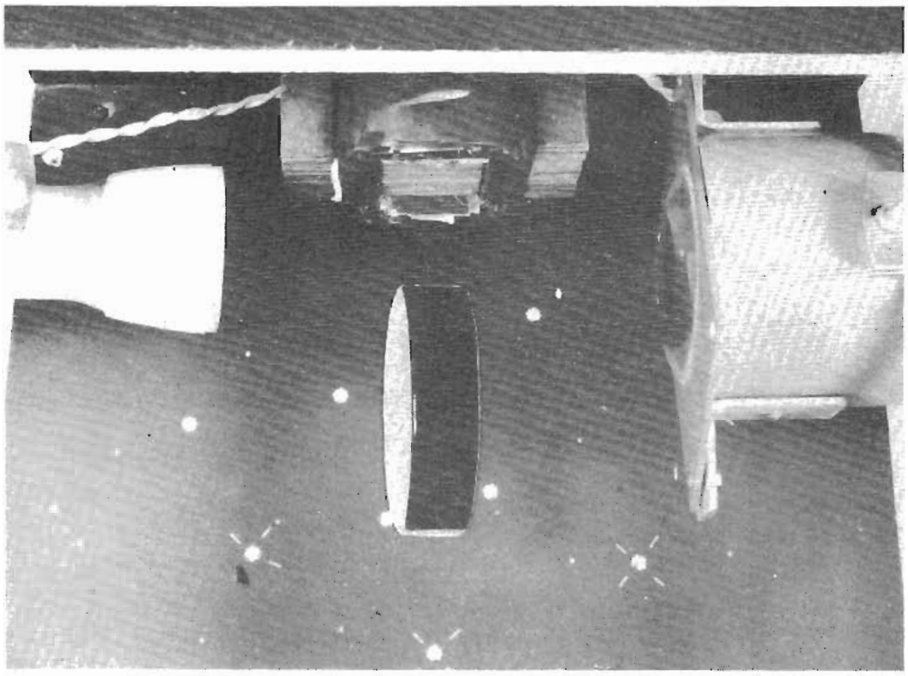
When the object is not in the desired position then the reference voltage provided by P2 is obviously different from the feedback voltage from the phototransistor. This difference is known as an error voltage, since it represents the positional error. This error voltage is amplified and used to drive the electromagnet to provide a restoring force which tends to return the object to the correct position. Obviously, the closer the object gets to the correct position the smaller is the error voltage and hence the restoring force, so that, unless the error voltage is amplified an infinite amount the object can never achieve exactly the correct position. This is where the integral term comes in.

Integral term

This integrates the error voltage over a period of time. The integrator output will thus ramp positive or negative depending on the polarity of the error voltage. The integrator output is added to the proportional output and also drives the solenoid. When the object is in exactly the correct position and the error voltage is zero then the integrator output will remain constant. In fact, in this condition the only restoring force is that provided by the integrator output.

Differential term

The differential term enables the control system to respond rapidly to any sudden displacement of the object. If this occurs then there will be a sharp step in the error voltage. The differential of the error voltage is simply its slope. Since the leading edge of the step has an extremely large slope (in theory infinite), the differentiator output will be a large, very short spike. The differentiator output is added to the integral and proportional terms and provides an initial large 'kick' to send the object in the right direction.
However, if the differential output is too large it can cause the object to go too far and overshoot the correct position. This can cause the system to become unstable when the object will oscillate about the correct position with ever increasing amplitude until it fianlly falls to the ground.
To overcome this problem a damping control P5 is provided, which limits the differential term.



The operation of the complete system may perhaps better be understood by reference to figure 3. If the object is displaced from the rest position and released then (depending on the degree of damping) it will oscillate about the rest position with a damped sinusoidal motion. Figure 3a shows the error voltage which decays in a similar fashion. In order that the action of the three terms may more easily be understood, this is simplified to a damped squarewave oscillation in figure 3b. Figure 3c shows the PID output corresponding to this.
The differential term can easily be recognised as the short positive and negative spikes. The integral term can be recognised as the positive and negative-going ramps, while the proportional term is simply the continuous level of the waveform.

Complete circuit

The complete circuit of the levitator is given in figure 4. The power supply circuit occupies the lower left-hand corner of the diagram. A 723 regulator IC with an external series pass transistor (T5) is used to provide a stabilised supply of 24 V at up to 3 A. A simple zener and transistor stabiliser D3/T8 provides a 12 V supply for the lamp. A zero volt reference for the op amps is provided by IC6, T6 and T7.
The proportional term of the controller is provided by IC1. This is simply an inverting amplifier with a summing input. The phototransistor current produces a voltage drop across P1 and a proportional current flows through R3 into the op amp. A reference voltage is provided by P2, and a proportional (negative) current flows through R4. The output of the op amp is a voltage which is proportional to the difference between these two currents, and this obviously depends on the setting of the reference potentiometer, the position of the object (and hence the phototransistor current) and the setting of the gain potentiometer P3. When the object is in the desired position then the currents through R3 and R4 will be equal and the output voltage of IC1 will be zero.
To sum up, IC1 produces a DC error voltage proportional to the displacement of the object from the correct position.
The integral term of the controller is provided by IC2. Any output voltage from IC1 will cause a corresponding voltage to appear across P4.
Since this voltage must cause a current to flow, which cannot come from the op amp input, a current must flow from the op amp output into C2, thus charging it. No matter how small the error voltage from IC1, a current will flow into C2, slowly charging it up. The output of IC2 will thus ramp positive or negative depending on the polarity of the error voltage. Only when the error voltage is exactly zero will C2 cease charging.
The integral term is thus responsible for the ultimate positional resolution of the system, since it will, over a period of time, integrate an error voltage, no matter how small, into a much larger voltage.
Since the output voltage of IC2 is equal to the voltage across C2 plus the voltage across P4 (which is equal to the error voltage) the output of IC2 is equal to the sum of the proportional and integral terms of the controller.
The differential term of the controller is provided by IC3. If the object is suddenly displaced an error voltage step will immediately appear at the output of IC1, and hence at the output of IC2. By definition this voltage must immediately appear (or try to appear) at the inverting input of IC3, i.e. across C3. The output of IC3 must thus swing either positive or negative (depending on the polarity of the input voltage) to charge C3 via P6. Since C3 must charge as quickly as possible the output of IC3 will swing hard against either the positive or negative supply rail.

To look at it another way, assuming P5 is set to zero the closed loop gain of IC3 is given by

$$\frac{P_6 + X_{C3}}{X_{C3}}$$

As far as the input voltage is concerned, C3 initially presents a very low impedance, so the closed loop gain of IC3 is very high and the output will saturate in response to a small step input. However, once C3 has charged IC3 simply acts as a voltage follower and the output is simply equal to the steady state input voltage, i.e. the sum of the integral and proportional terms.

P5 introduces resistance in series with C3 and damps the response of the differentiator. Without P5 the system would be unstable.

The function of the differentiator is to amplify the leading edge of the step error voltage by a large amount to make the system respond quickly to any displacement of the levitated object.

Voltage-current converter

The output voltage of the PID controller is converted into a current to drive the electromagnet by the voltage-controlled current source comprising IC4, IC5, T2, T3 and T4. Basically it consists of a power amplifier consisting of IC4 and the three transistors. IC5 monitors the voltage across R12 and R13, which is proportional to the current through Tr1, and thus provides current-dependent negative feedback.

Construction

A printed circuit board and component layout for the levitator circuit are given in figure 5, and the construction should pose no problems. Potentiometers P2 to P6 may be presets, or leads may be brought out to normal potentiometers so that easy adjustment of the circuit parameters is possible for demonstration purposes. T3 and T8 should be mounted on heatsinks of not less than 3°C/W thermal resistance.

Adjustment

Sockets should be provided for mounting IC1 to IC5 and initially only IC6 and IC7 should be mounted on the board. Set all presets to their mid-positions. Power can now be applied and P8 adjusted until the collector emitter voltage of T6 is exactly 12 V. P2 should now be adjusted until the slider voltage of P2 is −8 V with respect to ground. The other ICs can now be plugged into their sockets.

The object can now be placed in the light beam and P1 be adjusted until the object is attracted to the electromagnet. It will usually begin to oscillate violently. This can be controlled by adjustment of the damping potentiometer P5 and the gain potentiometer P3. Further improvement may be effected by adjustement of the integral and differential controls P4 and P6, and by the voltage-current converter feedback potentiometer P7. The effect of these various controls is obviously a matter for experiment. ◾

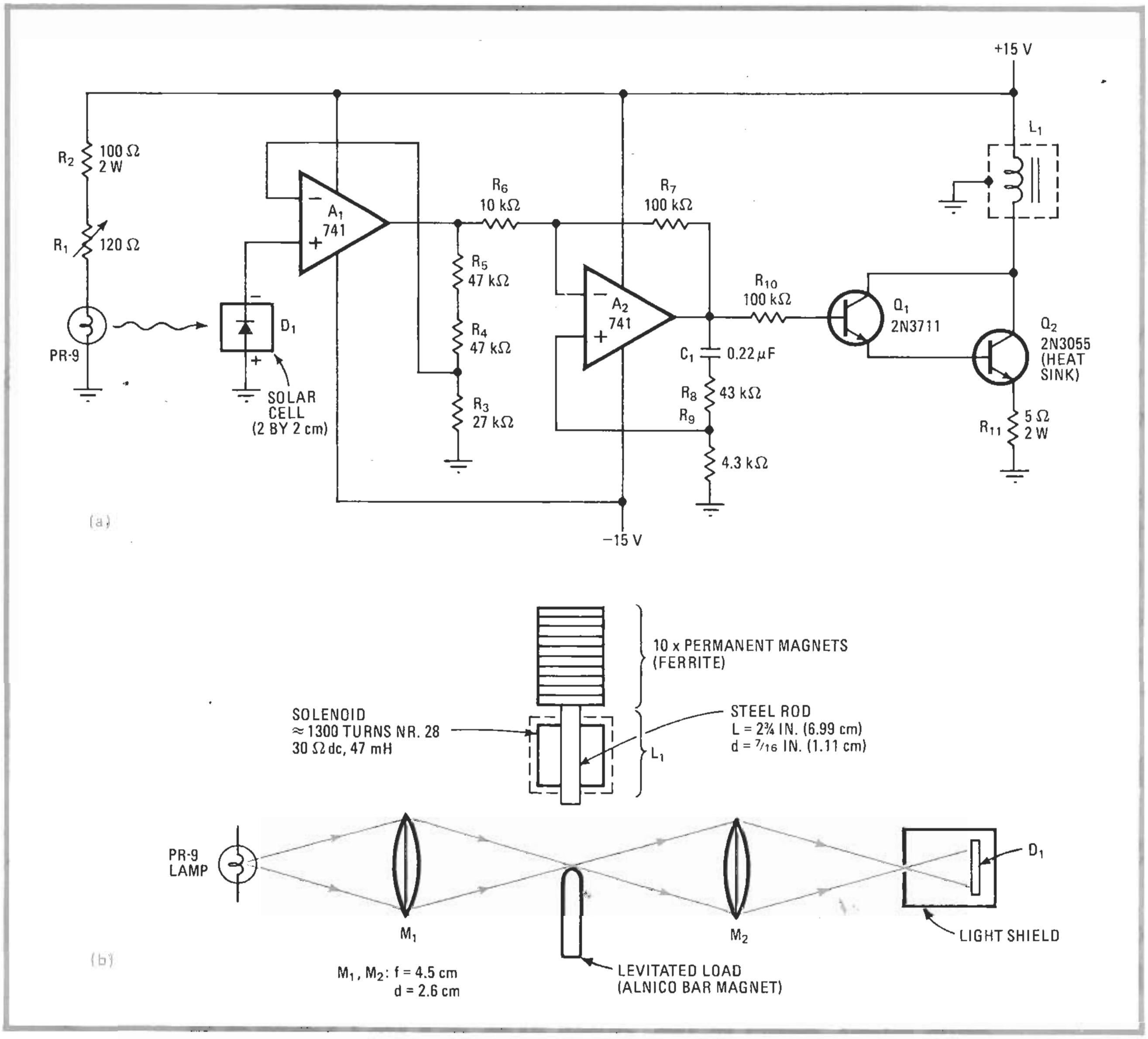
Magnetic levitator suspends small objects

by Bob Leser
Desert Technology, Las Cruces, N. M.

This circuit is a modern solution to the problem of securing frictionless bearings for small rotors and levitating small magnetic objects a few millimeters in space. Operational amplifiers replace the tubes used in earlier approaches, and an optical arrangement replaces the radio-frequency induction circuit originally used to position the object.

Potentiometer R_1 (a) sets the current through the PR9 lamp and thus its brightness and the gain of the position-sensing circuit. R_1 thus provides a fine adjustment of the position of the magnetic object that is suspended beneath the levitation coil L_1. The optical position-sensing circuitry (b), which should be mounted horizontally under L_1 if possible, includes two lenses to focus the beam via the levitated load to solar cell (photodetector) D_1. The light shield, with an aperture of approximately 3 millimeters, effectively eliminates background light. The suggested focal lengths and lens diameters are shown; as a check on the optics system, the beam should be aligned to yield a short-circuit current of 4 to 25 microamperes in D_1.

As for the basic circuitry, D_1's output is amplified by about 5 by operational amplifier A_1 and is then introduced to A_2, which is the all-important servo-loop stage. C_1, R_8, and R_9 provide positive feedback of the high-frequency components of the positioning signal. The stage thus generates the voltage derivative of the amp's output, preventing oscillations in the closed loop that would otherwise occur because of the lack of damping in

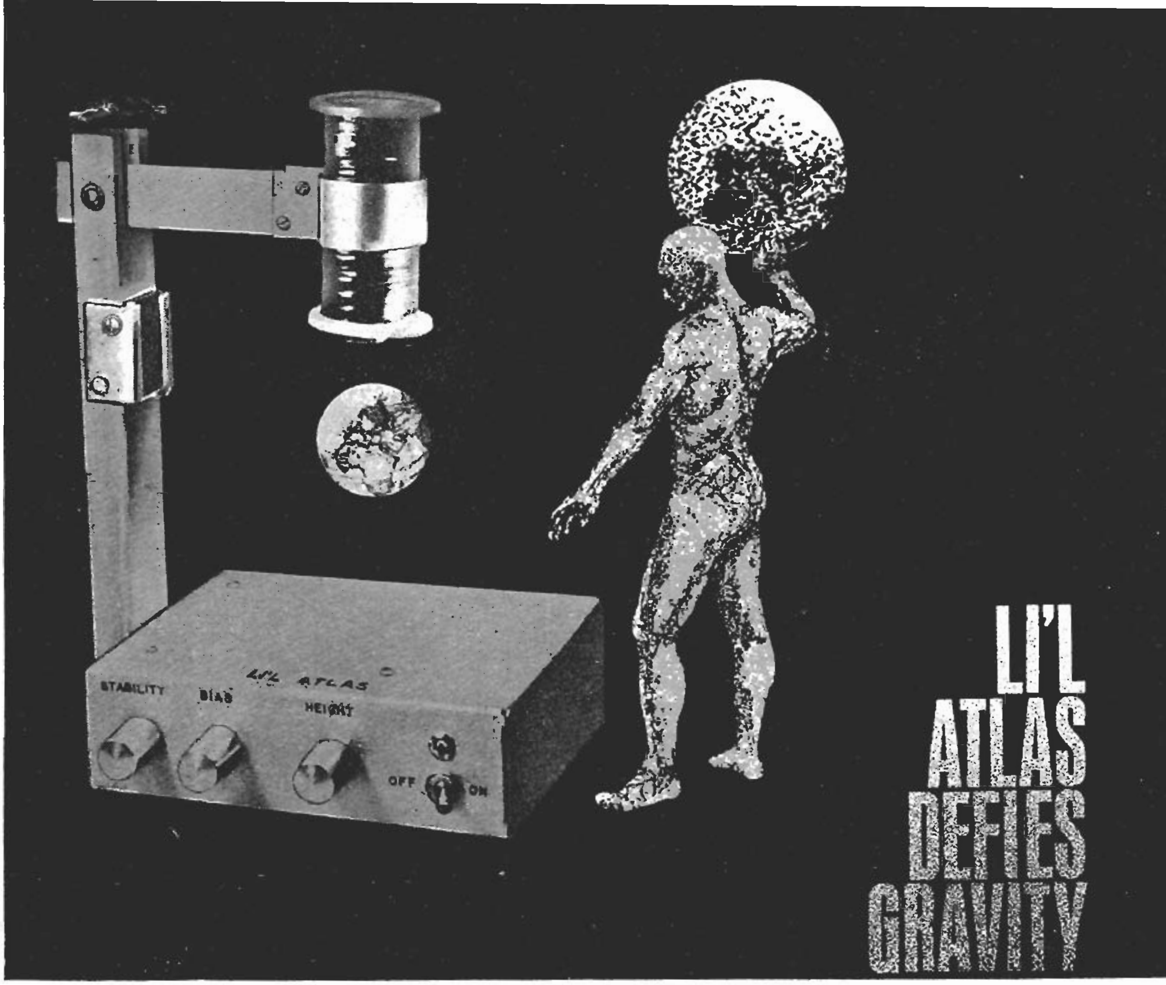


Rising rotors. Levitator circuit (a) suspends 1-in. steel spheres up to 2½ millimeters off reference surface. Optical arrangement (b) sets object distance. Details of levitation coil construction are outlined. Permanent magnets set ultimate levitation range.

the position servo portion of the circuit. Any closed-loop oscillation will be manifest as vibration of the levitated object.

Output stage Q_1 to Q_2 is a discrete darlington pair that drives L_1. The coil itself has 1,300 turns around a steel rod 2.75 inches long and 7/16 in. in diameter. A stack of 10 small permanent magnets atop the coil provides a bias field extending the range of levitation beyond that which would be normally attained. The coil is surrounded by a grounded shield to reduce the amount of stray coupling to the op amp inputs.

The most stable closed-loop condition is set by adjusting Q_2's collector voltage to about 7.5 volts by altering the levitation distance between the sensing optics and L_1. Levitation distances in this circuit range from about 20 millimeters for a small Alnico bar magnet to 2½ mm for a steel ball with a diameter of 1 in. □



LI'L ATLAS DEFIES GRAVITY

Like orbiting satellites, objects just float in space when magnetic attraction overcomes the pull of gravity

By WILLIAM J. PRICE

UNLIKE the Atlas of Greek mythology, condemned to carry the heavens on his shoulder for all time, "Li'l Atlas" is no myth. It's an electromagnetic photoelectric type of servo system that can establish a weightless condition on small metallic objects. And it's sure to steal the show at any Science Fair.

You place an object—an ordinary door key, a child's tin toy, or a small metal globe like the one shown—in the device's "sphere of influence." Then, like the boys at the Cape, you man the controls to suspend the object in space. You can move it up or down, or even wiggle it, if you wish.

How It Works. A photoelectric cell serves as a position sensor, and controls the intensity of a magnetic field that is used to counteract the pull of gravity on the object being suspended. (See photo.) Photocell *PC1* is mounted on a wooden column opposite a light source. When an object is suspended, it breaks part of the light beam reaching *PC1.*

If the object begins to fall, more light reaches the photocell, increasing the photocell's output current (Fig. 1). This current increase is amplified by *Q1* and *Q2*, and direct-coupled to power transistor *Q3*, whose output is in series with an electromagnet (coil *L1*). The resulting current increase through *L1* causes an increase in its magnetic field to overcome the pull of gravity, raising the object back up in place.

Similarly, if an object is raised above its predetermined height, less light falls on *PC1*, reducing the current to *Q3*. The magnetic field intensity is decreased, al-

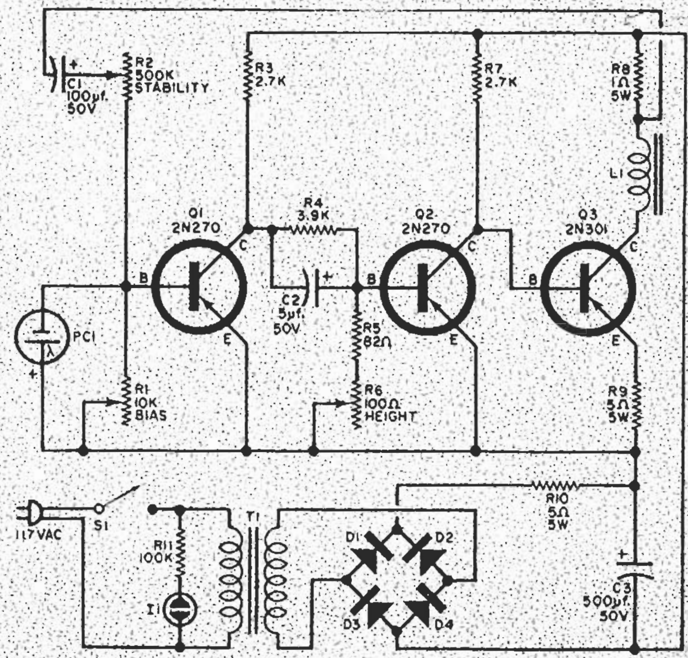


Fig. 1. Like a Palace Guard, photocell PC1 keeps an eye on the object in space. If the object tends to fall, the photocell rushes the information via the transistors to coil L1 (the electromagnet) which, in turn, acts to increase the pull on the object to prevent it from falling. Conversely, if the object is being pulled too close to the coil, PC1 detects this condition and reduces magnetic pull to re-establish equilibrium.

lowing the object to drop down to its proper position.

The *BIAS* potentiometer, *R1*, controls the amount of current through *Q1* for proper operation under existing lighting conditions. Similarly, the *HEIGHT* control, *R6*, adjusts the bias on *Q2*, and establishes the height range through which an object can be suspended. The *C2-R4* coupling network stabilizes *Q2*'s base current for a smooth response. *STABILITY* control *R2* stabilizes the oscillatory tendency of the suspended object by adjusting the amount of feedback voltage developed by *R8* and fed back to *Q1* through *C1*.

The power supply is comprised of filament transformer *T1*, a full-wave bridge rectifier (*D1* through *D4*), limiting resistor *R10*, and filter capacitor *C3*.

Construction. If you use the chassis listed here, your first task is to lay out and drill the holes as shown in Fig 2. If you elect to use a different chassis, the suggested layout can still be followed except for the dimensions—which may change.

Once the chassis has been drilled and deburred, lay it aside temporarily while you proceed to make the wooden bracket,

PARTS LIST

C1—100-µf., 50-volt electrolytic capacitor
C2—5-µf., 50-volt electrolytic capacitor
C3—500-µf., 50-volt electrolytic capacitor
D1, D2, D3, D4—1N2859A silicon diode or equivalent
I1—NE-2 pilot light
L1—Coil—see text
PC1—1½" x ¾" selenium photocell (Lafayette Radio 99 R 6244 or equivalent)
Q1, Q2—2N270 transistor
Q3—2N301 or 2N2869 transistor
R1—10,000-ohm potentiometer, linear taper
R2—500,000-ohm potentiometer, audio taper
R3, R7—2700-ohm, ½-watt resistor
R4—3900-ohm, ½-watt resistor
R5—82-ohm, ½-watt resistor
R6—100-ohm potentiometer, linear taper
R8—1-ohm, 5-watt resistor
R9, R10—5-ohm, 5-watt resistor
R11—100,000-ohm, ½-watt resistor
S1—S.p.s.t. toggle switch
T1—Filament transformer: primary, 117 volts a.c.; secondary, 25.2 volts at 1 amp. (Stancor P-6469 or equivalent)
TS1—Single-lug terminal strip
1—5" x 7" x 2" aluminum chassis (Bud AC-402 or equivalent)
1—3½" x 4" Vectorbord
2—1¾" x 2" x ⅛" pieces of Lucite or Bakelite
1—TO-3 insulated transistor mounting kit
1—10"-long wooden column
1—4½"-long wooden cross arm
Misc.—Photocell mounting brackets, electromagnet mounting bracket, No. 26 Formvar insulated magnet wire (1 lb.)—see text, transistor sockets, ⅜" rubber grommet (2), #6 solder lug; ⅜"-o.d. rubber feet (4), knobs, etc.

photocell mounting bracket, and the coil support strap, as shown in Fig. 3.

Winding the Coil. The coil is wound on a ½″ x ¾″ x 3½″ core made from laminated strips of mild steel (Fig. 4). You can have these strips made up by your local sheet metal shop, or they can be salvaged from an old power transformer core.

Clamp the laminations tightly together, then wrap a layer of black plastic tape around the core to hold the laminations close together while the coil is wound. This will also prevent the wire forming the first layer of the coil from being stripped by the sharp edges of the core. At one end of the core, keep the tape ⅜″ away from the edge.

Cut a ½″ x ¾″ opening in the center of one of the two Lucite or Bakelite end stops. Insert the piece with the cutout over the end of the core with the ⅜″ recessed tape. Center the other piece of Lucite over the other end of the core. Then, cement both pieces of Lucite in place using epoxy cement.

Allow sufficient time for the epoxy to dry thoroughly, and close-wind 800 feet of #26 Formvar magnet wire (approximately 2500 turns) on the core. Wrap one or two layers of plastic tape around the finished coil to protect the wires and hold the turns in place. Remove about one inch of varnished insulation from both ends of the coil using a fine file or sandpaper, then tin the bare wire. The d.c. resistance of the finished coil is approximately 30 ohms.

Installing the Parts. You are now ready to begin mounting the components on the 4″ x 3½″ prepunched Vectorbord. Do not mount *Q1* and *Q2* any closer to the 5-watt resistors than is shown in Fig. 5. Also, make certain the capacitors and diodes are connected with polarities as shown.

Mount the filament transformer and terminal strip using *8-32* x ½″ screws

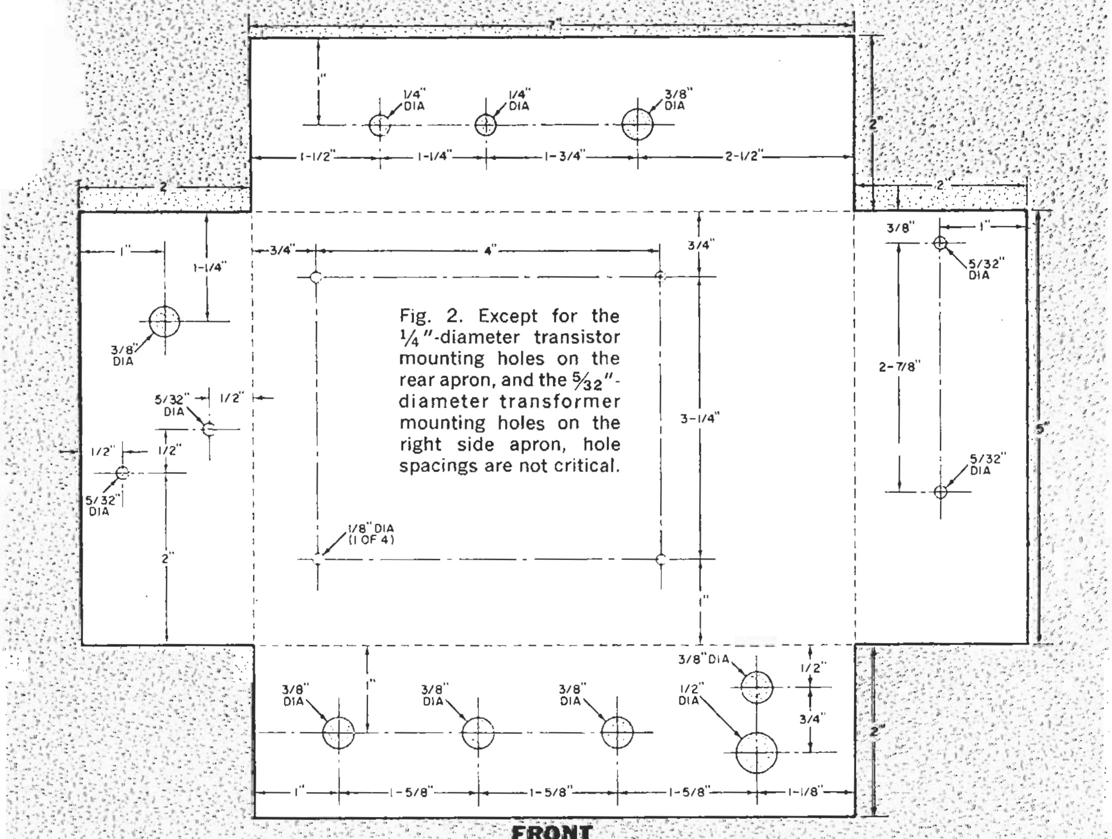
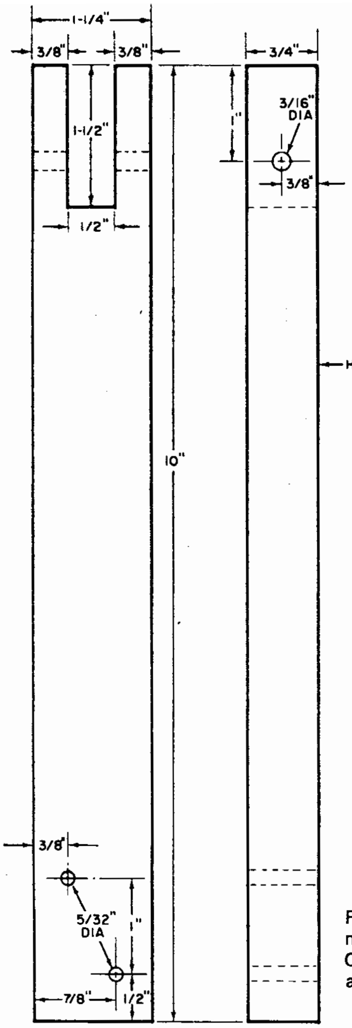
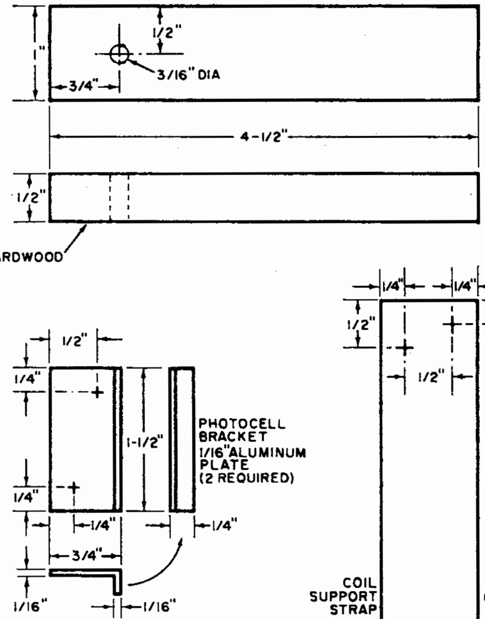


Fig. 2. Except for the ¼″-diameter transistor mounting holes on the rear apron, and the 5⁄32″-diameter transformer mounting holes on the right side apron, hole spacings are not critical.

Fig. 3. These are the dimensions of the wooden support and crossarm that were used in the author's model. If desired, ¼" hardwood can be substituted for the aluminum photocell bracket.





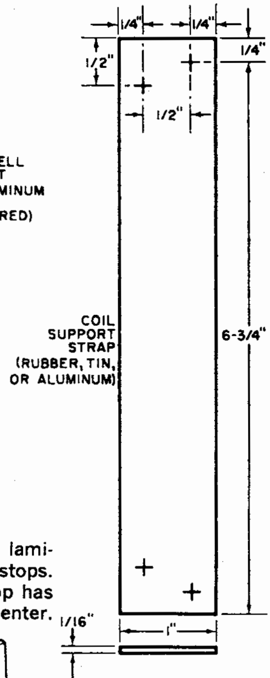
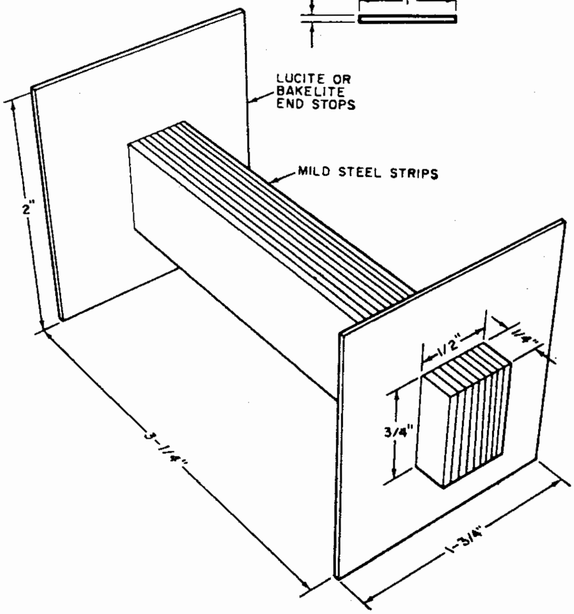


Fig. 4. Coil core showing laminated steel strips and end stops. Observe that only one end stop has a ½" x ¾" cutout in its center.



and nuts. Note that the terminal strip is held in place with one of the transformer screws.

To mount *Q3*, drill the *base* and *emitter* holes using the mounting kit's diamond-shaped mica washer as drill guide. Apply silicon heat-sink grease to the transistor mounting surface to insure good heat transfer. The base terminal must be positioned toward the top of the chassis while the emitter faces toward the bottom. The collector is grounded to the case. Be sure the #6 solder lug is mounted on the screw as shown.

Now install the two ⅜" rubber grommets, controls *R1*, *R2*, and *R6*, and the pilot light assembly. Connect a 100,-000-ohm resistor (*R11*) from one of the

(*Continued on page* 84)

LI'L ATLAS DEFIES GRAVITY

(*Continued from page 70*)

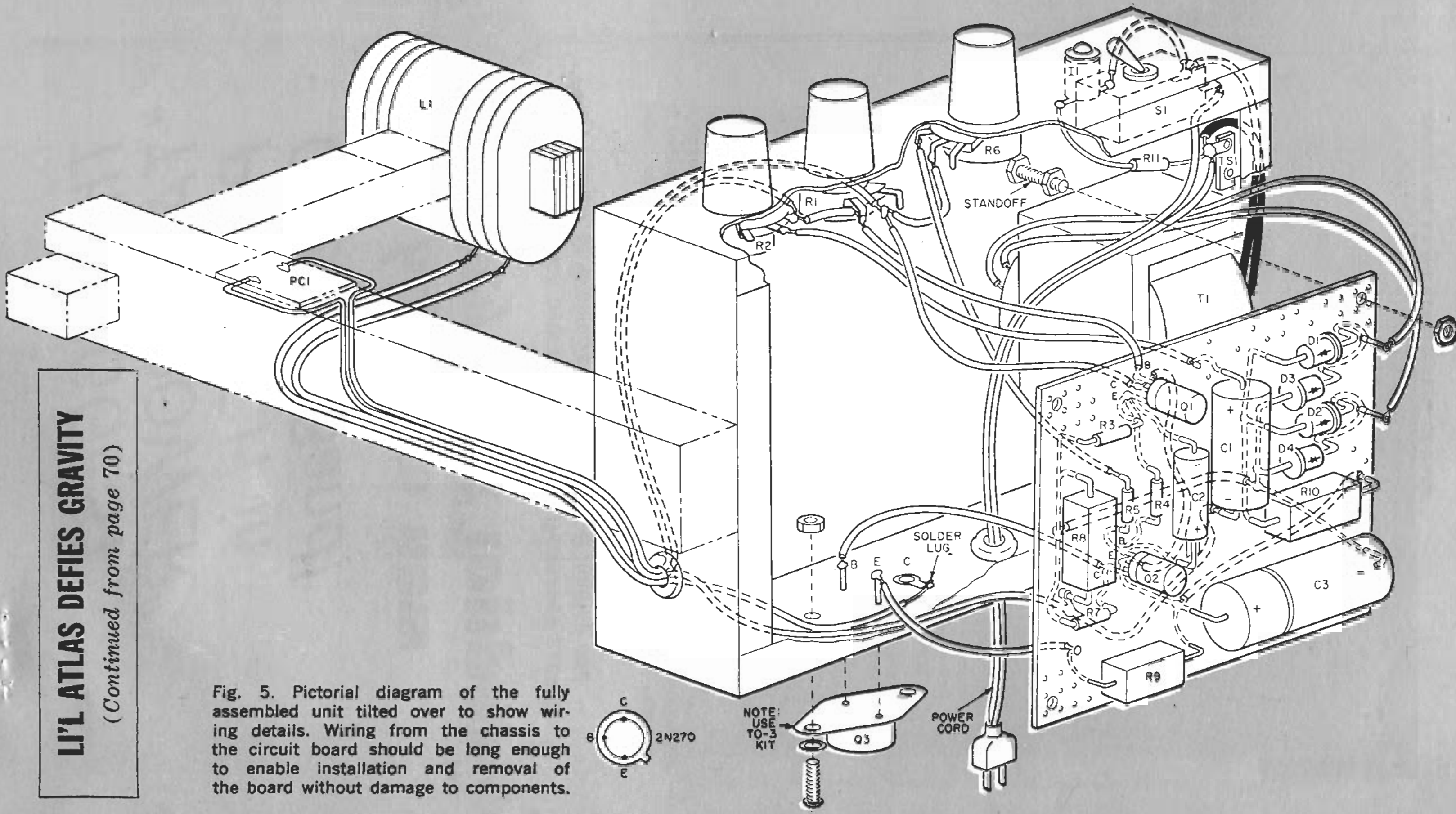


Fig. 5. Pictorial diagram of the fully assembled unit tilted over to show wiring details. Wiring from the chassis to the circuit board should be long enough to enable installation and removal of the board without damage to components.

pilot light terminals to the terminal strip, and connect one end of a 3″ length of insulated hookup wire to the free terminal of the pilot light. Insert the line cord through the grommet provided, and connect one of the leads to the terminal strip. Then connect one of the transformer primary leads (black) to the terminal strip. Solder all leads.

Position the power switch (*S1*) close to its chassis mounting location. (Do not mount the switch at this time.) Connect the remaining transformer black lead to one of the switch terminals. Then connect the free end of the hookup wire from the pilot light to the same switch terminal, and the free lead from the line cord to the other switch terminal. Solder all leads and mount the switch on the chassis.

Mount the coil and photocell on the assembled wooden bracket as shown in Fig. 6, and secure the bracket to the chassis. Feed the leads through the grommet, and connect the wires as shown in Fig. 5.

Finally, insert four *6-32* x 1¼″ screws down through the top of the chassis,

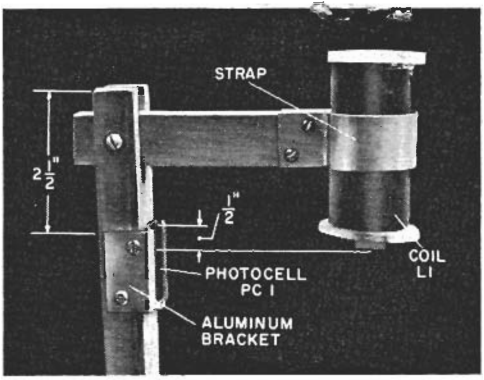


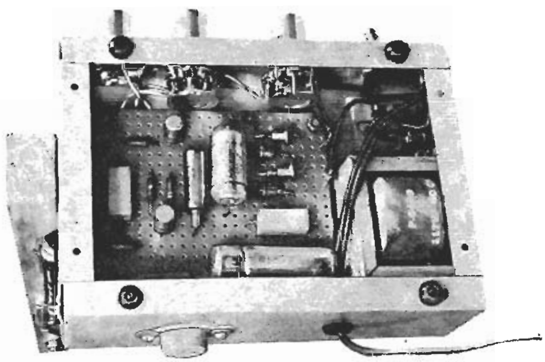
Fig. 6. The distance of the photocell from the coil is not critical. You may prefer to mount the photocell entirely away from the unit, perhaps on a wall. The coil should be aligned as shown, however.

tightening the nuts against the inside of the chassis. Thread a second nut ¼″ down on the screw to act as a standoff for the component circuit board. Then mount the circuit board and complete all wiring.

Operation. Before plugging in the Li'l Atlas, check to make sure that (1) exposed coil terminals are not grounding out against the supporting metal strap, if one is used; (2) the coil and photocell are properly positioned as shown in Fig. 6; (3) all connections have been soldered, and there are no shorts.

Place a light source (a 50- or 60-watt desk lamp will do) opposite the photocell, and about two feet away from it. Position the light so that the exposed end of the coil core casts a shadow on the upper portion of the photocell. If Li'l Atlas is to perform in a strongly lighted room, shield the photocell with a piece of cardboard or paper tubing.

Now all you need is a small object that will remain suspended in space. Almost any small iron or steel object, such as a key, can be used. If you want something that will spin as it floats around, obtain a round object such as a tiny globe which you can get in a dime or stationery store.



Interior view showing components mounted on perforated phenolic board, suspended on standoff screws. Transistor Q3 is mounted on the chassis back panel while transformer T1 is on the inside of the right panel, directly behind the on/off switch.

Turn on Li'l Atlas and set its *STABILITY* control for maximum resistance, the *BIAS* control for minimum resistance, and *HEIGHT* control to midpoint. Loosely hold the object about ¼" below the magnet, and advance the *BIAS* control until the magnet begins to pull. Then adjust the *STABILITY* control to "settle down" the object as it begins to oscillate. Remove your hand and the object will remain suspended.

You can cause the object to vibrate rapidly for special effects by advancing the *STABILITY* control. —30—