SINCE the first digital control systems began to appear 3 or 4 years ago, inevitable comparison with analog systems indicated digital superiority in most areas, particularly resolution and reset accuracy. Further study showed that the "digital" servo was and is an analog servo with the same limitations and a bit more complication. A better name for the Digital Servo is a pulse width feedback servo.

Could a D.C. feedback servo be made as good as a pulse width feedback servo? Just a bit more than a year ago I had the chance to compare the two approaches on as nearly equal footing as is practically possible. Both servos used the same mechanical parts with both amplifiers pruned for peak performance.

As analysis predicted, there was **no** discernible difference. The difference in performance lay in the circuit design of the amplifiers. Beginning at the motor driver transistor, the first important difference appeared. It is imperative that these transistor switches have very little voltage drop when they are in the conducting state. This in turn means that they must be saturated and that they must be overdriven. In practice saturation requires that the load be placed in the collector or that the base be "pulled" above the collector if the load is placed in the emitter of the output unit. Figure one illustrates the basic circuits most often used. Figure 1(a) substitutes

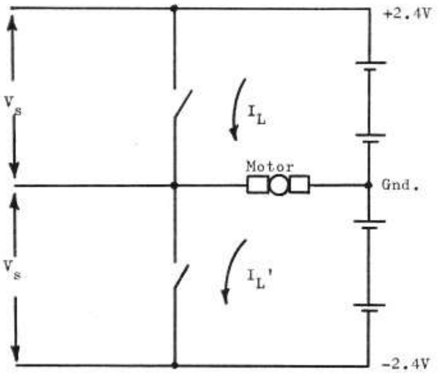

Fig. 1A: Two switch equivalent of a transistor output stage.

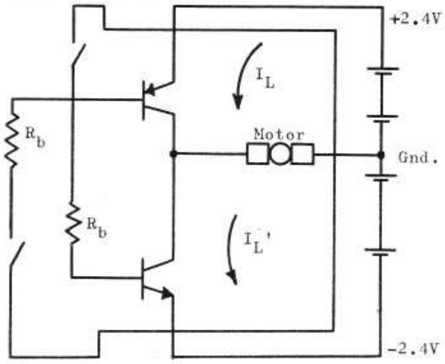

Fig. 1B: Complementary (NPN & PNP) output with 4-cell battery supply.

switches for the transistors. Ideally I^L should be equal to $I^{L'}$. The motors of most servos demand currents between

ANALOG FEEDBACK SERVO

By JOHN PHELPS

Step-by-step construction of an analog feedback servo adaptable for use with commercial analog systems—easily built from scratch or currently available in kit form.

0.5 and 1.0 amperes with the motor not running (armature blocked). No-load current can run between 1% and 80% of the blocked current, depending on the motor losses. Running current is

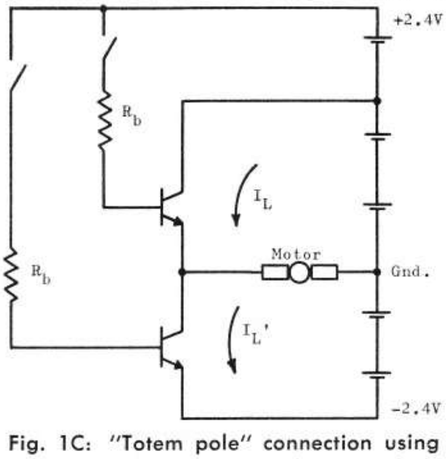

Fig. 1C: "Totem pole" connection using transistors of the same polarity and an extra cell to saturate the top transistor.

seldom less than 0.1 amperes in actual service with a useful load. The saturated voltage drop, v^s, should be less than 0.3 v. with a battery voltage of 2.4 v. (nominal). Higher drop reduces speed, resolution and torque.

The Totem pole connection, see Fig. 1c, widely used in reed and pulse-width servo design was devised to sidestep the need for similar NPN & PNP transistors. Historically, PNP transistors with the required "guts" and low cost were available first and so were used first. The extra battery required was, and is, no particular burden, since it eases receiver design and as many as seven batteries are used in well designed systems. The current availability of good NPN & PNP transistors allows more freedom in design and also eases the battery weight problem, since only 4 cells (4.8 v.) are necessary (see Fig. 1b). In any case, the output transistors must never be al-

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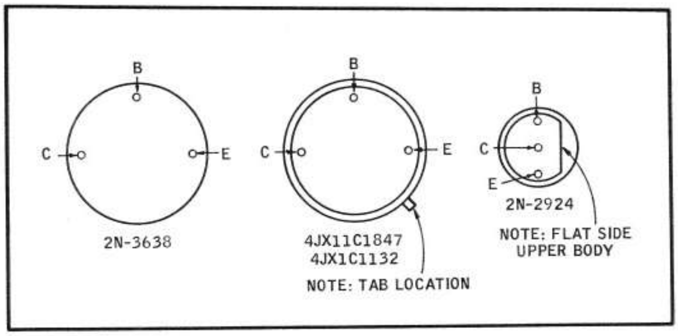
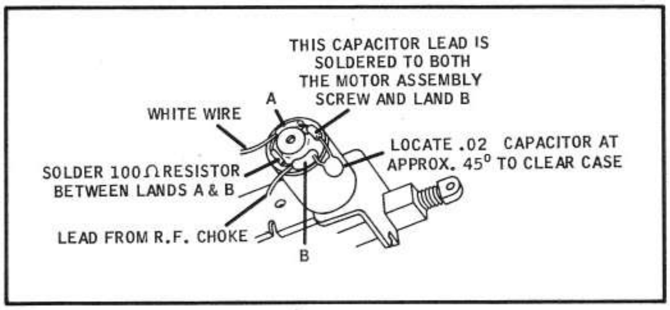
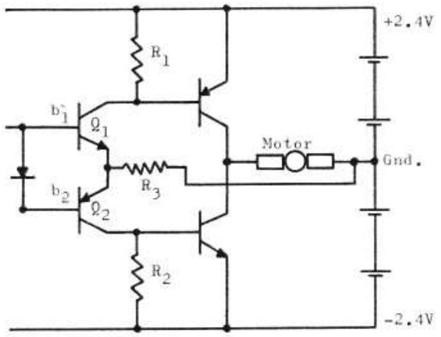
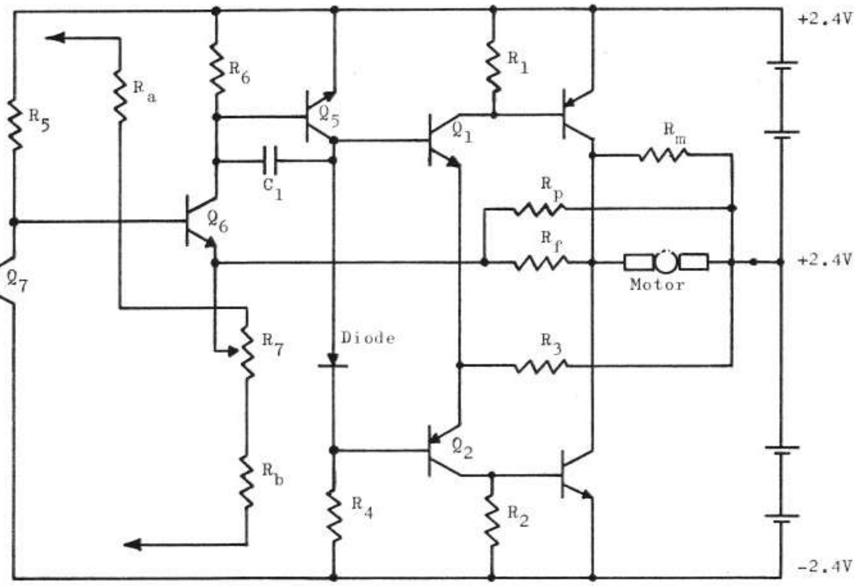




lowed to conduct simultaneously. If they do, Pow! Tremendous current flows from +2.4 to −2.4 battery taps, limited only by the transistor's bulk resistance (for the short time it's around). Figure 2a adds the driver transistors. Note that



Above: Fig. 2A. Right: Fig. 2B.



their emitters are tied together and returned through a common resistor R_3 to the supply side of the load. R_3 is chosen to limit driver current to a safe value and assure generous drive current to the switch transistors. R_1 and R_2 divert collector base leakage current and prevent unwanted transistor turn on at elevated temperatures. This is essential for all types of output transistors, particularly germanium. The use of hermetically sealed (metal can) transistors is advisable for long life in the output units. R_1 and R_2 also speed transistor turn off so that switching time overlap (period during which both output transistors are on) is held to a safe value. This period must be less than 10% of the thermal time constant of the chosen transistor and can be reduced to zero as will be shown. If b_1 and b_2 are tied together, Q_1 will conduct if their juncture is made positive by several tenths of a volt (.2 for germanium drivers, .5 for silicon) with respect to ground (battery center-top) or Q_2 will conduct if the polarity is negative. Note that 0.4 volts dead-band exists for germanium drivers, 1.0 volt for silicon and 0.7 v. for a mixed pair. Any voltage within this range will not turn on either and so it

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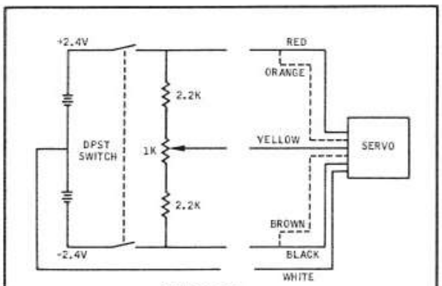
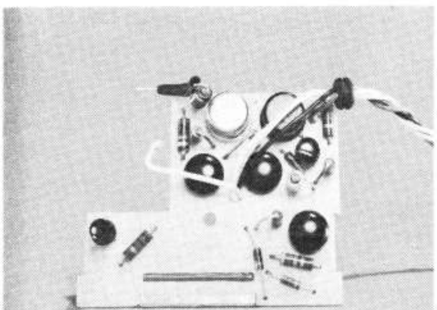
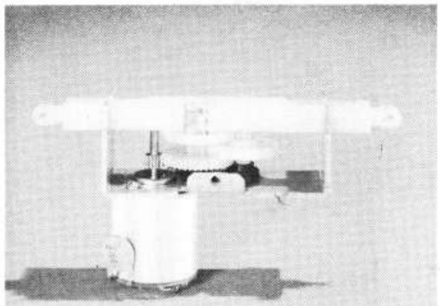
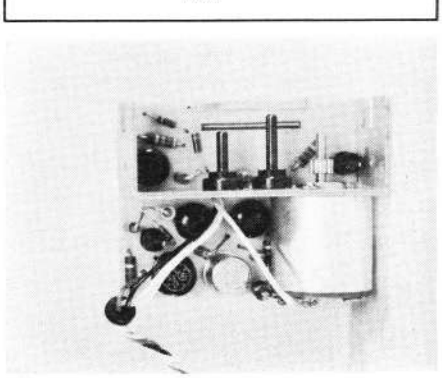
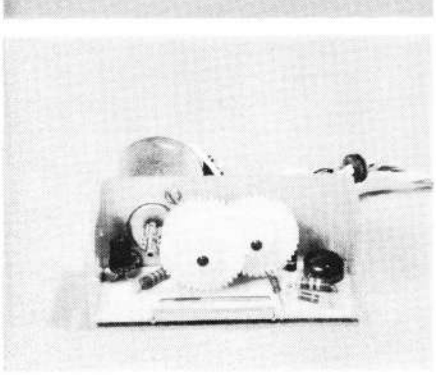


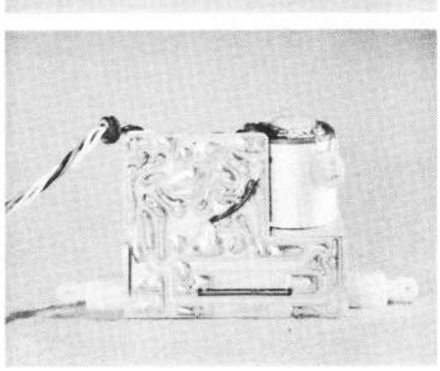
ANALOG SERVO
FIG. 6











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represents a region of no response, thus the term dead-band. One or more diodes (depending on their type), can be connected, as shown, between b_1 and b_2 to offset this dead-band and improve resolution. One silicon diode is sufficient and allows a voltage margin which can be converted to a time delay to prevent any conduction overlap in the output transistors, with the addition of C_1 in Fig. 2b.

Fig. 2b adds a resistor R_4 and transistor to provide voltage gain. The value of R_4 is chosen to be approximately equal to the product of the current gains of the output and driver transistors and the blocked armature resistance of the motor. The voltage gain of the stage is $= \frac{R_4}{hib} = 10$. Dead-band is now only 20 millivolts or 2% in a system furnishing $\pm .5$ v. of error signal. If the collector current of Q_5 is just enough to set the drop across R_4 at 2.4 volts, both output transistors will be off. More or less collector current will cause either Q_1 or Q_2 to conduct. Q_6 compares the voltage at its base and the voltage at its emitter and meters current flow in Q_5 accordingly. R_6 protects Q_5 & R_7 if R_7 goes to the -2.4 v. end of travel. If a voltage is set at the base of Q_6 say .2 v. then Q_1 or Q_2 will conduct and run R_7 (connected to the motor shaft until it reaches (0.2-0.5) v. or -0.3 volts. The 0.5 volt figure represents the base emitter drop of Q_6, the silicon input transistor. Unfortunately, the .5 v. figure is nominal and temperature sensitive. For any given error voltage there can be any number of servo positions satisfying the balance condition depending on ambient temperature.

The drift rate is 2mv/$^\circ$c. A change of 25° C. will move the neutral 50 milli-

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(*Continued from Page 59*)

volts in a ±500 mv system or represent a drift of 5% in neutral setting. One additional transistor can offset this variation and provide drift-free performance. The base emitter junction of the PNP emitter follower has a drop equal but opposite to that of Q_6. Its base tracks the divider arm of R_7 and its drift rate of -2 mv/o^c compensates for the drift rate of Q_6. Although a diode could have been used, there is usefulness in the current gain afforded by Q_7. The required error current is typically less than **one microampere.**

The feedback resistor (Rf) reduces and stabilizes the overall power gain, and is selected in conjunction with servo motor and gear train to balance between resolution and fast settling time. R^a and R^b determine the shaft rotation for a given input error voltage change.

With closure of the feedback loop by Rf comes the danger of high frequency oscillation. Use of a capacitor across the motor brushes provides a convenient way of reducing brush arcing noise but virtually guarantees oscillation in the 50 to 500 kc frequency range. If allowed to exist, this oscillation will destroy the output transistors in short order. A 100 ohm resistor, Rm, across the motor brushes and reduction in high frequency gain of the amplifier through gain "break" networks effectively removes the oscillation threat.

Returning to the resistors R^a and R^b, their value is determined by the value of the feedback pot and the desired output arm travel for a given maximum change in error voltage. If the servo is to be at mid-position for an error voltage of +2.4 volts, relative to ground, then R^a and R^b cannot be equal because of the extra drop in R^b caused by the several hundred microamperes of emitter current flowing through R^b from Q_6. This imbalance complicates setting the values of R^a and R^b needed for replacement of servos in several existing, popular systems. A further complication is the interaction of the values of R^a, R^b and R^f. Because of the foregoing mess a simple scheme was sought which would solve the complication of optimizing the servo for several applications. The resistor R^p does this neatly.

	Value of R^p for equivalent push-rod travel
Airborne Control labs (MK II)	**Omit**
Citizenship	**Omit** to 4700
Sampey (404 and Starlight series)	**470 ohms**
Space Control	**Omit** to 4700 ohms
Orbit	**1200 ohms**

If, in any application, additional servo travel is desired, R^p can be decreased

(*Continued on Page 62*)

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(*Continued from Page 60*)

with **no sacrifice in performance.** Resolution which is **better** than most digital servos is preserved. R[D] may be reduced to 100 ohms — at this value full servo travel is had with **±100 millivolts** — again, the resolution is not even slightly compromised.

CONSTRUCTION

The printed circuit board can be duplicated by the standard photo process. Your local blueprint shop can produce an actual size negative from the P.C. board artwork included with this article. All electronic parts are available from major electronic suppliers. A complete kit of the analog servo is available from Controlaire, division of World Engines.

ASSEMBLY INSTRUCTIONS

( ) 1. During installation of components to board, refer to illustrations for component locations and hole numbers.

( ) 2. Install R — 1, a 47 K ohm ¼ watt resistor (yellow, violet, orange) in holes 8 and 9, lying flat.

( ) 3. Install R — 2, a 1.2 K ohm ⅛ watt resistor (brown, red, red) in holes 6 and 7, lying flat.

( ) 4. Two identical 1.2 K ohm ¼ watt resistors (brown, red, red) are installed in this step. Install R — 7 in holes 30 and 31. Stand vertically over hole 30. Install R — 3 in holes 23 and 24. Stand vertically over hole 24.

( ) 5. Install R — 5, a 680 ohm ¼ watt resistor (blue, grey, brown) in holes 4 and 5, lying flat.

( ) 6. Two identical 820 ohm ¼ watt resistors (grey, red, brown) are installed in this step. Install R — 8 in holes 32 and 33. Stand vertically over hole 33. Install R — 6 in holes 43 and 44, lying flat.

( ) 7. Install R — 9, a 33 ohm ¼ watt resistor (orange, orange, black) in holes 13 and 14. Stand vertically over hole 13.

( ) 8. Install R — 10, a 10K ohm ¼ watt resistor (brown, black, orange) in holes 34 and 35, lying flat.

( ) 9. R — 11 is installed next. Its value is determined by what brand of equipment the servo is to be used with, and in many cases, R — 11 is omitted entirely. If R — 11 is required, it is installed in holes 48 and 49, lying flat.

A 1.2 K (brown, red, red) ⅛ watt resistor is furnished as a representative nominal value for R — 11. If after experimentation, some other value is determined to be more desirable, it could be obtained from your local electronic parts dealer.

( ) 10. The next step is the installation of the DHD 806 diode. Examine the diode closely and notice on one end there is a band encircling it. The band indicates the cathode end of the diode. Insert the cathode lead in hole 29 and lay it flat with the other lead (the anode) in hole 28.

( ) 11. Examine C — 1, the 1 mf capacitor. Notice that on one end there is a plus sign indicating the positive lead. The unmarked lead is negative. Install the negative lead in hole 21 and stand vertically. Install the positive lead in hole 22.

( ) 12. Next is the installation of the 1.3 MH RF choke. Install one lead in hole 36 and stand vertically. Do not cut the lead short on the other end as it is later soldered to the motor.

( ) 13. The transistors are installed in the next steps.

( ) 14. Install Q — 2, a 2N2924 transistor in holes 1 (emitter), 2 (base), and 3 (collector). Stand ⅛" above the circuit board.

( ) 15. Install Q — 4, a 2N2924 transistor in holes 26 (emitter), 27 (collector) and 25 (base). Stand ⅛" above the circuit board.

( ) 16. Install Q — 3, a 2N3638 transistor flush with circuit board in holes 12 (collector), 11 (base), and 10 (emitter).

( ) 17. Install Q — 1, a 2N3638 transistor flush with circuit board in holes 17 (collector), 16 (base), and 15 (emitter).

( ) 18. Install Q — 5, a 2N3638 transistor flush with circuit board in holes 18 (collector), 19 (base), and 20 (emitter).

( ) 19. Install Q — 7, a 4JX11C1847 transistor in holes 37 (emitter), 38 (base), and 39 (collector). Install flush with circuit board.

( ) 20. Install Q — 6, a 4JX1C1132 transistor in holes 40 (collector), 41 (base), and 42 (emitter). Install flush with circuit board.

( ) 21. Refer to Fig. (1) and locate the two small slots cut into copper lands E and F on the circuit board. Bend the 5/64″ x 1¼″ x .006 brass wiper strip as illustrated and fit to slots in circuit board. Solder to lands E and F.

( ) 22. The 1 K ohm wirewound feedback potentiometer (R — 4) is installed next. Care should be exercised in the handling and soldering of this component. Its position in relation to the circuit board is important. If it is installed too high or too low in the slot on the circuit board, the wiper finger on the traverse rack will not contact it correctly.

( ) 23. Locate the slot in the circuit board that the potentiometer is installed in. Check the slot for correct size by attempting to slide the pot into it. If it requires more than light pressure to achieve a firm fit, do not force it in. Remove it and file or cut the slot until the pot will seat snugly with light pressure applied.

( ) 24. After insuring the slot is the correct size, notice the copper tabs at each end of the pot. One will be soldered to copper land G, the other to land H. Insert the potentiometer into the circuit board slot with the tabs facing the copper lands they will be soldered to. Position the potentiometer so that it is exactly even with the under side of the circuit board. This will allow the correct amount of protrusion on the component side of the board. Using as little heat as possible, solder one tab to land G, the other to land H.

( ) 25. Strip ⅛″ from the ends of the four 9″ wires and one 3″ wire provided and tin them. Thread the yellow, black, and two white wires through hole 46 from the component side of the circuit board. Solder the two white wires to the copper land containing hole 48 and the yellow wire to the land containing hole 16 and the black wire to the land containing hole 17. Thread the red wire through hole 45 from the component side of the circuit board and solder it to the land containing hole 44.

( ) 26. Notice that the lands containing holes 5 and 7 are shown jumpered to adjacent lands with short pieces of resistor leads. In the event the system this servo is to be used with has a separate reference voltage supply, these jumpers are omitted and the 9″ orange and brown wires are stripped, tinned and soldered in place, the brown wire (negative reference voltage) going to the land containing hole 5 and the orange wire (positive reference voltage) to the land containing hole 7. Route these wires through hole 45. If the servo is to be used in an experimental circuit and there is some question of the need for a separate reference source, in general, the requirements are: If you are using more than two Analog servos in an installation and are not using 1.2 amp-hr capacity servo supply cells, you will need a separate reference voltage source to prevent interaction among the servos.

( ) 27. At this point, check all of your work for improper component installation and bad solder joints.

( ) 28. Inspect the "C" frame and motor for proper assembly. Place the "C" frame on a table with the slots for the traverse rack down and the

(*Continued on Page 64*)

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(*Continued from Page 63*)

straight edge of the frame to your right. Notice that there are a red and a blue lead cut flush with the rear surface of the motor. Insure that the red lead is to your left. If not, remove the motor and reinstall it correctly. Check the tightness of the screws holding the motor to the "C" frame, then proceed to install the 100 ohm (brown, black, brown) ½ watt resistor to the rear of the motor. Prebend and form the resistor leads and solder them to the motor terminals "A" and "B" as shown. Locate the .02 mf capacitor on the motor. Notice that one side of it is soldered to both a motor case screw and motor terminal "B." Remove all the paint from the motor case screw to insure a good solder connection. Prebend and form the capacitor leads and solder one lead to motor terminal "B" and the case screw. Solder the other lead to motor terminal 'A" and bend both leads so that the capacitor is against the side of the motor case.

( ) 29. Using the following procedure, install the circuit board to the "C" frame. Place the "C" frame on its flat edge with the traverse rack notches toward you and lay the circuit board on top (foil side up) in its approximate location. Fit the notched portion of the circuit board to the "C" frame tab on the left side with the board trapped under the small metal finger at the front. At this point, the right hand side of the circuit board is prevented from going into place by the small metal finger on the right side of the "C" frame. Pull the right side of the circuit board forward till it clears the finger. Spread the "C" frame slightly and press the circuit board down into position and back under the metal finger. The circuit board should be a good fit with the "C" frame, that is, the "C" frame should not be sprung out of shape and the front of the circuit board should be even with the "C" frame on the left and right side. If you are not satisfied with the fit, remove material from the circuit board in the problem areas with a small file, being careful not to overdo it and produce a sloppy fit or file into the copper land areas causing shorts after assembly. Use a No. 2 x 3/16 sheet metal screw to secure the circuit board to the "C" frame.

( ) 30. Place insulated sleeving on the remaining lead on the RF choke and solder to motor terminal "A". The

(*Continued on Page 68*)

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(Continued from Page 64)

short, white wire coming from the circuit board is now soldered to motor terminal "B."

( ) 31. Inspect the brass wiper strip on the top of the circuit board for dirt or corrosion. If dirt or corrosion is found, scrub the wiper with a common pencil eraser until bright and shiny.

( ) 32. Install the plastic gears. As each gear is installed, check it for free running clearance. If any gear binds or has excessive mesh clearance, remedy, using the following procedure: Examine the riveted idler shafts and note that by bending them closer or farther away from one another, gear clearance will be increased or decreased accordingly. Normally, no adjustment should be required, however, if a case of binding or excessive clearance exists, bend the idler shafts until the condition is eliminated.

( ) 33. Inspect the contact fingers located on the plastic traverse rack. These are prebent to the proper angles. Do not alter them unless one of the fingers is twisted or bent out of shape in relation to the others. Inspect the portion of the wiper fingers that contact the copper land and potentiometer and remove any burrs with a small file.

( ) 34. Align the traverse rack with the rack slots on the front of the "C" frame, but do not install it. Note that the contact arms extend down close to the bottom surface of the circuit board. The point here is to adjust contact finger preload. All fingers should extend even with the bottom surface of the circuit board. If they do not, extend them to the correct position. With the arms correctly adjusted, installation of the traverse rack in the "C" frame will compress the fingers the thickness of the circuit board or about .045".

( ) 35. To install the traverse rack, use the black phenolic insulator board as a "Shoe Horn" to prevent damage to the arms. Place the board on the component side of the circuit board. Place the rack into position compressing the fingers against the surface of the insulator board and carefully slide the traverse rack into the notches in "C" frame and then remove the insulator board. Always use this procedure when removing or installing the traverse rack.

( ) 36. At this point, the servo is ready for operational testing. Refer to the illustration for a suggested test hookup. It is also possible to install the servo into your system to test its operation. Neutral position of the servo is set by adjusting trim on your transmitter. If the suggested check-out circuit is used, full rotation on the pot shaft will correspond to limit operation of the servo. Initially, set the test pot somewhere near its mid-point position before applying power to the servo.

( ) 37. Using the insulator board as a "Shoe Horn," remove the traverse rack and all gears. Check mechanical orientation of "C" frame into top case as shown. Grouping all wires together, slide the 1/4" rubber grommet onto them aligning all wires and grommet into case slot as pictured. Next, align the front edge of the "C" frame to the front edge of the side panels of the top case. Secure "C" frame to top case with two #2 x 3/16" sheet metal screws. If the screw holes on the "C" frame do not align properly with those of the case, an X-Acto knife can be used to elongate the case holes. Insure that the "C" frame remains aligned with the front edge of the top case side panels.

( ) 38. Inspect the traverse rack slots now that the top cover is installed. In some cases, the rack slots in the top case do not align properly with the rack slots in the "C" frame. This could cause the traverse rack to bind. Again, using an X-Acto knife, trim away any part of the top case slot that could cause interference. Do not allow any metal chips to get into the servo case.

( ) 39. Re-install all gears and, using the "Shoe Horn," re-install traverse rack. Be careful not to damage, misalign, or reduce tension of the contact fingers. After rack is installed, inspect the contact of the fingers to the brass wiper and potentiometer.
Contact should be even and not riding on the twisted edge of the finger.

( ) 40. Use "Plio-Bond" or similar contact cement to cement the black insulator board to the inside of the bottom case cover. Using the cement lightly, cement the insulator board to the center of the case bottom.

( ) 41. Install the bottom cover to the assembly. Use four #2 x 1/8" sheet metal screws to secure cover.

( ) 42. Insure that the addition of the bottom cover does not cause the rack to bind. Misalignment of the front edge of the "C" frame in reference to the top cover can also cause the rack to bind against the bottom cover. Minor correction can be obtained by loosening "C" frame attachment screws, pressing on the front section of case at the traverse rack and retightening screws.

( ) 43. This completes assembly of the servo. An operational test should be carried out with the case installed in the same manner as step 37.

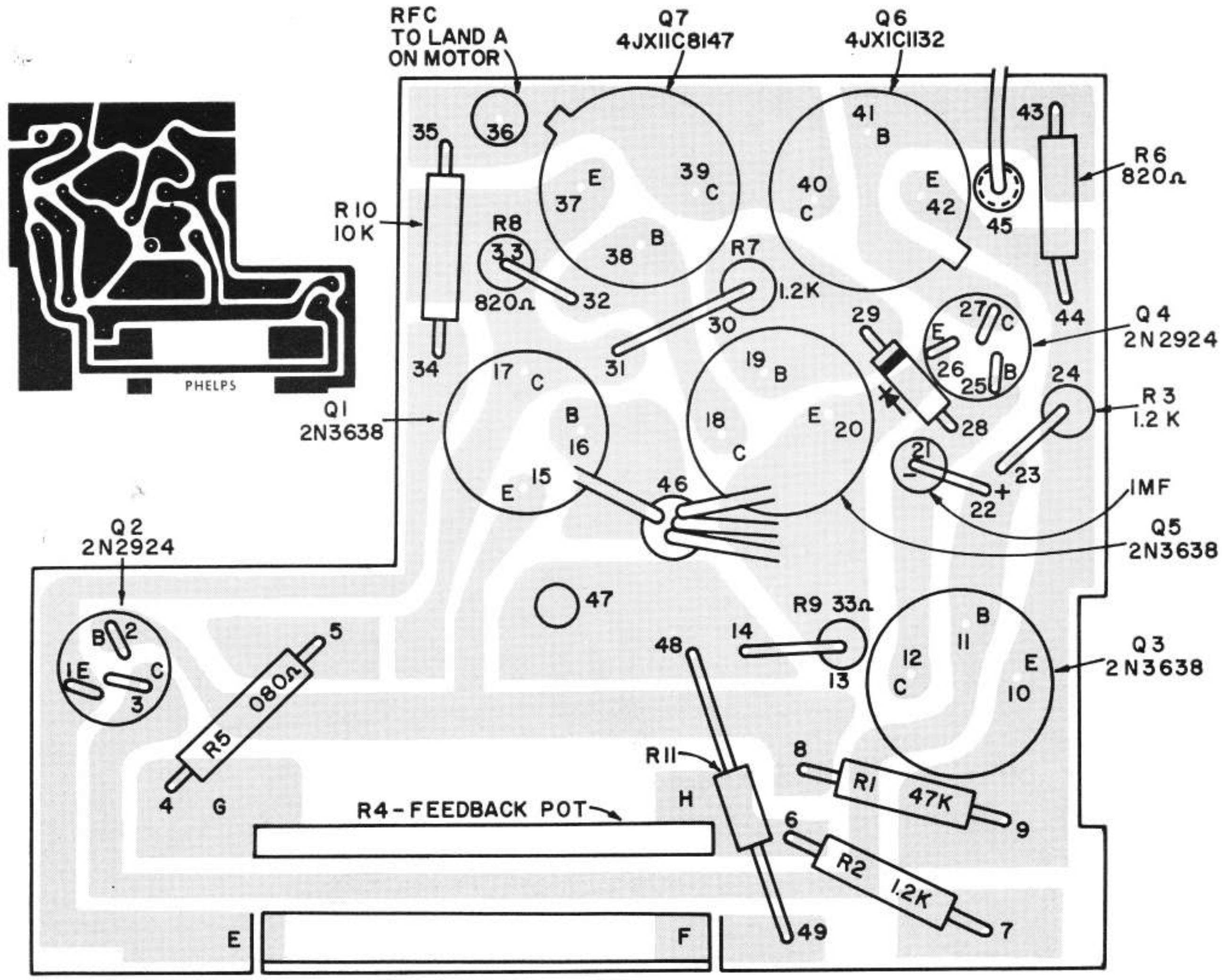

FIG. I

PHELPS ANALOG POSITION FEEDBACK SERVO FIG. 2C