PROJECT

Analog Computer, Part 2

Continuing the construction and use of the analog circuit.

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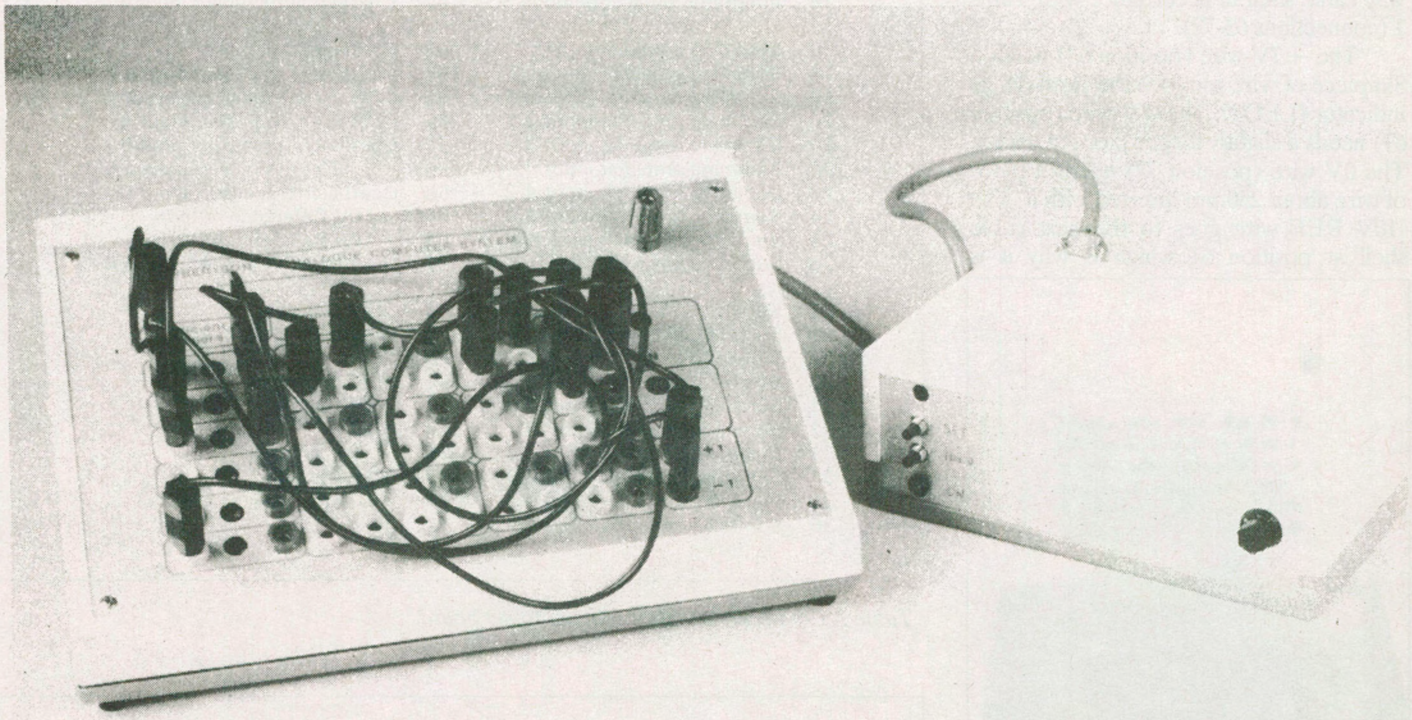


Last month I described the construction of the analogue computer's power supply. This month it is the turn of the main computer unit itself.

The suggested front panel layout is shown in Fig. 1. Use a punch to mark the centre of each hole and a hand drill to drill a 2mm pilot hole at each position. Hold the panel firmly in a vice near the hole position (with a clean piece of rag in the vice to prevent marking the panel) to prevent it bending. With a little care good results can be had. Be particularly careful with the potentiometer holes as these have the edges showing.

Drill 6.5mm holes for the green terminal and the LEDs. 8mm for the 4mm sockets and large holes up to a limit of 8mm or 9mm for the pots. If in doubt drill a hole too small, try it out and then work up. Use an instrument file or similar to cut a small slot in the edge of the hole for the spigot on the terminals.

Fit and tighten all the panel components except for the yellow sockets at the top and bottom of the coefficient multiplier section. A 3/8in socket spanner held in the hand can be a good tool to use here. Don't overtighten them as the threads can strip.

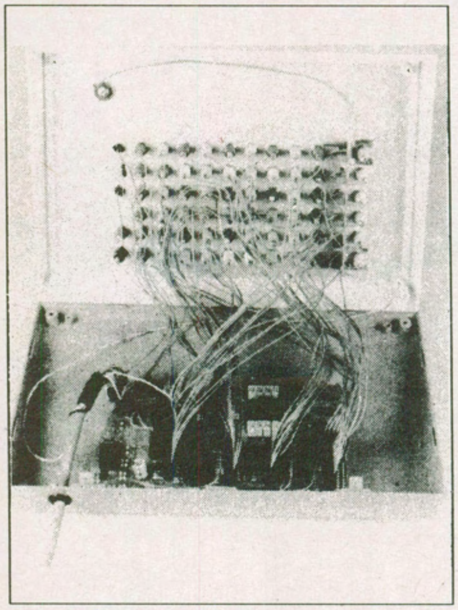
Now solder the six potentiometers in place on the pot board (Fig. 2). To fix the pot board to the front panel, you'll need a couple of special brackets made from scrap aluminium — see Fig. 3. There's a left handed bracket and a right handed one.

No precise measurements are given because these will depend on your exact front panel layout. The last two yellow sockets tighten down on the fork, and the pot board then screws down to the small

Solder a 15-way D-plug on the end of the 15-way cable trapping the braid in the cable clamp for earthing.

Drill a hole in the back right of the case, no further than 50mm from the end of the case for the 15-way cable. Use a grommet. Solder a length of earth wire to the braid and either trap the other end of this between the bracket and the pot board or use a solder tag onto the bolt which secures a pot board. Trim all but the − 10V REF wire down to about 40mm length. Strip and crimp tags to the ends of the wires and push them into a 10-way cable shell in accordance with Table 1 (connections 63-72).

The +7V wire (position 63) needs a 8in piece of wire to reach the overvoltage indicator (LED2). The -7V wire (position 67) needs a slightly longer piece in with it. The 0V wire (position 72) needs a piece of wire about 250mm inserted with it. The -10V REF wire goes to the next cable shell at position 61 which is why it is



longer than the rest.

Begin populating the main board by fitting all the connectors and all the IC sockets as shown in Fig. 4. Next fit all the links using insulated single stand wire.

Fit all the other components as shown in Fig. 4 making sure all the diodes and the translator are the right way round. Don't fit the ICs yet.

Several points on the board (labelled A-I) must be connected with insulated wire on the underside of the board. Some of these are corrected mistakes, some are there because there is no room elsewhere on a single sided board and others are an attempt to preserve the designers sanity.

1	Summing amplifier input 1,1	37	Integrator output 1
2	Summing amplifier input 1,2	38	Integrator output 4
3	Summing amplifier input 1,3	39	Integrator initial conditions 2
4	Summing amplifier input 1,4	40	Integrator initial conditions 1
5	Summing amplifier input 1,5	41	Integrator output 2
6	Summing amplifier input 1,6	42	Integrator output 3
7	Summing amplifier input 1,7		
8	Summing amplifier input 2,1	43	Summing amplifier input 7,1
9	Summing amplifier input 2,2	44	Summing amplifier input 7,2
10	Summing amplifier input 2,3	45	Summing amplifier input 7,3
		46	Summing amplifier input 8,1
11	Integrator input 4	47	Summing amplifier input 8,2
12	Integrator input 3	48	Summing amplifier input 8,3
13	Integrator input 2	49	Coefficient multiplier input 1
14	Integrator input 1	50	Coefficient multiplier output 1
15	Integrator initial conditions 4	51	Coefficient multiplier output 2
16	Integrator initial conditions 3	52	Coefficient multiplier input 2
17	Summing amplifier output 1	53	Coefficient multiplier input 3
18	Summing amplifier output 3	54	Coefficient multiplier output 3
19	Summing amplifier input 3,1	55	Coefficient multiplier output 4
20	Summing amplifier input 3,2	56	Coefficient multiplier input 4
21	Summing amplifier input 3,3	57	Coefficient multiplier input 5
22	Summing amplifier input 4,1	58	Coefficient multiplier output 5
23	Summing amplifier input 4,2	59	Coefficient multiplier input 6
24	Summing amplifier input 4,3	60	+10V Reference output
25	Summing amplifier output 4	61	−10V Reference input
26	Summing amplifier output 2	62	Coefficient multiplier output 6
27	Summing amplifier output 7	63	+7V Supply
28	Summing amplifier output 5	64	Overvoltage warning LED
29	Summing amplifier input 5,1	65	NC
30	Summing amplifier input 5,2	66	SET
31	Summing amplifier input 5,3	67	−7V Supply
32	Summing amplifier input 6,1	68	HOLD
33	Summing amplifier input 6,2	69	−15V Supply
34	Summing amplifier input 6,3	70	+15V Supply
35	Summing amplifier output 6	71	−10V Reference output
36	Summing amplifier output 8	72	0V

Table 1. Connections to the main computer board.

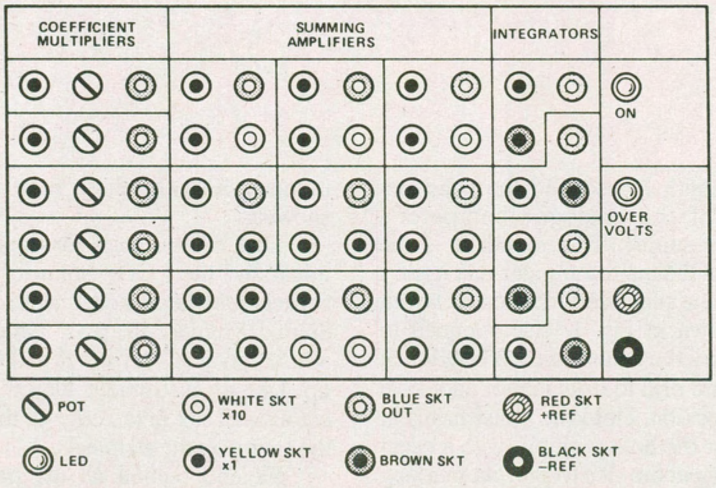


Fig. 1. The front panel layout.

Connect the pads with the same letters. There are two of most but five each of pads B and C and three each of D and E.

Testing

Most parts of the system can be tested at this stage before the front panel wiring goes in. Don't insert the ICs into their sockets yet but plug the leads from the power supply into the board.

Switch on the supply and quickly check that all supplies are present in the

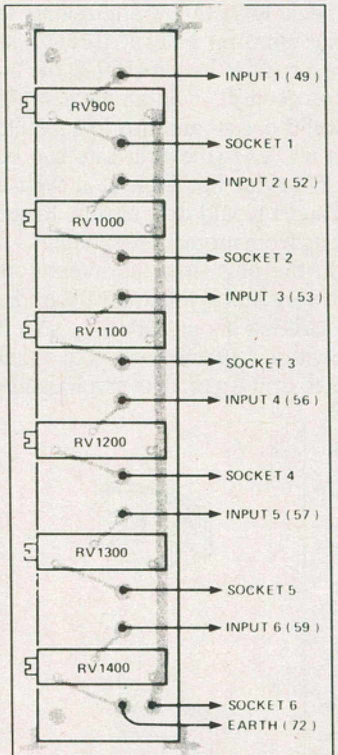


Fig.2 The component overlay for the pot board

Parts list

Resistors

(1/4W, 5% unless noted)

R25,29,31,107,111,114,207,208, 214,307,308,314,407,408,414,507- 509, 514,607-609,614,707709,714, 807-809,814,1502,1508,1509, 1602,1608,1609,1702,1708,1709, 1802,1808,1809 ....1m 1%

R30 ....470k

R32-35,39,40,41,1503,1505....................100k

R36,38 .... 33k

R37....................180k

R42,1504,1604,1704,1804....................1M

R43 ....22k

R44.................... 680

R100-106,200-202, 300-302, 400-402,500-502,600-602,700-702,800 ,802,1507,1607,1707,1807 ....10k

R112,113,209,309,409....................100k 1%

R115 ....39k

R215,315,415 ....82k

R515,615,715,815 ....330k

R1500,1501,1600,1601,1700, 1701,1800,1801 ....4k7 1%

R1506,1606,1706,1806 ....470k

RV6,7,900,1000,1100,1200,1300, 1400 ....10k multiturn pot

RV1500,1600,1700, 1800 ....1k multiturn pot

Capacitors

C1500,1501,1600,1601,1700,1701,1800, 1801 ....470n

Semiconductors

IC6,7,100,500,900,1500, 1502,1503 ....LM324 quad op amp

IC1700 4066 ....CMOS quad switch

Q5 2N3904 ....or equiv

D1-1804 ....1N4148 or 1N914 (39 total)

LED1,2 ....red LED

Miscellaneous

15-way D-type plug (PL1), stacking 4mm plug (PL2-22), green socket (SK1-4), white socket (SK5-9), blue socket (SK10-27), yellow socket (SK28-50), green socket (SK51). Case, IC sockets, 2 x 6-way PCB connectors).

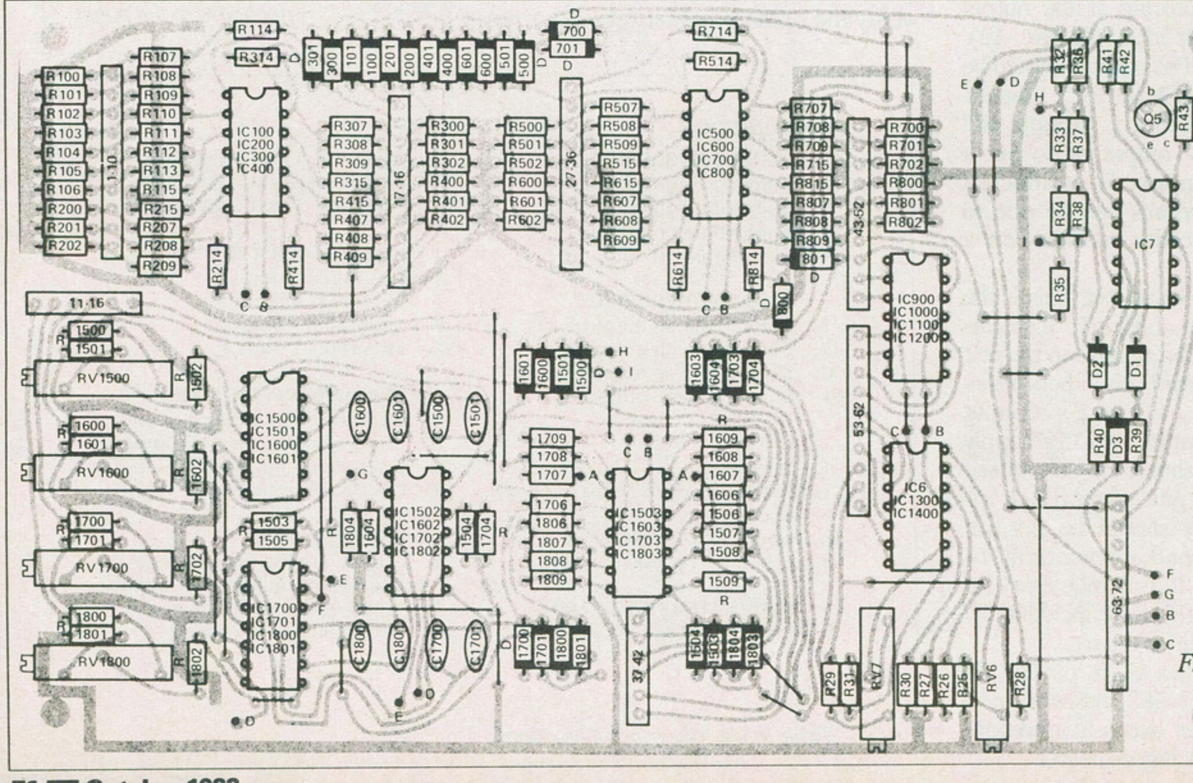


Fig.4 The component overlay for the main board

right places. If not, switch off immediately and investigate.

A rather strange property of all the ICs used in this project is that they are symmetrical. If the supplies are present but the wrong way around, you can plug the IC in upside down rather than rewiring!

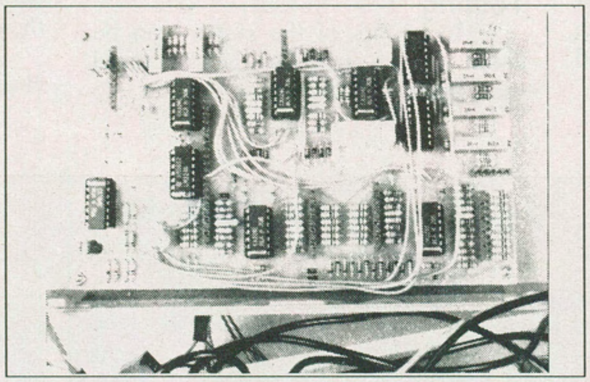
Make yourself a couple of test links by crimping tags onto 200mm or so piece of wire. Bare about 10mm at the other end. Now you can push each of these into a six way cable shell or other test position as appropriate to apply signals to the various parts of the circuit. Refer to Fig. 3 and Table 1 to see whereabouts you are and to Table 2 to see which quarter of the op amp is responsible for different functions.

Insert IC6/1300/1400. Power up and check you have about +/- 10V at each of the corner pins on the right of the IC. Then adjust the two pots at the bottom of the board to give precisely 10.00V. Look at the 10V master reference too to see it hasn't changed. Power down each time before inserting the next IC.

Insert the top left IC (IC100-/200/300/400) into its socket. Power up and check that all the outputs are at OV by probing the corner pins of the IC. (In reality you may expect up to about 10mV either way — about 0.1% full scale). Now apply each of the +/- references to each input in turn, monitoring at the output connector pin +10V in should give -10V out, and vice versa. The outputs should be well within 1% of full scale, for x 1 inputs. Applying this input to a x 10 input will result in about 14V output or so but it does mean the inputs is connected properly. Strange results can be due to misconnection, solder bridges or a reversed diode.

Insert IC7 into its socket. This is the window comparator and latch. Remember this one is reversed relative to the rest (unless you've reversed any others yourself). By applying +/-10V to a x 10 input of a summing amp or the +/-15V supply to a x 1 input, you should be able to see the leftmost corner pins of the IC dropping negative. They should be positive normally and respond momentarily to overrange outputs. It isn't necessary to test all the inputs this way incidentally, just one for each summing amp.

Next monitor pin eight of IC7. It should be positive if SET has not been pressed since the last overvolt condition. Press SET and check it goes negative.



The prototype showing the wiring over the board.

Insert IC500/600/700/800 and use the same procedure for each summing amp — checking for zero, checking all inputs and finishing with an overvolt check on one input of each amp.

Now insert IC1500/1501/1600/-1601.IC1700/1701/1800/1801 and IC1502/1602/1702/1802. These form the heart of the integrators. Power up, press SET and see that the four corner pins of the LM324 go close to 0V. You can expect a good 30mV here actually — about 0.3% full scale. Release SET. The op amp outputs should drift very slowly. (In an ideal world this drift would be zero).

Apply +/-10V to the integrator input at the connector pin. The op amp output should attain -5V in a second (approximately). Press SET a few times to verify the op amp output returns to zero and ramps from there each time. It may be easier to monitor this on a scope or an analogue meter rather than a DVM. While this is in progress check the overvolt system responds to the op amp output voltages.

Check HOLD by attempting to catch the op amp halfway through its headlong rush. When in HOLD the integrators do drift — in an ideal world they would not — and this looks quite bad on a DVM (the drift rate can be about 50mV/s) but look at it with a scope and I would defy anyone to see it drifting from moment to moment.

On the plus side, the integrators behave very well if you apply 0V to the inputs — drifting about 1mV/s — so left to their own devices they will take about two hours to drift up to an overvolt condition! It is wise not to use HOLD for extended periods of time but see my comments on performance improvements below.

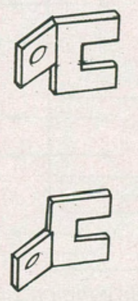


Fig. 3. Brackets to hold the pot board to the panel.

PIN	FUNCTION
	IC100/200/300/400
1	Summing amp output 1
2	Summing amp output 2
8	Summing amp output 4
14	Summing amp output 3
	IC500/600/700/800
1	Summing amp output 5
7	Summing amp output 6
8	Summing amp output 8
14	Summing amp output 7
	IC7
1	This output not used
7	Latch output (drive to overvolt LED)
8	Upper (+ve) comparator
14	Lower (-ve) comparator
	IC1502/1602/1702/1802
1	Integrator 2 first stage output
7	Integrator 4 first stage output
8	Integrator 3 first stage output
14	Integrator 1 first stage output
	IC1503/1603/1703/1803
1	Integrator 3 output
7	Integrator 4 output
8	Integrator 1 output
14	Integrator 2 output
	IC900/1000/1100/1200
1	Coefficient multiplier 2 output
7	Coefficient multiplier 3 output
8	Coefficient multiplier 4 output
14	Coefficient multiplier 1 output
	IC6/1300/1400
1	Coefficient multiplier 5 output
7	Coefficient multiplier 6 output
8	+10V reference output
14	10V reference output

Table 2. Useful test point locations.

Insert the last IC (IC1503/1603/-1703/1803) and check the outputs follow those of the previous stage (x2) and that when an input is applied to the IC (initial conditions) connector position this voltage appears inverted at the output. Keep SET asserted for this, using a shorting link if you like, as it is easier to see what's going on.

Also put +/-15V in at the initial condition inputs (without SET asserted) to check the action of the overvolt connections. Calibration of the integrators must wait until the internal wiring is installed.

Wiring

Drill holes in the base of the case and bolt in the board, using spacers. The board should lie right at the back of the case where it just clears the 4mm sockets nicely.

Use small lengths of bare single strand wire to connect each of the yellow coefficient multiplier sockets to the clockwise end of each potentiometer on the pot board. Trim down the anode (long) leads of both LEDs and solder a 680R resistor between them. Lay the front panel face down with the back edge just learning on the front of the case, so that it can't 'hinge' back into position when the time comes.

Starting with those sockets and connections at the back, which would be awkward to reach with the rest of the wiring in place, cut and solder an appropriate length of wire to the socket. Refer to Fig. 3 and Table 1 continuously. I have chosen to number the inputs to the summing amps starting at the top left working right, then bottom left working right. The really essential thing is that groups of connections to one amp or integrator are kept together and a white (x10) socket always connects to an input with a 100k resistor.

The coefficient multipliers are numbered one to six from top to bottom. Connect a wire from each pot wiper pad to the input connector. The outputs go direct to the blue sockets. Connect a wire between the thick 0V track on the pot board and the green terminal. Connect the 0V wire from position 72 to the green terminal as well. Trim and connect the overvolt LED cathode to the appropriate connector position. Trim and connect the power LED cathode to the -7V position. Connect +7V position to the overvolt LED anode along with the 680R resistor which is already in place.

Lower the panel into position. Now is a good time to make up the patch leads. Two meters of extraflex wire will make ten leads of various lengths; I used six 0.25m lengths and four 0.125 ones. Connect 4mm plugs on both ends of each lead.

More Testing

All that remains is to check the summing amp and coefficient multiplier connections by applying inputs, checking outputs and by checking the integrator wiring and calibration of the integrators. Calibrate the integrators by applying a 0.50V signal derived from a voltage reference passed through a coefficient multiplier. Use your nice new patch leads to do this.

Using a stop watch, release SET, wait for 20 seconds and press HOLD. Make a quick mental note of the voltage attained before it wanders too far off. Adjust the integrator, using one of the four pots at the left edge of the board, using the 20s check each time an adjustment is made, until the integrator reaches ten volts plus the offset apparent when SET is asserted. That's the simplest method. If you've stuck with the wiring scheme outlined, you'll see that the pots are numbered one to four from back to front.

If you have a pulse generator which will give you a good pulse of known and stable amplitude and duration, you could use it to pulse the integrator and adjust the potentiometer to give a known final voltage. A +1V pulse for one second should result in -1V on the output. The important thing is that the integrators are the same. The only reason for having adjustment here, and not for any other circuit, is to remove the effects of the tolerance of the capacitors (5%) and to account for using two 470n rather than 1u0.

Improvements

The LM324ICs used in the computer are the biggest source of error, particularly in the integrators where their bias currents cause drift in the HOLD mode and very slight asymmetric operation and drift when running.

If any improvement is considered necessary, the biggest single step would be to replace those op amps in the critical positions of summing amplifier and integrator. Some possibilities might be the LF347 which offers vastly improved bias currents or the OP400 with its very low offset voltage of 150uV maximum. If selecting an improved op amp, do not be concerned with bandwidth or slew rate for this application.

There are no other easy or relatively cheap roads to improvement. The next item on the list is perhaps the capacitors but closer tolerance types at 1u are likely to be bulky and expensive. Using 100n instead of the 1u in the prototype will speed up the computer by a factor of ten but will also express drift rates tn times faster. The important resistors could be relaced by 0.1% types but these are likely to be expensive too.

Having said all this, the computer is still more than adequate for control experiments and dare I say it, a lot better than certain offerings I have come across recently.

Further Uses

The individual building blocks of the computer can be used for many other purposes. Variable and fixed gain amplifiers are easily implemented. There are sufficient integrators to build two rather fine, high Q state variable filters, although the range of operating frequencies may be restricted.

Don't be afraid to use external components in the patching. For example, a 10k resistor in series with any input will attenuate the signal by a factor of two, 90k by a factor of ten. This can be used to slow down integrators.

A very low frequency sine wave generator is another possibility, with the added advantage of quadrature, outputs and high spectral purity (since it is a 'proper' sine wave and not something cobbled up from a triangle wave) but the amplitude will change slowly. Set up a state variable filter with a damping of zero for this.

The whole computer can be easily expanded adding further main boards operating off the same power supply unit. Wiring up further D-connectors in the power supply is the way to do this.

Other functional blocks could also be added either to this main board or to an additional one. The possibilities are almost boundless. One thing is certain. Once the analogue computer is built, you will never again look at a digital computer with quite the same admiration. ■