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POLYPHONIC 'TOUCH ORGAN' TO BUILD

two octave range
two voices
speaker output

60W Amp. module

very low distortion using two nested differentiating feedback loops

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Polyphonic organ features 'touch sensor' keyboard

Barry Wilkinson
Roger Harrison

Featuring a 'touch sensor' keyboard constructed right on the printed circuit board, this polyphonic organ project covers a two-octave range, has loudspeaker output plus two 'voices' and can be operated from a battery or plug pack.

BACK IN August 1976 we published the "ETI Mini Organ", Project 602. This featured a 'touch sensor' keyboard utilising tracks on the printed circuit board which, when bridged by a finger, turned on a CMOS switch. The switch turned on an RC oscillator and set the pitch of the note produced. The technique was novel and effective. An added tremolo circuit could also be switched in and out using the same technique. However, the technique had one drawback. Moisture from the fingers would sometimes build up on the keyboard and bridge the key tracks for one note or another, and the note would hold on. Wiping the keyboard with a tissue or cloth would solve that, but it proved an occasional problem nevertheless.

The ETI 602 Mini-Organ was only monophonic, that is, could only play one note at a time, a limitation that did not escape many readers and constructors. In defence, one might point out that the entire brass and woodwind family of traditional acoustic instruments are also monophonic, but an 'organ' is traditionally polyphonic, which means any number of notes in its compass can be played simultaneously. Hence, this project is a polyphonic organ.

Many notes

There are two basic ways to generate many notes that can be sounded simultaneously. You can commence with a 'master' oscillator at some suitably high frequency and have a series of frequency dividers that divide this down stage by stage to produce the required range of notes. This has the advantage that only a single tuning control is required to set all the notes on frequency. That's fine and dandy, but the pitch interval between notes in the chromatic scale (i.e: the ratio of a note to the note above or below) is based on the twelfth root of two. This means that, to produce a scale based around middle C, at least, the lowest frequency you can start off with is around 2 MHz. A string of dividers constructed from discrete ICs would consist of many devices and be quite expensive. However, there is a device called a 'top octave synthesiser' which performs this task — but further dividers are required to produce the 'usual' range of notes. The drawback is the cost — the crystal and top octave synthesiser will set you back around $30 to start with!

For cost reasons, we've chosen the second method. Twenty five oscillators have been used to generate each of the notes in a two octave-plus-one range from F below middle C to F" above middle C.

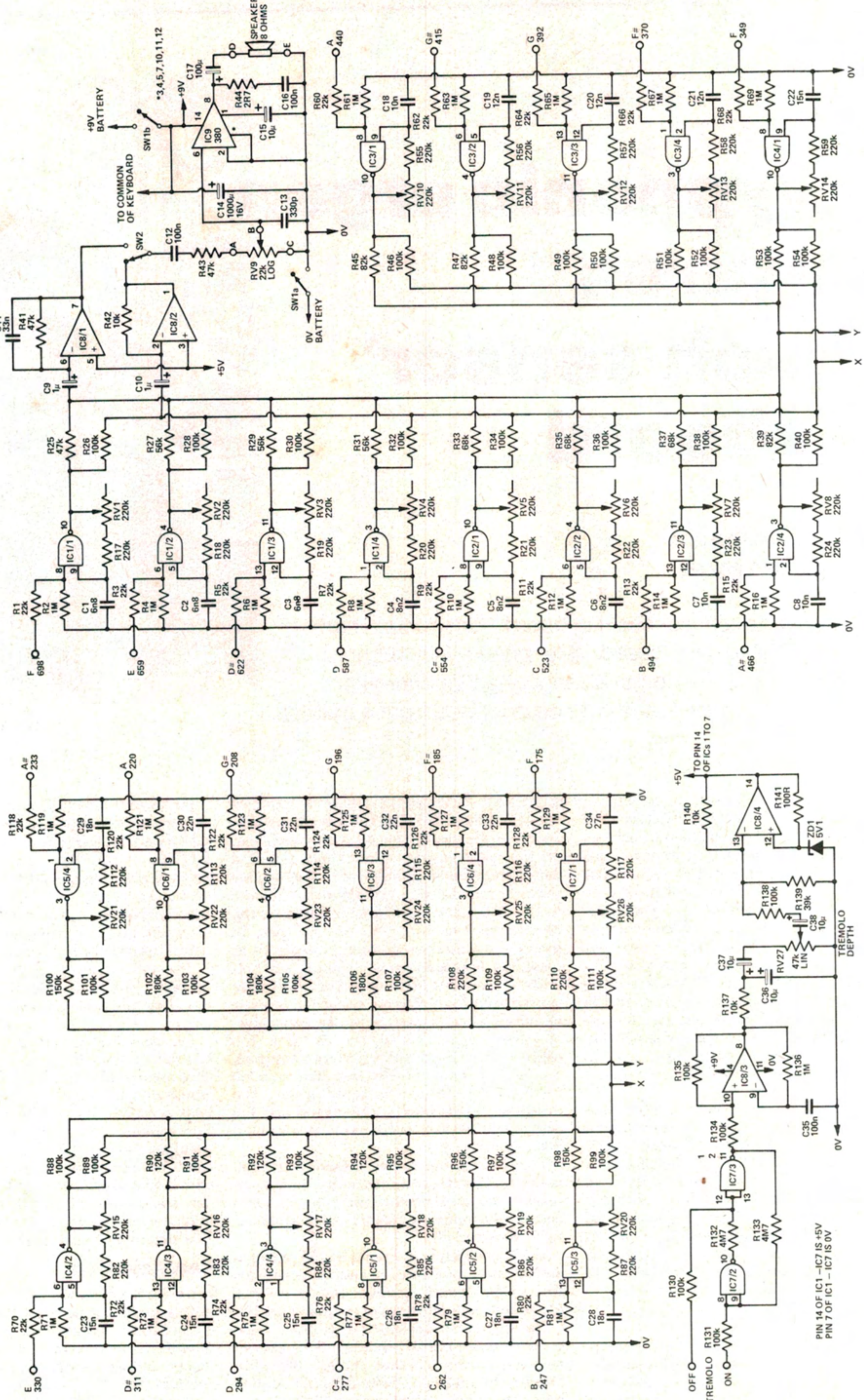
Each oscillator is implemented using a single two-input gate — and that includes the touch sensor keying! Hence all the oscillators require only seven quad-gate ICs — leaving two spare gates which have been used in the tremolo circuitry. This project uses even fewer ICs than the ETI-602 Mini Organ! In addition, Schmitt-input CMOS gates have been employed (4093s) as they have two distinct threshold points on the inputs which means they can be driven on or off with certainty, unlike conventional CMOS gates, such as the 4011s used in the ETI-602 which have only one threshold point. Using this, the problem with moisture on the keyboard holding notes on has been largely overcome. The action of each oscillator and how they are keyed is explained in detail in the *How It Works* panel.

This project has tremolo circuitry and two 'voices', just like the ETI-602, but the circuitry has been arranged differently this time.

Loudspeaker output is provided by an LM380 audio power output amplifier IC. This is capable of driving 1 W into a four ohm load from a 9 V supply and for this reason we have specified the use of two small speakers. The common 50 — 75 mm diameter loudspeakers generally have an eight ohm voice coil. Connecting two in parallel gives a four ohm load and considerably more output. You can add a jack socket to take the organ's output to an external amplifier if you wish, in which case you'll get a much richer sound.

Construction

For clearly obvious reasons, you'll get best results using our pc board design. However, if you intend making your own pc board, we should point out that tarnishing of the copper on the keyboard area can be a problem. We solved that on the prototype by coating it with solder. It's a fair solution, but not all that pretty! However, we have recom- ▶


+9V BATTERY
0V BATTERY
TO COMMON OF KEYBOARD
SPEAKER 8 OHMS
TREMOLO DEPTH
TO PIN 14 OF ICs 1 TO 7
TREMOLO
ON
OFF
PIN 14 OF IC1 – IC7 IS +5V
PIN 7 OF IC1 – IC7 IS 0V

A total of 25 separate oscillators are used to provide polyphonic output covering two octaves. Each oscillator is individually adjustable so that they can be accurately tuned to the required note. Apart from the set of note oscillators, there are three other sections to the circuitry: the tremolo circuitry, the voice selection/mixing and the audio output stage.

THE NOTE OSCILLATORS

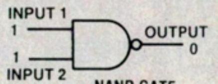
All the note oscillators have identical circuitry, only the frequency determining components are varied to provide the individual frequencies for the notes. The note oscillators are based on one gate from a 4093 CMOS two-input Schmitt trigger NAND gate. The basic circuit is shown in Figure 1.

The one gate combines both an oscillator and the keying action. What makes the gate oscillate is the feedback loop from the gate output to Input 2 via the trimpot and resistor in series and involving the capacitor C.

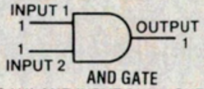
A NAND gate is a digital IC and it operates according to certain 'rules', spelled out in a 'truth table'. Voltage levels on the gate's inputs or output are either 'high' or '1', which means they're at the positive supply voltage, or they're 'low' or '0', which means they are at the 0 V rail. With a two-input AND gate, the output will be high if Input 1 AND Input 2 are high, otherwise the output is low. Hence the name, AND. The NAND gate is a NOT AND gate which simply means that its output is inverted to that of the AND gate. Thus, if Input 1 and Input 2 are both high, the output will be low, not high. The truth table for a NAND gate is given in Table 1.

TABLE 1.

Input A	Input B	Output
'0' (low)	'0' (low)	'1' (high)
'1' (high)	'0' (low)	'1' (high)
'0' (low)	'1' (high)	'1' (high)
'1' (high)	'1' (high)	'0' (low)



NAND GATE
INPUT 1(1) NOT AND INPUT 2(1) = OUTPUT (0)



AND GATE
INPUT 1(1) AND INPUT 2(1) = OUTPUT (1)

While we said that a '1' or high normally means the supply voltage and '0' or low the 0 V rail, the inputs of a NAND gate are generally

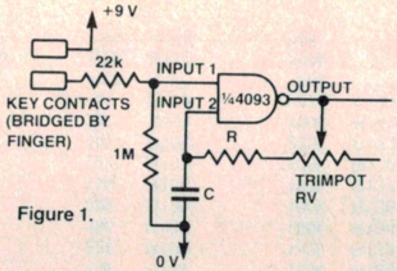


Figure 1.

specified to operate for voltages between these extremes. With a normal CMOS gate there is an input level threshold of about 50%. This means that if the input is at a level above 50% of the supply voltage it is high, if it is at less than 50% of the supply voltage it is low. The actual percentage (threshold) can vary from device to device (the limits are 30% to 70%). However, there is a point above which it is definitely high and a point below which it is definitely low. This is the *normal* input characteristic of CMOS gates. They only have one threshold point.

With a gate having Schmitt inputs, there are two distinct thresholds: there is a low threshold which, if the input level is below that limit, the input is low and there is a high threshold which, if the input level is above that limit, the input is high. Between the two thresholds, the inputs do nothing. The low threshold may be at 40% of the supply rail, the high threshold at 60% of the supply rail.

Referring to Figure 1, in order for this circuit to oscillate, Input 1 must be driven high. Initially, it will be held low by the 1M resistor. If you look at the truth table, if either input is low, the output must remain high. Input 1 is taken high by the action of placing a finger across the key pads. Just before Input 1 goes high, the output of the gate must be high and, owing to the trimpot RV and the resistor R, Input 2 will also be high and capacitor C will be charged. Thus, when Input 1 goes high the output will immediately go low as both inputs will then be high. Input 2, however, now starts to go low due to the feedback via RV-R, but this action is slowed down by the capacitor having to discharge via RV-R. When the voltage on Input 2 reaches the low threshold, the output will suddenly go high. Thus, C will begin to charge again via RV-R. When Input 2 reaches the high threshold, the output will revert to the low condition once more and the whole cycle will be repeated.

This continues with the output going high/low/high at a rate largely determined by the RC network formed by RV, R and C. (The difference between the low and high thresholds, the hysteresis, affects it too.) By varying the resistance of the trimpot RV, the frequency of the note oscillator can be varied. The circuit will oscillate so long as Input 1 is held high by placing a finger on the key pad.

Note that each oscillator has been given a frequency variation range of 2:1 because of the values assigned to RV and R in each oscillator. The major frequency determining component in the actual circuit is thus the capacitor (C). Only standard value (E12 series) components have been specified so that components are easy to obtain and inexpensive as these are the most common values available.

VOICE SELECTION, MIXING

The output waveform of the oscillator described is a square wave, as you would no doubt have already realised. The output signals from each of the 25 oscillators are mixed together via a resistor network to the inputs of IC8/1 and IC8/2, two op-amps from an LM324 quad op-amp package. Apart from performing the mixing, this stage provides the 'voicing' as well. IC8/1 has a capacitor (C11) across the feedback resistor (R41) which changes the waveshape into a triangular form. This removes most of the harsh odd-order harmonics of the square wave, producing a 'sweeter' sound. As this type of circuit is frequency dependent, the mixing resistors from the oscillator output have different values so as to keep the amplitude constant across the frequency range. The desired voice is selected by switching between the outputs of IC8/1 and IC8/2 using SW2.

AUDIO OUTPUT STAGE

Final amplification of the signal, to drive a loudspeaker, is done by an LM380 IC power output amplifier (IC9). This can drive low impedance speakers and will deliver over one watt into a four ohm load. One or two miniature 8 ohm loudspeakers can be used for audio output. We used two 8 ohm speakers in parallel to give four ohms so that the LM380 will deliver maximum output. However, the output can be coupled to an external loudspeaker mounted in a proper enclosure (i.e: a hi-fi speaker), better sound being obtained in this way. The larger speakers are generally more efficient, which is opposite to what most people first think, and the LM380 generally clips when several notes are played together while driving the very inefficient miniature loudspeaker(s).

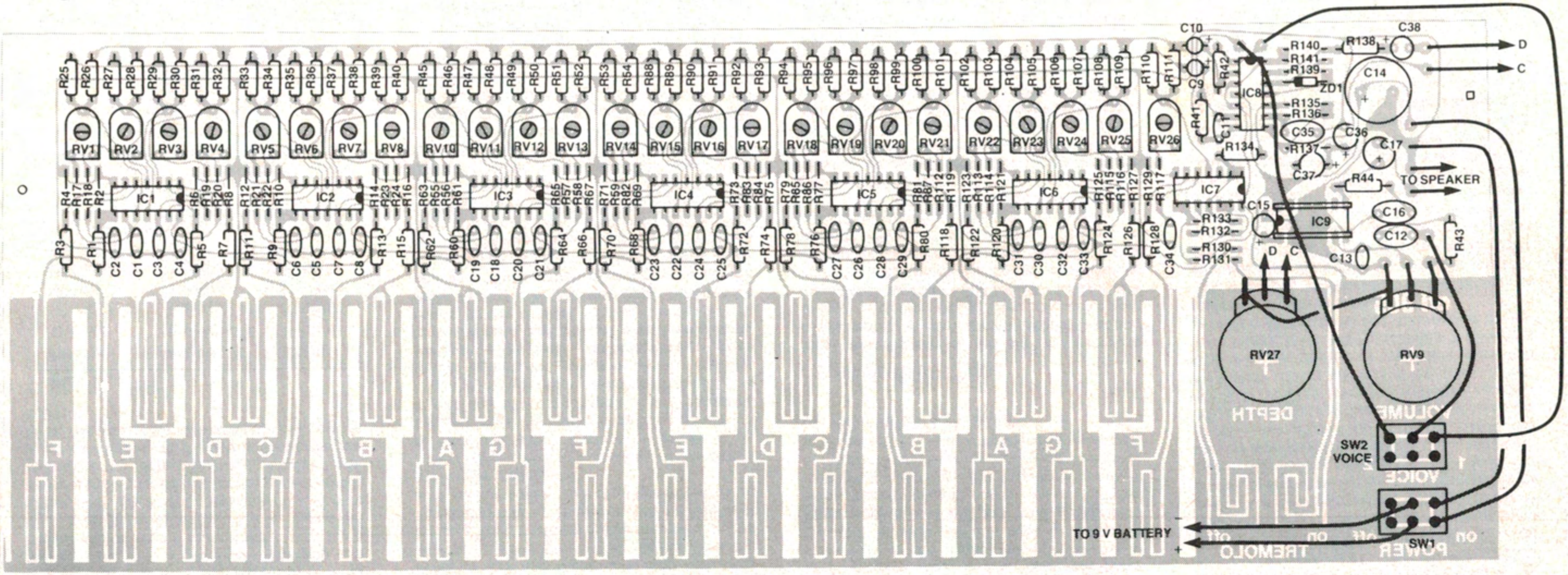
Capacitor C12 and resistor R43 provide some low frequency roll-off, reducing 'thump' when you touch a keypad. Volume control is provided by RV9. C13 rolls off the high frequencies, reducing the harshness of the sound. The RC network across the speaker outputs from IC9 (R44-C16) helps stabilise the LM380 at high frequencies. C17 provides dc isolation for the speaker.

TREMOLO CIRCUITRY

This part of the circuitry involves two gates from IC7 and the remaining two op-amps from IC8. Tremolo is started and stopped by touching the appropriate key pads. IC7/2 and IC7/3 are arranged as a RESET/SET (R/S) flip-flop. If pins 12-13 of IC7/3 are high, pin 11 will be low and thus pin 8-9 will be low, pulled down via R133. This is the 'tremelo off' condition. If pins 8-9 of IC7/2 are pulled high by touching the ON key pad, pin 10 of IC7/2, which would have initially been high, will go low, as will pins 12-13 of IC7/3. Thus, pin 11 of IC7/3 will go high. This is the 'tremolo on' condition.

Now, IC8/3 is arranged as a low frequency oscillator. When pin 10 of IC8/3, the non-inverting input, is low, pin 8 is held low, and so will pin 9 because of the feedback via R136. C35 will be discharged. When pin 10 of IC8/3 is driven high, pin 8 will go high too and C35 will begin to charge via R136. The voltage on pin 9 of IC8/3, the inverting input, will begin to rise at a rate determined by the RC combination of C35-R136. As the voltage on pin 9 rises, the voltage on the output of IC8/3, pin 8, will begin to fall — and so will the voltage on pin 10, the non-inverting input, because of feedback via R135. At a certain level, the op-amp output will be rapidly driven low by the feedback action, C35 will discharge and the whole cycle will start again. Thus, IC8/3 oscillates. It will do so at a rate of about 10 Hz, determined by the component values chosen.

The output is filtered to more or less a triangular shape by the RC network of R137-C36. Capacitor C37 provides dc blocking, the output being applied to the tremolo depth control, RV27. The signal is applied to the inverting input of IC8/4 which is a dc amplifier stage. The output of this stage is set to an average of about 5 V as the non-inverting input is 'clamped' at about 5 V by the zener ZD1. When the modulating signal from the 10 Hz oscillator is applied to the inverting input of IC8/4, the output voltage will swing about a 5 V mean, modulating the supply voltage to all the oscillators. The amplitude of the swing is determined by the tremolo depth control. Varying the supply voltage to the oscillators causes a small frequency variation, producing the tremolo effect. ▶



ETI-905 POLYPHONIC ORGAN PARTS LIST

Resistors

R1	22k
R2	1M
R3	22k
R4	1M
R5	22k
R6	1M
R7	22k
R8	1M
R9	22k
R10	1M
R11	22k
R12	1M
R13	22k
R14	1M
R15	22k
R16	1M
R17-24	220k
R25	47k
R26	100k
R27	56k
R28	100k
R29	56k
R30	100k
R31	56k
R32	100k
R33	68k
R34	100k
R35	68k
R36	100k
R37	68k
R38	100k
R39	82k
R40	100k
R41	47k
R42	10k
R43	47k
R44	2R7
R45	82k
R46	100k
R47	82k
R48	100k
R49-54	100k
R55-59	220k
R60	22k
R61	1M
R62	22k
R63	1M
R64	22k
R65	1M
R66	22k
R67	1M
R68	22k
R69	1M
R70	22k
R71	1M
R72	22k
R73	1M
R74	22k
R75	1M
R76	22k
R77	1M
R78	22k
R79	1M
R80	22k
R81	1M
R82-87	220k
R88-89	100k
R90	120k
R91	100k
R92	120k
R93	100k
R94	120k
R95	100k
R96	150k
R97	100k
R98	150k
R99	100k
R100	150k
R101	100k
R102	180k
R103	100k
R104	180k
R105	100k
R106	180k
R107	100k
R108	220k
R109	100k
R110	220k
R111	100k
R112-117	220k
R118	22k
R119	1M
R120	22k
R121	1M
R122	22k
R123	1M
R124	22k
R125	1M
R126	22k
R127	1M
R128	22k
R129	1M
R130-131	100k
R132-133	4M7
R134-135	100k
R136	1M
R137	10k
R138	100k
R139	39k
R140	10k
R141	100R

RV1-8	220k miniature trimpot, horizontal mounting.
RV9	22k log. pot. (or 20k)
RV10-26	220k miniature trimpot, horizontal mounting.
RV27	47k lin. pot (or 50k)

Capacitors

C1-3	6n8 greencap
C4-6	8n2 greencap
C7,8,18	10n greencap
C9-10	1u/16 V tant.
C11	33n greencap
C12	100n greencap
C13	330p ceramic
C14	1000u/16 V RB electro.
C15	10u/16 V RB electro.
C16	100n greencap
C17	100u/16 V RB electro.
C19-21	12n greencap
C22-25	15n greencap
C26-29	18n greencap
C30-33	22n greencap
C34	27n greencap
C35	100n greencap
C36-38	10u/16 V RB electro.

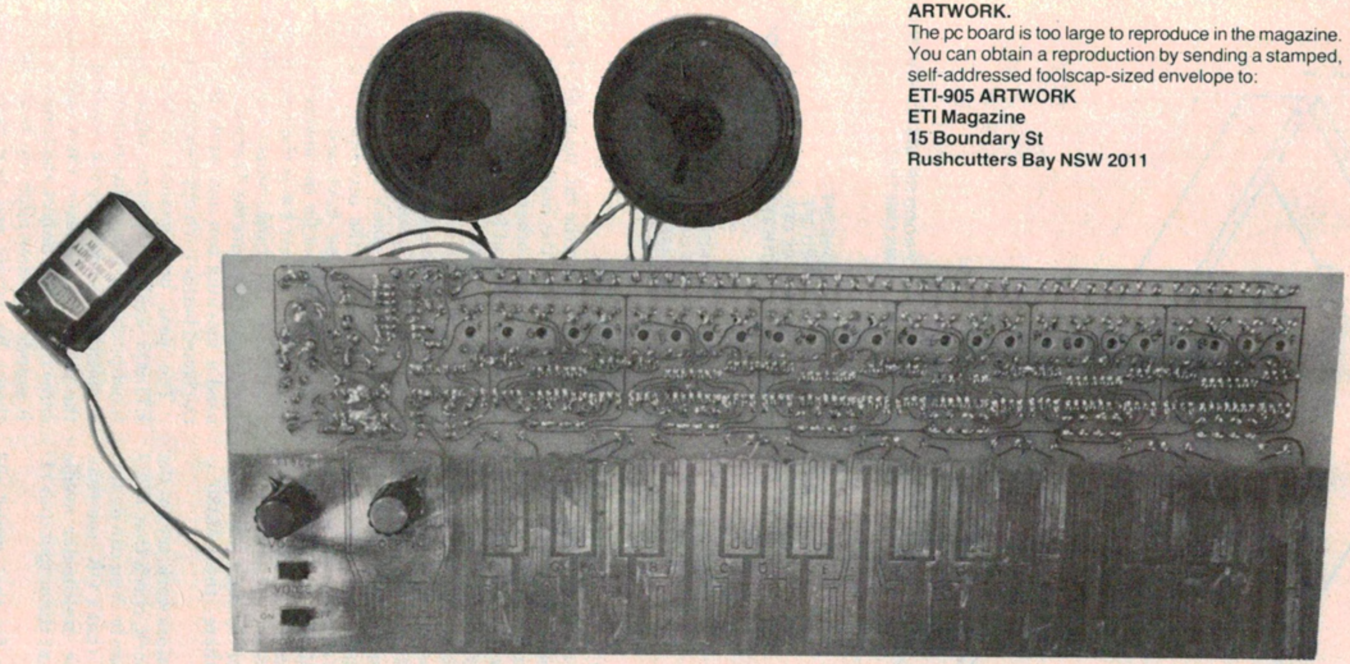
Semiconductors

IC1-IC7	4093B
IC8	LM324N, uA324PC
IC9	LM380N
ZD1	5V1 zener

Miscellaneous

ETI-905 pc board; SW1 — DPST slide switch; SW2 — SPDT slide switch; one or two 50 mm diameter 8 ohm speakers; battery holder to take 6 x AA cells; two small knobs; 30 x 30 mm square of tinplate or copper shim; hookup wire; case, etc.

Price estimate
$50 — $55



ARTWORK.
The pc board is too large to reproduce in the magazine. You can obtain a reproduction by sending a stamped, self-addressed foolscap-sized envelope to:
ETI-905 ARTWORK
ETI Magazine
15 Boundary St
Rushcutters Bay NSW 2011

RESISTOR SHOPPING LIST

As there are so many resistors used, here is a 'shopping list' to assist you. The Parts List can be referred to in conjunction with the component overlay when assembling the pc board.

2R7	x1	**82k**	x3
100R	x1	**100k**	x34
10k	x3	**120k**	x3
22k	x25	**150k**	x3
39k	x1	**180k**	x3
7k	x3	**220k**	x27
56k	x3	**1M**	x26
68k	x3	**4M7**	x2

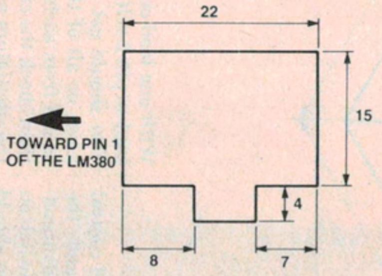
POTS & TRIMPOTS

22k	(or 20k) log pot.	x1
47k	(or 50k) lin pot.	x1
220k	min. horizontal mount trimpots	x25

mended to all the pc board manufacturers making boards for this project that the keyboard area either be nickel plated or gold flashed over nickel plating. The choice of homemade board versus a bought one is up to you.

No matter whether you buy one or make your own, make a careful check of the pc board before commencing construction. Check that all the holes are drilled to the correct size. This is particularly important with the row of trimpots. You may need to drill holes near the two ends of the board, above the keyboard area, so that mounting pillars can be screwed to the board. Exactly where and what size will depend on how you're going to mount the board, and that we'll have to leave up to you. Some suggestions are given later. Check that the two slide switches fit in the slots in the pc board. Enlarge the slots with a small flat file if necessary.

Having satisfied yourself that the board's all OK, all the trimpots can be fitted first. All the resistors can be soldered in place next, mounting them right down on the pc board.



HEATSINK FLAGS, LM380
MATERIAL: TINPLATE OR COPPER SHIM TWO OFF
ALL DIMENSIONS IN MILLIMETRES

The LM380, IC9, should be soldered in place next. Make sure you orient it correctly. Now cut two 'flag' heatsinks, as shown in the accompanying illustration. You can use tinplate or thin copper 'shim'. Both can be obtained in small sheets from hardware stores. Motor spares stores may also stock copper shim. Tin the two tags at the botton, each on the side that solders to the LM380 pins. You'll need an iron capable of supplying quite a bit of heat and having a 'chisel' bit (see ETI, October '81, A Good Joint is Hard to Find . . .). Don't overdo the solder. Then, carefully tin pins 3-4-5 and 10-11-12 on the LM380. Take one of the flags and orient it as shown in the diagram. Hold the tag with the solder side against the appropriate pins of the LM380 using a pair of pliers. Apply the flat of the iron to the tag until you see the solder flows freely. Remove the iron and *keep the flag steady until the solder sets.* This process is known as 'sweating'. If you hold the flag with your fingers while doing this you'll know exactly what it means! Now sweat the other flag to the other set of pins of the LM380. Do this carefully. While the LM380 is quite rugged, don't overdo it with the soldering iron. If you make a slip and have to resolder it, let it all cool down first.

Having accomplished that task, insert all the other ICs and solder them in place, making sure — as always — you have them correctly oriented. ICs 1 to 7 are CMOS types. Use either an isolated soldering iron or an iron with an earthed tip. Handle the ICs by their ends, avoiding touching the pins. Solder the supply pins (7 and 14) first.

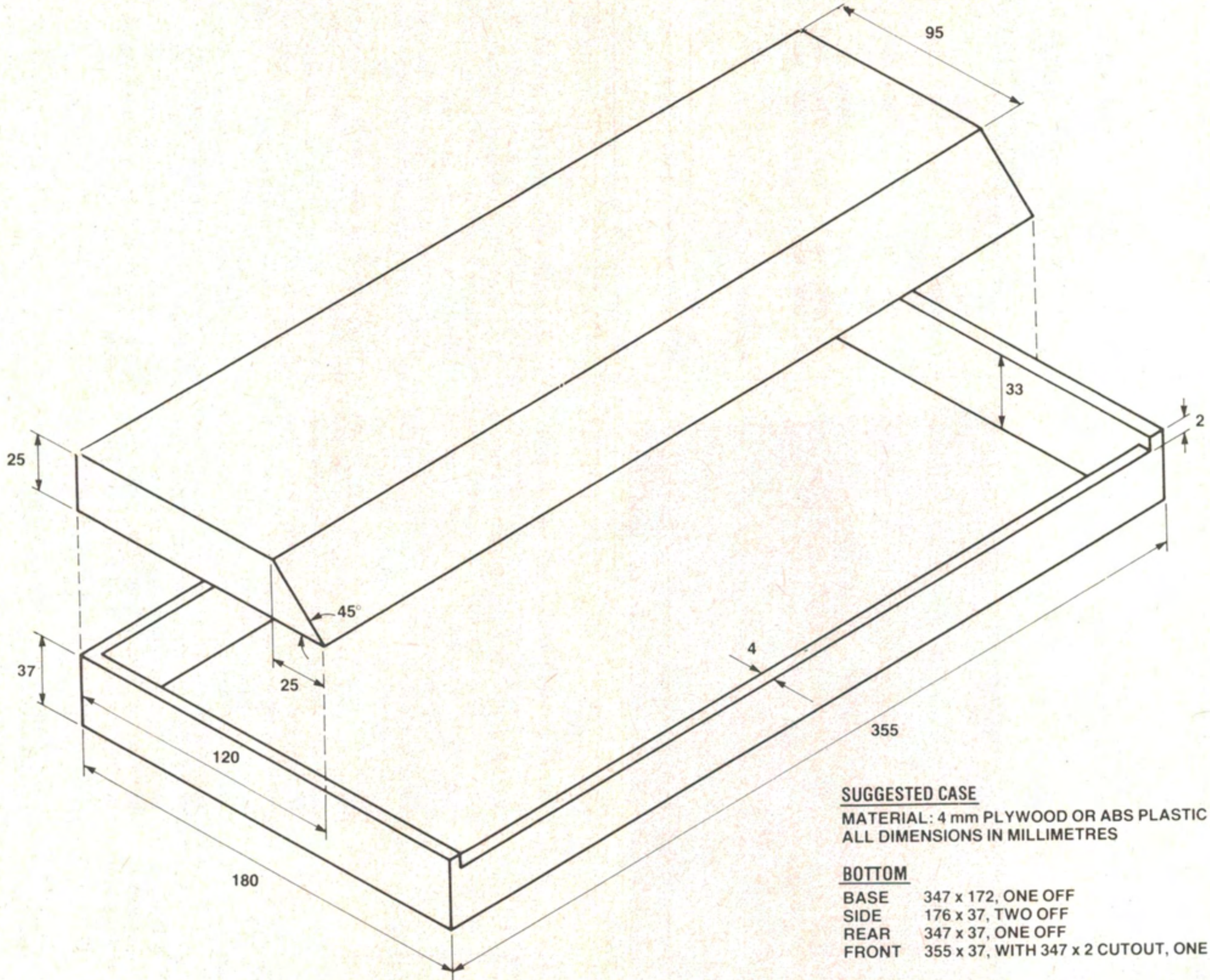
Now come the capacitors. The only thing you have to watch for here is the polarity of the electrolytics and tantalums.

It's probably a good idea at this stage to have a quick check over what you've done so far.

Now attach all the leads that run from the pc board to the two potentiometers, the two switches and the speaker(s). The three wires adjacent to C12 that run to the volume pot RV9 should be tinned copper wire. It makes life easier in a moment.

Now mount the two potentiometers, RV9 and RV27, and wire them up. Follow with SW1 and SW2. We glued our switches in place with quick-setting epoxy, but they could be screwed to the board. Attach the speaker(s) and the battery clip. Put knobs on the two potentiometer shafts.

Resist the urge to plug in a battery and try it out (it'll be out of tune anyway). First, *check everything.* Check the IC orientations especially. All OK? Now you're ready for the next bit. ▶



SUGGESTED CASE

MATERIAL: 4 mm PLYWOOD OR ABS PLASTIC SHEET
ALL DIMENSIONS IN MILLIMETRES

BOTTOM

BASE	347 x 172, ONE OFF
SIDE	176 x 37, TWO OFF
REAR	347 x 37, ONE OFF
FRONT	355 x 37, WITH 347 x 2 CUTOUT, ONE OFF

COVER

TOP	355 x 95, ONE OFF
SIDE	120 x 25, 25 x 45° CUTOUT, TWO OFF
FRONT	355 x 35, CHAMFERED EDGES, ONE OFF
REAR	347 x 21, ONE OFF

First try out

Set the VOICE switch to 2, DEPTH control fully anticlockwise (minimum) and the volume control about one-quarter advanced. Set all the trimpots to half travel. Switch on and touch one of the note keys. You should get a sound in the speaker. If not, try several other keys up and down the keyboard. Try VOICE 2 if you still get no response. If nothing happens there either, switch off and check connections and component orientations again. Correct any faults and try again. If you still have problems, check the voltage across pins 2 and 14 (+ve) of IC9 and pins 11 and 4 (+ve) of IC8. There should be 9 V or so on each. Also check that there's about 5 V across ZD1. With the TREMOLO off, check the voltage between the 0 V rail and pin 11 of IC8. There should be 5 V there. Then check the voltage between pins 1 and 14 (+ve) of ICs 1 to 7. There should be 5 V on each IC.

If all this checks out OK, you're going to have to do a bit of signal tracing. All this needs is a high impedance crystal earpiece and a 100n capacitor in series with one lead. With one lead on the 0 V rail, put the other lead on pin 2 of IC8 and touch one of the keys. You should get a sound. Try several other keys, or all of them, to see that you get a sound from each group of oscillators. If not, then check the circuitry around ICs 1 to 7. If the oscillators work, check that you're also getting signal across the two outer terminals of the volume control, RV9. If not, the fault is probably in the wiring of SW2 or IC8 is faulty. If you do get signal there, check with the earpiece that you're getting signal at pin 6 of the LM380. If not, RV9 wiring is probably faulty. If signal's there, check to see that it may be on pin 8 of the LM380. If so, then the speaker(s) or speaker wiring is faulty. If no signal there, the LM380 is probably faulty.

When the note oscillators work, try out the tremolo. If it doesn't work, check that IC7/2 and /3 is working correctly. You can do this with a multimeter. If that's OK, see that, with Tremolo ON, the multimeter needle vibrates when looking at the output (pin 11) of IC8/4.

Got it going? Now for that grand old Chinese ceremony "chu ning".

Tuning it up

First of all, put out the cat, tie up the dog and send the rest of the household away. This may be painful to others. If you possibly can, get hold of a digital frequency meter. Using one of these is by far the easiest way to tune each note oscillator to the required frequency. Simply attach the DFM input across the speaker terminals, sound each note in turn and adjust that note's trimpot to the frequency given in the accompanying Table. Looking from the keyboard side of the project, the trimpot for the lowest F is at the extreme left, lowest F# is the next trimpot, lowest G is the third trimpot from the left, and so on. Make sure the Tremolo is OFF. We used a marking pen and wrote the note on the board beside each appropriate trimpot.

The next best method is to tune the ETI-905 against a piano, organ or other fixed-pitch keyboard instrument. This is simple to do by sounding the required note on the piano, or whatever, then sounding the same note on the project and tuning it so that it sounds the same pitch (no 'beats' between them). Be patient and do it carefully, don't swing the trimpot violently one way then the other. Tuning up this way is best done with the organ set to VOICE 2 and Tremolo OFF (turn the DEPTH fully anticlockwise).

There is another way, it's a little more tedious than the other methods, but yields good results, nonetheless. Get hold of a tuning fork (you could even build up and use the ETI-606 Electronic Tuning Fork, in Nov. '79 or Top Projects Vol. 6). Common tuning forks are "A 440" and "C 262" or middle C. You'll need three arms for this or a spare person. Seat yourself at a table or bench. Put a book or piece of sponge under the ETI-905 speakers. Set the VOICE switch to 2. Tremolo should be OFF. Set the tuning fork thrumming and hold the end of its shaft on the table or bench top to get a good, loud, sustained note. Touch the same note on the keyboard and adjust its trimpot so that its pitch is the same as the tuning fork's (i.e: no beats). Put the tuning fork aside and send your friend away, this next bit can be painful.

Say the note you just tuned was middle C (that's the C at the leftmost end of the keyboard). Now sound that C and the C above simultaneously, then tune the C above (C') so that there are no beats. But make sure that C' *is* above middle C. The trimpots should generally bring each oscillator into tune within a variation of ±30° of rotation from centre travel.

Now, count five notes up from middle C — C#, D, D#, E to F. Now sound F and middle C together. Tune F so that you get a pleasant sound with no beats. These two notes are now tuned a 'fifth' apart. Now sound the lowest F (right at the leftmost end of the keyboard) and the F you just tuned together. Tune the lower F so that you get no beats — making sure it's an octave lower. Now sound the topmost F and the F above middle C together and tune the topmost F for no beats. All three Fs should now be in tune. Starting at F above middle C, count up a further five notes — F#, G, G#, A to A# (B flat). Once again, tune for a pleasant sound with no beats. Then tune the A# an octave lower. The next one you will tune is D# (E flat) right up the top end of the keyboard. Tune its partner an octave lower. Where to go from here? Simple. Start down at the lower D#.

Count five notes up from the D# just above middle C — that's the G# to the right. Once again, tune for a pleasant sound with no beats, then tune the companion note an octave lower. Commencing at *that* note, count five notes up — to C#. Tune as before, then tune the octave companion (now to the right, higher in pitch). From C# above middle C, count another five notes up (F#), tune it, then the octave note. Count up to B, tune it, then the octave note. Continue — B to E, E to A, A to D, D to G, then check that the Gs are in tune with the Cs — the first notes tuned. They should be. If not, they should only be a little out and you can go back around the loop and make minor adjustments.

All tuned? Now learn to play Bach's Toccata in D minor!

PLAYING TIPS

The 'keys' should be played with the ball of the finger, not the tip. There is no "touch" to the instruments — hitting the key hard will not alter the sound in any way. This is much like a real organ. Touch the keys smoothly and firmly.

Under extremely humid conditions, or if you have greasy fingers, some trouble may be experienced with notes holding on. Wipe your hands thoroughly and the keyboard, too.

NOTE FREQUENCIES

F	698.5
E	659.3
D#	622.3
D	587.3
C#	554.4
C	523.3
B	493.9
A#	466.2
A	440.0
G#	415.3
G	392.0
F#	370.0
F	349.2
E	329.6
D#	311.1
D	293.7
C#	277.2
C	261.6 (middle C)
B	246.9
A#	233.1
A	220.0
G#	207.7
G	196.0
F#	185.0
F	174.6

A case

We have not described complete details of a case for this instrument as we would expect constructors to 'customise' a case to suit individual tastes or circumstances. However, we have drawn up the dimensions of a suitable case that may be constructed of 4 mm thick material — such as plastic sheet or plywood. The design has a 'top' and a 'bottom' and each need only be glued together. The board can be mounted in the bottom on standoff pillars. Several standoff pillars screwed onto the board could then support the case top. The accompanying drawings show the rudimentary details. The completed case could be covered in suitably patterned 'Contac', or something similar.

Batteries, supply

The project was designed to be powered by a 9 V battery or other sort of dc supply. It draws around 40 mA at average volume during playing, somewhat over 100 mA at full volume. You can use a No. 216 9 V (transistor radio) battery, but we recommend you get either an extra heavy duty type or an alkaline battery. Alternatively, you could use 6 x AA cells in a 'six pack' battery holder. You can dispense with the battery and use an appropriately rated plugpack if you like. A plugpack rated at 6 V/200 mA will deliver voltages around 8 - 9 V at current loads under 100 mA, and such a plugpack would be the best to use if you want to power the project from the ac mains. ●