

Simple, sensitive metal detector

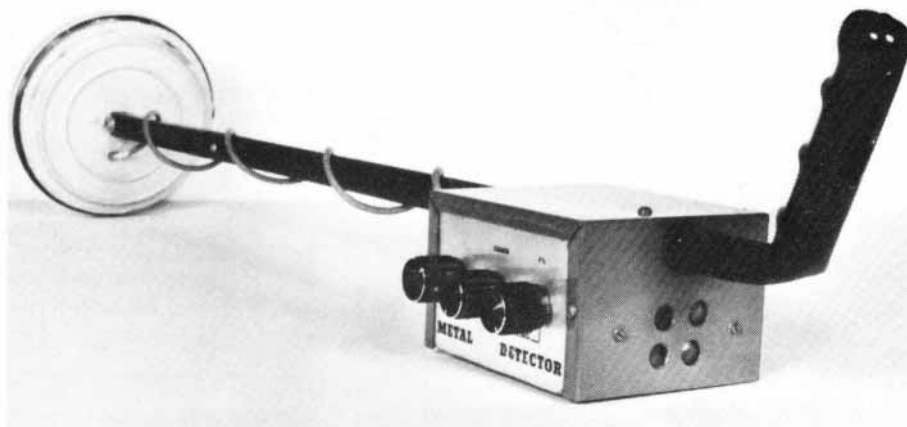
Phil Wait

The metal detecting hobby is enjoying quite a boom at the moment and treasure hunters are not just after gold. Though the price of the precious metal has fallen in recent months, at around \$600 an ounce its worth going after. Old coins and relics fetch high prices too, so there's lots to find out there...

METAL DETECTORS depend on detecting one of several effects that can be observed when a metal object influences the magnetic field surrounding a coil of wire carrying an alternating current. The principal effects are: the pattern of the magnetic field surrounding the coil will be altered and the inductance of the coil will change.

The various types of metal detector devised exploit these changes, electronically detecting the alteration induced in the coil by the metallic object. Non-metallic objects or material can also affect the coil in similar ways.

There are three basic methods employed to exploit the above effects. "Induction Balance" (IB) metal detectors employ two coils. One is driven by a modulated oscillator. The other is connected to a detector and amplifier. The two coils are carefully positioned with respect to one another such that the receiver coil picks up very little of the energy radiated by the transmitter coil when no metal or mineral material is nearby. When the coils are brought near a metal object, the field pattern is distorted, greatly increasing the transmitted energy picked up by the receiver coil. The modulated signal is detected and can be indicated by amplifying the recovered modulation to speaker level as well as indicating it on a meter. For obvious reasons, this type of metal detector is often referred to as a "transmit-receive" or TR detector, sometimes as an IB/TR detector. Chief advantages are good pinpointing ability and good depth penetration, and they are not sensitive to small ferrous objects.



Sensitivity suffers badly in mineralised or ironstone ground. We described an IB/TR metal detector back in our May 1977 issue (Project 549) and it is still a popular project. The problem for the home constructor lies in correct construction and alignment of the coils.

Most IB detectors operate at a frequency between 85 kHz and 150 kHz. As they are badly affected by mineralised ground a technique was developed using very low frequency to energise the transmit coil. The 'VLF' types operate at frequencies around 4 - 6 kHz, a frequency range which penetrates all types of soil quite well. However, they need to run at a fairly high power to achieve sufficient sensitivity with small objects, hence battery drain is quite high, and pinpointing ability is poor.

"Pulse Induction" detectors employ coils in the search head that are set up in much the same manner as the IB detector. However, the transmitter is pulsed so that high energy bursts are transmitted by the search coil. The receiver then

compares the phase of portion of the received pulse with the transmit signal. When a ferrous or magnetic object is brought near the search coils the phase of the received signal is *advanced* with respect to the transmit signal. The *opposite* occurs when a non-magnetic conductor is brought near the search coils. Thus, this type of detector can effectively 'discriminate' between ferrous and non-ferrous metals as well as exclude ground effects — simply by setting the detection circuitry to exclude signals of the unwanted phase characteristics. Thus, a "Ground Exclusion"

FEATURES

- **Good sensitivity**
- **Excellent stability**
- **Good pinpointing ability**
- **Loudspeaker output**
- **Simple construction and set up**
- **Tuning allows for ground**
- **Low cost**

control is often featured with these detectors. As the strength of the received signal also varies, depending on the 'target' object's characteristics, this effect may also be included in the detection process.

Clearly, an IP detector presents many problems to the home constructor.

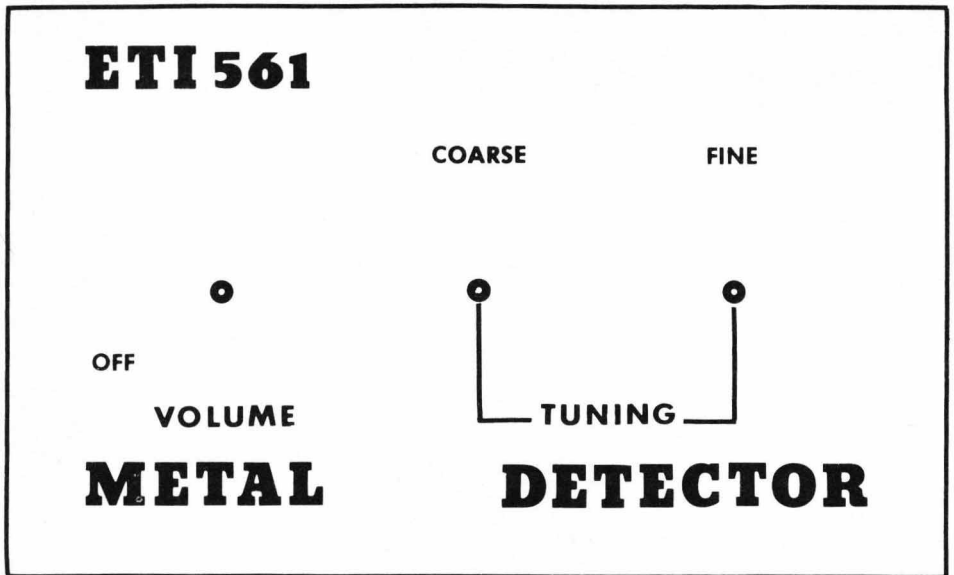
The simplest technique detects the change in inductance of a single search coil. If this coil is part of the tuned circuit of an oscillator, then comparing the frequency of the 'search' oscillator with a stable reference oscillator will indicate the presence of a metal object. This detector is called the "Beat Frequency Oscillator" or BFO type. The two oscillators are set such that there is a slight difference in their frequencies and their outputs mixed. The resultant will be a 'beat' frequency which is equal to the difference between the two oscillator frequencies. The main advantages of this type are simple circuitry and setting up along with good pinpointing ability. In the past, most published designs have suffered from a distinct lack of sensitivity as well as poor tuning stability. A cunning mixing technique and a few other fillips can overcome these problems.

Hence, our new metal detector is a BFO type incorporating some modern refinements. It has proved to have similar sensitivity to our IB detector, the ETI-549, but is generally easier to build and set up, there being no critical adjustments.

Design features

Our new metal detector has three controls: COARSE frequency adjust, FINE frequency adjust and VOLUME on/off. The coarse frequency control is used to initially set the frequency of the search oscillator, compensating for the various factors affecting any drift in this oscillator (mainly temperature and battery voltage). The fine frequency control is then used to set the note to a low pitch when the detector is placed over the ground, permitting compensation for the effect of the ground on the frequency of the search oscillator. The volume control adjusts the loudness of the output from the speaker.

The two main design problems this type of detector presents are the fre-



quency stability of the two oscillators and the minute frequency change which has to be detected.

The search oscillator we finally used was settled on after some experimentation. Our first try employed an LC oscillator built around a CMOS gate chip. This proved to be not as stable as we required and we found that trying to obtain dc control of the frequency by varying the supply rail voltage had drawbacks. After some experimentation with oscillator configurations we hit on a discrete component oscillator which we found behaved much as we were seeking.

The search coil in the circuit we used is the inductor in a Colpitts oscillator. However, this particular circuit may be a little unfamiliar to many readers. To increase the RF current in the coil, it is placed in the collector circuit of Q1. Feedback is between collector and emitter and the base is effectively at RF ground. The frequency determining capacitance of the tuned circuit is 'tapped' to provide feedback, C2 and C3 performing this function. Careful attention has been paid to the basic frequency stability of this oscillator. Good quality styroal capacitors have been used for C2 and C3. These have a temperature coefficient roughly opposite to that of other temperature influences on the frequency of the oscillator. In general, the short-term stability of this oscillator is quite good.

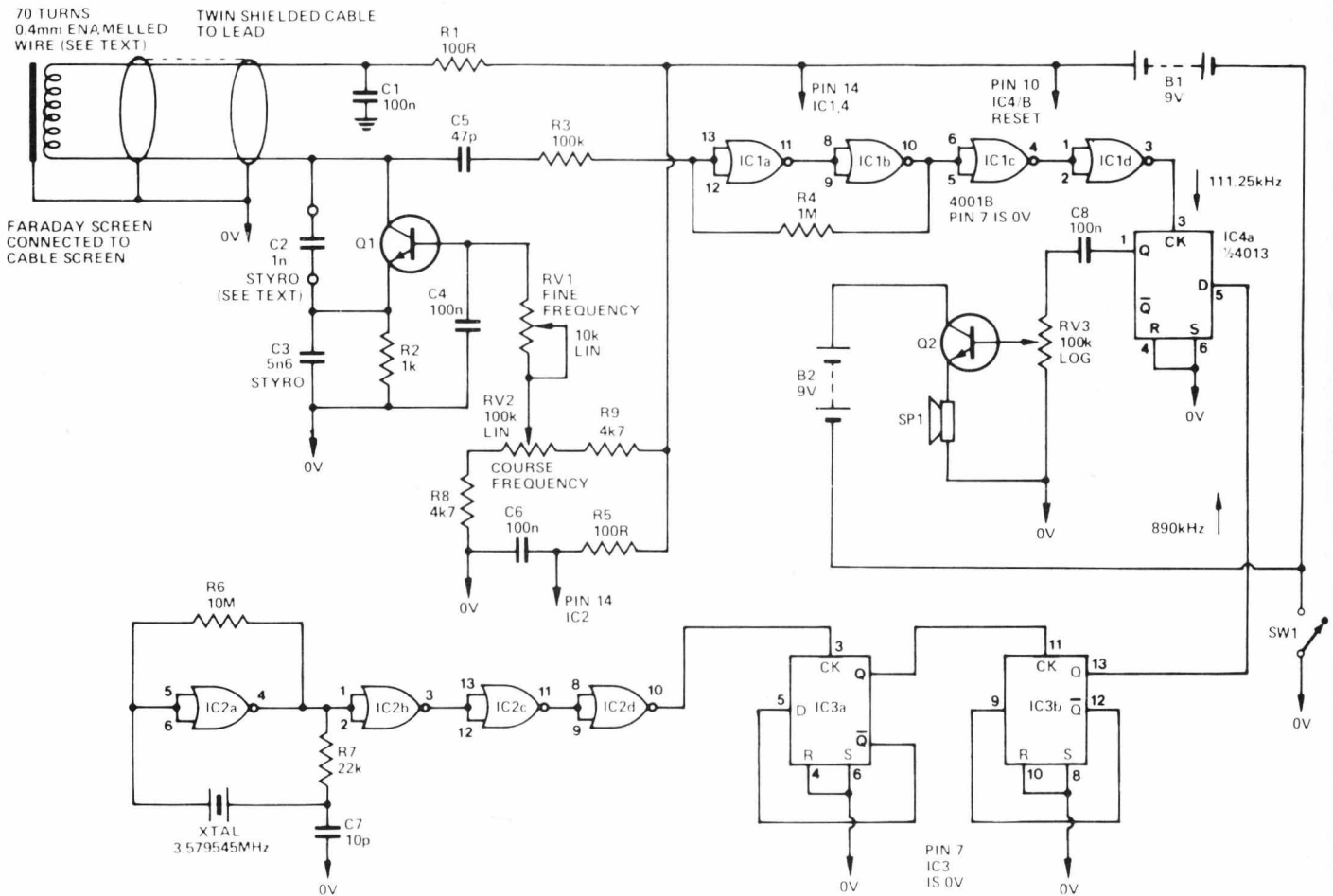
The particular circuit configuration of the oscillator gave us a very useful bonus — dc control of the oscillator fre-

quency over a small range. Varying the base bias on a transistor will vary the collector-base capacitance. In this circuit, the c-b capacitance is part of the overall 'stray' capacitance that determines the exact frequency of oscillation. As the base bias is increased the c-b capacitance decreases, increasing the oscillator frequency. In this way, the oscillator frequency can be varied over a range of about ten percent. We have provided two controls, the FINE control providing a variation of about one-tenth that of the COARSE control.

The search oscillator is loosely coupled via a 47pF capacitor to a following CMOS Schmitt trigger and two inverters which square the output. The loose coupling isolates the oscillator from the subsequent circuitry, further enhancing die stability of the search oscillator.

For the reference oscillator, we chose to use a crystal, because of its inherent stability. It has been argued that if an ordinary LC circuit is used for the reference oscillator it will have similar drift characteristics as the search oscillator and the overall drift will be reduced. In fact, the reference oscillator can be made using a standard 455 kHz IF transformer. In practice however the two tend to drift at markedly different rates. We think the best approach is to make both oscillators as stable as possible. Hence the crystal — which is an easily available type and cheaper than an IF transformer!

The reference oscillator is a simple 'inverter' crystal oscillator built around one gate from a CMOS quad NAND



HOW IT WORKS - ETI 561 Metal Detector

The beat frequency metal detector employs two oscillators: a very stable reference oscillator and a search oscillator. The search oscillator uses a tuned circuit designed to be influenced by metal or mineral objects which are brought into its field. The two oscillators are adjusted so they are harmonically related and fed to a mixer. When the search frequency is adjusted so the reference frequency fed to the mixer is eight times the search frequency, the output of the mixer is zero. The search frequency is slightly adjusted so that an output appears from the mixer which is the difference between the two input frequencies. This can be adjusted to an audio tone.

When a piece of metal or mineral is brought near the search coil the frequency of the oscillator varies, which in turn varies the output frequency from the mixer. The change in pitch can easily be heard from the speaker.

The reference oscillator employs a crystal in a CMOS oscillator circuit using one gate from IC2a. The resistor R6 biases the gate into its linear region. IC2 b, c and d, are used as buffer stages to prevent oscillator pulling and to further square its output waveform. Two flip-flops, IC3a and b, divide the reference signal by four to 890 kHz.

The search oscillator uses a discrete transistor in grounded base configuration, with the search coil in the collector. Using the coil in the collector increases the strength of the field around the coil and hopefully overcomes some of the losses in the ground. Feedback is set by the ratio of C2 to C3 from collector to emitter and their value determines the frequency of the oscillator. The base is grounded at RF by C4.

By varying the bias on the transistor the inter-element capacitances can be varied. This varies the oscillator frequency as the transistor capacitances form part of the strays in the LC circuit. RV1 and RV2 provide fine and coarse frequency control. The resistors R8 and R9 limit the maximum and minimum voltage on the base to prevent over-dissipation in the transistor or drop-out of the oscillator.

The output of the search oscillator is fed to a Schmitt trigger, consisting of IC1a and b, where it is squared and further buffered by IC1c and d. The search frequency is then fed to the mixer.

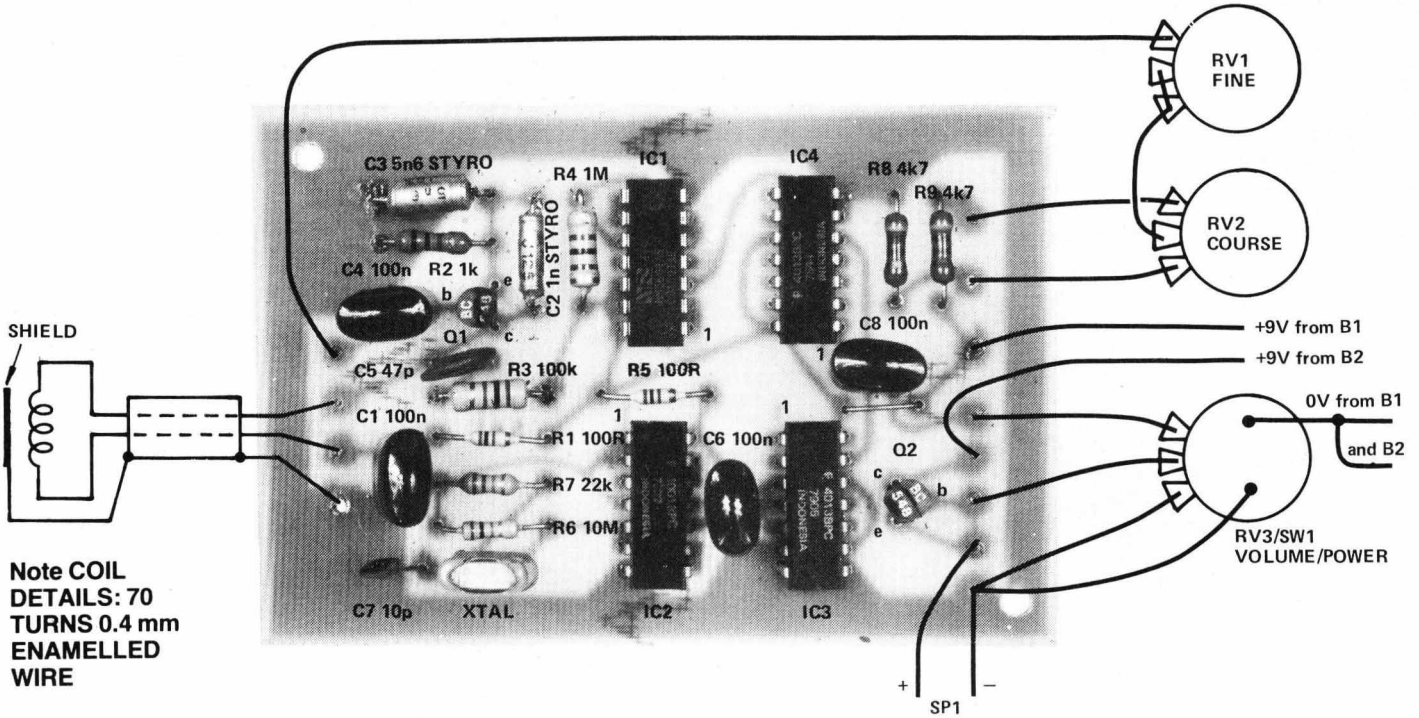
Both oscillators are decoupled from each other by supply line decoupling R1C1 and R5C6.

The mixer consists of half a dual-D flip-flop. The search and reference frequencies are fed to the clock and O inputs

respectively. The flip-flop looks at the reference oscillator (DI on every positive transition of the search oscillator clock), and transfers this level to the O output until the next clock transition. If the two oscillators are exactly evenly harmonically related (i.e: 2nd, 4th, 6th, or in our case 8th, harmonic) the D input will always be the same level at each clock pulse. The output from the mixer at the O pin will always be the same — no pulses.

However, if the search frequency is varied and the O and clock inputs are no longer harmonically related but are changing in phase with respect to each other, after a few clock pulses the D input will no longer be the same — the output will change state. The effect of all this is to produce a chain of square waves at the O output, the frequency of which is eight times the change in frequency of the search oscillator.

Capacitors C8 and RV3 form a differentiating network which feeds a pulse to the audio amplifier, Q2, for each output transition from the mixer. Each cycle from the mixer produces two pulses in the speaker. If the frequency of the search oscillator is shifted one hertz the output of the mixer changes by eight hertz, producing an output of eight pulses per second in the speaker.



gate, IC2. This has a square wave output and drives a divide-by-four circuit, IC3, via the other three gates in IC2, acting as buffers.

The crystal we used is a 3.579545 MHz type (NTSC chrominance sub-carrier frequency) commonly available from a number of suppliers. We used one in our Electronic Tuning Fork (ETI 606) published November 1979. The output of IC3 is at a frequency of about 890 kHz. The *exact* frequency is unimportant, just so long as its *stable*.

The search oscillator operates at a little above 100 kHz, about one-eighth of this frequency.

The secret of our metal detector's overall sensitivity lies in the mixer circuit. This employs one section of a 4013 flip-flop. The reference oscillator's divider output (at 890 kHz) is applied to the D input of IC4a and the squared-up search oscillator's output is applied to the clock input. If the clock frequency (i.e the search oscillator frequency) changes by 1 Hz, the output beat (from the Q output of IC4a) will change by 8 Hz (see 'How it Works'), thus considerably *multiplying* the smallest changes in oscillator frequency.

The output of the mixer is fed to a simple audio amplifier driving a loud-

speaker. The search and reference oscillators must be well decoupled from each other and buffered from the mixer stage to prevent 'pulling' of the oscillators, which would result in erratic operation, especially when set for a low frequency output. We have used supply line decoupling as well as buffer stages after each oscillator. We also found it necessary to use a separate battery for the audio stage to prevent the very short, but high current pulses to the audio stage affecting the oscillators.

The search coil

The most important characteristic of the search coil is its size. Surprisingly enough the actual inductance doesn't seem to have much effect on sensitivity. The greater the coil diameter the greater the penetration depth, but the less sensitive it is to small objects. As a general rule the penetration is about equal to the search coil diameter, while the sensitivity is roughly proportional to the cube of the object diameter (as expressed as a function of the search coil diameter). Sensitivity is also inversely proportional to the sixth power of the distance between the coil and the object.

All this means is that if the object size is halved the sensitivity is reduced to one-eighth. Also, if the depth is dou-

PARTS LIST - ETI 561

Resistors all 1/2W, 5%

- R1 100R
- R2 1k
- R3 100k
- R4 1M
- R5 100R
- R6 10M
- R7 22k
- R8, R9 4k7

Potentiometers

- RV1 10k lin
- RV2 100k lin
- RV3 100k log switch pot

Capacitors

- C1 100n greencap
- C2 1n styroséal
- C3 5n6 styroséal
- C4 100n greencap
- C5 47p ceramic
- C6 100n greencap
- C7 10p ceramic
- C8 100n greencap

Semiconductors

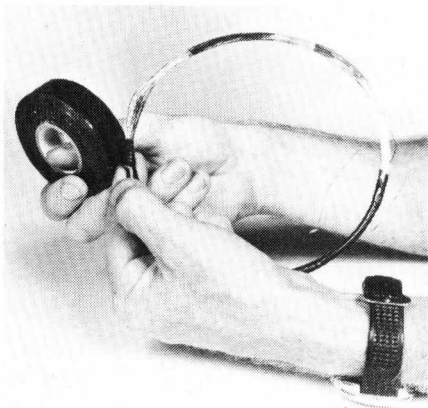
- Q1, Q2 BC548, BC108, etc.
- IC1, IC2 4001B
- IC3, IC4 4013

Miscellaneous

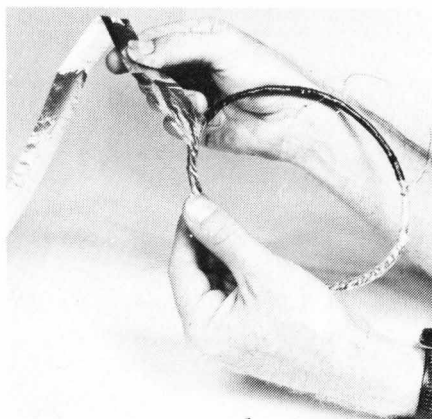
- SP1 8 ohm speaker
- B1, B2 9 Volt battery (type 216)
- XTAL 3.579545 MHz NTSC colour xtal
- ETI-561 pc board

Length of twin shielded cable, plastic pot stand (approx 150 mm dia), length of steel or aluminium tube (approx 600 mm long, 20 mm dia), length of plastic rod or wood dowel to fit inside pipe (approx 200 mm long), 0.4 mm enameled wire, aluminium foil, Araldite, box to suit (approx 105 x 125 x 75 mm), three knobs, battery clips, insulation tape, two right angle brackets.

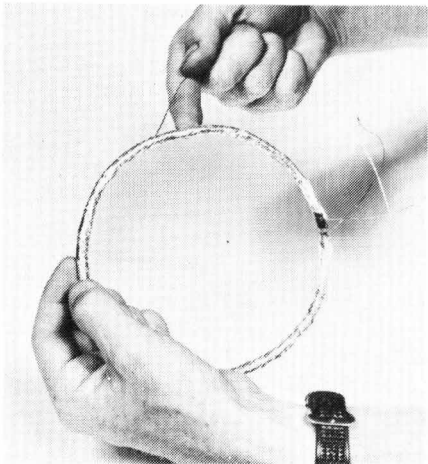
SEARCH HEAD CONSTRUCTION



1: Having wound the coil as described, wrap it with two layers of insulation tape.



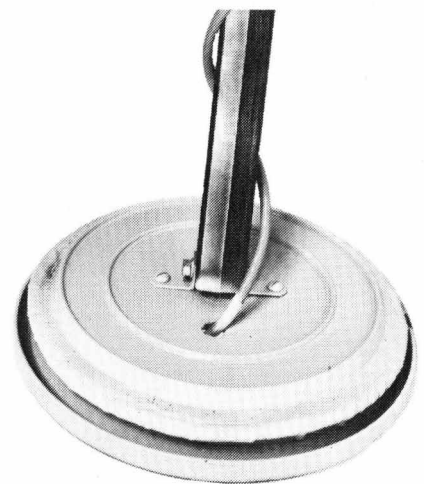
2: Next wind the Faraday shield using two strips of aluminium foil, leaving a break where the coil ends come out.



3: Wind tinned copper wire over the shield, passing the end out where the coil leads pass out.



4: Cover the whole coil assembly with two more layers of insulation tape.



5: Press the assembled coil into the rim of the pot stand, terminate the wires as described and epoxy the coil to the pot stand.

bled the sensitivity is reduced to one sixty-fourth. Its easy to see why all metal detectors which are designed to pick up small objects use small coils, (150 to 300 mm diameter) and really only skim the soil surface. If the search coil is doubled in diameter for greater penetration the sensitivity to small objects falls to one-eighth. You rapidly encounter the law of diminishing returns.

Some of the more expensive metal detectors improve the penetration, while retaining sensitivity, by using a very complex arrangement of coils which modifies the field pattern. This can be done to some extent by making the coil on the BFO detector oval in shape.

We chose a round coil of 150 mm diameter to give good sensitivity to small objects giving about 100-150 mm penetration which is easy to build, but this is open to considerable experimentation. Remember though, that if the coil diameter is increased the number of

turns will have to be reduced so that the search oscillator remains at the same frequency (about 110 kHz).

Faraday shield

If the search coil is moved around, the capacitance between it and the ground or other objects changes. This changing capacitance 'pulls' the oscillator frequency and can completely swamp out the small change in inductance we are looking for. The coil can be screened from this capacitance effect by using a Faraday Shield around the coil. This consists of a ring of tubing, or in our case — a wrapping of aluminium foil, around the coil but broken at one point so it does not make a shorted turn. This shield is then connected to the common supply rail (0V) on the oscillator.

Construction

We have deliberately chosen commonly available mechanical and

electronic components so that construction of this project is as easy as possible — especially for the newcomer. The search coil is mounted on a 165 mm diameter plastic pot stand which may be purchased at hardware stores and nurseries (if you must know, we used a Decor *497!). The electronics is mounted inside a simple aluminium box attached to a stem made from a length of tube which extends down to the search coil and serves as the handle. Connection to shield the search coil is via a length of shielded cable. The controls mount on one side of the box housing the electronics. Which side you mount them depends on whether you are right or left handed. The speaker mounts on the end of the box facing the operator. As can be seen from the picture, the handle was made with an upwards bend at the end which you grip. This balances the instrument reasonably well, avoiding arm strain.

Construction should commence with the electronics. Mount the components on the pc board, taking care with the orientation of the transistor (Q1) and the ICs. Do not substitute another type of capacitor for the styroal types specified for C2 and C3 or performance may suffer. The crystal specified comes with flying leads and may be soldered in place. Don't use too much heat though, solder quickly and you will avoid possible damage to the crystal.

The next step is to make the stem. The easiest way is to take a length of 25

mm diameter electrical conduit about 850 mm long and make a bend about 100 mm from one end for the grip. To do this, heat the point of the bend over a flame (not *in* the flame) until it softens and then carefully bend it about 60° from straight.

A length of aluminium tube may also be used for the handle. The bend for the grip can be made by first flattening the point of the bend somewhat with a hammer then placing the short piece in a vice and carefully making the bend. A section of wood dowel or plastic tube should be placed between the search coil and the end of the metal tube to keep the mass of metal about 200 - 250 mm away from the search coil. A piece of wood dowel of the right size, jammed in the end of the aluminium tube, is generally the easiest way to go about it.

We used a small aluminium box which comes in two pieces. We drilled a hole in either end of the bottom of this box so that it could be slipped over the stem (see accompanying photograph). A nut and bolt was used to secure it to the stem on the side 'below' the grip. The small speaker is mounted in this part of the box, before it is secured to the stem, on the end which faces upward toward the operator. A small hole is drilled in the opposite end and a grommet inserted. This permits entry of the cable

to the search coil.

The pc board and controls are mounted to the 'lid' of the box. Position the controls on the side that suits your handedness. Our model was made for right handed operators.

Now for the search coil. This is wound so that it can be tucked inside the rim of the up-turned plastic pot stand. First make a cardboard former of the appropriate diameter. Roll a strip of heavy cardboard around the rim such that it fits loosely and tape or staple it securely (to avoid it popping open at an awkward moment).

Lift the former off the pot stand and then wind the coil onto this former as per the details given in the parts list. Leave a short length of wire spare on each end to make the connection. Tie the coil up with a few lengths of string at various places and then slide it off the former. Now wind two layers of insulation tape around the coil, leading the two ends out at the same place.

Next, wind the Faraday screen. Cut some aluminium kitchen foil into strips about 15 mm wide and wind this around the coil to make two layers but leaving a small gap about 5 mm to 10 mm wide where the coil ends come out. It is very important that the two ends of the Faraday shield do not connect as this would make a 'shorted turn' and the coil would not work as intended.

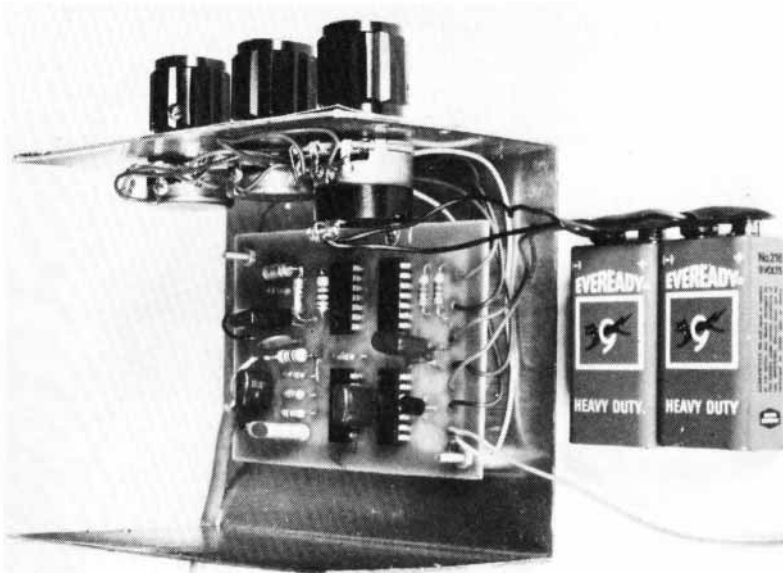
To secure the foil tightly around the coil, and to make connection to the shield, wind a length of tinned copper wire around the shield with about a 10mm pitch (i.e: about 10mm between successive turns). The end of this wire is taken out at the same place as the coil connections.

Now wind another two layers of insulation tape around the whole assembly. Drill a 3 mm hole in the side of the pot stand and then press the coil down into the rim with the connecting wires adjacent to the hole. Pass the wires through the hole. Pour quick-setting epoxy over the coil to hold it in place.

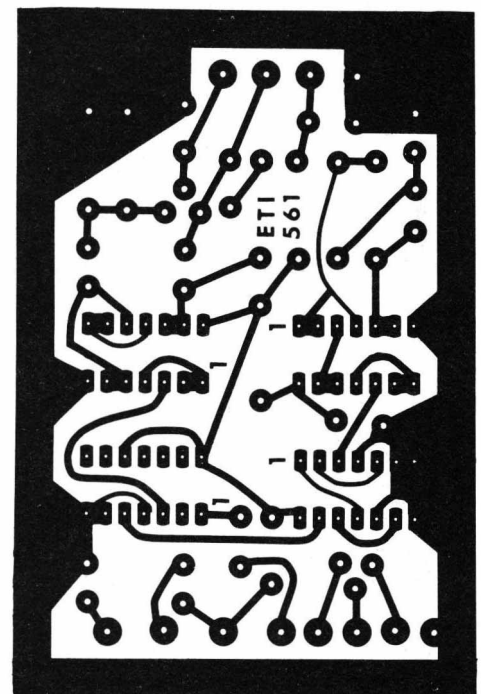
The search head is mounted to the stem using two right-angle brackets and a bolt passed right through the end of the stem. Small pieces of metal here don't seem to adversely affect the operation of the detector.

Solder the coil connections to the twin shielded cable, the Faraday shield connecting to the cables shield, and glue the cable and wires underneath the pot stand to hold them rigid. If you wish, the 'underside' of the pot stand may be completely filled with epoxy.

Wind the cable around the stem to keep it mechanically rigid and pass it through a grommeted hole in the box. Terminate the cable to the pc board.



Internal view of the metal detector electronics showing general placement of the major components. We mounted the pc board using some 12 mm spacers, nuts and bolts. The speaker mounts on the box 'lid'.



Using it

When the construction is complete, turn on the detector, advance the volume control and rotate the coarse frequency knob. You will hear a number of 'heterodynes' or beats, one being very strong. This heterodyne is the one commonly used, the others being odd multiples of the reference signal beating with multiples of the search oscillator. You may find that some of these weaker signals are more sensitive to buried objects than the stronger one.

Set the fine frequency control to midrange and set the course frequency control to near the strong heterodyne with the search head held away from the ground. Lower the detector to the ground and you will notice a frequency shift. This is the effect of the ground and will vary between different types of

soil. Use the fine frequency control to set the beat to a low pitch and sweep across the surface. A metal object will cause a change in the pitch which is clearly audible.

The ear is more sensitive to changes in pitch at low frequencies than at high frequencies and thus it is best to adjust the fine frequency control to a low pitch that can be heard at a comfortable volume from the loudspeaker.

Theoretically, the frequency of the search oscillator should *increase* when a non-ferrous object comes within range of the search coil and *decrease* when a ferrous (or diamagnetic) object is within range. This effect is difficult to detect in practice as eddy currents in ferrous materials swamp the effect and they react much the same as non-ferrous metals. However, minerals such as

hematite may show the effect. With the search oscillator set on one side of zero beat, metal objects near the search coil will cause the pitch to *increase*, while magnetic minerals will cause the pitch to *decrease*. With the search oscillator set to the other side of zero beat, the opposite will occur.

You could try a few experiments to show up this effect.

Enough theorising. In general operation, try to keep the search head a constant distance from the ground and sweep from side to side in a regular pattern. The right technique is easily developed with a little practice.

There are a number of books on metal detecting available and these show the sort of techniques the successful treasure hunter employs.