ELECTRONIC fluxgate compass

The technology described here lends itself to nautical and aeronautical navigation either as a direct reading compass or the sensing heart of an autopilot. The system could equally well be adapted to providing directional information for deaf people.

By Richard Noble.

The fluxgate magnetic sensing head is an extremely sensitive detector of magnetic fields. These cover from tiny field probes, no larger than 0.03 inches in diameter, through current probes, impurity detectors, compasses, metal locators, prospecting equipment, even to submarine detectors. Granted, not many people will wish to detect submarines but how many underwater diving enthusiasts would love to have a "diveable" hand-held wreck-finder?

The compass designs presented here, though carried out in detail and mostly tested, are primarily intended as illustrations of the technique and suggestions for experimentation. Considerable scope exists for variation and final presentation or even use of the basic signals made available.

An earlier article (*EW & WW* September 91) entitled *A Simple Magnetometer* described the principle and use of a fluxgate sensor to produce an earth field measuring device sensitive enough to detect the influence of solar flares on the ionosphere.

It determined the magnitude of two horizontal field components at right angles to one another. Given that information, it is obvious that one can calculate the direction of the principal horizontal component, which is precisely what we ask a compass to tell us.

The magnetometer, however, needed to detect very small variations in the field to fulfil its proper function and consequently needed a high signal to noise ratio. A compass makes no such demands, happily coping with a much lower signal to noise ratio and allowing the circuitry to be even simpler than before. Three common integrated circuits suffice for the sensor conditioning and in the simplest case, the output indicator need be no more than a centre-zero meter.

The simplest systems could well be regarded as the poor man's autopilot since if the pilot is considered to be the device closing the feedback loop, that is exactly what it is. If you are steering a boat or flying an aeroplane, all you really need are steady-as-you-go turn left/turn right instructions to maintain a heading.

The technique has much to recommend it as the equipment is minimal and hopefully therefore more reliable and the steering arrangements if properly arranged are non-confusing, key elements in safe navigation.

Sensor circuits

The presence of an external magnetic field passing through a toroidal core produces an asymmetry in the magnetic induction waveform in the core. The previous design exploited the subtly changing widths of the less noisy pulses produced by induction in a sense winding over the two legs of the core. This design is less fussy and simply extracts the even harmonics produced by the asymmetry and, in particular, the second harmonic of the switching frequency. A rather crude resonance with the sense winding also enhances the size of the signal being sought.

The core, as before, is a tape wound toroid of HCR alloy, designed by Telcon Metals for magnetic control systems. This is wound with approximately 170 turns of 0.5mm enamelled wire to provide a switching primary winding. The drive circuit, shown in

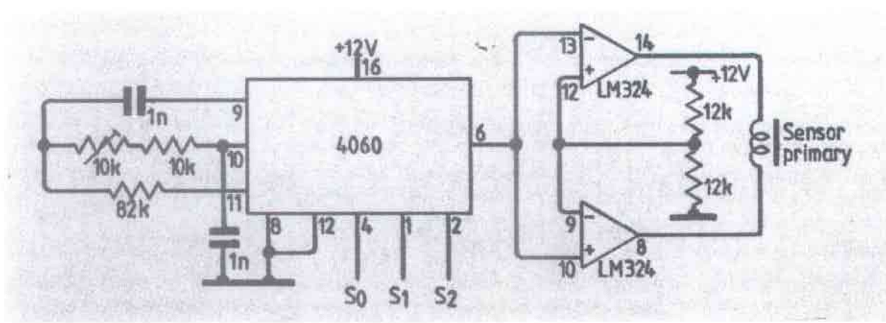


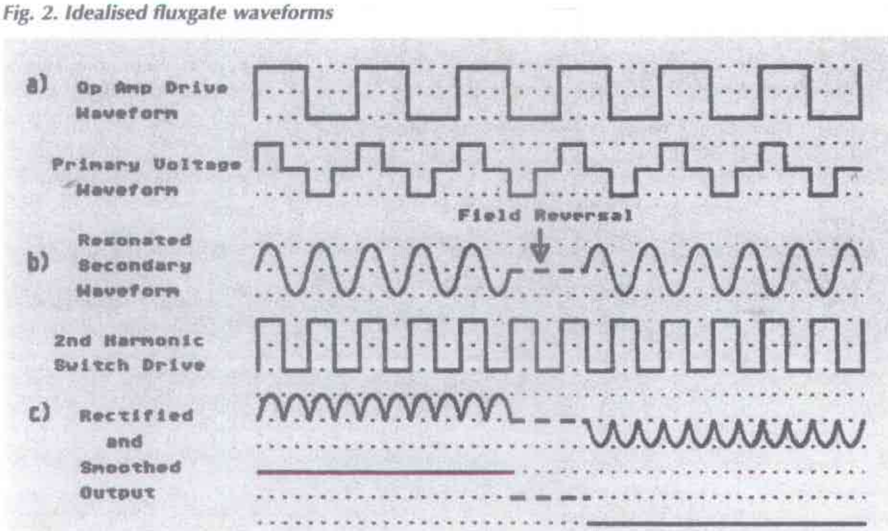
Fig. 1. The driver circuit used in all version

Fig.1, is provided by two of the operational amplifiers in an LM324 quad package working in a push-pull configuration. The input is a square-wave at the fundamental frequency of approximately 110Hz. This is provided by a 4060 cmos oscillator and divider chain which also supplies the second harmonic switching pulse for the phase detector from an appropriate tapping. This is needed because, although the second harmonic sensor signal varies as the external field, there is an abrupt change of 180° in the phase as the field reverses through zero, calling for a synchronous phase detector to preserve polarity correctly.

Returning to the drive system, the square-wave input does not produce a square-wave output voltage across the primary. Before the flux in the core reaches saturation, the primary core has inductance but at saturation the inductance collapses to zero and at this point the output voltage also disappears, producing an output waveform like that shown in **Fig 2a**. This does tend to warm the integrated circuit chip, but is within the short circuit protection capability of the device and makes the circuit delightfully simple. The frequency of the oscillator is adjusted to make the output waveform as symmetric as possible so as to avoid the transformer coupling even harmonics into the pickup winding. **Figure 3** shows the detector circuit.

The pickup winding is a single 500 turn winding of 0.2mm wire over the outside of the core, roughly resonated with the 10μF paper capacitor and fed to a unity gain amplifier which can have its phase reversed by 180°. The phase reversal is controlled by the analogue switch which either shorts the non-inverting input to ground or does nothing depending on its control voltage. When it is shorting to ground the circuit becomes a unity gain inverting amplifier. When it is open, the amplifier has a gain of -1 from the inverting input and +2 from the non-inverting input. The net result is a gain of +1.

Fig. 2. Idealised fluxgate waveforms



When the control is switched at the second harmonic frequency and in the appropriate phase, the amplifier neatly rectifies the signal and correctly converts the 180° phase change into a polarity change. In this way the DC output is a proper 4-quadrant vector component with a one-to-one correspondence to the equivalent earth field component. Two windings at right angles to each other will allow the reconstruction of an electric vector simulating the horizontal magnetic vector.

Idealised waveforms illustrating this process are shown in Fig. 2. All that remains is to amplify and smooth the rectified half sinusoids in an integrating circuit, the time constants chosen allowing some control over the damping of the instrument output. An oscilloscope will not show waveforms like the illustration because the signal is small and swamped by the interfering unbalanced signals. However if the external magnetic field is increased considerably then something much more like the idealised version can be seen. This is easy to do with a small bar magnet, held close to the sensor core, giving an increase in field strength of several orders of magnitude.

Fortunately the interfering signals which spoil an oscilloscope image have no effect on the final output and a large voltage swing is obtained for the tiny 0.18 gauss horizontal component of the earth's field.

The output from this single channel device is fed to a centre-zero meter. When the axis of the sense winding is at right angles to the earth's field the meter reading is zero. Any departure from this orientation will make the meter deflection positive or negative, providing a heading error indication. The sense of the correction can be chosen to provide a steer left/steer right type of display. By rotating the sensor to the desired angle relative to the vehicle, the instructions to steer, if followed, will eventually bring the vehicle on to the correct heading as the meter reading approaches zero. Maintaining the zero reading will maintain the vehicle heading.

Heading-set mechanism

The following is a suggested design requiring no special tools and may obviously be improved upon by those with special facilities.

Fig. 4 (on p18) shows an exploded diagram of the parts and their method of assembly as made by the author.

Setting and calibration

The more observant reader may be wondering about what looks like an anomaly at the octant boundaries. The analogue x or y value barely changes as the octant code switches suggesting that the two different outputs correspond incorrectly to the same angle. However this is no different to what happens at any other threshold. In reality there are a number of lamps all spaced equally around a circle and only one is ever showing at any time; it is only necessary to point that one in the right direction. In fact the sensor can be placed in any orientation as long as the dial is fixed to the indicator in the right place.

This is most noticeable in the simple 8-point compass. No one really wants a compass that indicates NNE, ENE, ESE, SSE, etc. The sequence N, NE, E, SE, S, etc is much more acceptable and in boxing the compass the adjustor will naturally make this happen. What he actually does is offset the zero octant boundary by around 22° so as to make north appear in the middle of the lamp's "on" range. In the same way the 72-point compass will be offset by 2.5° and the 360-point version by 0.5°, though the latter is almost certainly masked by the precision limits of the system.

A reasonable target to aim for would be ±1° though this may not be achievable without considerable care. Certainly the second pickup winding on the sensor will have to be wound over a separate card or plastic sleeve to allow for some small adjustment during calibration. After the best position has been found it can be glued or varnished into place. The best position is that for which the zero-crossing points of the x and y signals are genuinely at right angles to one another.

Prior to checking this the amplifier zero offsets must have been set to ensure that the maximum excursions of the x and y signals are symmetrically disposed about zero volts. Some iteration of these adjustments may be necessary as they are interactive.

All of the above should be carried out while keeping the core in the horizontal plane though this need not be more complicated than temporarily securing it to a circle of card with blue-tack. If the card is first marked with a set of 15° protractor type markings and rotated over a cross marked on a flat surface the results can be reasonably accurate.

Subsequently the channel gains should be adjusted to match exactly the input span of the bar driver or A/D converter, whereupon the compass display should read correctly. Final tweaking may be beneficial while rotating the card over the cross to check the readings at 15° intervals. Once installed, careful checking in the usual manner is essential as navigation is sometimes a life-and-death matter and at this stage no effort is too great to ensure accuracy and reliability. Unless a good location can be found for the sensor the use of a deviation chart is recommended.

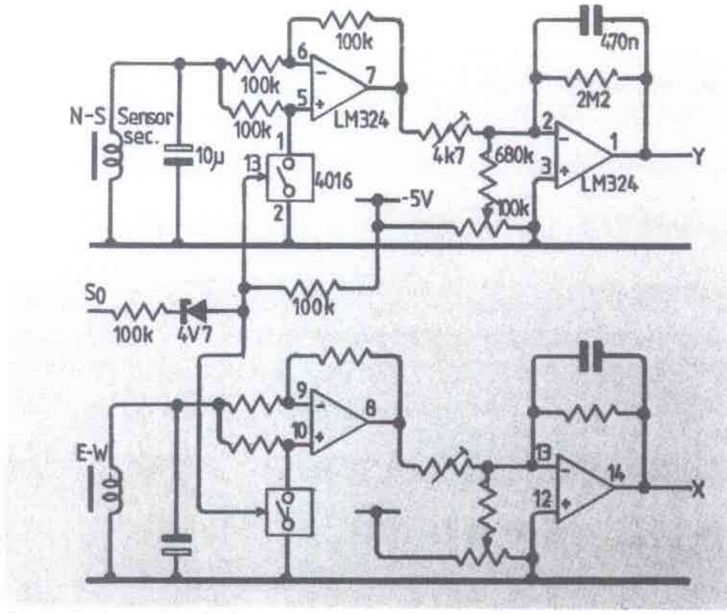


Fig. 5. Twin sensor circuit

The final fitting is left to the ingenuity of the installer, but should be such that the sensor is horizontal in the normal cruising attitude of the vehicle and reasonably removed from the influence of ferrous metal. In the case of a sailing boat, the first requirement means at least a fore and aft gimbal pivot to counter the vessel's heel. With an aeroplane, gimballing is pointless as apparent gravity can be markedly non-vertical in manoeuvres and a fixed mounting is all that is required. The usual "northerly turning error" will be present but, unlike a normal compass, no violent swinging results and the indicated reading becomes smoothly stable as levelling occurs.

Direct reading remote compass

At the cost of some additional circuitry, the sensor can be mounted remotely in an iron-free area and the display fitted in any convenient position. The sensor electronics need an extra LM324 operational amplifier chip to provide a second channel as shown in **Fig. 5**.

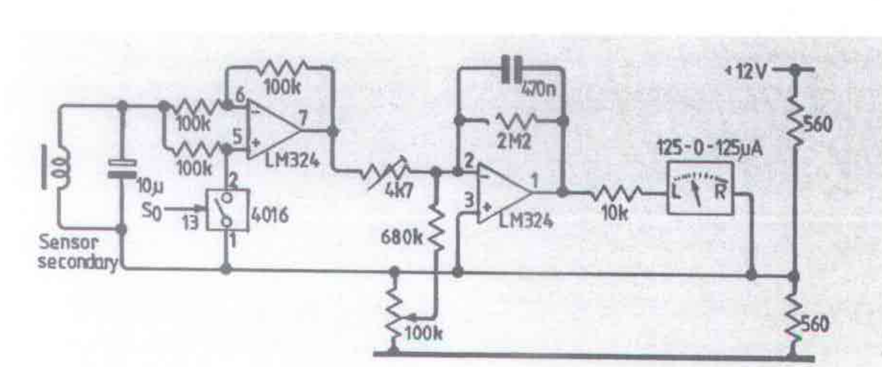
The sensor is wound, like the magnetometer version, with a second 500 turn pickup winding at right angles to the first. The electronics then provides two output signals, for convenience referred to as x and y, which represent the vector components of the horizontal magnetic field. From this point many different options are available to convert the signals into a display, with the usual tradeoff between precision, cost and complexity.

Before going into detail, however, it is instructive to examine the basic properties of the signal information the sensor system provides. The first obvious and familiar one is that the angle the magnetic vector makes to the axes is the arctangent of the ratio of x to y. One approach therefore would be to convert the analogue signals to digital and feed them to a single board computer. An eprom stored program written in assembler or a higher level language such as compiled Basic or Forth could solve for the arctangent and send the output to a port fitted with a three digit liquid crystal display. Using a chip such as the Motorola 68705R3 it could even be a single chip computer. To those with the ability to put together such a combination and program it, this is probably the most straightforward solution and can have additional options incorporated such as stored way-point lists for a flight plan or sailing pattern.

For a more subtle solution, a close look at the basic properties suggests some intriguing alternatives. At the very lowest levels, the signals range through both polarities and a glance at **Fig. 6a** reveals that the polarity combinations are a code for the quadrant the vector resides in, + + for 0 to 90°, + – for 90 to 180° and so on.

Another simple property is that the abso-

Fig. 3. Detector circuit for "steer-on-heading"



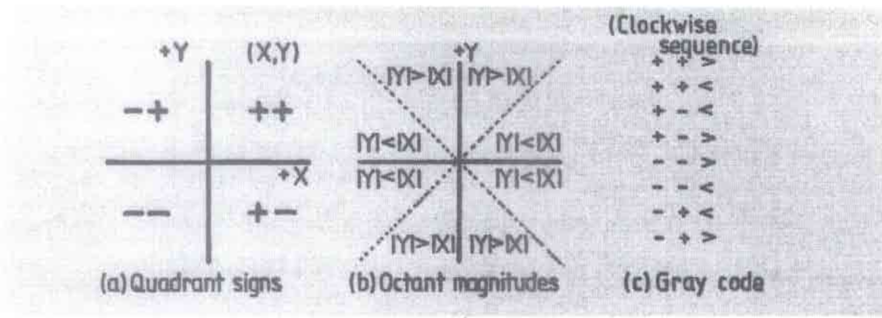


Fig. 6. Mapping out the octants with translation to Gray code equivalent

lute magnitude of x is either greater than that of y or vice versa, most of the time. **Fig 6b** reveals that this binary feature provides a third coded contribution increasing the resolution from quadrants to octants, x<y implying 0 to 45° for example in the first quadrant. All of which makes good sense as three bits exactly codes eight states.

Additionally it should also be noted that in one of those delightful accidents of nature the code developed this way falls into the class known as Gray codes, namely sequences in which the state transitions are marked by single bit changes. Our encoded output never gives false or ambiguous readings as the values change, simply because there is only ever a single bit changing at any time. All this, without any deliberate design effort!

The underlying idea is also very easy to implement electronically. Two more LM324 amplifiers will provide comparators delivering the first two sign dependent bits. The absolute magnitude circuits are just two more again, with a handful of identical resistors and some diodes. The outputs go to yet another comparator which outputs the third bit and the job is done. The greatest cost is probably the circuit board which the parts are soldered to.

Simple 8-point compass

At this point the first somewhat crude compass display is possible as in **Fig. 7**. The three coded bits are used as the address inputs to a 4051, 3-to-8 line analogue switch and the outputs are connected to eight leds arranged in a circle (in the straight numeric order to decode the Gray code, of course). The result gives a heading indication of eight directions with a precision of ±22.5°. This may not seem very good, but is entirely adequate for a road vehicle, to give one that comforting feeling of definitely heading in the right sort of direction when more or less lost. It should also be remembered that so far the analogue properties of the x and y signals have not even been considered. This gives a strong feeling that taking even a little notice of the analogue features should permit a major step forward.

One last convenient accident remains to be exploited. Between 0 and 45° the sine function is almost linear. A best fit line can be found for the ten points at 5° spacing by linear regression and this linear function used instead of the sine. The worst angular error is 1.3° at the 45° position and all the others are less than 1°, averaging about 0.6°.

Over this angular range the analogue x signal is theoretically a sine function of the angle being sought after, so a linear interpretation of its analogue value will give a low-error solution. Over the range 45 to 90°, the y signal is theoretically a cosine function of the angle, which is just the sine of 90° minus the angle and therefore has the same convenient linear properties. The electronic implementation is obviously to transform the x and y signals into the first quadrant and use an analogue-to-digital converter to create the increased resolution. The first part needs no components, because it already exists in the shape of the absolute magnitude circuits introduced earlier. Two alternatives exist for the second part, one for the analogue enthusiast, the other for those who like digital displays.

Analogue 72-point compass

The analogue version, **Fig. 8**, uses an LM3914 led bargraph driver in dot mode to drive nine led cathode lines, the anode lines being multiplexed as eight common anode lines, one for each octant. These octant switches are provided by a 4051 1-pole 8-way analogue switch decoding the 3-bit octant code derived earlier. The input to this A/D converter system needs to be switched between the x and y signals at the octant boundaries, but again no components are required because there is still one amplifier and two analogue switches left over in previously used chips and the driving signal is just the third bit of the already available octant code. This economically consumes all of the remaining spare parts.

The leds are arranged in a circle at 5° intervals and result in a display with ±2.5° precision and a worst error of about half that. Admittedly 72 leds are required, but bulk buying reduces the cost to no more than that of the digital version and some traditionalists just hate digital displays anyway.

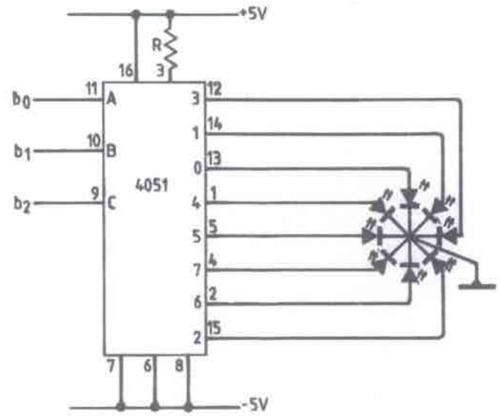
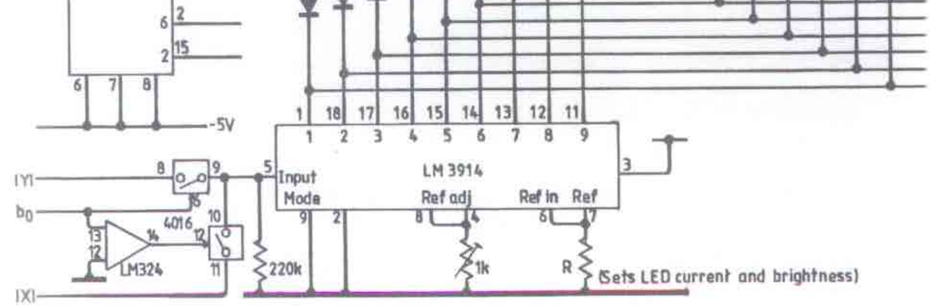


Fig. 7. A simple octant compass display

Digital 360-point compass

To make a digital version, the bar code driver is replaced with a CA3306 6-bit A/D flash converter, all earlier circuitry remaining the same. This divides the 45° octant into 64 levels providing the opportunity to correct for the slight non-linearity of the sine function, while providing even higher resolution. The technique is to use the six output bits as address bits for an eprom, together with the three octant bits, which are used to segment the EPROM into eight regions. In this way



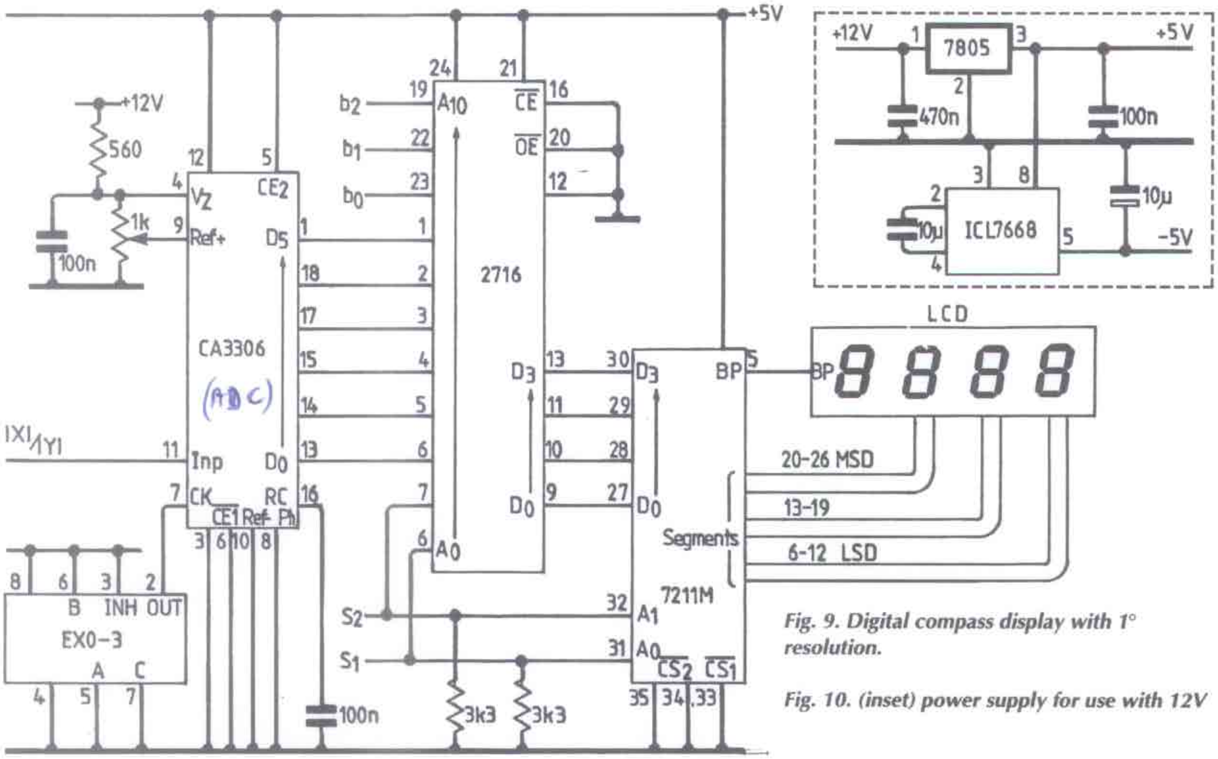


Fig. 9. Digital compass display with 1° resolution.

Fig. 10. (inset) power supply for use with 12V

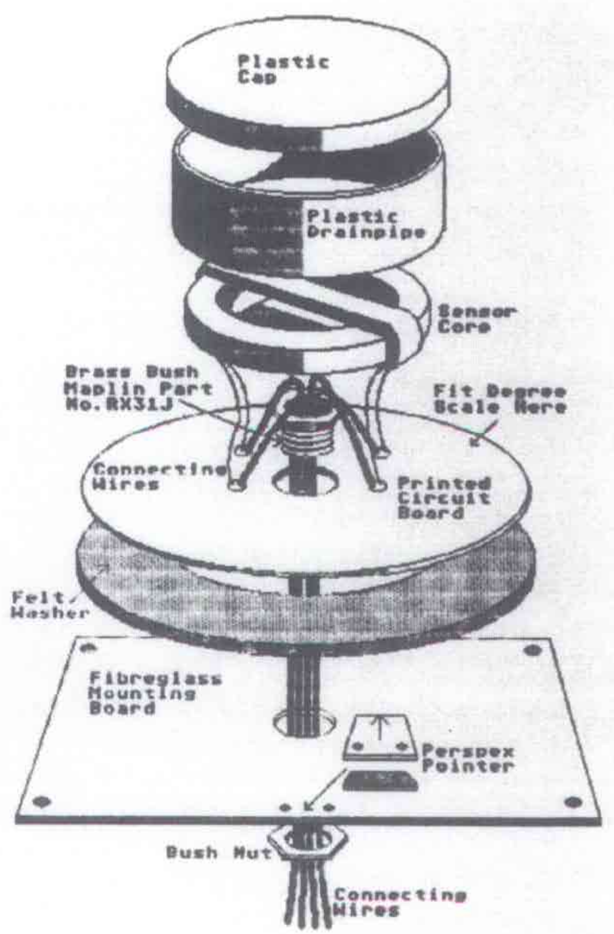
each combination of nine bits corresponds to a unique angle with a unique address, which can be programmed to output that angle to a display. Unfortunately the three digits needed for a compass display require twelve bits to code in BCD form and most eproms are only eight bits wide.

The solution is to give each digit an address of its own and multiplex them continuously to an appropriate display by providing two more address bits from a slowly cycling two bit counter. The same two bits are fed to the multiplexing address lines of the display driver to synchronise the eprom output to the digit position. A suitable display driver is the four-digit 7211M and the two bit counter needs no components as it already exists as the bottom end of the 4060 divider used in the sensor electronics. Bits 12 and 13 of this divider switch at approximately 7 and 3.5Hz respectively, giving a display update rate of about once per second.

Regrettably the serendipity of finding free parts just when they are needed does not extend to the 2MHz clock needed by the A/D converter. An EXO-3 crystal divider chip can be programmed to provide this.The 64 eprom locations in each octant are programmed to deliver the nearest integer degree value to the exact value predicted by the sine function. The nineteen duplicated values scattered through the 45° range automatically provide the linearisation to give a 1° resolution.

There is no reason why the digital display cannot be inserted into the centre of the analogue compass rose. ■

Fig. 4. Head/sensor assembly as made by the author.



The Telcon 7a cores mentioned in this article are available directly from the author price £10.50. PCBs for driver and sensor circuitry are also available price £12 for the pair. Contact R & W Noble, Penbidwal House, Pandy, Abergavenny, Gwent NP7 8EA. Phone 0878-890367.