ELECTRONIC COMPASS USING A FLUXGATE SENSOR

A device to fill the gap between the old-fashioned compass and expensive gyro-based navigation systems – an all-solid-state, high-resolution magnetic sensor.

by Neil Pollock

With the ready availability of micro-computers, simple dead reckoning navigation systems for boats and cars can be constructed, if suitable distance and direction inputs are available. A 'distance-travelled' signal can usually be obtained quite easily, but the provision of a digital magnetic heading is more difficult. It would be possible to arrange a servo pointer follower and angle digitizer attachment for a conventional moving magnet compass, but this would be mechanically complex and unattractive for amateur construction. An inherently digital solid-state compass is a much more elegant solution. A compass of this type would be valuable in any application where multiple output displays are needed, a computer readable output is required or where the sensor will be subject to high vibration or accelerations. In addition, the electronic nature of the sensor permits its location far from large metallic masses which can locally distort the field.

All solid-state compasses operate by sensing two or three resolutes of the horizontal component of the earth's magnetic field and then perform appropriate trigonometry with these resolutes to obtain the resultant magnetic flux direction. Using Hall-effect sensors, it is possible to produce very simple arrangements[1]. Unfortunately, during preliminary testing none of the low-cost, commercially available Hall-effect probes, including those with integral ferrite flux-concentrators, were found to have sufficient accuracy at magnetic field levels appropriate for compasses. Even when extra flux-concentrators formed by 2cm long Mumetal strips attached to each side of the sensor were added, increasing their output from microvolt to millivolt levels, the temperature drifts were of similar magnitude to the output produced by the earth's field. The disappointing results obtained with Hall-effect sensors forced the adoption of a fluxgate sensor with its inherently greater circuit complexity.

The theory of fluxgate magnetometers and compasses is beyond the scope of this paper and interested readers are referred to References 2 and 3. For a brief description of the principle of operation, see box.

An initial prototype of a fluxgate sensor used magnetic cores cut from Mumetal sheet, but an inconvenient post-fabrication annealing operation in a hydrogen atmosphere was required to obtain the desired magnetic properties. To overcome this difficulty, attention was directed to magnetometer designs which could be constructed using readily available commercial ferrite components.

Circuit

The arrangement finally chosen (based on a design intended for sounding rockets[4]), uses a 14mm diameter Philips ferrite toroid type number 4322-020-97140 (grey coating) or the equivalent uncoated toroid 4322-020-31390. Notes on adapting the design to use other toroid types are included later.

The circuit diagram and coil winding details are shown in Figs 2 and 3. The toroid is driven into saturation in alternate directions at about 10kHz by a magnetic multivibrator circuit of the type often used in inverters.

Windings P_1 and P_2 are the drive primaries while P_3 and P_4 provide the necessary feedback to maintain oscillation. The two secondary coils S_x and S_y are arranged so that in the absence of an applied external magnetic field they, at least in theory, experience no induced voltage. In practice, due to imperfections in the toroid and coils, voltage spikes are induced in the secondaries as the toroid goes into and out of saturation. These spikes have amplitudes varying from barely detectable to over one volt for different coil assemblies (Fig. 4).

When an external field is applied in the plane of the toroid some initial magnetization is induced in it. This initial magnetization results in one part of the toroid being driven into saturation before the part 180° away from it during one half of the oscillator cycle and the reverse situation occurring during the other half cycle. This non-symmetrical saturation of the core produces a flux unbalance and an induced voltage in the secondary windings. The magnitude of this induced voltage is closely proportional to the applied flux

Fluxgate magnetometers

There are very few means of measuring absolute values of magnetic fields. The most popular one is the Hall effect sensor, but most commercial units are designed for relatively high values of field.

The fluxgate configuration can measure very low field magnitudes by using the chopper-amplifier principle. Briefly, it is based on the fact that all parts of an uniformly excited toroidal magnetic circuit would be equally magnetized in the absence of external magnetic fields and therefore no voltage would be induced into a coil encompassing the whole magnetic circuit.

The introduction of external field in the plane of the toroid would result in a slight unbalance between the two halves of the magnetic circuit (see Fig. 1).

The flux at point A equals $\phi_A=\phi_0+\phi$, whereas point B, situated 180° away would correspond to a flux $\phi_B=\phi_0-\phi$. Where ϕ_0 is due to local toroid excitation and ϕ, to the external field.

Although the unbalance is very slight, it can be measured through one of its side effects: If we cyclically change the local excitation so as to switch the toroid between its two magnetic saturation points, we find that due to the unbalance, one half would be driven into saturation a short time before the opposite half and the toroid as a whole would, for a short period of time act as a small magnet. The net result is that a coil encompassing the complete magnetic circuit would pick up an induced voltage impulse, proportional to the external field.

By mounting two such coils perpendicularly to each other onto the same toroid, we can resolve any external field into its X and Y components in the toroid plane.

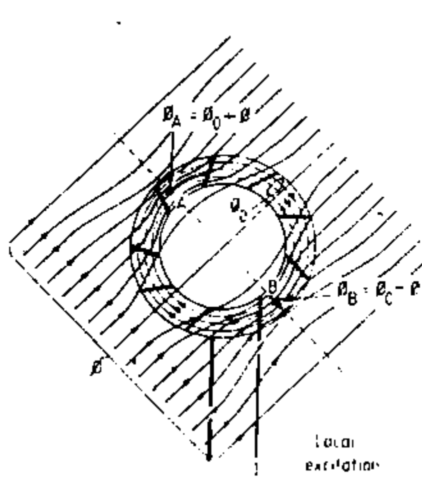


Fig. 1. Flux interference pattern.

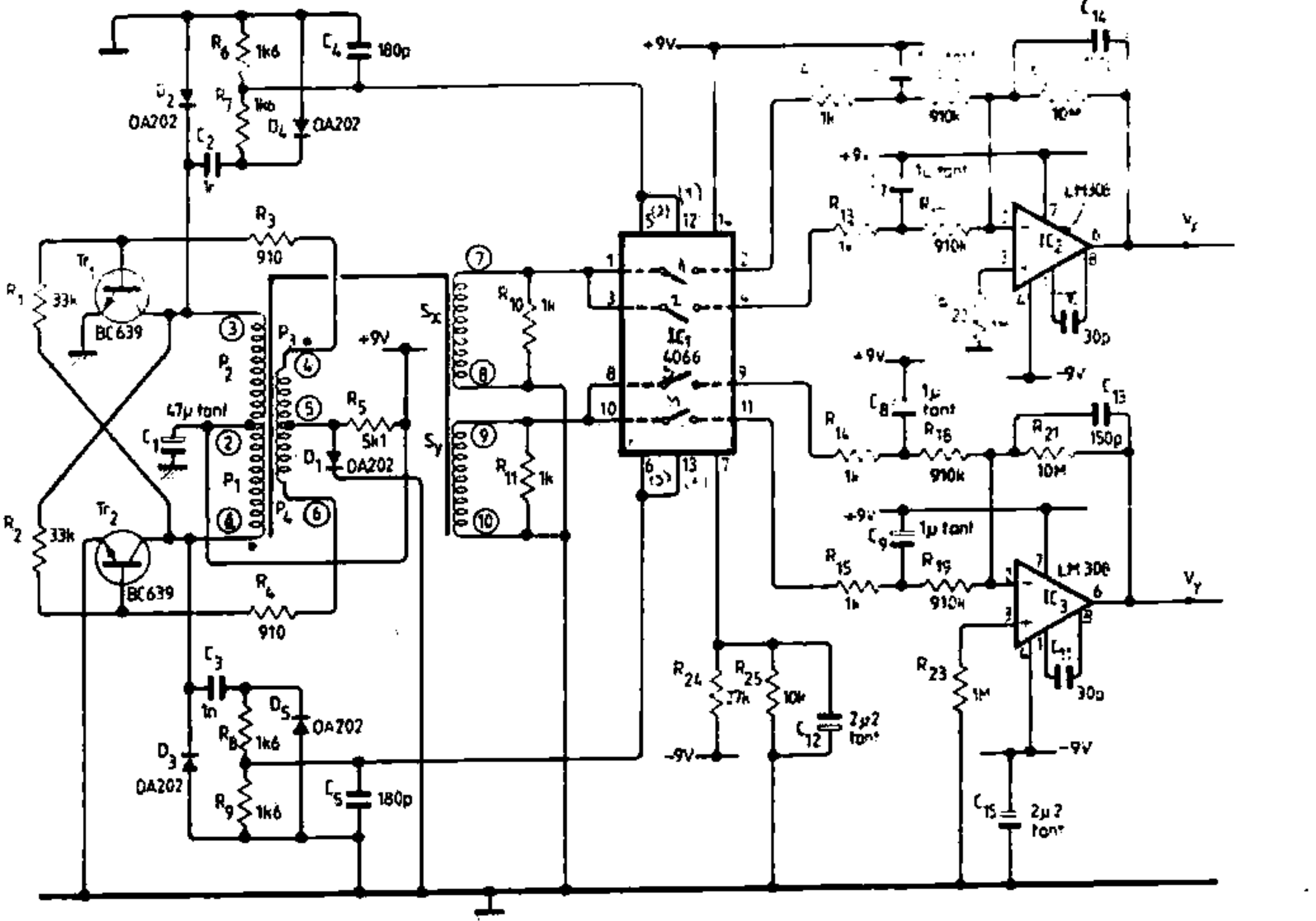


Fig. 2. Fluxgate sensor circuit diagram.

component perpendicular to the plane of the appropriate secondary coil. In practice, the effect of applying an external field is to change the amplitude of the pre-existing secondary voltage spikes. The amplitude of these spikes is also quite strongly temperature dependent. Figure 5 illustrates how the effect of an applied field is separated from the effect of temperature.

To perform the necessary arithmetic on spike amplitudes, a phase sensitive detector and summing amplifier is used for each secondary. The detector control signals (Fig. 6) are generated by differentiating, half wave rectifying and attenuating the primary drive voltages. The phase detector outputs are summed and the resulting mean voltages (outputs V_x and V_y) are proportional to the sine and cosine of the angle between the applied field and the plane of the S_x coil. In principle the compass output is simply the arctangent of the output voltage ratio. It is essential that the coil assembly and the associated electronics be located on the same circuit board because the zero offset is very sensitive to the relationship between the wires connecting the coil to the electronics.

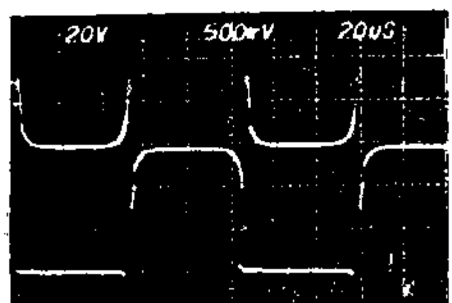


Fig. 4. Primary drive voltage (lower trace) and resulting secondary (S_X) voltage spikes (upper trace).

Construction details

The coils are the heart of the device and, although they are relatively non-critical, an effort applied to winding them carefully and neatly will be well repaid. The primary drive windings P_1 and P_2 are wound on the toroid first and fill it about 1½ layers deep. These two coils are bifilar wound, that is they are wound with two wires side by side to produce two closely identical windings. The feedback windings P_3 and P_4 are bifilar wound on top of P_1 and P_2. The two secondary windings can either be wound on a tubular former with notches at 90° intervals, which fits around the pre-wound toroid (Fig. 7) or wound separately and then glued in place. If the latter method is adopted it is suggested that each secondary be wound around a 6mm by 16.5mm rectangle formed by four pins. On removal of the pins the preformed rectangular coil should be bound with another piece of coil wire (taking care not to create a shorted turn) so that is is bundled together. The two secondaries can then be placed around the toroid and secured with quick-setting epoxy glue. However the secondaries are wound, it is essential that they are a neat fit and closely coupled to the toroid. On completion of the windings the toroid assembly should be glued to the circuit board and the leads connected, being careful to observe the correct hand of the P_1, P_2, P_3 and P_4 windings. All windings should be securely glued to prevent any relative movement between them.

The remainder of the circuit is straightforward and a board layout and component positions are reproduced in Figs. 8 and 9. The use of metal-can transistors and integrated circuits should be avoided, since they could distort the applied magnetic field.

If it is desired to use a toroid other than the one specified, the following procedure

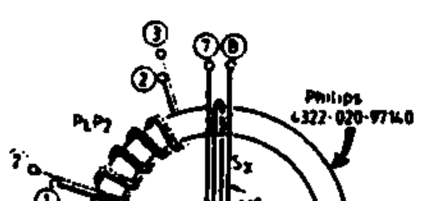


Fig. 3. Toroid windings.

is recommended. If necessary, change the number of turns on the primary windings, keeping the same ratio between drive and feedback windings, so that the operating frequency is in the range 5kHz to 50kHz. Change the value of C_2 and C_3 so that the phase sensitive detector control pulses are similar in length to the secondary spikes. Alter the value of R_{20} and R_{21} to obtain the desired overall sensitivity. Although they have not been tried, their specifications suggest that the following toroids could be used with only minor component value changes: Philips 4322-020-97060 (blue coating); Philips 4322-020-31390 (uncoated); Siemens B64290-K0045-X026 (coated); Siemens B64290-A0045-X026 (uncoated).

Performance

To facilitate calibration, the sensor board should be taped to a 360° plastic protractor which can be rotated inside a circle drawn on a piece of paper placed on a wooden table top. Care must be taken not to move any ferrous or magnetic objects near the compass sensor during calibration. The author experienced inconsistent results which were eventually traced to the effect of his metal belt buckle. A typical calibration chart is shown in Fig. 10. The V_x and V_y outputs are usually within ±1° of best fit sine curves with zero offsets in the range ±2volts. A peak-to-peak amplitude of about 1.2volts was produced by a horizontal flux density of 2.2 × 10 tesla (weber/m² – the value for Melbourne, Australia). Similar outputs should be obtained

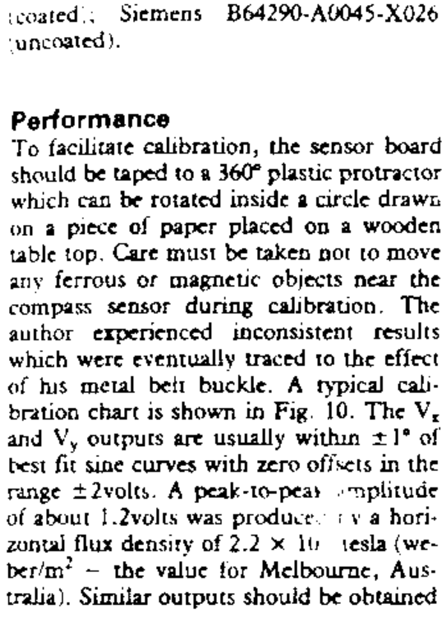


Fig. 5. Effects of temperature versus applied magnetic field on secondary waveform.

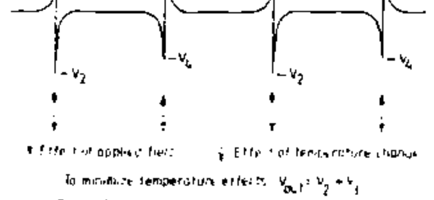


Fig. 6. Secondary output (S_X – IC1, pin 1 – upper trace) and phase sensitive detector's control signals: middle trace: IC_1, pin 5. lower trace: IC_1, pin 6

Fig. 7. Toroid with primary windings and former for secondaries

in Europe and the USA. In other parts of the world the horizontal flux density varies from zero at the magnetic poles to 4.13 × 10^{-5} tesla in the Bay of Bengal. If the sensor is not horizontal, total flux densities exceeding 6 × 10^{-5} tesla may be found. The sensor peak-to-peak output voltages are directly proportional to the field strength in the plane of the toroid. For carefully wound coils the phase angle between the two output voltages will be within a few degrees of the desired 90°. It is suggested that any departure from 90° is treated as a correction in the angle computation, but if desired the coils can be bent by trial and error prior to final glueing to produce the desired angle between them.

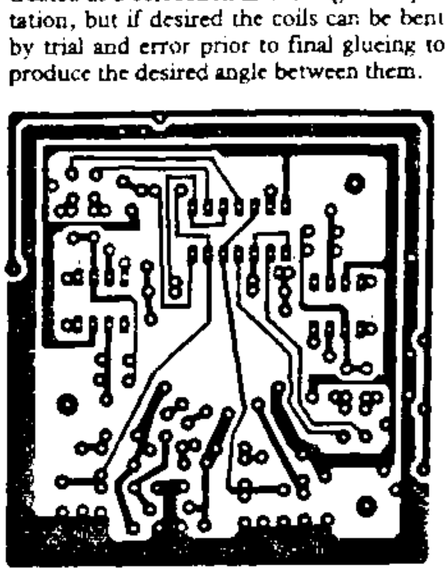


Fig. 8. Fluxgate sensor p.c.b. layout.

The sensitivity of the sensor is quite strongly temperature dependent (about [illegible] affected equally the indicated angle is unchanged. The zero offsets vary by about 10mV/°C and for operation in environments which are not temperature controlled, these changes would have to be corrected for, if maximum accuracy was required. The repeatability of the sensor calibration is excellent with no measurable change over a one month test period, and presumably for much longer periods since there is no obvious mechanism for long term drifts. The sensor is very sensitive to temperature gradients in the ferrite core and it is essential that it be protected from draughts. The sensor board draws 17mA from the +9volt supply and 2mA from the -9volt supply.

Installation

The sensor must be mounted in a horizontal attitude if accurate results are to be obtained. In a boat, where large attitude changes are often experienced, the sensor would have to be mounted on a set of gimbals. In a land vehicle subject to large accelerations but normally operating on an approximately level surface, it may be better to rigidly mount the sensor. If mounted near large ferrous objects or sources of magnetism, the sensor must be compensated as for a normal compass[3]. Fortunately with the freedom to remotely mount the sensor it is often possible to find a location where compensation is not required and the small residual errors can be treated as part of the calibration. If very long connecting leads are to be used between the sensor board and readout electronics, it may be necessary to include 1kΩ resistors in series with the V_x and V_y outputs to decouple the operational amplifiers from the cable capacitance.

Microprocessor readout system

In a microprocessor-based system the sensor outputs V_x and V_y would be multiplexed into an analog-to-digital

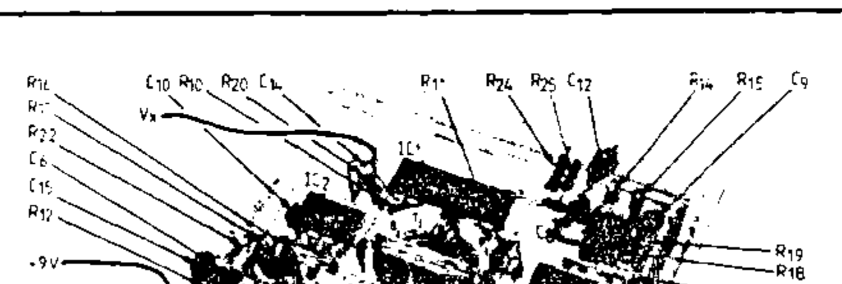
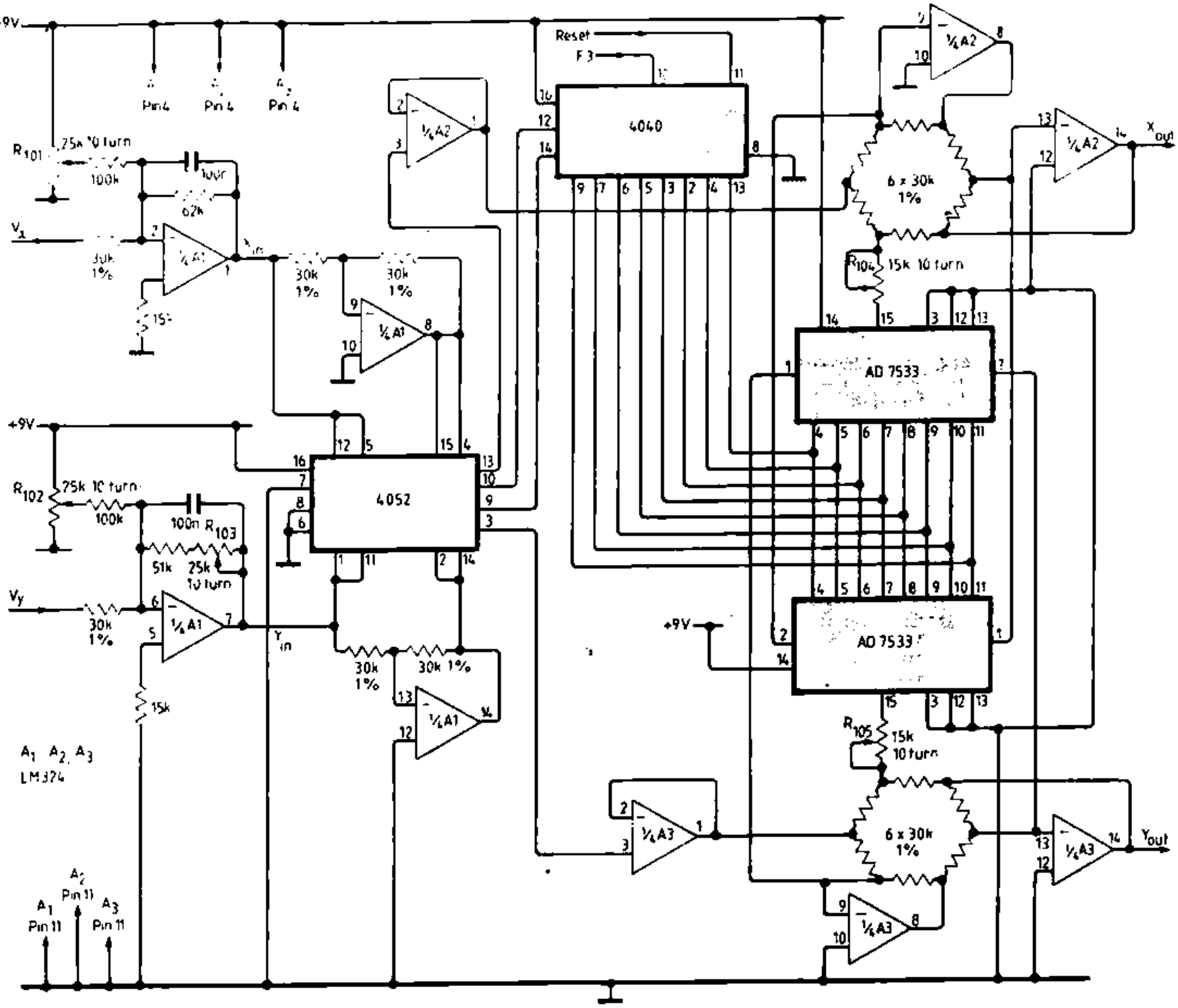


Fig. 9. Fluxgate sensor component positions



converter with a useful resolution of at least 10 bits. An a. to d. converter like the Intersil ICL7109 would be the first choice in this application since it could be simply interfaced to most microprocessors using parallel or serial data transfer. When the digital values of V_x and V_y were read in, the ratio $R = (V_x - V_{xo})/(V_y - V_{yo})$ should be calculated, where V_{xo} and V_{yo} are the zero offsets which should be varied with the measured sensor temperature unless it is placed in a temperature-controlled enclosure. Using the value of R and the signs of $V_x - V_{xo}$ and $V_y - V_{yo}$ it would be possible to construct a look up table to give the heading angle with 1° resolution. The actual sensor will resolve heading changes of much less than 1° but when all sources of error are considered there is little point in aiming for greater overall resolution. Alternatively, if a dedicated arithmetic chip like the National Semiconductor MM57109 was available, it may be more efficient to take the arctangent of R and apply any necessary corrections to the computed heading later.

Hard-wired logic readout

In applications where a microprocessor is not available, it may be desired to have a dedicated hard wired readout system. A relatively simple, low cost, arrangement which was used during the development of the sensor is shown in block diagram form in Fig. 11. The operation of this system depends primarily on a vector rotator which has as inputs two analogue voltages X_{in} and Y_{in} which are taken as the X and Y components of an input vector and a digital angle θ (0 to 1024 for 0 to 360°). The outputs X_{out} and Y_{out} are the X and Y components of the input vector rotated through the angle θ. The heading angle is given by the value of θ which reduces the X output to zero (ie. the angle through

Fig. 12. Angle decoder: input circuitry and vector rotator.

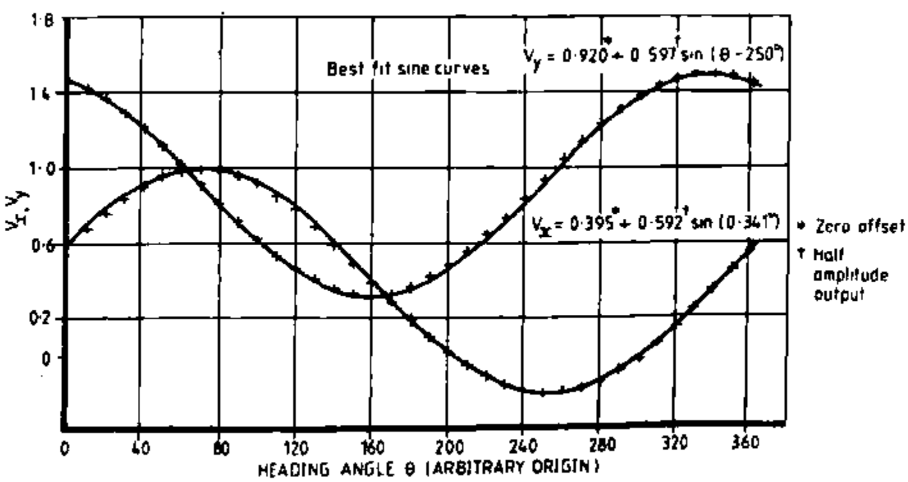


Fig. 10. Typical calibration chart.

which the input vector must be rotated, to align it with the system Y axis).

When a reading is initiated by the 2Hz update clock, the binary and b.c.d. counters start counting from zero. When X_{out} passes through zero in a negative going direction, a latch enable pulse is generated which gates the current b.c.d. counter contents into the display. The RS flip-flop is needed to ensure that only the first zero-crossing in each update clock cycle produces a latch-enable pulse. The 360/1024 ratio between F_2 and F_3 produces an output in degrees. Outputs in other units, eg. tenths of degrees or grads, could be produced simply by changing this ratio. For this system to work correctly, the X_{in} and Y_{in} inputs must have the same sensitivity and no offsets; this is achieved with a pair of offset and gain adjustment amplifiers.

The circuit which is designed around a simple vector rotator[5], using a pair of Analog Devices AD7533 low-cost multiplying digital to analog converters, is presented in Figs. 12 and 13. This circuit, which has an overall decoding accuracy of about ±1°, draws 15mA from the +9volt supply, 7mA from the −9volt supply and 170mA from the +5volt display supply.

The set up procedure, which consists of adjusting offsets, sensitivities and balance is as follows: with the sensor board not connected, adjust R_{101} and R_{102} to set X_{in} = 5volts and Y_{in} = 0. Remove the 4040

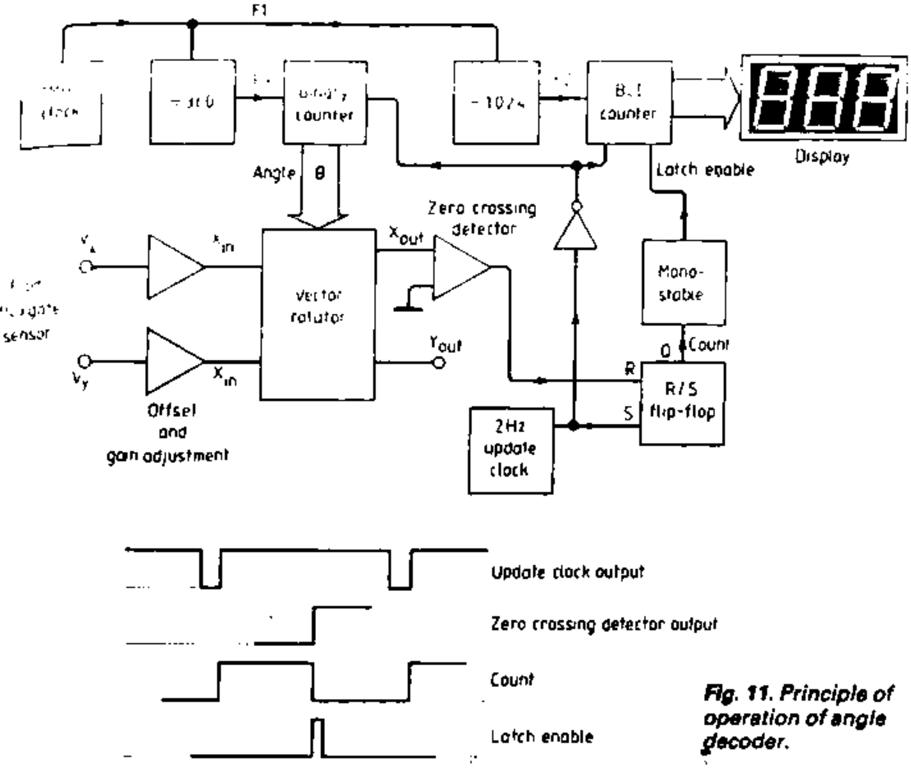
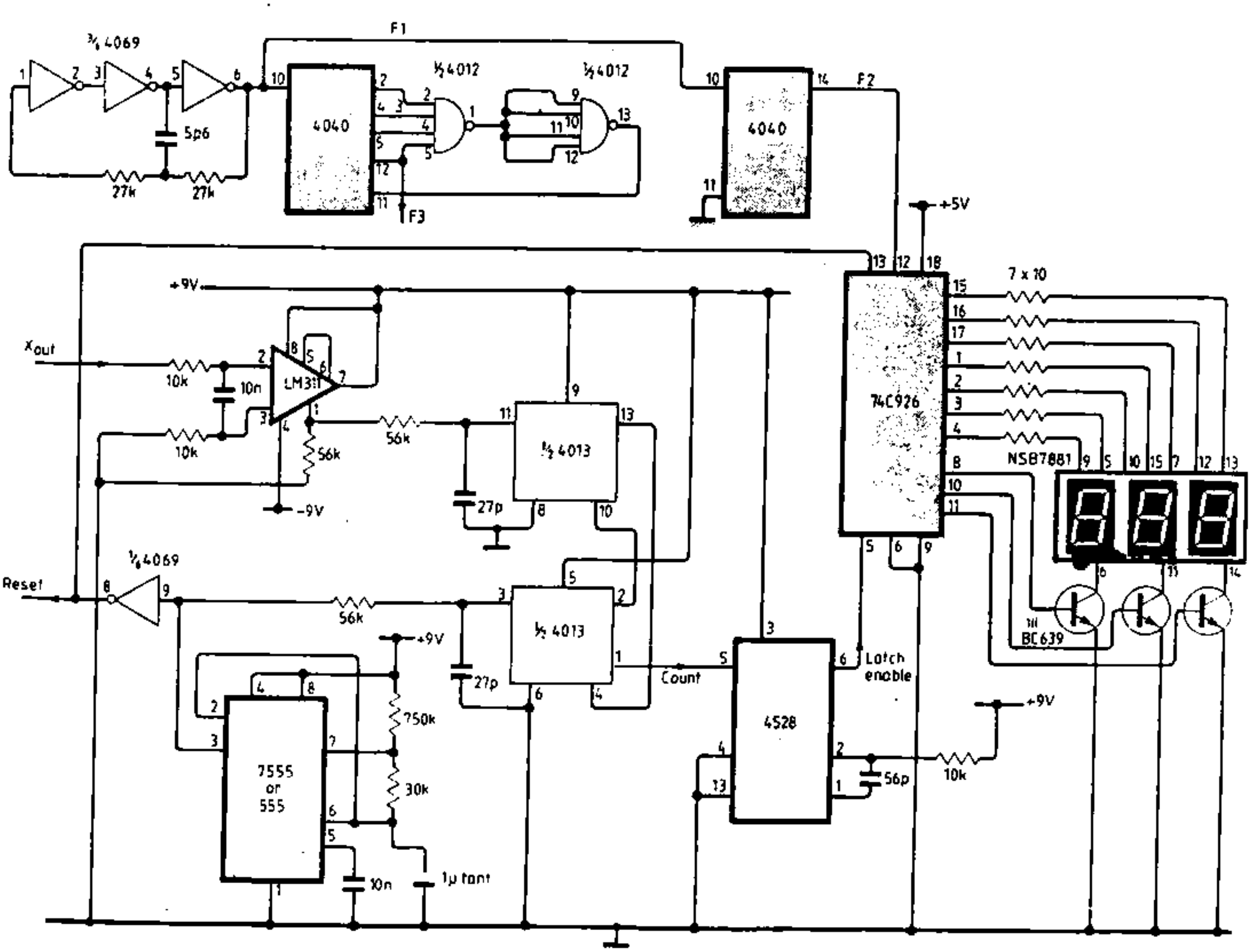


Fig. 11. Principle of operation of angle decoder.

Fig. 13. Angle decoder: control logic and display.



counter and ground its socket's pins 2-7, 9 and 12-14. Adjust R_{104} and R_{105} to set $X_{out} = -Y_{out} = 5/\sqrt{2} = 3.54$volts. Readjust R_{101} and R_{102} to obtain $X_{in} = O$ and $Y_{in} = 5$volt. Check that $X_{out} = Y_{out} = 3.54$volts. This set up procedure for R_{104} and R_{105} is sufficiently accurate for most applications, but if maximum accuracy is needed an interative procedure[4] should be adopted. Replace the 4040 and connect the sensor board. While rotating the sensor board through 360° set R_{101} to remove the V_x zero offset so $X_{in,max} = -X_{in,min}$. Set R_{102} to remove the V_y zero offset so $Y_{in,max} = -Y_{in,min}$ and finally set R_{103} to equalize X and Y sensitivities so that $X_{in,max} = Y_{in,max}$. Since this circuit was developed primarily for bench testing, no compensation for changes in X and Y zero offsets with temperature is provided. An enthusiastic analog circuit designer could perform this compensation with thermistors in resistor networks around the input amplifiers.

Power supply

Since this system will normally be used in mobile applications, it is desirable that it should operate off a 12volt supply. A regulated power supply suitable for this purpose is shown in Fig. 14. Two alternative methods, (1) or (2) of generating the −9volt supply are shown. The Fairchild μA78S40 universal switching regulator was used for most of the development of this project. However quite recently the Intersil ICL7660 voltage converter became available and proved to have equal performance in this application with a considerably simpler circuit.

Magnetic compasses and the precautions required for their effective use are complex and it is strongly recommended that potential users read Ref. 3 and thoroughly check the accuracy of their own installation before relying on it in circumstances where life or property might be at risk. WWW

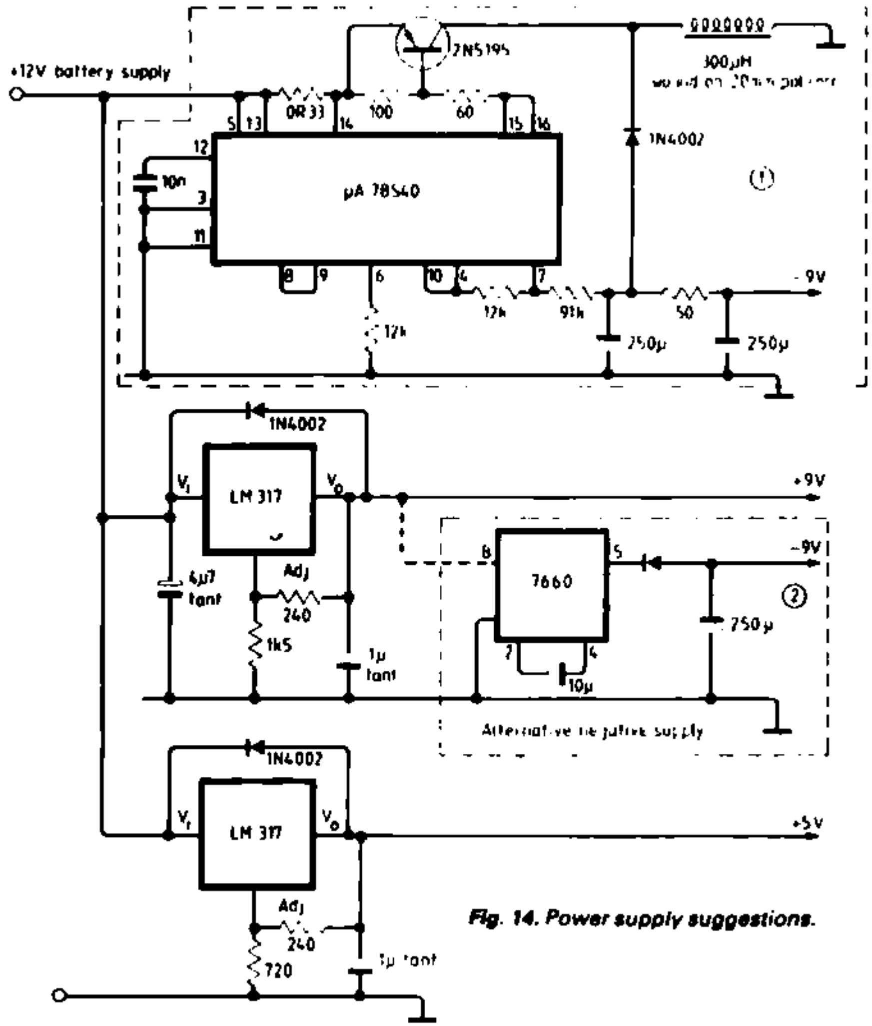


Fig. 14. Power supply suggestions.

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