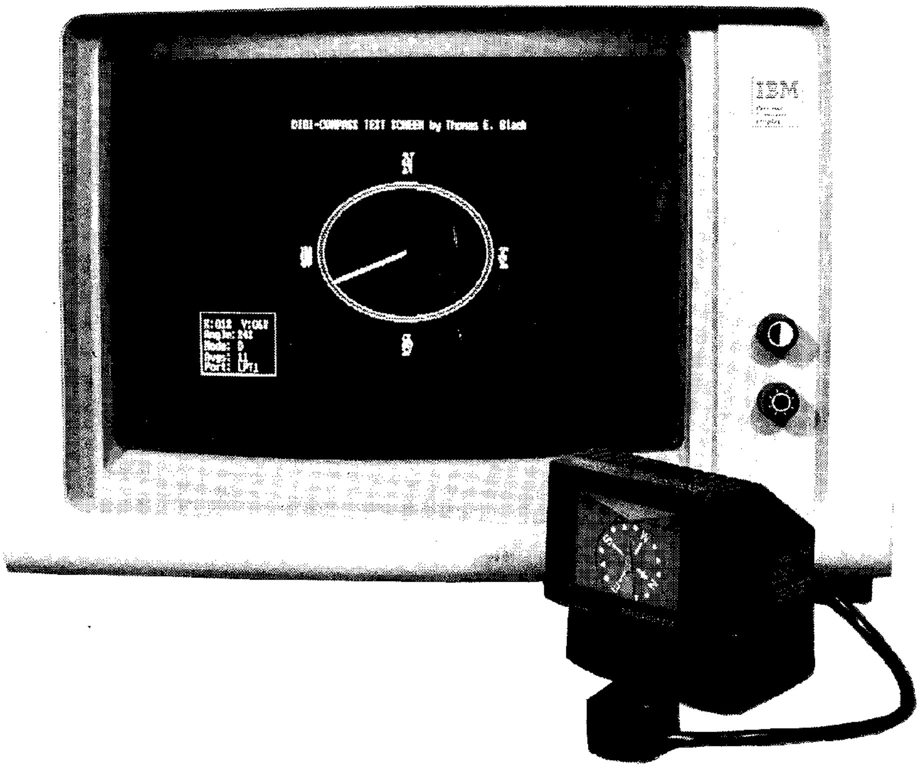
THERE IS NOTHING MORE FRUSTRATING than not knowing where you are going. Consider ancient mariners, nervously navigating mysterious waters, unsure of what lay ahead in their travels. They soon learned to read the heavens and were eventually assisted by the mysterious powers of the navigational compass. Now consider the modern mobile robot, unsure of where it is going, anxiously prodding with tactile sensors and acoustic ranging equipment. It, too, is a little relieved by the information contained in its compass system. All of us have probably experienced the utility of a delicately balanced magnetic needle, carefully suspended on a cork floating in water—a most typical compass experiment from our grammar school days.

Of course modern technology has overshadowed our first experience with the compass. The compass design met a major milestone when the gyro-stabilized remote-indicating compass was introduced during World War II. Suddenly, navigation was automated, freeing the pilot from routine maneuvering. But modern technology has further improved on that massive electro-mechanical device, and now there are new, affordable alternatives for your next robotic project.

We introduce our Digi-Compass project. Actually it's a Radio Shack electronic flux-gate compass, intended for automobile use, with added circuitry that provides it with an output that can be fed directly into a personal computer. That makes it suitable for applications such as a computer-controlled model airplane, an automobile navigation assistant, or a video camera that intelligently films your journey.

Magnetohydrodynamics

The iron-nickel core of our planet generates a weak magnetic field. The phenomenon is due to a large moving and highly conductive liquid mass in Earth's core. The study of magnetohydrodynamics (MHD) suggests that by applying an electrical current under those conditions, a magnetic



DIGI-COMPASS

Is your house rotating...what about your computer?

THOMAS E. BLACK

field is produced (conversely, applying a magnetic field will produce an electrical current). The magnetic field is what causes compasses to point North.

It should be noted that magnetic North is somewhat different than true North (due to what's called magnetic declination), and it may even wander over time. It is also dependent on your geographical location. You can determine the difference between magnetic North and true North by consulting a *US* Geological *S*urvey (USGS) topographical map. True declination is computed as:
(Map-indicated declination + (annual drift rate × (current date − mappublish date)))

There is also a magnetic inclination, which is the vertical component of Earth's magnetic field. Compass accuracy can be severely affected by its horizontal position, so it is important to keep your compass as level as possible.

Flux-gate magnetometer

There are a number of different methods used in modern solid-state compasses, but one of the most practical is the *flux-gate magnetometer*. Although the difficulties in building such a device have eliminated by integrating an off-the-shelf flux-gate automotive compass into the Digi-Compass, we will discuss the theory behind the device.

Many magnetic materials exhibit linear magnetization up to a certain flux level. At that point they saturate and lose their magnetic properties.

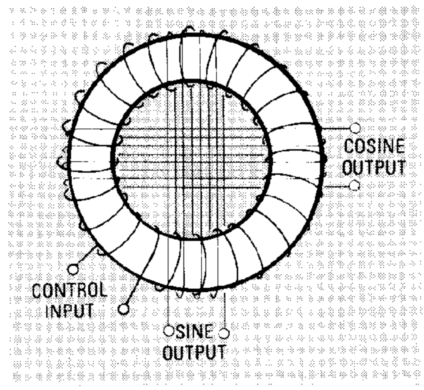


FIG. 1—A TYPICAL FLUX-GATE magnetometer is constructed by wrapping control, sine, and cosine windings on a toroidial core.

Unsaturated magnetic material will pull in magnetic flux lines, whereas saturated material will not (it completely ignores magnetic fields). So, if you gate Earth's magnetic fields into and out of saturation, they will alternately be concentrated and ignored. If you place a sense winding near your magnetic material, you can measure the strength of Earth's fields entering or leaving the material. The magnitude of the signal is proportional to the Earth's field strength along the axis that has been sensed.

As shown in Fig. 1, a typical flux-gate magnetometer is constructed by carefully wrapping *control*, *sine*, and *cosine* windings on a *toroidial* core (a donut-shaped core made of iron particles). The sine and cosine windings give us quadrature outputs, which are analog outputs that are separated by 90 degrees. The toroidial core must be carefully chosen for the proper "square" saturation curve. The combination of materials and winding direction prevent the drive current that is induced into the saturation-control winding from being picked up by the sense windings. External circuitry also protects against that condition, which would cause measurement errors. Extra windings and circuitry can be added to minimize magnetic inclination—bulky gyro mechanisms contain a similar feature.

The two quadrature signals pick up magnetic pulses that are related to the sine and cosine of the surrounding magnetic fields. External circuitry switches the control winding on and off at a low frequency, and the resulting ratios of the integrated sine and cosine output voltages provide the data necessary to interpret direction.

Inside the flux-gate compass, the sine and cosine voltage outputs are used to steer an *air-core resolver* (see Fig. 2). The resolver consists of a pointer and magnet, both attached to a freely rotating axle. Surrounding the magnet are two coils oriented at right angles with one another. The magnet will align itself with the vector sum of the two magnetic fields generated by the coils, which is a direct product of the currents applied to them. Therefore, by varying both the polarity and magnitude of the coil voltages, the axle assembly can be made to rotate a full 360 degrees.

The compass was intended to be mounted in a environment with some vibration (car, boat, etc.) to aid the movement, as it tends to stick. While sitting on your workbench, the compass may have to be tapped occasionally while moving the sensor. Fortunately, our digital interface ignores the position of the electro-mechanical movement, so it does not suffer from that mechanical problem.

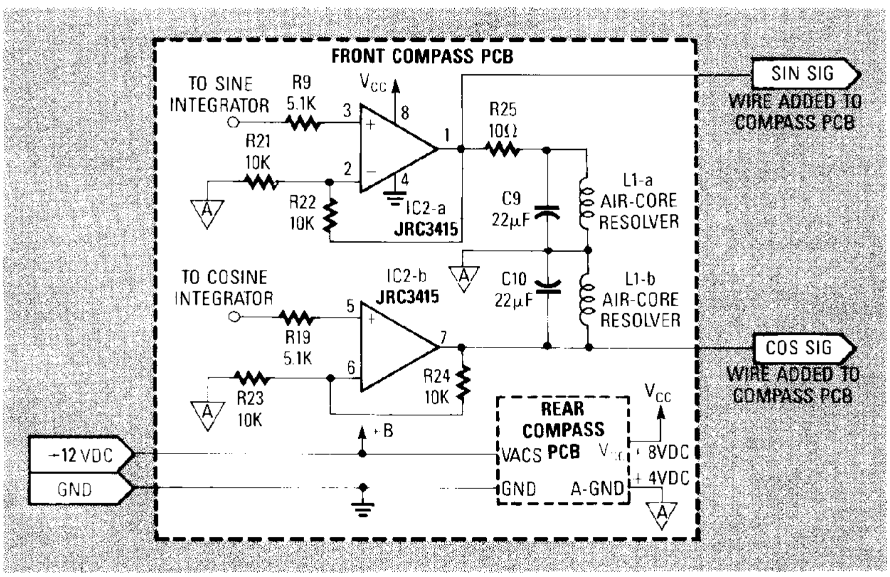


FIG. 2—INSIDE THE FLUX-GATE COMPASS, the sine and cosine voltage outputs are used to steer an air-core resolver.

Digi-compass interface

Because the Digi-Compass must have as universal a computer interface as possible, it is designed to be used with an IBM PC or compatible, and communication to the compass occurs through the standard LPT1, LPT2, or LPT3 printer ports. The software is provided as a learning tool, and it would not be difficult to adapt the Digi-Compass to any computer that has four available I/O lines. The two programs available for the Digi-Compass provide both a graphic display of compass direction as well

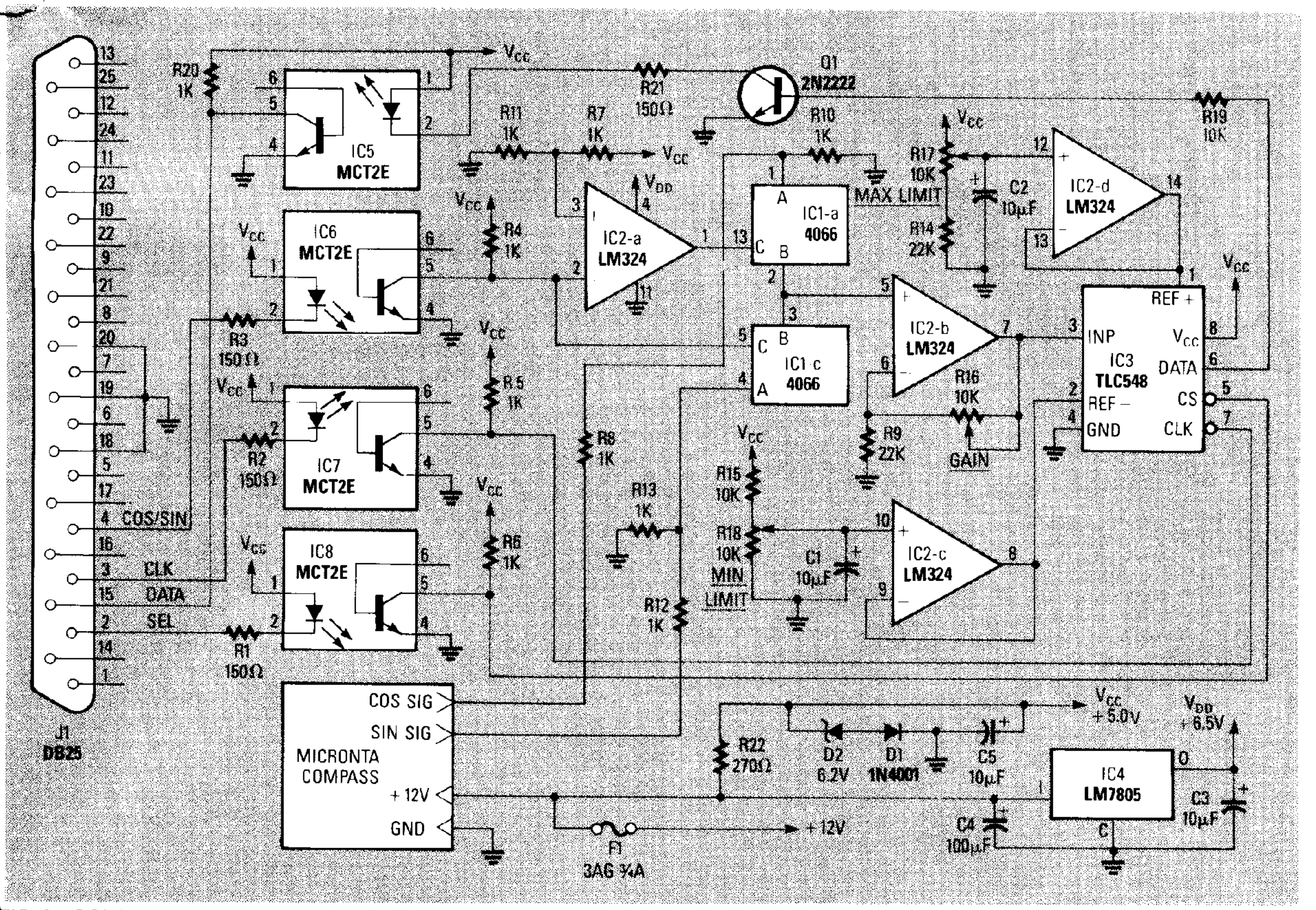


FIG. 3—SCHEMATIC OF THE DIGITAL-COMPASS INTERFACE. Two signals taken from the compass (COS and SIN) are use to generate direction-related data, which is then fed into a computer.

as a simple text-only display of directional degrees (from 0 to 360).

The interface circuitry used to monitor the compass's output is rather simple. All that is required is an *A*nalog-to-*D*igital *C*onverter (ADC) for each compass output. To keep the cost down, only one eight-bit ADC is used, and it is multiplexed between the two outputs. The eight-bit resolution of the ADC is adequate for the chosen off-the-shelf compass, and it provides more than two degrees of resolution. In order to use a standard IBM-compatible printer port with its limited I/O lines, a serial ADC that needs only four I/O lines was used (twice as many would be required on a typical eight-bit ADC).

As shown by the interface schematic in Fig. 3, the printer port is connected to the Digi-Compass interface circuitry by four opto-couplers. They provide some isolation between the computer and the compass but, most significantly, provide a high degree of noise immunity on long cable distances, which can typically exceed 25 feet.

The COS/SIN control line is used to switch between the sine (Y) and the cosine (X) compass output voltages. When the control line is high, the cosine voltages are available to the ADC, and when it is low the sine voltages are available.

With COS/SIN high (cosine mode), the analog switch IC1-c is on and IC1-a is off. Op-amp IC2-a is a used as an inverter—a somewhat abstract use for the device. The cosine voltage from the compass is attenuated by R8 and R10 before being passed by IC1-a. It is important to limit the compass voltages to less than 5-volts DC, or linearity will suffer. When COS/SIN is low (sine mode), IC1-c is off and IC1-a is on, and attenuation is provided by R12 and R13.

Gain control over the switched signal is provided by IC2-b before it is passed to IC3 (the TLC548 ADC), and it sets the minimum voltage applied to IC3. However, IC3 could be damaged if the analog input voltage exceeds $V_{CC}+0.3$ volts DC, but by using 6.8-volts DC to power the op-amp we have avoided the condition. The LM324 op-amp's output can swing only to $V_{DD}-1.5$-volts DC, so as long as V_{DD} remains at or below 6.8 volts, no trouble will arise. The LM324 output can also go as low as 0 volts, a must for extending the dynamic range of the input. Be forewarned; other op-amps will behave differently, so be sure to observe that requirement.

As mentioned before, the ADC is a serial device. That means that the data, which is in single-bit form, is presented to the host computer over a series of host-provided clock cycles. It is up to the host to repack the data bits into byte form, a process that is performed in software. There are considerable hardware advantages to using that type of device, but such ADC's are not useful in high-speed applications due to the overhead in handling their data output.

The ADC (IC3) requires two reference voltages, a clock, and a select line. The two reference-voltage inputs set the analog input thresholds that result in minimum and maximum digital outputs (0 to 255 decimal). As we will see during calibration, R17 and R18 are adjusted to set those limits.

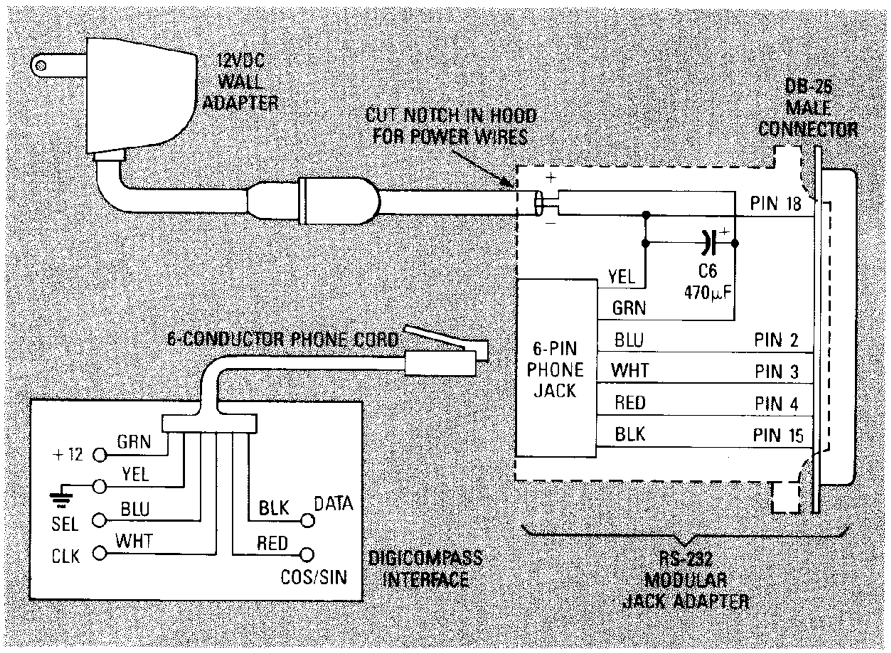


FIG. 4—THE RS-232 MODULAR JACK ADAPTER is wired as shown here. The capacitor will fit inside of the adapter.

The host then scales the digital numbers into meaningful units such as "volts," but that doesn't involve the Digi-Compass.

Conversion of the input voltage is initiated when the ADC's active-low CS line (chip select) goes low. The ADC then waits for two rising edges and then one falling edge of the CLK line before recognizing the CS condition (the delay debounces the CS input).

The most-significant bit (D7) then appears on the ADC's DATA OUTPUT line. The next seven clock pulses shift out the remaining bits, highest to lowest. The computer controls the clock and select line through one of the LPT printer ports, as we mentioned previously.

It is important to note that the data shifted out represents the voltage that was latched during the previous conversion. On the fourth falling edge of the clock the ADC samples the input voltage, which is not available until the next acquisition. That is not a problem if you continuously access the ADC, but in an input multiplexing mode such as that used in the Digi-Compass, you must always read the ADC twice, throwing out the first measurement.

In ideal applications, the TLC548 can provide conversions in less than 25 microseconds. However, in this project, acquisition is deliberately much longer due to limited bandwidth of the opto-couplers.

Construction

The Digi-Compass interface is suitable for perfboard construction using point-to-point wiring techniques. The prototype is mounted in a plastic enclosure (metal could affect the flux-gate sensor), which is attached to the bottom of the compass and serves as a base. If you mount the interface separately from the compass, use shielded wiring and keep the cable as short as possible.

If you intend to operate the interface board more than ten feet from your computer, you should mount IC5 and R20 at the computer end, perhaps inside of the DB-25's housing. That may not be necessary, depending on the environment the cable will be in.

Be sure to use sockets on the IC's just in case you need to replace one later. The voltage regulator does not need a heatsink, and a 6.8-volt Zener diode can be used instead of the 6.2-volt Zener (D2) and 1N4001 diode (D1) combination shown. Just make sure that you use a 12-volt DC power supply that can deliver at least 750 mA.

Connecting the interface involves dismantling the compass. Inserting a coin or a masking-taped screwdriver blade into the left and right sides of the bezel's groove and carefully twisting will allow the bezel to pop off. Of course you have just violated the compass's warranty, so be sure that it works correctly before you dismantle it. Remember that you are on your own once you take the compass apart.

Once inside the compass, find the 8-pin DIP IC (IC2 in Fig. 2) on the bezel-mounted circuit board marked "JRC3415" or "NJM3415" (R23 is right next to it on the PC board). Pin 7 of that IC is the COS SIG output and pin 1 is the SIN SIG output. Solder a labeled 10-inch 26AWG wire to each pin, and trim as necessary.

Find the 3-pin power connector at the rear of the horizontal PC board. Solder a 22AWG wire for +12-volts DC and one for ground directly to the pins—+12 is the middle pin and ground is the one toward the center of the circuit board (ignore the outer unused pin). You can double check for +12 and ground, as well as continuity in the newly installed power wires by temporarily plugging in the compass's factory cigarette-lighter plug and verifying proper voltages. Now you can remove the cigarette-lighter plug and throw it in your junkbox.

Pass the four new wires out of the compass cabinet through one of the vents on the bottom. Re-assemble the compass, being careful not to crush any wires. Temporarily connect +12 volts to the new power wires, and ver-

PARTS LIST

All resistors are ¼-watt, 5%, unless otherwise specified.
R1–R3, R21—150 ohms
R4–R8, R10–R13, R20—1000 ohms
R9, R14—22,000 ohms
R15, R19—10,000 ohms
R22—270 ohms, 1/2 watt, 10%
R16–R18—10,000 ohms, 15-turn trimmer potentiometer
Capacitors
C1–C3, C5—10μF, 16 volts, Tantalum
C4—100μF, 35 volts, electrolytic
C6—470μF
Semiconductors
IC1—CD4066 quad switch
IC2—LM324 quad op-amp
IC3—TLC548 serial ADC
IC4—LM7805 5-volt regulator
IC5–IC8—MCT2E opto coupler
Q1—2N2222 NPN transistor
D1—1N4001 1-amp, 50-volt diode (see text)
D2—6.2-volt, 1-watt Zener diode (see text)
Other components
J1—DB25 modular-jack adapter
F1—¾-amp fuse
Miscellaneous: Plastic cabinet (prototype used 4 × 2$\frac{7}{16}$ × 1$\frac{1}{16}$ inches), 12 VDC 1A power supply, Micronta high-accuracy auto compass, wire, sockets, perfboard, etc.

ify that both the sine and cosine outputs vary from about 1.5–7.5 volts as you move the sensor in different directions. Do not allow the two outputs to touch each other, power, or ground, and don't be concerned if your compass doesn't quite reach the mentioned voltages; they may be within a volt or two.

The DB-25 connector used for the prototype is actually an *RS-232 modular jack adapter*; its a male DB-25 connector on one side, and a 6-pin phone jack on the other. The DB-25 side plugs into your computer, and a 6-pin phone cord plugs into the jack side; the other end of the phone cord is wired to the interface circuitry. The green wire is used for +12, the yellow wire is ground, and the other four are for COS/SIN, CLK, DATA, and SEL. The prototype's color coding is shown in Fig. 4, but it doesn't matter as long as you connect the proper points in the interface circuitry to the proper pins of the DB-25 connector. A photograph of the finished adapter is shown in Fig. 5. Don't forget to install the 470μF capacitor (C6) inside the adapter.

Software

Software is supplied in both compiled and ASCII text source code forms, and it is available for free as an archive file (COMPASS.ARC) on the RE-BBS (516) 293-2283. The source code should provide sufficient examples as to the methods used to access and convert the Digi-Compass data. Because of the graphics code in COMPASS.C, you may find the simpler TEXTCOMP.C source much easier to read. The two programs are meant to get you started in developing your own applications.

There is a graphics-based program and one that relies strictly on text output. As shown in Fig. 6, COMPASS.EXE produces a likeness of a handheld compass. The program requires an EGA graphics adapter and monitor, or a CGA adapter that can display the CGA high-resolution monochrome mode.

There are some clever features included in COMPASS.EXE. On startup, the program will attempt to automatically choose the printer port by exercising all of the BIOS configured LPT ports. If a properly operating compass is found, the respective printer port is selected. You can skip that feature by including "LPT1," "LPT2," or

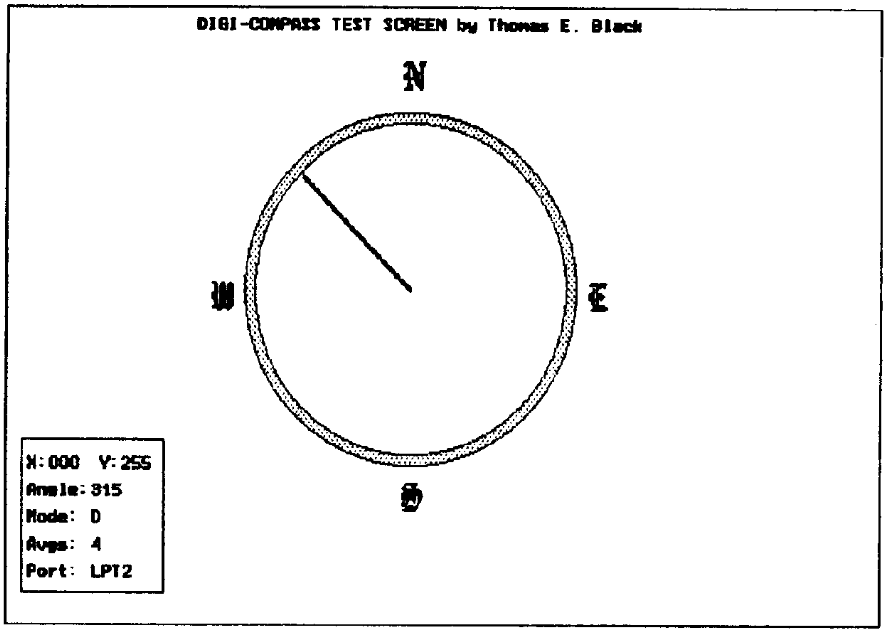


FIG. 6—THIS IS WHAT YOUR COMPUTER'S SCREEN will look like when operating the digital compass.

"LPT3" as the only argument to the program. Be sure to input a port name that is installed in your computer, or the program will not execute (appropriate error messages are echoed). Standard command-line syntax is: COMPASS LPTn, where "n" is the printer port desired (1, 2, or 3).

The data display in COMPASS.EXE provides current acquisition information. The X and Y values indicate the digitized cosine and sine values from the compass interface. The "angle" value is the number of degrees from North in the clockwise direction. It is interesting to note that North is both 0 and 360 compass degrees, depending on your heading.

The "mode" value shows when you are in the *D*igital, *A*nalog or *B*oth mode; it can be changed by pushing the "D," "A," or "B" keys. The digital mode is the default and it plots

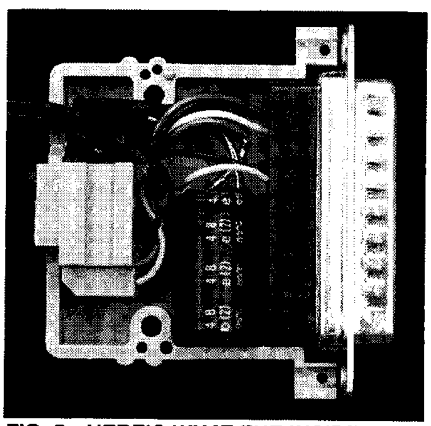


FIG. 5—HERE'S WHAT THE INSIDE of the adapter looks like.

the compass needle using geometry based on the X and Y values. It shows compass direction in the form of a pivoting compass needle. The analog mode is capable of displaying both direction and magnitude of Earth's magnetic fields. While in the analog mode, if you rotate the flux-gate sensor off the horizontal plane you will see the compass needle length shrink and grow. The longer the needle length, the greater the magnetic field.

There is considerable loss in accuracy while in the analog mode due to the software method in plotting the needle. The analog mode converts the X and Y values to Cartesian coordinates based on fixed center. The accuracy of the analog mode is only fair at best, but could be improved by optimizing the code. The angle value and the digital mode's compass needle are displayed with accuracy that exceeds the compass's electro-mechanical movement. You can display both the digital and analog needles at the same time while in the *B*oth mode.

The number of data acquisition averages can be changed by pushing the "" keys. When the average is at the minimum value of zero, the X, Y, and angle values will be somewhat unsteady. The values become increasingly more stable as you move to the maximum of thirty-one, but acquisition time will be very slow. The default of four is fine for most of the applications.

continued on page 82

DIGI-COMPASS

continued from page 51

The "port" value shows the currently used LPT port. You can switch between the available LPT ports by pushing the "P" key. That is extremely handy while debugging the compass or if you have two compasses attached to your computer.

The text-only program, TEXTCOMP.EXE, must be used if your display adapter is not compatible with COMPASS.EXE. It too will auto-configure the LPT port and provide default acquisition averages. You can include the LPT port on the command line as well as the number of acquisition averages to perform (up to 255). To include the average argument, you must include the LPT port argument. Standard syntax is: TEXTCOMP LPTn10, where "n" is the printer port desired (1, 2, or 3), and "10" is the number of averages (0–255).

Calibration

All adjustments must be made on a flat non-metallic surface, and the compass unit must be calibrated according to the manufacturer's instructions first. Keep the compass sensor away from the compass display, computer equipment, metal objects, etc. Any magnetic fields generated by electronic equipment or appliances, or nearby ferrous metals could affect the calibration accuracy of your Digi-Compass. Also, do not use a metal screwdriver to adjust the compass or your adjustments will be meaningless; use the supplied non-magnetic adjusting tool.

To run the text-based compass program, plug the interface into the parallel printer port of an IBM PC/XT/AT. On the command line type "TEXTCOMP LPTx" (where x is a 1, 2, or 3, depending on the port used). Be sure to specify directory paths as required. For example, suppose you plugged Digi-Compass into LPT1 and had TEXTCOMP.EXE on a floppy in the A drive. At the command prompt, you would type "A:TEXTCOMP LPT1."

To calibrate the interface unit, adjust the "max-limit" potentiometer (R17) to 4.15-volts DC at pin 1 of IC3 and the "min limit" potentiometer (R18) to 1.15-volts DC at pin 3 of IC3. With the interface unconnected from the computer, carefully direct the flux-gate sensor exactly to the Northeast, keeping the sensor perfectly horizontal. Adjust the "gain" potentiometer (R16) on the interface so that pin 2 of IC3 is 4.25-volts DC.

Aim the sensor up to 5 degrees towards the North, and then up to 5 degrees to the East, and verify that the voltage does not exceed the adjustments—otherwise re-adjust. When aiming the sensor for the 5-degree test, ignore all measurements beyond the 5 degrees.

With the Digi-Compass interface connected to the computer and TEXTCOMP.EXE running, verify that at the Northeast direction, when the X and Y readouts match (±2), that the highest value is 220 (±5). Adjust R17 to set the highest value. Next, verify that at the Southwest direction, when the X and Y readouts match (±2), that the lowest value is 30 (±5). If necessary, adjust R18 on the interface to set the lowest value. Now go back and recheck those steps, as they are interactive. Verify that the compass readings match the computer's readouts while in the "digital" mode. The Digi-Compass interface is now adjusted. **R-E**

Certain errors made their way into the Digi-Compass story (**Radio-Electronics**, November, 1989). In the schematic of Fig. 3, the labels V_{CC} and V_{DD} should be transposed, and V_{DD} should be 6.8 volts instead of 6.5. Also, the two voltages are outputs, and should therefore have open circles instead of arrows. The labels for pins 2 and 3 of IC3 should also be transposed; pin 2 is INP and should be connected to IC2 pin 7, and pin 3 is REF and should be connected to IC2 pin 8. On page 51, in the right-hand column toward the bottom of the page, the text states that "the number of data acquisition averages can be changed by pushing the ',,' keys." It should have read "by pushing the ">" and "<" keys." And, last, on page 82, "TEXTCOMPLPTn10" should contain spaces between arguments; it should be written as "TEXTCOMP PTn 10."—*Editor* **R-E**

DIGI-COMPASS PARTS

I've heard from a number of "Digi-Compass" builders (**Radio-Electronics**, November 1989) that the TLC-548 ADC IC is impossible to find. It has been discontinued by Radio Shack, although it's possible that some stores may have still have a few available (part #276-1796, $6.95).

As a special service to **Radio-Electronics** readers, I will supply the part for $6.95. Those who don't want to download the software file can also purchase that from me, for $6.00. (That might be cheaper than downloading the 100K file at 1200 baud from the RE BBS.) It will be supplied on a 360K PC data floppy diskette.

To order, please send a check or money order only (California residents add 6.5% sales tax) plus $1.75 shipping and handling to Digital Products Company, c/o Thomas E. Black, 134 Windstar Circle, Folsom, CA 95630. This offer is subject to change and is valid for a short time only.

Thanks for publishing my article. I'm thrilled that it has stirred up some interest.

THOMAS E. BLACK
Folsom, CA