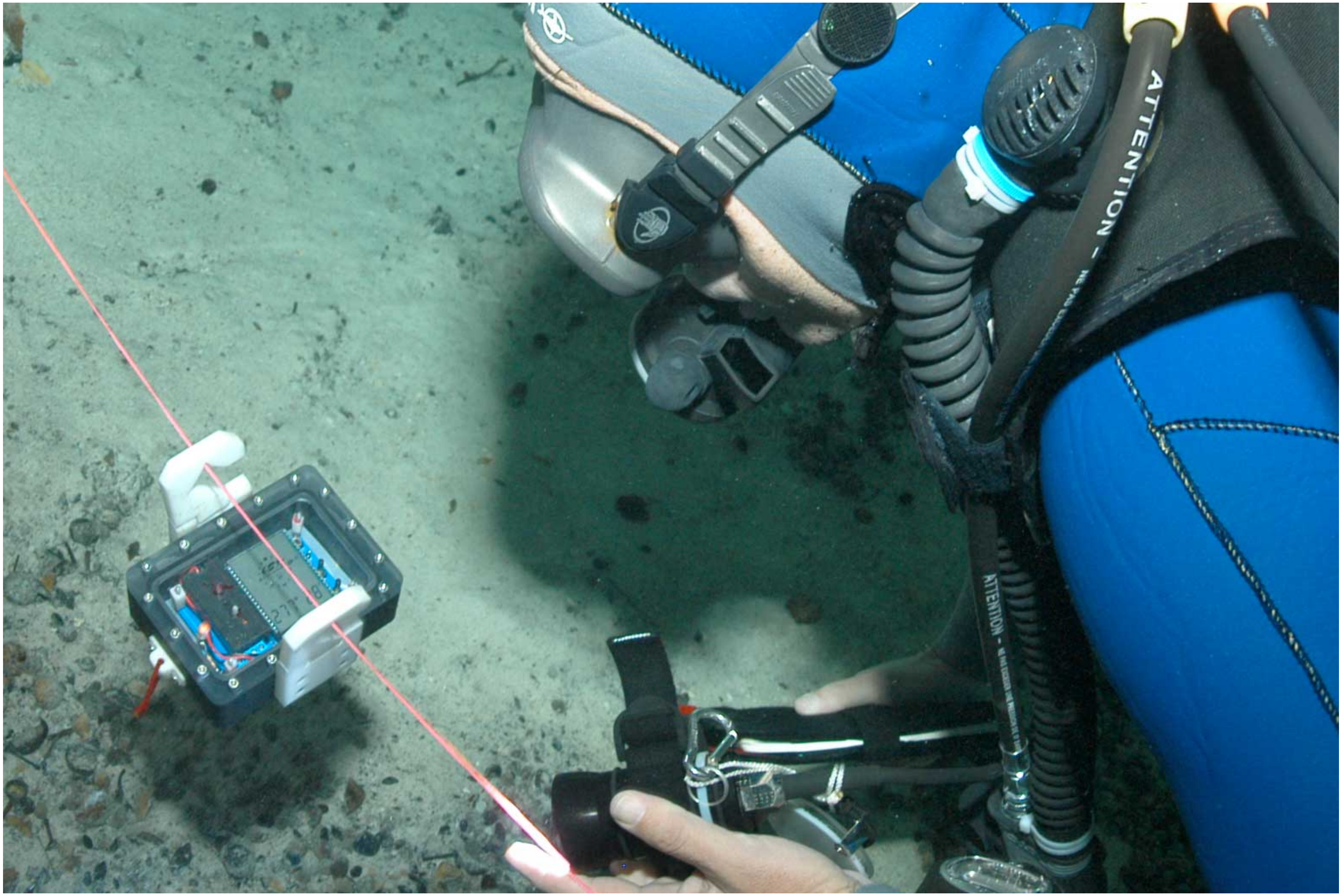
NOTES ON THE CONSTRUCTION OF A PROTOTYPE DIGITAL UNDERWATER LINE COMPASS FOR UNDERWATER CAVE SURVEY



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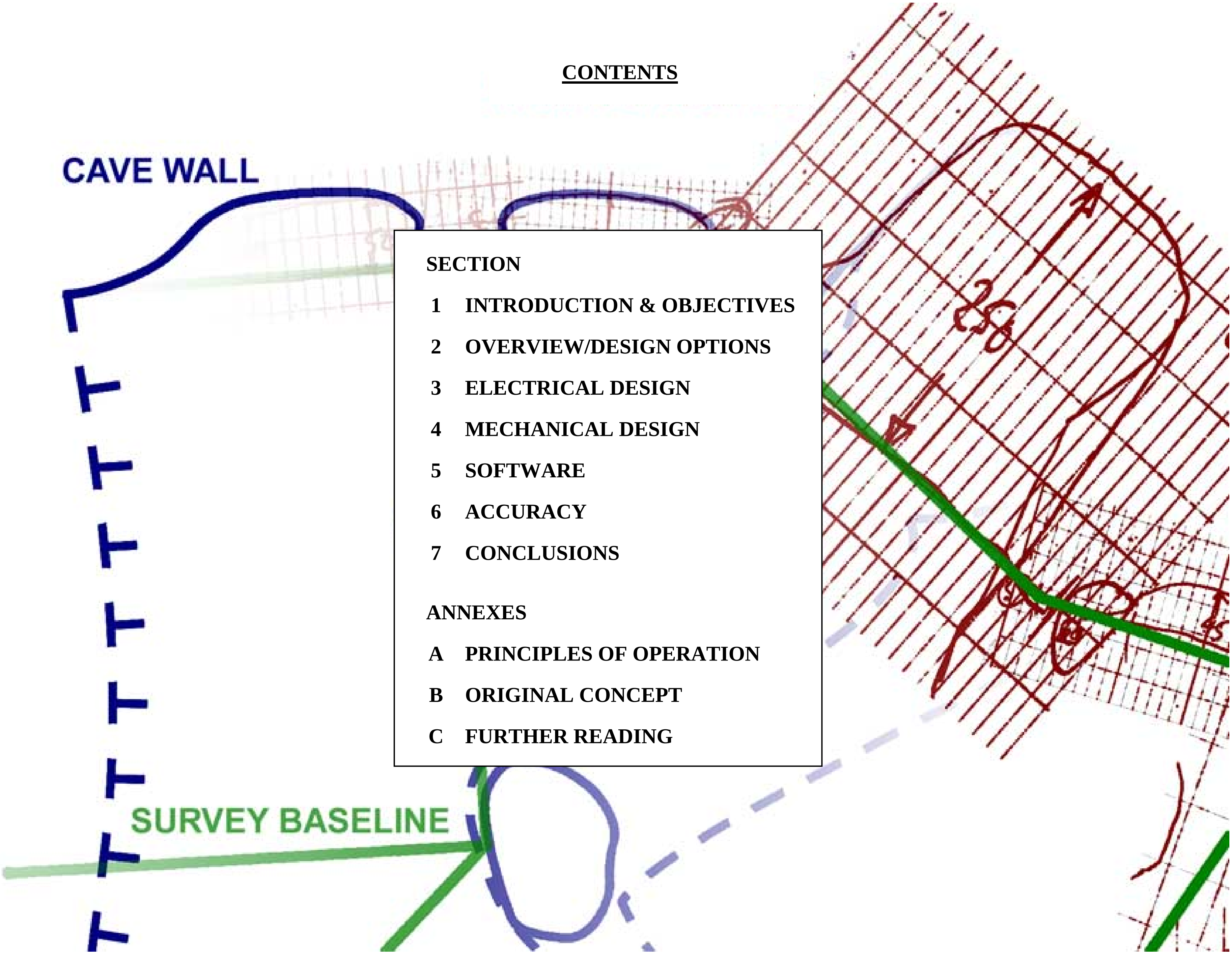

SECTION 1 - INTRODUCTION & OBJECTIVES

Introduction

Although cave diving equipment has developed significantly over the last ten or twenty years, there has been little advance in underwater surveying equipment: distances are still measured using pre-knotted line, and azimuths using cheap orienteering compasses which must be aligned with the cave guideline by eye. Although surveys made in this way by a skilled surveyor can be surprisingly accurate, the surveying process can be seen as difficult and time-consuming. As a result, the process can be off-putting, and newcomers may be disheartened. Even surveys by very experienced divers contain a high frequency of what are known as "blunders" - large errors in reading or writing down data. Analysis of survey data shows that many of these blunders arise in azimuth measurements. This is no surprise given the limitations of the compasses used.

Over the last five or so years there have been a number of advances in the development and application of magnetic sensors and digital compasses. In principle a digital compass is attractive because it can be made easy to operate and read, reducing the frequency of azimuth blunders. However, most consumer grade digital compasses currently available are simple two-sensor designs, which means that they must be held very close to level (within a couple of degrees) in order to provide accurate azimuths. Furthermore, few of these have been made available in housings suitable for use underwater.

In principle it is now straightforward and economic to construct a more sophisticated digital compass which is compensated for tilt and so does not need to be held level. Additionally, with a suitable mechanical design, the compass can be hung from the line rather than aligned with it by eye, simplifying the process and improving the resulting accuracy. Over the last year or so we have been experimenting with these approaches for developing a better underwater cave survey compass, and the results of these experiments are described in this note.

Objectives

(1) To develop a prototype which is fully functional, usable, and sufficiently accurate (one or two degrees) to represent a major advance over traditional underwater compasses in terms of ease of use and quality of results.

(2) To publicise the results of this work so other constructors, and ideally equipment manufacturers, may be encouraged to make better units.

It should be noted that our objective is not to "dumb down" the cave survey process so that it can be done thoughtlessly, but rather to develop the right tool for the job so that a thinking diver can bring back more and better information about the cave, and have a more enjoyable dive.

Important Caveats

(1) We lack the knowledge, skills and experience to develop a device incorporating known best practice in all aspects; as a result some of the design decisions and construction approaches are imperfect and can be improved upon by suitably knowledgeable people.

(2) The software in the Silicon Laboratories digital compass board must be modified for proper operation in this application (see notes in the section on "Software"). Recompiling the source code requires purchase of the full version of the Keil "C" compiler and a Silicon Laboratories development kit to download the compiled object code. When we have completed all our planned work on the software we will make a compiled object file available which will only require the development kit to download.

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SECTION 2 - OVERVIEW/DESIGN OPTIONS

Problems with Existing Compasses

The two major problems with the simple compasses commonly used to survey caves are:

(1) They must be aligned with the guideline by eye - this is difficult to do (and quite frequently gets done 180 degrees in reverse), and reduces the accuracy achieved.

(2) An analogue scale must be read and interpolated (backwards, depending on how the compass is used), and this introduces a high frequency of "blunders".

The first problem is solved very simply by using a hanger system to suspend the compass directly from the line. This has the advantage of also freeing up one hand of the surveyor for writing (rather than requiring the surveyor to remember the azimuth reading until the compass has been put away and the pencil taken out). Regardless of other design options, we think that this approach should always be taken where possible

Use of hanger system to align compass with guideline and free up one hand (Freiberger mining compass, photo courtesy [Clausen Instrument Company, Inc](), and our prototype digital line compass)

We decided to address the second problem by using a digital compass to provide a direct reading of the azimuth (it should be noted that avoidance of large blunders is the primary reason for this, not pursuit of extreme accuracy).

Digital Options

Within the realm of digital compasses, the choices are:

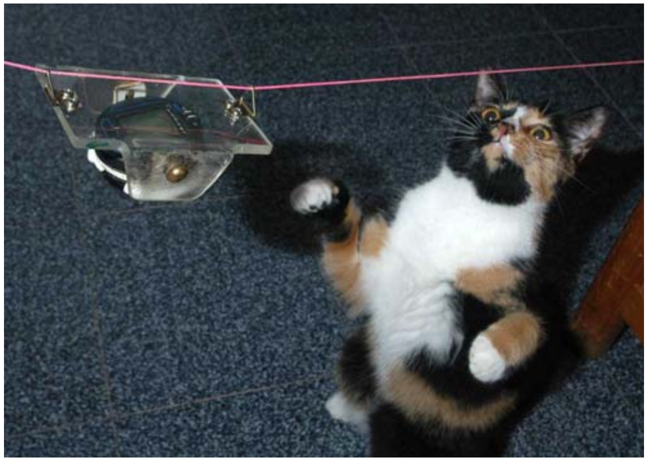
(1) A two-sensor uncompensated digital compass, with gimballed suspension mechanism to keep it level

(2) A three-sensor digital compass with electronic tilt compensation.

Simple two-sensor compasses need to be held almost dead level to provide acceptable accuracy, and this can be achieved by a gimbal mechanism. More sophisticated three-sensor compasses can provide electronic compensation for the errors introduced by tilting compasses (see Annex A - Principles of Operation).

Initial Approach

Our initial approach was to use an existing commercial underwater digital compass (see Annex B - Original Concept) mounted on a gimbal system. The attraction of this was that the hanger system already provides half the gimbal mechanism, so construction of the remainder is relatively simple - the compass module simply needs to be mounted free to rotate about one axis.



cave-exploration.com team member evaluates proof-of-concept digital line compass

Comments on Proof of Concept

This worked as a proof of concept subject to the following comments:

(1) Because the line hangers were not fixed, two hands were required to place the compass on the line, which was inconvenient (this is easily solved).

(2) The gimbal mechanism we made was fairly crude, but there is in fact another more precise gimbal mechanism inside the UWATEC compass module which provides additional levelling of the sensors (but not the rest of the electronics).

(3) The resolution of the UWATEC is only five degrees, and its accuracy is not known. One or two degrees accuracy would be required, with say one degree or better resolution.

Next Steps

This did not leave an obvious future direction - there are at present few digital underwater compasses of any type available which have the required accuracy. One reason for this may be that manufacturers are aware that a two-sensor compass will anyway have its useful accuracy limited by tilt, so there is little point in making the mechanism itself more accurate. From our perspective that meant that there was little benefit in taking a crude two-sensor underwater compass with low accuracy and gimballing it.

We therefore considered building a more accurate two-sensor compass ourselves and mounting that in an underwater housing. Because we were concerned about our ability to build an external gimballing system which would be robust enough to survive cave diver usage and the mineral deposition resulting from exposure to cave waters, we intended to mount the gimbal mechanism inside the housing, with just the magnetic sensors gimballed. This would have resulted in some exposure to tilt, because magnetised or permeable metal components which were not mounted on the gimbal mechanism would rotate relative to the magnetic sensors. Because of this and other considerations, we decided to develop a prototype using an electronically tilt-compensated compass with no gimbal mechanism.

Prototype Tilt-Compensated Digital Underwater Line Compass

The prototype was based upon a Silicon Laboratories "Reference Design" board. We mounted this inside a box, wired up some magnetic switches to it so that it could be operated from outside of the box by magnets, and added an LED and some driver circuitry to an unused output from the microcontroller to allow the compass to signal to the user.

The use of magnets for switching would have interfered with the calibration of the compass. The problem is that the calibration software begins reading the sensors immediately after being selected by the "menu" switch, and if the menu switch is operated by a magnet, then the compass will pick up the field of the magnet and incorporate that into the calibration. We considered using a light sensitive switch, but decided to add a simple delay into the start of the calibration routines to allow the user to move the magnet out of range of the sensors.

One of the other features we wanted to incorporate was a facility to freeze a reading, for use in poor visibility conditions.* Newly explored "active" caves in particular can suffer from intense bubble percolation removing sediment from the cave ceiling to fall into the water column below, which may then reduce visibility to little or nothing. A "freeze" option would allow the user to place the compass on the line, let it acquire an azimuth reading, and then remove the compass and swim to clearer water to read the azimuth and record it in the notebook. Again, we initially thought of using light sensitive switches to accomplish this (because a magnet would affect the azimuth reading), but then realised that suitable software design could avoid this. When turned on, the compass spends several seconds acquiring a reading. When the reading stabilises (which hopefully means that the magnet used to turn the compass on must have been moved out of range), the compass freezes the reading, and signals this to the user using the LED.

The need to modify the compass software guided the choice of electronics for the prototype: we needed a module where we could download new program instructions, and ideally where we would have access to the source code. The neatest solution was to use an existing manufacturer's "reference design" or a kit produced for experimenters (for example, robot constructors) - our choice was the Silicon Laboratories reference design.

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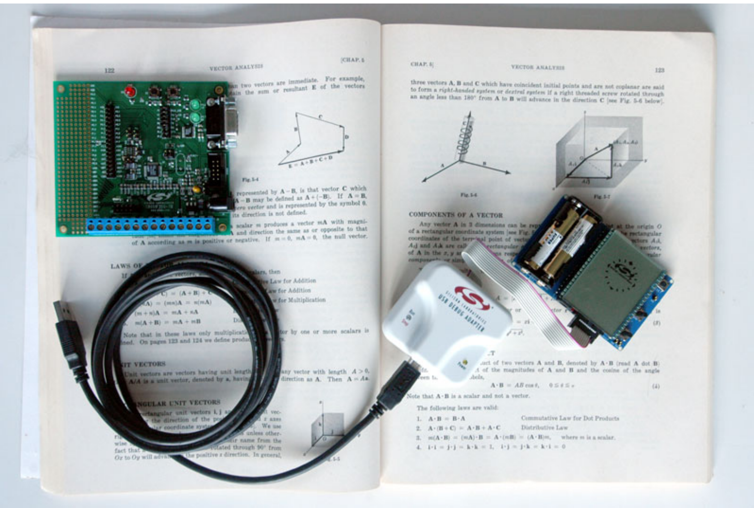
* *We are grateful to Fred Devos for suggesting this*

SECTION 3 - ELECTRICAL DESIGN

The Silicon Laboratories Reference Design

The Silicon Labs reference design is a single board digital tilt-compensated compass, based on their C8051F350 mixed-signal CPU which incorporates on-chip digital and analogue inputs and outputs. The CPU's current consumption is typically 16 uA at 32 kHz and 17 mA at 50 MHz, from a supply voltage in the range 2.7 to 3.6V. Data RAM is 768 bytes, and on-chip flash RAM for program storage is 8 kB. 17 programmable input/output ports are provided, including 8 inputs to a 24-bit analogue to digital converter with 0.0015% linearity, and two 8 bit current digital to analogue converters. Additionally, there is a built-in temperature sensor, an internal voltage reference, and a variety of programmable and general purpose counter/timers.



Silicon Labs C8051F350 compass board (right) connected to USB debug adaptor Silicon Labs C8051F350 development kit (left). For scale, batteries are AAA

An additional 8 kB of electrically erasable programmable read only memory (EEPROM) is provided on the compass board using a CAT24WC65K. This offers 1 million program/erase cycles and 100 year data retention, and is accessed via a simple serial bus formed by two of the 8051 input/output pins. In the reference design this is used to store lookup tables for trigonometric functions, and the parameters derived from the calibration process.

Sensors

A Honeywell HMC1052 dual axis magnetic sensor is used for the X and Y sensors, and a HMC1051Z single axis sensor for the Z sensor. Each sensor element consists of a Wheatstone bridge incorporating magnetoresistive elements to produce a balanced output proportional to field strength. Supply voltage is 1.8 to 20 V, sensitivity is up to 1 mV per gauss field strength per volt across the bridge (the earth's field is approximately 0.5 gauss). The sensitivity ratio of the X and Y sensors within the HMC1052 is +- 5% and their orthogonality is 0.01 degrees. Linearity error is 0.1% of full scale at 1 Gauss, hysteresis is 0.06% and repeatability error 0.1% of full scale after 3 sweeps of 3 Gauss. The sensors may be operated in a "passive" mode, as in the Silicon Labs design, or in a clocked reset mode for higher sensitivity (or for processors with less sensitive ADC inputs).

A Memsic MXD3334UL dual axis accelerometer is used for pitch and roll sensing. The sensor contains a cavity with a gas inside, which is heated and then rises vertically by convection. Temperature sensors around the cavity measure the direction of convection, which can then be equated to the orientation of the device and hence of the compass. The MXD3334UL provides digital square-wave outputs for pitch and roll, whose duty cycle varies with the pitch and roll.

Integration

The outputs from all sensors are fed directly into the relevant inputs of the microcontroller without any intervening amplifier or buffer circuitry. In turn the processor interfaces with a custom LCD display and a UART driving a USB connector, through which it sends tilt, temperature, and azimuth data.

The C8051F350 controls power to all sensors and the display, so that power consumption can be limited and a "sleep" (apparently off) mode can be implemented, with only a few tens of uA of current draw. There is therefore no need for a true on-off switch, even when battery operated.

Manufacturers neither explicitly nor implicitly warrant anything about their reference designs - they are intended purely to demonstrate the capabilities of the microprocessor to product design engineers, and to illustrate the way in which they can be used.

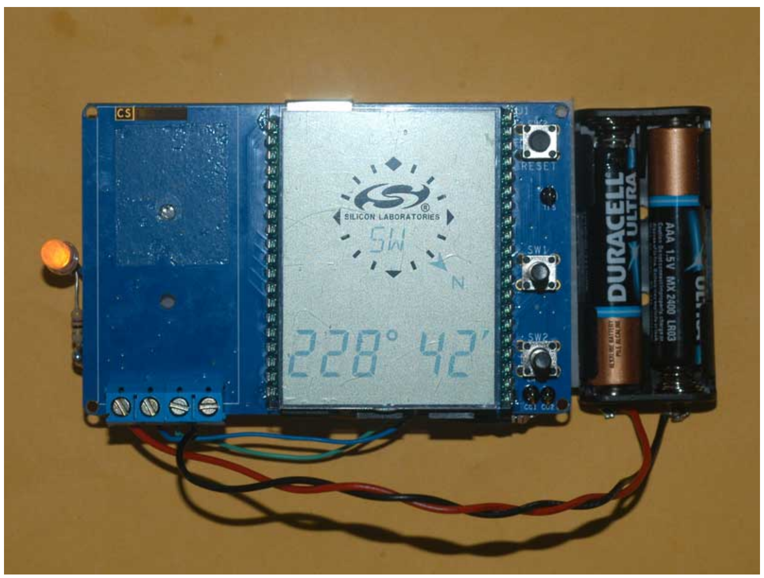
Modifications for the Prototype

The following electrical modifications were made to the compass board:

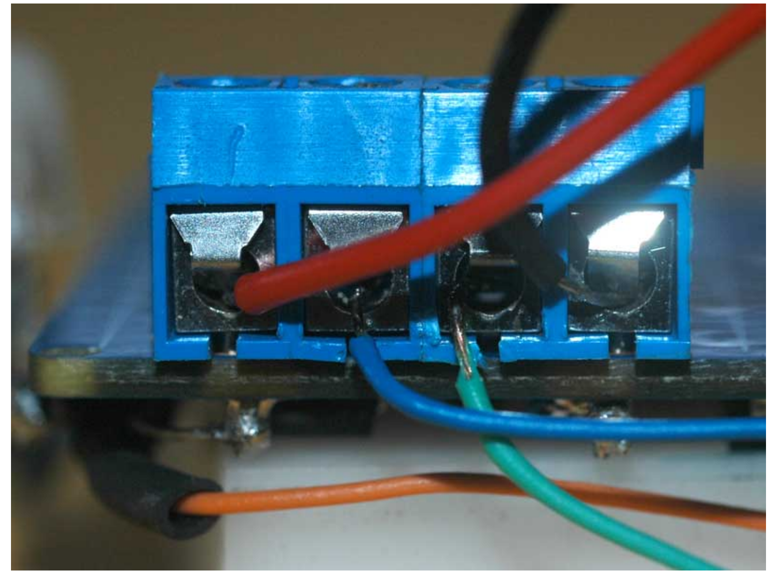
(1) The battery holder was unsoldered from the board for separate mounting. The intention of this was to remove weight from the board. This freed up space for a connector block, two terminals of which connect into the 3V battery supply point.

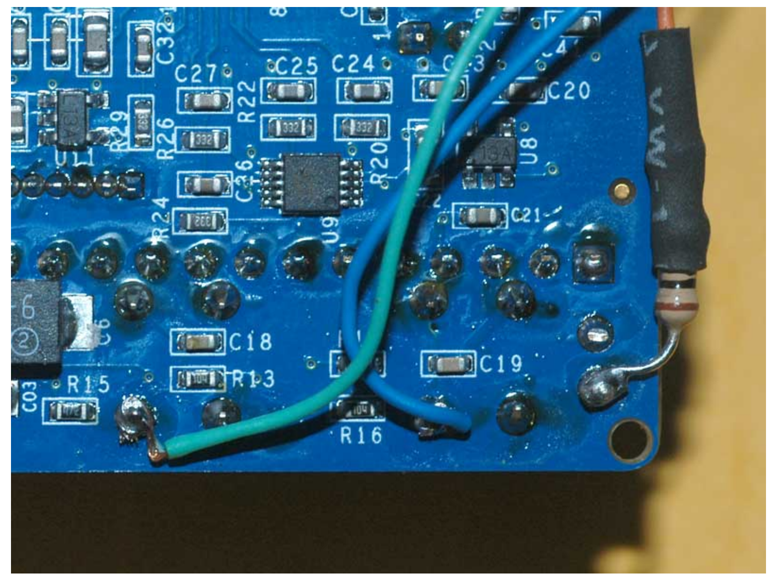
(2) Wires were run from the "menu" and "enter" microswitches to the connector block, for connection via this to the magnetic switches.

(3) An LED was added, driven by an emitter follower circuit from the unused "CO2" connector, which allows digital or analogue control (general purpose NPN silicon transistor with hFE of 100 or more, 10K current limiting base resistor, 47 ohm resistor in series with the LED to ground). An amber LED was chosen in hope of achieving maximum brightness underwater.



Off-board battery holder, connector block, and LED

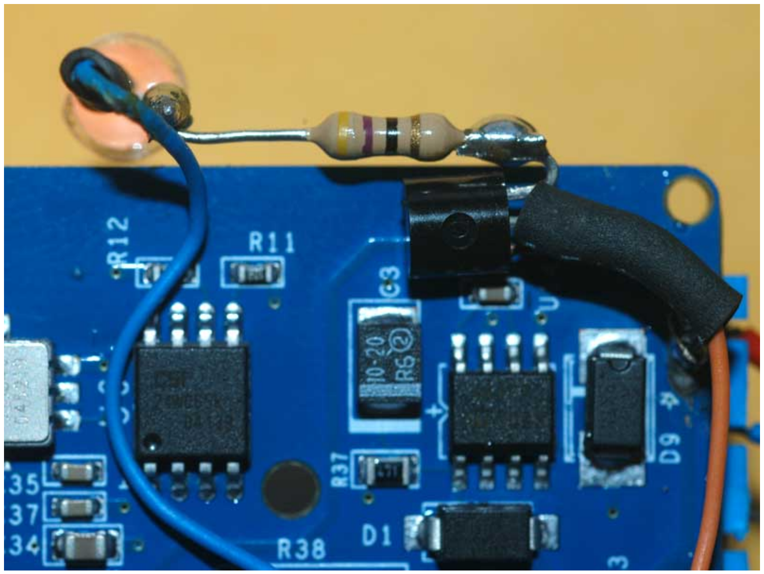

Connector block



Flying wires for magnetic switches, and the base resistor for the LED emitter follower

Power Supply

The reference design is intended to run from either the 3V produced by the two AAA batteries, or from a higher voltage delivered via the external power connector or the USB port via a voltage regulator. Power consumption when driven from the batteries is approximately 15 mA with the LED off, and 25 mA with the LED on (current consumption varies as the compass switches the sensors on and off to make azimuth measurements).



LED and emitter follower circuitry

One objective was that the compass should run from rechargeable batteries which could be charged from outside the case, in order to reduce the need to reopen the unit. We had originally intended to use two NiMH or NiCad rechargeable batteries, with arrangements to trickle-charge these through two stainless steel bolts run through the housing (with a diode in series to prevent any reverse voltage appearing on the bolt heads and causing electrolysis and surface contamination). Although trickle charging is slow, it has the advantage of not requiring any voltage sensing and is achieved via a constant current source circuit, which would be robust to variations in the contact resistance with the bolts. Unfortunately a pair of NiMH batteries develops only about 2.7V, which is insufficient for the circuitry to run properly (at least for the LCD).

Alternative Rechargeable Options

We considered using three or four NiMH cells running through the external power connector, but we couldn't find cells small enough to fit. We also considered using a Lithium Ion rechargeable cell, for example a cellphone battery. These develop a higher voltage (4V or so per a cell) and have a high energy density. Charging is more complex and they cannot be trickle-charged - however by cascading a constant voltage source inside the box with a constant current source driven from outside the box, a reasonable charge level could probably have been achieved with still quite simple circuitry, and with high reliability.

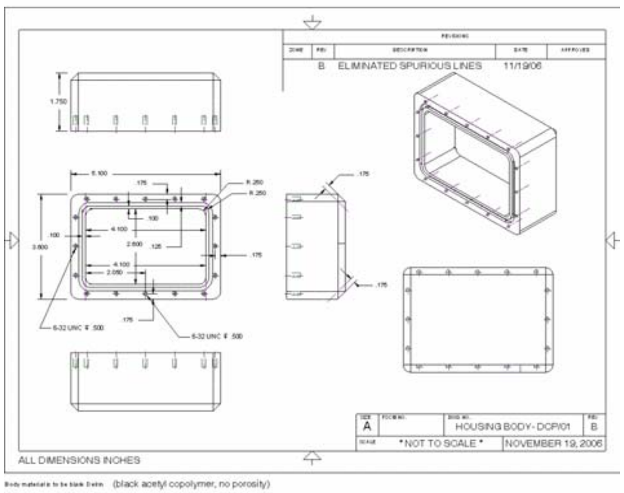
One limitation with using the external power connector is that the current drain when off will be higher. In part this is due to the presence of a power LED (which we would have removed), and in part because a couple of voltage divider resistors within the power regulator circuitry will draw about 100 uA at all times. Another limitation is that the regulator is actually a 3.3V regulator, and so a minimum of 4.1V or more would be required at its input to prevent dropout, which is more than can be provided by a single Lithium Ion cell throughout its discharge cycle. Both of these problems could have been avoided by using an off-board 3V regulator and then taking the 3V from that into the board at the battery connection point.

Rough calculations suggest that battery life may be acceptable using non-rechargeable Lithium batteries, perhaps allowing 20 or more dives between changes, and we intend to evaluate these. Until then, we are using Duracell alkaline cells. With hindsight, we would have had a lot more flexibility if we had allowed 5mm more depth in the housing.

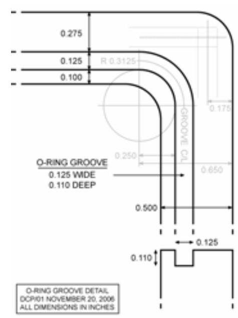
SECTION 4 - MECHANICAL DESIGN

Introduction

The biggest challenge was the construction of a waterproof and pressure proof housing. Ideally we wanted an operating depth of 100m, although 40m would have covered the majority of our requirements. If we had constructed the housing ourselves, we would have used a circular acrylic housing like a much shortened light canister. This would have created problems in fixing and aligning the hangers correctly, and would not have provided a straight surface to permit the compass to be used free-standing (for example on almost vertical lines).



Housing design, modified from a design by Karl Denninger

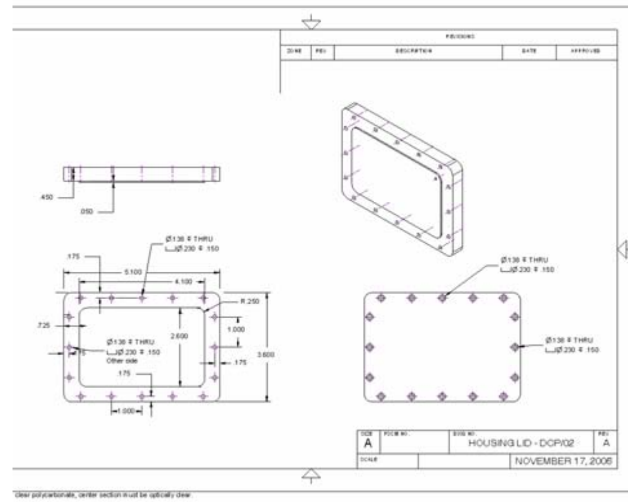


O ring groove detail

We were fortunate in that [Karl Denninger] had designed a housing for his K1 rebreather electronics which was almost exactly the size required for our compass. Karl kindly supplied us with his drawings and some suggestions, and we made some modifications, reducing the depth to about 1.75 inches and eliminating some features which were not necessary for our usage. The box itself is made from black delrin ("black acetyl copolymer, no porosity") and the lid from clear polycarbonate. External dimensions, including the lid, were approximately 2.25 inches by 3.60 by 5.10 inches, with a 0.5 inch lid and wall thickness.

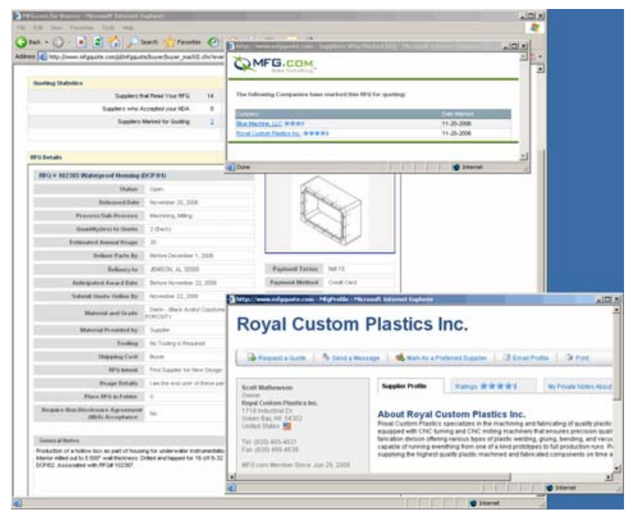
The lid is retained by 16 off 6-32 half inch stainless steel socket cap screws, and waterproofing is provided by a 2-242 neoprene O ring (note that this O ring has a fill factor of 100% or perhaps more, which may limit its life).

Karl's design criteria included a 200m theoretical collapse depth (to give a 100m operating depth) - we have not independently confirmed this, but it is waterproof shallow and at depths to about 25m.



Lid design by Karl Denninger

Tenders for construction of two prototype housings were sought through mfgquote.com, and awarded to RGM Machining, who produced some first class results within just a couple of days, for a few hundred dollars per set.



mfgquote.com provides a marketplace for manufacturing services

Magnetic Switches

The magnetic switches for the "menu" and "enter" buttons were mounted one at each end of the box - these are normally open switches, and one side of each is connected to ground. The switches have brass cases which were "flatted" on one side using a grinder, to provide some positive location. Heatshrink tubing was applied over them to provide something to "bite", and a small U-shaped stainless steel retainer fixed them to the box.

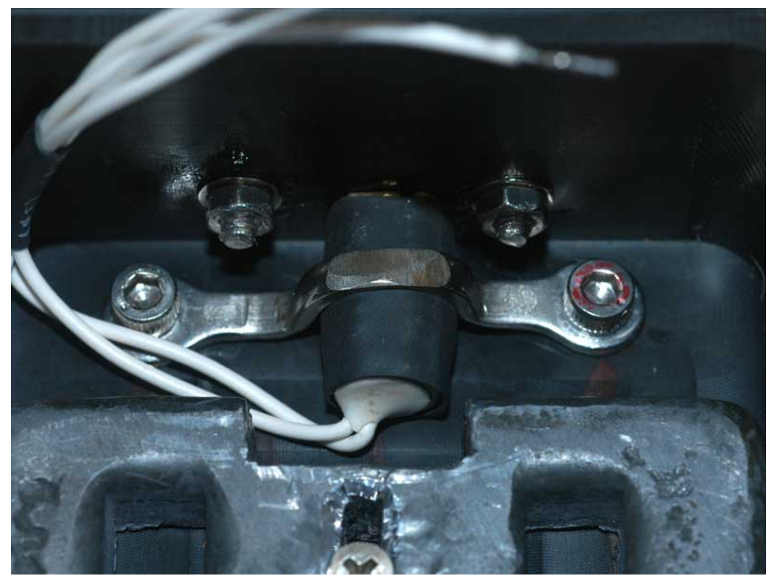
Magnetic switches and ballast weight mounted in box

A small bar magnet was sewn into the end of the notebook to operate the switches. One concern is whether the switching magnets will magnetise the compass sensors or other magnetic material. The field from the magnet we use is about as strong as the earth's field, 0.5 to 0.6 Gauss, at 2 inches. This is the closest it can get to the sensors and should not cause any problems. At one inch it will be closer to 5 Gauss, and at half an inch somewhat larger, say perhaps 40 Gauss. It would therefore have been better to use plastic or brass mounts for the magnetic switches rather than stainless steel, which could be partially magnetised by the magnet.

Ballast Weight

A ballast weight (1 lb trimmed down to perhaps 0.8 lb) was screwed to the base of the box. Slots were used to permit adjustment, but this was not necessary. This could perhaps be reduced to 0.5 lbs.

Ballast weight mounted in box

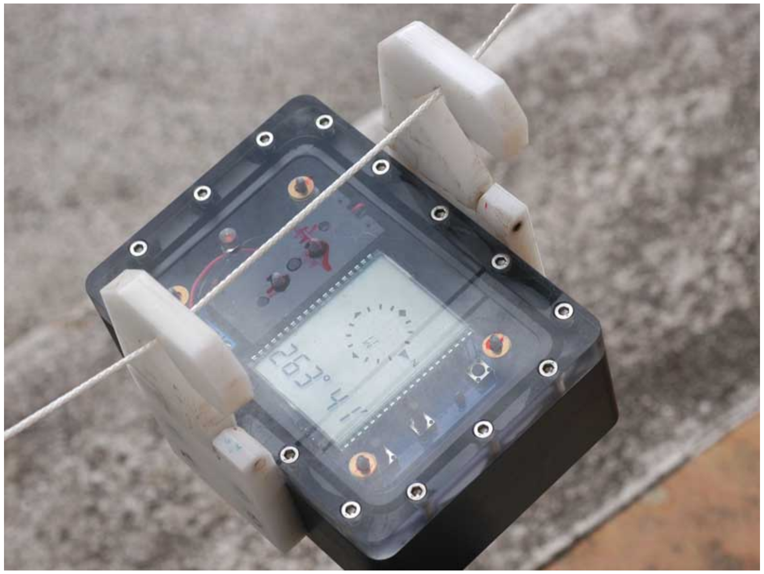


Magnetic switches. Plastic or brass retainers would have been better from a magnetisation perspective. Note screws penetrating from outside the housing - the original plan was to use these for battery charging. The threads are sealed with silicone.

Line Hangers

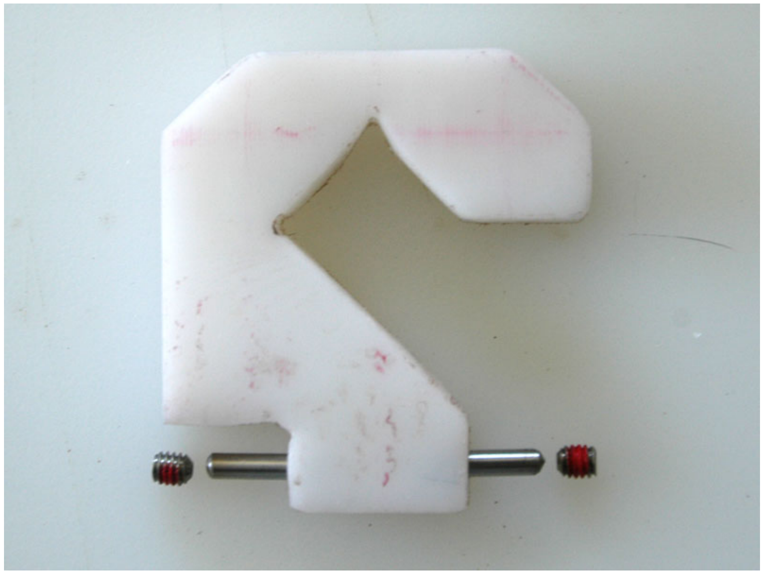
The line hangers are an important feature of the compass. They align the compass with the guideline more accurately, more quickly, and more easily than a surveyor could achieve by eye, and they free up a hand for note-taking.

They need to be precisely aligned with the sides of the box (so that the compass reads the same whether the hangers or the box are used for alignment), and they should have no free-play in them, so that repeatability is high. Both of these can be achieved by machining them and the box accurately, but ours were hand made and so we had to incorporate an adjustment mechanism. They should be unobtrusive when the compass is not being used, so that it can be stowed in a pocket, but they should be fixed when in use, so that only one hand is needed to place the compass on the line.



Compass suspended on line hangers

The hangers for the prototype were hand-made from 3/8 inch white delrin and hinge in the centre around two stainless steel half shafts. These are a friction fit into the delrin, and although we had originally intended to add a detent mechanism to hold them in an upright position when in use, this has not been necessary so far. In order to provide some adjustment for alignment, the half shafts are located within the fixed part using small stainless steel set screws.

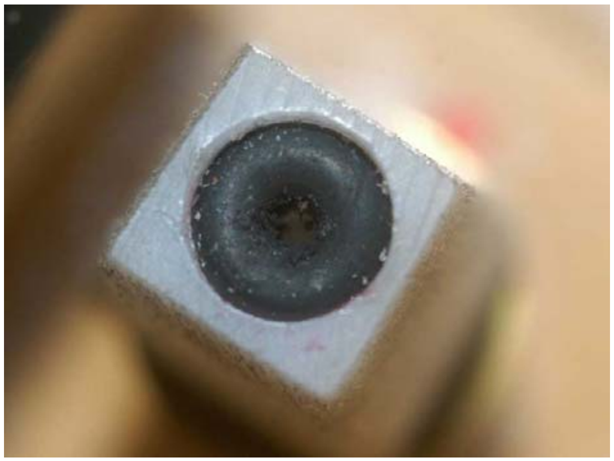


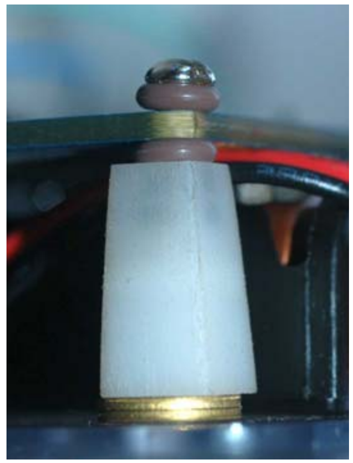
Rotating half of hanger is mounted on two half shafts (centre hole is not continuous) - this is located within the fixed half by set screws which can be adjusted. The holes for the half shafts need to be aligned well, and we constructed a simple jig for this.

When not in use, hangers fold flat against compass body for stowing in pocket

PCB Mounts

We were concerned about distortion of the board due to thermal expansion/contraction of parts of the compass, or flexing under pressure at depth. Therefore we mounted the PCB on flexible mounts. No manufactured mounts were available here, so we constructed our own from 0.5 inch thickness delrin. The flexible component was provided at the PCB end by arranging for the PCB fixing screw to thread into two SPG O-rings. These O-rings fit inside a slightly undersized hole, which has a light thread cut into it so that they lock in place under pressure from the screw.



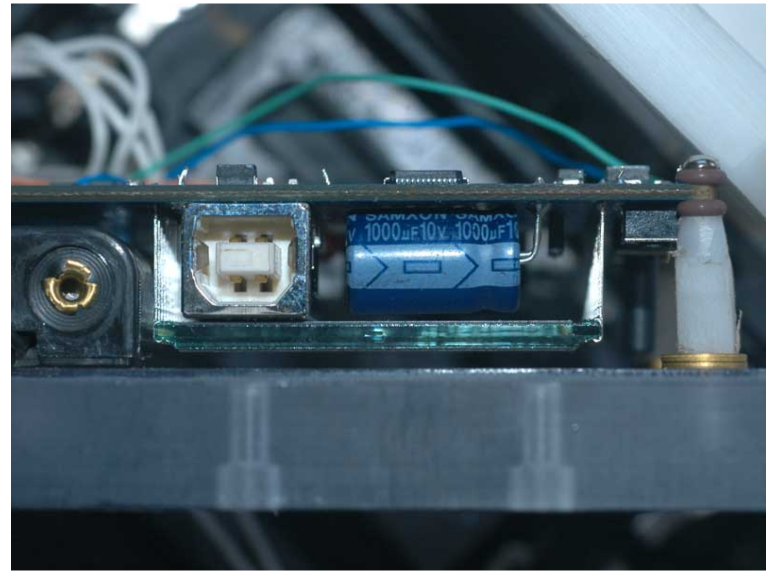


Two SPG O rings are recessed into the mount (one is below the visible one), and the PCB mounting screw "self taps" into these.

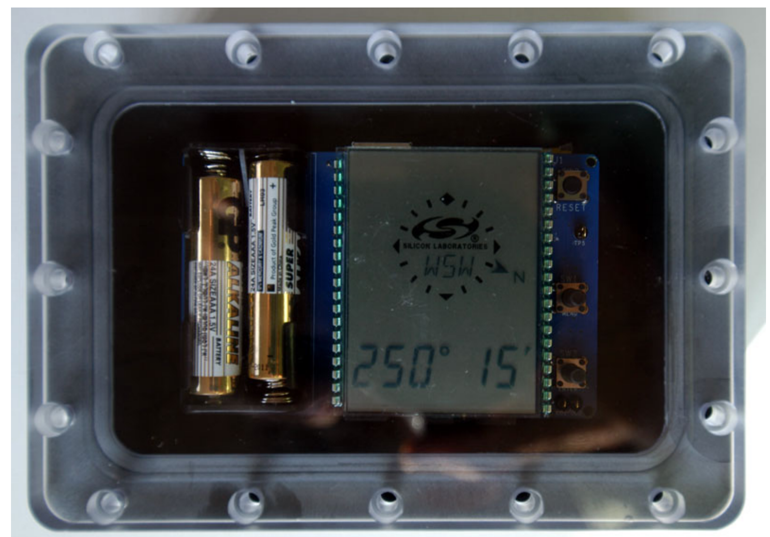
Another pair of SPG O-rings is used either side of the PCB to provide additional flexibility (the ones shown are viton, but buna O-rings would probably last longer).

Standoff washers were used to give a small clearance between the LCD display and the lid.

In the first prototype, the PCB was mounted to the lid, and the battery holder was separately also mounted to the lid. This provides good access to the debug adaptor to allow software revisions to be downloaded, but replacement of the batteries requires the PCB to be removed. Once the software is finalised, we would probably prefer to leave the battery holder on the PCB, and to mount the PCB to the base of the box, to make battery changes easier.



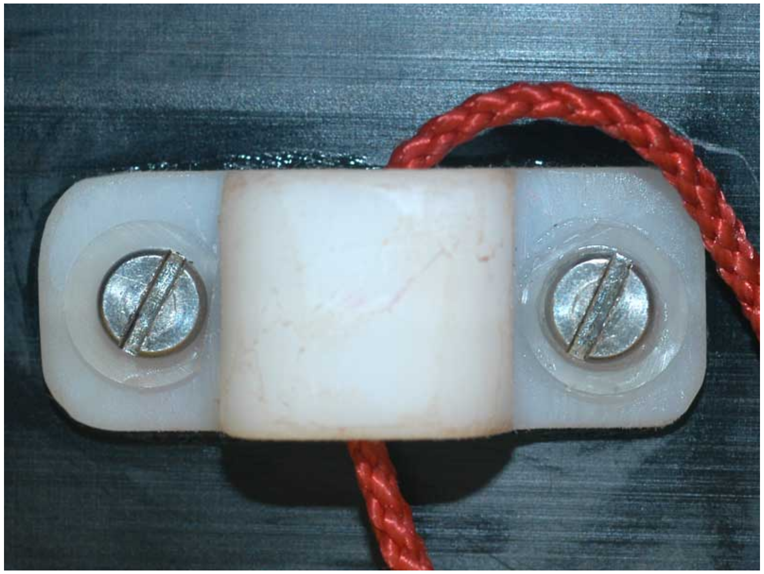
Clearance between LCD and lid
(we subsequently removed one washer)



Mounting the PCB to the base of the box would allow easy access for battery changes by just removing the lid (but not for software download/debugging)

Attachment Point

A fitting for an attachment loop was made from delrin and fitted over the "menu" magnetic switch. Besides providing an attachment point, it shields the magnetic switch, reducing the probability of accidentally operating it underwater (which is not required). The screws penetrate the housing as we originally intended to use them to supply power for battery charging. The threads were sealed with silicone sealant.



Loop attachment point

O-Ring

Care needs to be taken not to damage the O-ring or its groove when fitting or removing. The O-ring was cleaned and very lightly lubricated with silicone grease before fitting. Because it is a close fit in the groove, a plastic pen top is used for removal (a soft wooden stick would also do).

Screws from loop attachment point penetrate housing near the "menu" magnetic switch

Carefully removing the O-ring

SECTION 5 - SOFTWARE

Overview

The operation of tilt compensated digital compasses is described in Annex A, largely based on papers by Michael J. Caruso at Honeywell SSEC. The software for the Silicon Labs design was written by Sytron Technologies Overseas, and in the terms of Annex A, has calibration on demand using a simple maximum/minimum algorithm. In the X-Y (horizontal) plane, calibration adjusts for hard and soft iron distortions and sensor offsets, but not for variations in sensor gain. In the Z (vertical) direction, calibration adjusts for hard iron errors and sensor offsets only. Tilt sensors are calibrated for offset but not gain. Although it is possible to improve on this at the expense of increasing the program size and complexity, this appears to be about par for simple tilt compensated compasses. We have not formally evaluated the accuracy of the compass yet - however our biggest concern is tilt compensation, and (with a patch to the software to fix a bug in it) tilt error is about one degree for up to about 30 to 40 degrees tilt, which is more than adequate for our application.

The prototype provides a "test bed" for further experimentation, but at the moment our main focus is on:

(1) Changes which are necessary to make the compass usable underwater (for example, adding delays to avoid interference from the magnets used for switching)

(2) Improving the ergonomics and facilities of the compass, to make it more useful.

We have not completed the first part by patching the compass software at the object code level and downloading it to the compass using the Silicon Labs development kit. The second part requires that the changes be made to the source code and this recompiled, and that in turn requires a full compiler (the development kit includes only a limited capability evaluation version). We attempted recompilation using the freeware SDCC compiler, but the object code it produces is significantly larger than the Keil compiler (which optimises very vigorously indeed), and so we are awaiting a full version of the Keil compiler in order to proceed with the second part.

Changes for Underwater Use

The reference design may be obtained through various suppliers, including Mouser and Digikey. Some suppliers may stock versions which have the older software versions and which do not include the source code, but it is included in the latest release and Silicon Labs support staff were happy to provide this by to us by email. There is a small bug in the compensation routines in the version 1.23 software which can be corrected using a three byte patch.

In addition, the following changes are necessary for underwater use:

(1) Ideally, a bigger delay should be added between selecting "enter" from the calibration menu and the start of the X-Y sensor calibration process, so that the magnet does not affect the calibration results (there is already some delay while the LCD is refreshed and the sensors "warm up", so good calibration is possible without this).

(2) At the end of the X-Y sensor calibration process, the user is required to enter the declination adjustment, which requires use of the magnetic switches. During this process, the compass is calibrating the offset for the Z sensor, which could be affected by the use of the magnet. Our "quick fix" was to simply set the declination adjustment to zero (we feel anyway that declination adjustments are the job of the cartographer not the surveyor, and it is therefore better to have all azimuths measured relative to magnetic north), and to make the Z sensor process operate for a fixed number of samples.

With these few small changes, the compass works nicely and is without doubt far superior to anything we have yet used underwater. As noted above, we made these changes by patching the object code (an Intel Hex file in text format), and we will include the object code patches on the next website update. These require the Silicon Labs development kit to download to the compass board.

Additional Facilities

We are planning the following additional changes:

(1) At present the software applies 40 minutes of hysteresis to the displayed azimuth, so that the reading is stable. This can be reduced to about 20 minutes or so, at which point the readings fluctuate. We therefore intend to change the software to calculate a weighted moving average†, round this to either 15 or 30 minutes (higher resolution is pointless). We would also perhaps incorporate a small amount of hysteresis in this process, so that the display would not be changed if the new measurement were only 5 or 10 minutes in error from the displayed measurement

(2) An automatic "sample and hold" mode should be added. When the "enter" switch is activated, the compass would repeatedly acquire azimuth measurements, revise the weighted moving average, and display it. When the weighted moving average stabilises within a pre-set error level, the compass would freeze the reading and indicate this fact to the surveyor, for example by illuminating the LED steadily. We envisage that this process would be subject to minimum and maximum times - for example, the minimum time before the compass would freeze the azimuth might be 4 or 5 seconds, and the maximum time perhaps 10 seconds. If the azimuth had not stabilised within 10 seconds, the compass could freeze the reading anyway, but display a rapidly flashing light so that the surveyor would be aware of a problem and decide whether or not to try again. We see this facility as having advantage in poor visibility conditions, and/or where high current or bubble disturbance causes the compass to move on the line.

(3) Although a declination adjustment is not necessary (in our view), there does need to be some facility to allow for misalignments of the sensors and the edge of the compass housing, to allow for manufacturing variations. This can be achieved using the same logic as for the existing declination adjustments, but should not be included with the sensor calibration routines. This would allow the compass board to be calibrated, its accuracy/alignment relative to the case to be checked (using a high precision dry compass or known landmarks), and the alignment adjustment then entered.

(4) A simple logbook would be added, storing say the last one hundred or two hundred readings acquired in the "sample and hold" mode. There should be plenty of space in the EEPROM, which should have sufficient re-write capability. We would still advocate that the measurements be written down at the time in the cave, so that one is not relying on an electronic logbook, and so that they can be matched to depth and distance measurements correctly. However the electronic logbook would provide a means for checking for transcription errors.

(5) There is a potential problem which could result in inaccuracies in the calibration of the Z axis magnetic sensor offset. As things stand, the calibration routine runs while the compass is initially horizontal and is then inverted by the user. If during the inversion the Z sensor passes closer to the magnetic field direction, this may result in a spurious minimum or maximum value being recorded and being used as the basis for calibration, affecting the accuracy of tilt compensation. This can be avoided with a change to the calibration routine, using the LED for signalling when the user is to invert the compass, and requiring the user to operate the enter switch after the compass the inversion has been completed (with a suitable delay before that part of the calibration commences to allow for the magnet to be moved out of range).

(6) At present the compass has menu options to display temperature (which is not relevant to this application and will be inaccurate), and it also outputs azimuth and tilt data via its USB port. The code for these can therefore be eliminated, creating more space for the other changes.

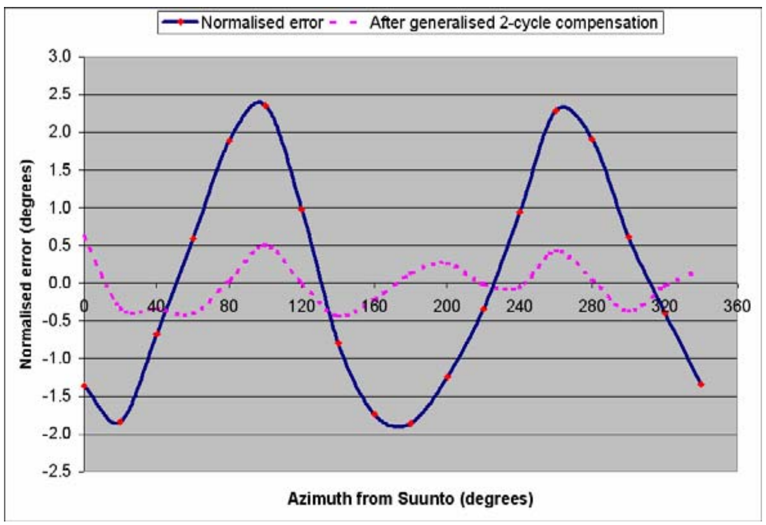
† *$Wt = C.W_{t-1}+(1-C).A$, where W_t is the weighted average at time t, A is the latest azimuth reading, and C is a constant between 0 and 1*

SECTION 6 - ACCURACY

Measured Performance

The prototype works correctly and is a pleasure to use underwater. With the software patch, the tilt compensation works correctly and results in no more than about 1 degree error for 30 degrees or more of tilt. Repeatability (short term) appears to be 10 minutes or better. A comparison was made with a Suunto KB14/360 over 18 points spaced at 20 degree intervals on a near level surface. The results from this were normalised to give zero average error to allow for misalignment of the board/sensors and the case (which would be achieved via the offset facility described under "Software - Additional Facilities"), and the results were as follows:

Azimuth Error (DULCE-Suunto) Normalised to Zero Mean
(dashed line shows residual error after eliminating two-cycle error)



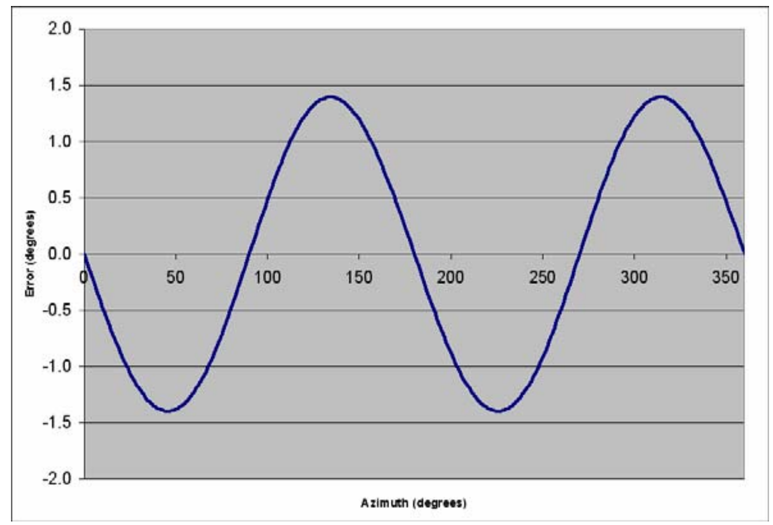
	Error in normalised azimuth (degrees)	Residual after eliminating 2-cycle error (degrees)
Minimum	-1.89	-0.44
Mean	0.0	0.00
Maximum	2.32	0.62
Mean absolute	1.25	0.25
RMS	1.41	0.31

We did not measure long term repeatability, sensitivity to supply voltage or temperature, or calibration repeatability.

Discussion

The principal source of error seems to be a two-cycle error, which might be introduced by an uncompensated soft iron distortion[‡], a difference in effective sensor gains, sensor misalignments and certain other things. For example, the sensor gain matching in the HMC1052 package is only specified to be within 5%, and the graph below shows the consequence of a 5% mismatch. Other sources of error could have a similar 2-cycle effect.

Azimuth Error from 5% Effective Sensor Gain Error



The software in the reference design does not fit a general ellipse and cannot compensate for sensor gain mismatch and certain other errors. It would be a straightforward matter to remedy this, and the results of our testing indicate that an *upper limit* on the resulting accuracy would be about 0.3 degree RMS error. There may be other small improvements that can be made, from a careful review of the scaled integer arithmetic and an improvement in the arctangent approximation formula (this is currently a second order polynomial and contributes about 0.1 degree RMS error, with a 0.4 degree step at 0/90 degrees; a third order polynomial would reduce the RMS error to 0.04 degree and eliminate the discontinuity).

[‡] From this test w*e cannot eliminate the possibility that there is a soft iron distortion in the Suunto which would cause the observed errors - for example the cell and wiring for the light- but other tests suggest the error is in the prototype*

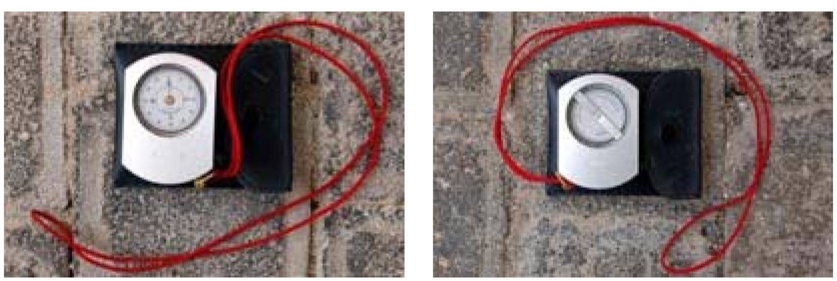
Considerations

In discussing accuracy, we need to distinguish between *instrument resolution*, *instrument accuracy* (which may be less), and the *overall accuracy of the measurement* made using the instrument in situ (which may be the limiting factor). Our efforts with the digital line compass have largely been focussed at increasing usability and thereby improving the accuracy of the *measurement*, rather than focussing exclusively on instrument accuracy, which is not the limiting factor at present.

Benchmarks

(1) In (routine) dry cave survey, the standard is a Suunto (or similar) compass. Some claim to be able to read this to 0.5 degrees resolution (we can read it to 0.25 degree resolution on the test bench, but not in a cave). It must be held horizontal but is not always being sighted horizontally, so some sighting error is introduced, perhaps reducing the accuracy of the measurement to one degree or worse. A clinometer with similar accuracy is used to measure inclination between stations.

(2) In underwater survey, the simple compasses normally used could be read to at best one degree resolution, and are in principle capable of good instrument accuracies, although the cheaper ones may not achieve this. A Suunto M3 tested showed a surprising 4 degrees error relative to a Suunto KB14/360, so as a minimum these simple instruments need to be calibrated against a more accurate compass. The overall measurement accuracy in an underwater cave is generally limited by the ability to align the compass with the guideline, and most surveys we have seen do not attempt anything better than a two degree azimuth resolution.



Suunto compass and clinometer used for dry cave survey

Discussion

For cave survey purposes, the most useful measure of accuracy is probably the mean absolute or RMS errors, which appear to be 1.25 degrees and 1.4 degrees for the prototype when calibrated for zero mean deviation against a benchmark compass. The effectiveness of the tilt compensation, the high repeatability, and the smoothness of the error curve indicate that it should be possible to improve on the accuracy of the prototype with a better calibration algorithm, and our analysis suggests that the *upper limit* with a generalised ellipse fit would be about 0.25 degree mean absolute error, 0.3 degrees RMS error, and 0.5 degrees maximum absolute error.

The first Honeywell/Michael J. Caruso paper referred to in Annex C suggests that it should be feasible to achieve one degree accuracy, and this seems entirely plausible given our results. Some commercial products claim 0.5 degree accuracy, but we suspect these use more sophisticated calibration procedures (curve fitting in one form or another), and we do not know whether there is some in-factory pre-calibration for sensor non-linearity.

With the current accuracy, the prototype should outperform the compasses normally used underwater in terms of instrument accuracy and especially measurement accuracy, and there should be far fewer blunders.

For dry cave surveys, the prototype probably does not compete with the standard for *instrument* accuracy. However, fitted with a laser pointer rather than the line hangers, the prototype would be easier to use than a Suunto, and it already incorporates the hardware and software for a clinometer with about one degree accuracy. With some improvements to the calibration algorithm it should be competitive in terms of overall measurement accuracy, and an attractive option when ease of use and other factors are taken into account.

Limiting factors on the accuracy are magnetic sensor linearity, tilt sensor accuracy, and calibration algorithm. Recently, very accurate tilt sensors have been developed, for example as used in the Smart Tool. Hence one can envisage development of a device which offers a quality digital compass and digital clinometer, and which is suitable for dry cave use with a laser pointer, or underwater use with line hangers. It may be more commercial to manufacture such a device than just a dedicated underwater compass.

SECTION 7 - CONCLUSIONS

Principal Features

The principal features of the prototype are:

(1) The hanger system for aligning the compass with the guideline

(2) Digital azimuth display

(3) Electronic tilt compensation, accomplished with three Honeywell magnetic sensors and a MEMSIC dual axis tilt sensor

(4) Use of a microcontroller with an integrated high-precision, high-accuracy, low signal level analogue to digital converter, avoiding the need for additional components.

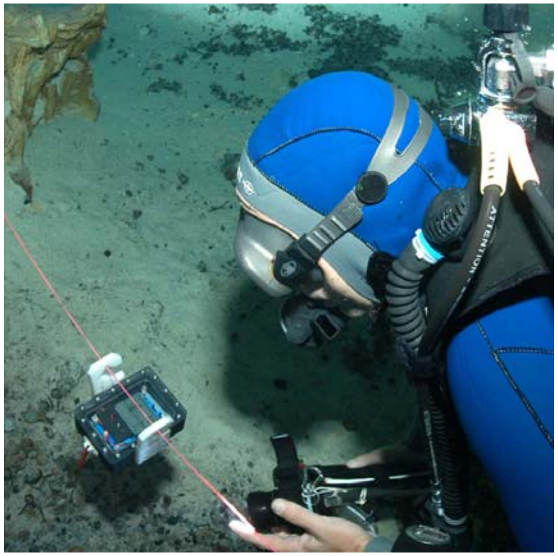
Items (2) to (4) were achieved using the Silicon Laboratories C8051F350 compass reference design PCB, with some simple hardware and software modifications. Further planned software modifications include the addition of a "sample and hold" mode for acquiring and freezing azimuth readings, and an electronic logbook for storing readings acquired in this way.

Practical Aspects

The prototype can be fitted into the "bellows" pocket on a DUI drysuit, although it is a tight fit if the left pocket is used with mask, spool and spare light head. A production version of the compass, or perhaps one based on a different PCB design, could be smaller by replacing the Silicon Labs custom LCD display with a simple single line serially driven LCD display, and the USB port and driver chip could be dispensed with. A metal box would be more compact and avoid the need for a ballast weight.

Amateur Construction

Although this document is not intended as an instruction guide for amateur constructors, it does demonstrate that amateur construction using a commercial PCB is feasible provided that the housing is professionally made. The principal challenges are the housing construction, the switching, battery selection/charging, and the need to modify software to be compatible with the use of magnetic switches and to incorporate facilities which make the most of the compass hardware for underwater use.



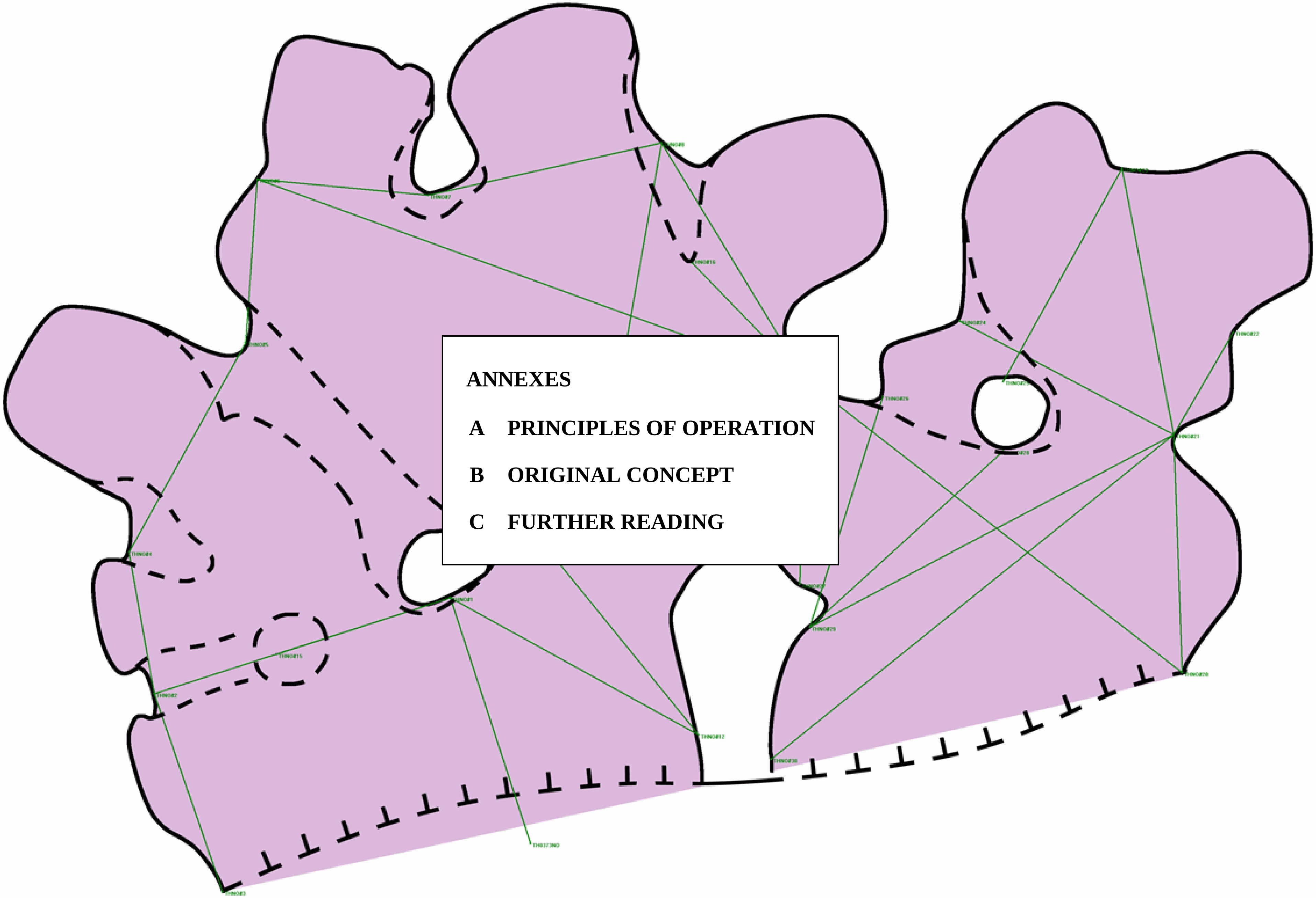
Commercial Manufacture

The only challenge to commercial manufacture would be the small market for underwater cave survey compasses. A product suitable for dry cave survey as well would find a much larger market, and there are advantages in dry cave equipment being robust and genuinely waterproof.

www.cave-exploration.com

Simon Richards
Quintana Roo, Mexico
Revised January 28, 2007

Helpful suggestions and advice on survey equipment and techniques in general, or on this project in particular, were provided by Jim Coke of the Quintana Roo Speleological Survey, Fred Devos, Patricia A. Beddows, PhD, of McMaster University, Canada and Bill Mixon at the Association for Mexican Cave Studies. Aude & Maurico Domenge kindly modelled for photos with the prototype. Donna Richards fed the monkey.



ANNEXES

A PRINCIPLES OF OPERATION

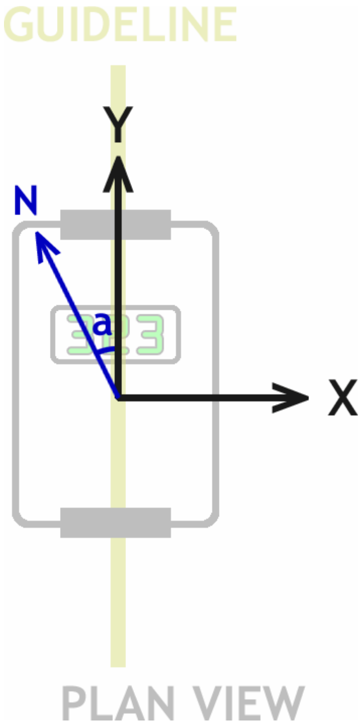
B ORIGINAL CONCEPT

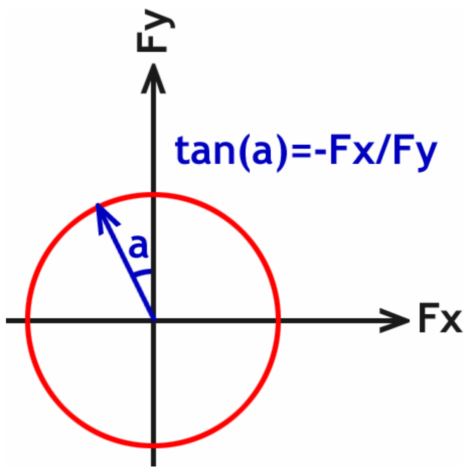
C FURTHER READING

ANNEX A - PRINCIPLES OF OPERATION

Principles of Operation

Two-sensor digital compasses have two magnetic sensors aligned horizontally and at right angles to each other, each sensor measuring the horizontal component of the magnetic field in the direction in which the sensor is pointing. In principle, rotating the compass in the earth's magnetic field will produce variations in the sensor measurements which represent a circle centred on the origin when plotted against each other. The compass azimuth can therefore be calculated from the arctangent of the ratio of the two sensor measurements.





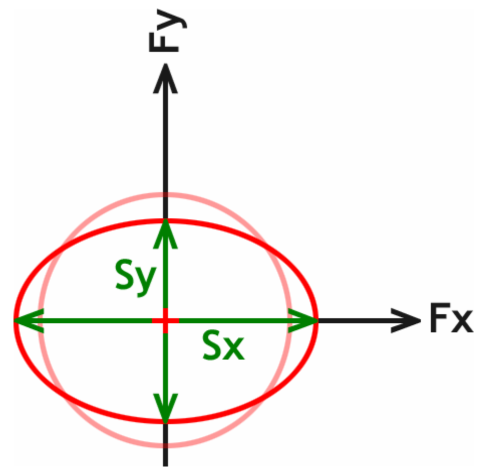
Measured magnetic field strength (Fx and Fy) versus compass azimuth

(Note that in the literature there is some variation in which directions are assigned to the X and Y axes, and so any formulas need to be checked for consistency and sign convention before being used.)

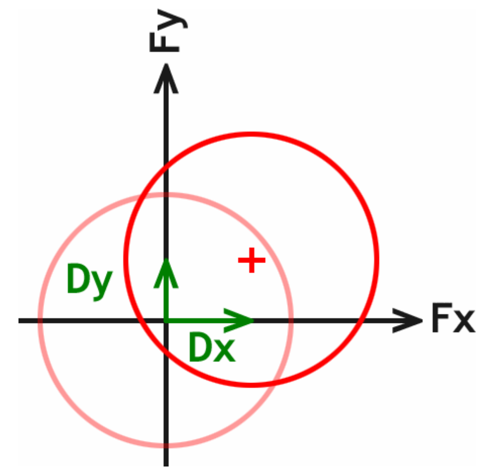
Real World Effects

In practice the sensor response will differ from this because of a number of effects, including offsets in the sensor zero points, variations in the relative sensitivities of the sensors, non-linearities in the sensor response curves, relative alignment errors in the sensors, the presence of random measurement errors (noise) and the presence of so-called "hard iron" and "soft iron" distortions in the magnetic field seen by the sensors. As a result, the plot of sensor measurements will deviate from a circle centred on the origin in distinct and identifiable ways.

Variations in the relative sensitivity of the sensors will distort the graph into an ellipse oriented along the X and Y axes. Offsets in the zero points of the sensors will move the centre of the graph horizontally and/or vertically relative to the zero points of the axes.



Effect of variations in relative sensitivity of X and Y sensors

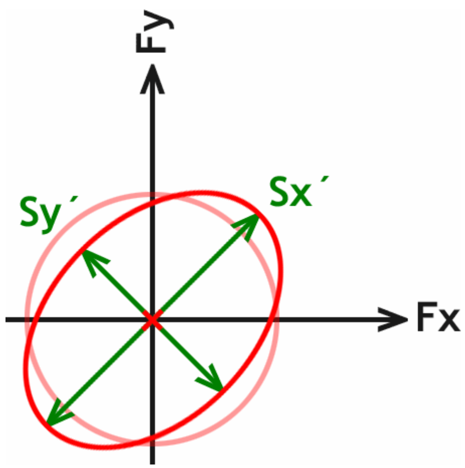


Effect of offset in sensor zero points or "hard iron" distortions

So called "hard iron" distortions arise from the presence of permanently magnetised material *in a fixed orientation relative to the magnetic sensors*. The effect of hard iron distortions is the same as the effect of sensor zero offsets, a shift in the centre of the circle.

Soft Iron Distortions

So called "soft iron" distortions arise from the presence of high magnetic permeability material *in a fixed orientation relative to the magnetic sensors*. The effect of soft iron distortions is to stretch the sensor response graph into an ellipse oriented at 45 degrees to the X and Y axes.



Effect of soft iron distortions

The effect of non-linearities in the sensor response curves will depend on the nature of the non-linearities. Some will manifest themselves similarly to the errors already discussed, and some differently. Misalignment of the sensors relative to each other will skew the response graph at an angle other than 45 degrees. The effect of sensor measurement noise can be reduced by simple statistical techniques such as appropriate averaging of readings, but may have a bigger impact on the calibration routines if they are overly simplistic.

All of these factors can be analysed and modelled, and then mitigated using more sophisticated calibration routines and mathematical techniques. The limiting factors are ultimately the available processing speed (which essentially equates to power) and memory, and the ease of calibration by the user. Analysis suggests that with cheap available technology, accuracy in the range of 0.5 to 1.0 degrees is achievable without using such techniques. This already represents a major improvement on the compasses currently used for underwater survey, and so these issues are not considered further in this note.

Compass Calibration

A mechanical compass can be constructed using non magnetic materials and will not be subject to these errors. However an electronic digital compass will inevitably incorporate "hard iron" (magnetised) and "soft iron" (high magnetic permeability) components in its construction, and may generate its own magnetic fields from currents flowing in the circuitry (equivalent in effect to "hard iron" distortions provided the currents are constant). Fortunately, because the effects of the major distortions are so distinct, they can be identified and largely compensated for by the use of appropriate calibration procedures and mathematical techniques.

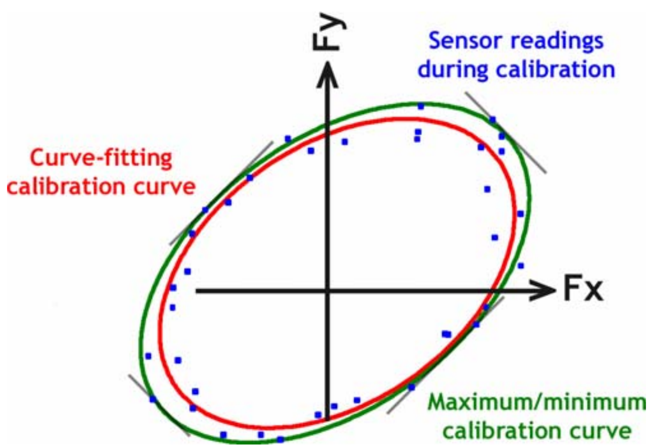
In essence, these procedures all involve the user rotating the compass during the calibration process. During the rotation the software in the compass makes a number of sensor readings, and then analyses how the resulting graph differs from a circle centred on the origin. The parameters for a sequence of mathematical operations are then computed to transform the graph into a circle centred on the origin, and these parameters are stored in the semi-permanent memory of the device. During use of the compass, the measurements from the sensors are then subjected to this same transformation before being used to calculate the azimuth.

In the absence of non-linearities or random errors (noise) in sensor readings, fairly simple procedures would in principle provide essentially perfect compensation against the errors described above. Even in the presence of non-linearities and noise, with typical sensor performance and modest mechanical design, effective compensation can be achieved to typically 0.5 to 1.0 degree accuracy.

Parameter Fitting Approaches

There are two main approaches to parameter determination for the transformations derived from the calibration process: simplistic "max/min" determinations, and more sophisticated curve-fitting techniques.

Max/min determinations simply look at the maximum X and Y sensor readings measured during the calibration process, and also the maximum and minimums of the readings rotated by 45 degrees. From these, the parameters for the fitted ellipse are estimated. The strength of this approach is its ease of implementation. Its weaknesses are that it has a higher susceptibility to sensor measurement noise (because no mathematical smoothing or averaging is applied to the critical measurements which set the maximum and minimum), and that it requires the compass to be rotated through its full 360 degree rotation range during the calibration process, which may not always be feasible.



Curve fitting approaches use mathematical techniques to estimate the parameters of an ellipse by optimising some goodness-of-fit measure, for example the well known least-squares method. The strengths of this approach are reduced susceptibility to sensor measurement noise (because of the averaging implicit in the curve-fitting) and no requirement that the compass be rotated through its full 360 degree range during calibration. This may be advantageous in some applications such a "bolt down" compass in a ship. If tilt compensation is being applied to such a compass (see below) then the calibration will require rotation of the compass *and ship* through a full 360 degrees in horizontal *and* vertical planes, which is not feasible. The disadvantages of such an approach is that it is more complicated to implement, and much more computationally intensive.

Continuous Calibration versus Calibration on Demand

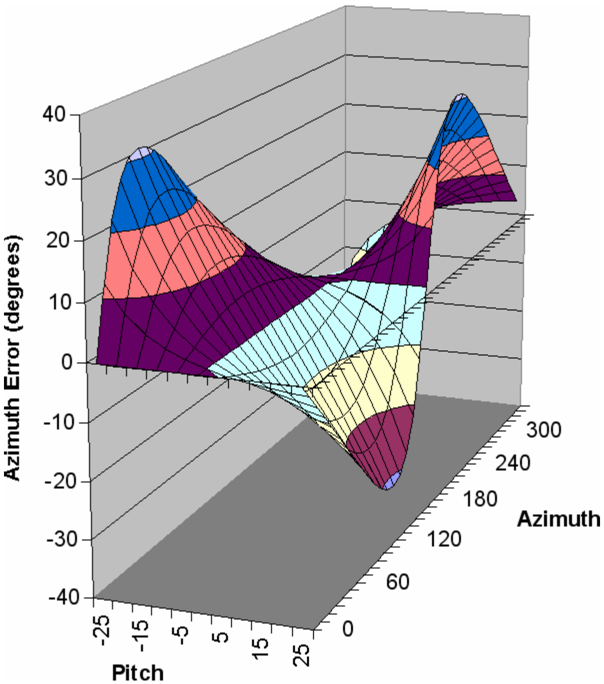
The calibration procedure above is described as a separate process performed by the user before using the compass for measurements. This is known as "calibration on demand". An alternative approach is "continuous calibration" - while the compass is being used, it continually updates its transformation parameters based on the sensor measurements being made.

These approaches have distinct applications for which they are suitable. Calibration on demand is suitable for a free-standing compass: it enables the use of the simplistic "minimum/maximum" algorithm, and it protects the compass from calibration errors resulting from temporary exposure to magnetic field distortions (for example, in the case of a cave diver, the magnetic field created by a dive light being held close to the compass). Continuous calibration is more suitable for bolt-down compasses on structures which cannot be rotated on demand, such as ships. However it will generally require that the more sophisticated curve-fitting approach to calibration be used, because there is no guarantee that the compass will be rotated through the full 360 degrees about all axes required for minimum/maximum parameter fitting.

In the context of our requirement for a compass for underwater cave survey, it therefore seems most appropriate to use a "calibrate on demand" approach, and the minimum/maximum parameter fitting seems to provide adequate accuracy within the processor, memory, and power limitations resulting from the size constraints for a usable device.

Tilt Errors

The largest potential source of error in a two-sensor compass arises from the compass being tilted from the horizontal. Tilting a sensor may reduce or increase the field seen by the sensor depending on whether it increases or reduces the angle between the sensor and the direction of the magnetic field. In general this will change both the X and Y sensor readings for a given compass azimuth, and therefore will affect the computed azimuth quite severely (as a rule of thumb, we can say one or two degrees of azimuth error per degree tilt).

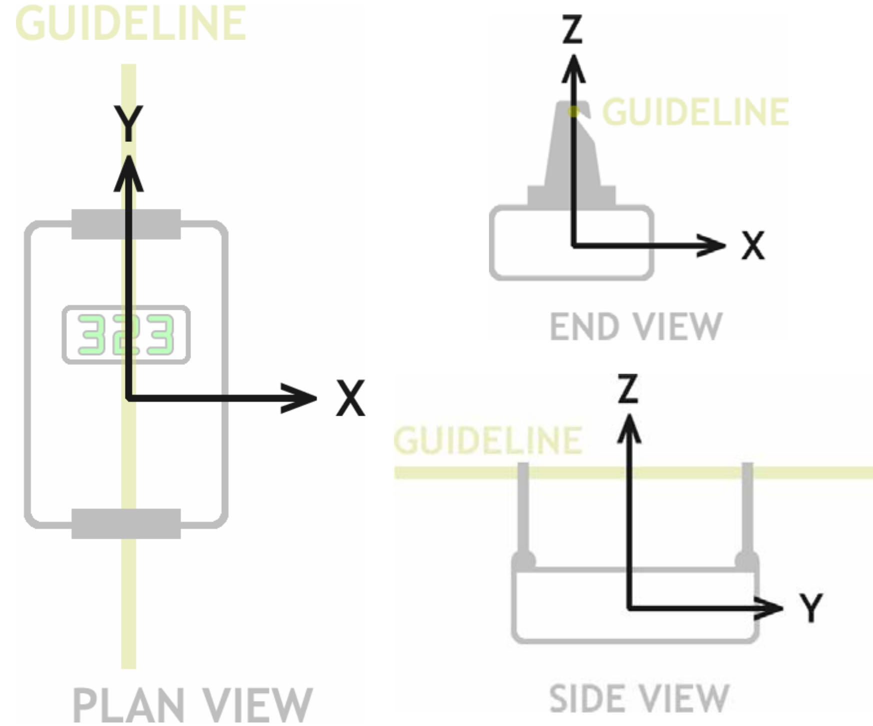


Tilt error versus azimuth assuming 48 degree field inclination

The inclination of the earth's magnetic field varies with geographic location and the effect varies with the orientation of the sensors relative to north, and hence the tilt error will vary with both geographic location and compass azimuth. (Note that it is a commonly held belief that it is the vertical component of the earth's field which causes a two-sensor compass to be sensitive to tilt; in fact even with a horizontal magnetic field this would be the case).

Tilt Compensation

Tilt-compensated digital compasses generally have three magnetic sensors and two inclination (tilt) sensors.

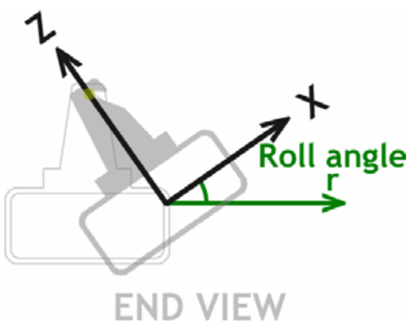


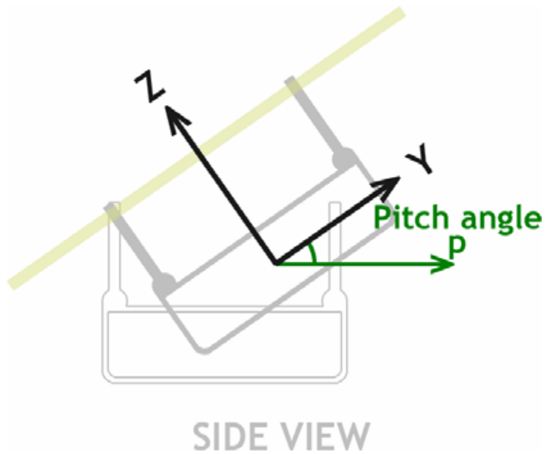
Arrangement of X, Y and Z magnetic sensors for atilt compensated compass

The third magnetic sensor (Z) measures the component of the field perpendicular to the X and Y directions (i.e. up or down relative to the compass plane), and the tilt sensors measure the angles of the X and Y magnetic sensors from the level, which we call the "pitch" and "roll" respectively.

Field Projection

The compass measures the three components of the magnetic field relative to the compass orientation using the X, Y and Z sensors, and the compass plane pitch and roll using the tilt sensors. Using the information about the compass orientation relative to the horizontal and some standard trigonometry, the compass then calculates in software *what the X and Y sensors would read if the compass were horizontal*, and then the azimuth based on this.





Formulas for tilt compensation are contained in the literature produced by Honeywell and others. In use, care should be taken in the sign convention and the designation of pitch and roll. Some of these formulas may only be approximate and may not compensate properly for combined pitch and roll at the same time. However, in the underwater line compass application, roll will generally be close to zero because of the pivoting around the line hangers, and so they are satisfactory.

Tilt Compensation versus Gimballing

In simple rule of thumb terms, the pre-compensation azimuth error from tilting will be about one or two times the combined roll and pitch, and hence the amount of compensation required will equal one or two times the combined roll and pitch. Hence the accuracy of a tilt compensated compass will generally be about 0.5 to 1.0 times the accuracy of the tilt sensors, plus whatever errors arise from the magnetic sensors.

Given good enough sensors, tilt compensation can work to any degree of accuracy. Gimballing cannot achieve this in the presence of hard or soft iron distortions which are not located on the gimballed compass mechanism, because the gimballing process will move those sources of distortion relative to the compass sensors, and no calibration routine can allow for this.

Hence in applications where the pitch or roll may vary significantly and there are relative movements in hard and soft iron distortions as a result, the accuracy of gimballed compasses is limited. For optimum performance, therefore, a free standing compass should have the entire compass mechanism gimballed, not just the sensors.

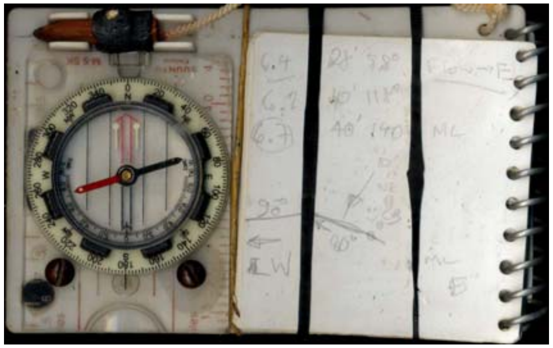
Calibration for three sensor compasses is more complex - as a minimum the offset for the Z sensor should be determined, because this will be affected by hard iron distortions. Additionally more complex calibration procedures may allow for Z sensor sensitivity and soft iron distortions to be calibrated.

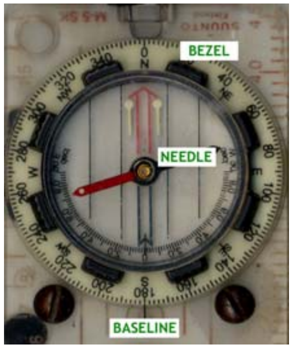
ANNEX B - ORIGINAL CONCEPT FOR A DIGITAL UNDERWATER LINE COMPASS

Introduction

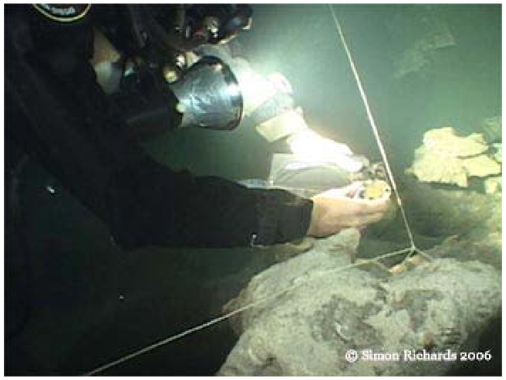
A cave survey consists of a number of "stations" - points where the guideline is tied to protrusions such as stalagmites or large rocks, connected by "shots". At each station, the depth is measured using the diver's digital depth gauge, along with other features of the passage and ideally its width and height. For each "shot" between stations, the diver measures the distance by counting knots tied into the line every 10 feet, and the azimuth, using a compass.

The traditional method for measuring azimuths and recording survey data is the "survey slate". This contains a compass and some sheets of waterproof material for recording survey data. In use, the edge of the slate is aligned with the guideline by eye, and the bezel of the compass is adjusted so that the north marking on the bezel lines up with the needle. The azimuth is then read from the bezel against the baseline. The azimuth and other data are then recorded on the relevant row of the writing material.



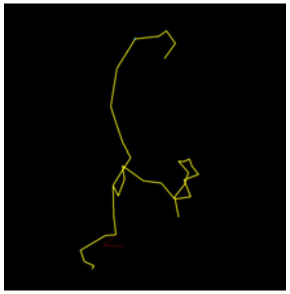


One weakness of using a survey slate is that data must be erased before the next survey (which may be the next day during a multi-day project), so the original survey is not retained for reference in case of subsequent transcription errors. To address this, we first adopted the procedure of scanning slates after each dive, and then of using a separate hand-held compass and dedicated underwater survey notebook (see Annex B). Unfortunately this requires more hands than most divers have.



Use of separate compass and notebook

The biggest errors we see in cave surveys are azimuth "blunders" - simple misreading or misrecordings of azimuth measurements. The diagrams below show a typical situation where these errors are very obvious, a closed loop. The surveyed line runs back over itself in several places as a result of azimuth blunders. In this case, some obvious corrections have been made (e.g. where the compass was just read backwards), and some "black magic" has been applied. The remaining closure errors are then spread through the loop by a "forced closure". Unfortunately, the finished result bears very little resemblance to what was recorded in the cave.



Original survey

Some "corrections" applied

Forced closure by mapping software

The Freiberger Mining Compass

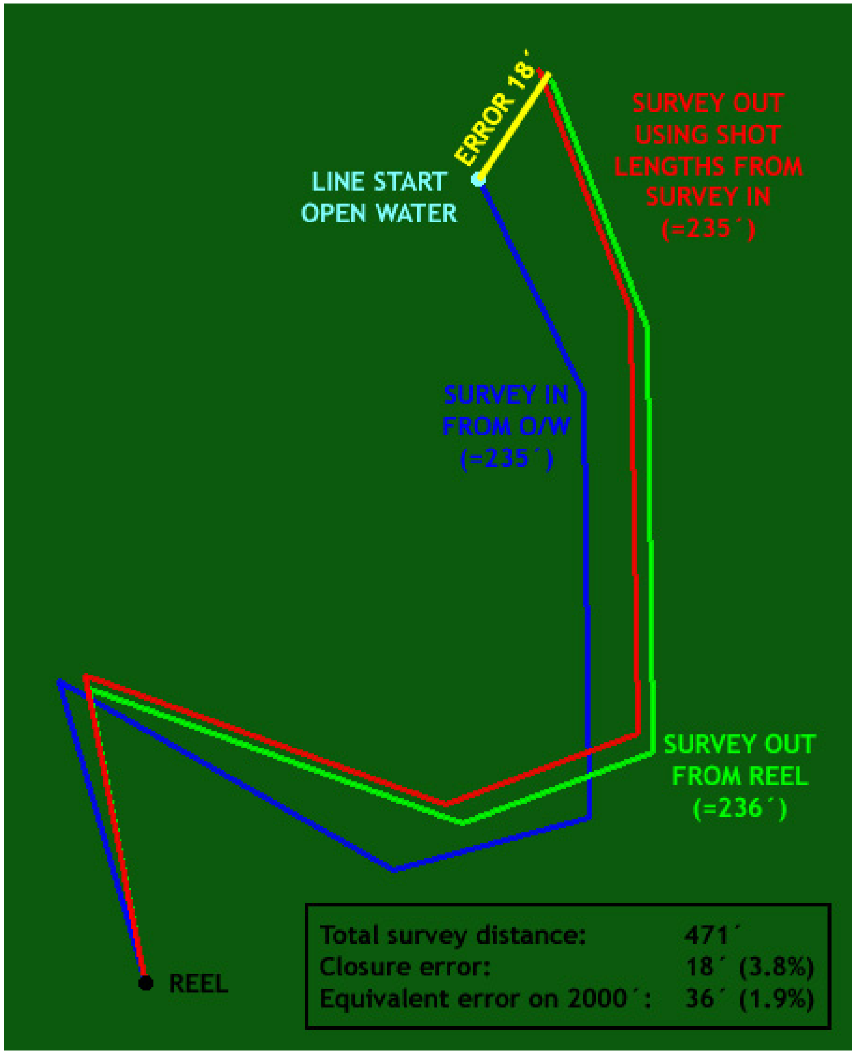
Mining engineers use the Freiberger mining compass for accurate surveys of mines. It simply hangs on a guideline and the azimuth is read directly from its large scale. The system of pivots/gimbals is necessary to keep the compass horizontal.

Freiberger mining compass, photo courtesy [Clausen Instrument Company, Inc]

Using the Freiberger approach, we constructed a simple digital line compass for testing in underwater caves, using some rather crude hardware and a commercial digital underwater compass.

Prototype digital line compass

Although the device is crude and the commercial compass we used has a resolution of only 5 degrees, the results from the trials suggest that almost *any* surveyor using this compass can conduct a survey close in accuracy to a good surveyor using traditional compasses or slates. There were no azimuth "blunders" on any trial surveys.



Results of test of prototype digital line compass- no large errors, but accuracy limited by 5 degree resolution of compass module used

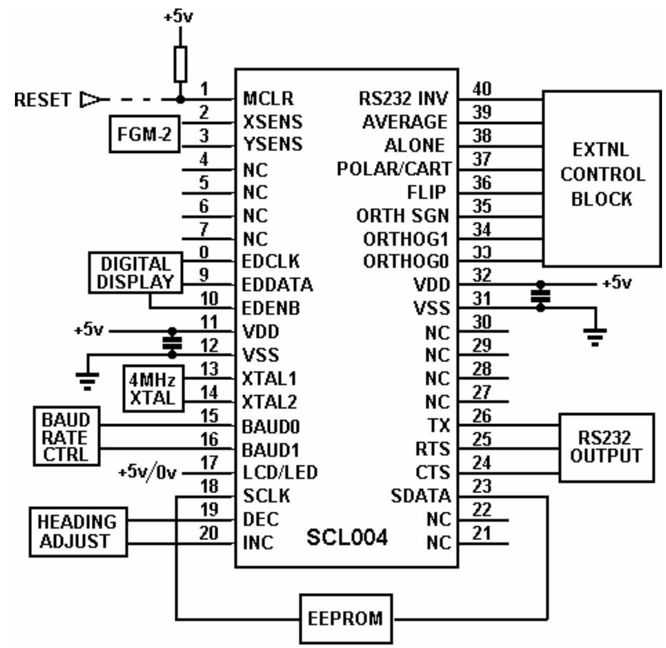
Outline for a Digital Underwater Line Compass

It therefore seems that making a proper digital line compass available to explorers and surveyors is the single action that will provide the largest increase in the quality of survey data. Unfortunately, no accurate underwater digital compasses are available (even the one we used for our trials is no longer in production).

The electronic "chip sets" to make accurate digital compasses are available from manufacturers such as Speake & Co in the UK and others at relatively modest cost. Using these components, the electronic design is not challenging. The only addition to the standard circuitry would be additional provisions to turn the compass on and off using a dive light or magnet/magnetic switch, and to switch it into calibration mode. Accuracy should be 1 degree, far in excess of what is actually achieved with any other underwater compass, and close to what is achieved with the standard high quality dry cave surveying compasses. Performance considerations are the physical size of the sensor and circuitry, and the relatively high power consumption, which requires rechargeable batteries. Unfortunately the physical principles on which these devices work dictate a minimum size and power consumption for accurate operation - however it will be worth researching alternative sensors and chipsets prior to committing to the electronic design.

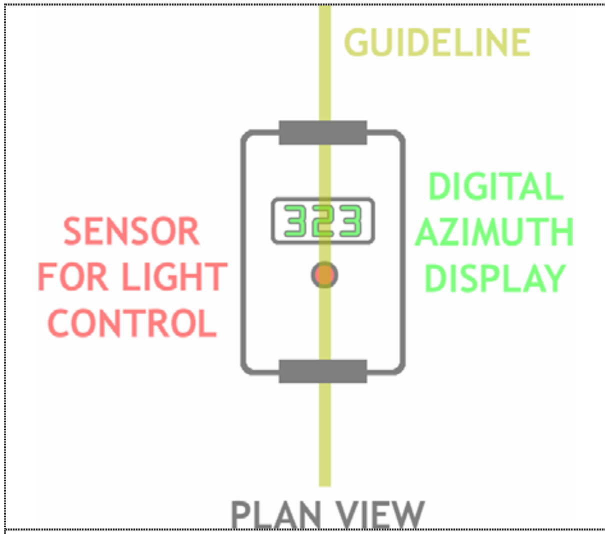
The construction of the pivot mechanisms and the housing are likely to be more expensive, depending on construction materials and depth rating. As a minimum a 40 metre depth rating would be required, although we would ideally have a 100-120 metre depth rating. From a reliability and longevity standpoint, a machined aluminium housing would be most desirable, but would be expensive. It should be noted that many "amateur" and even small-scale commercial housings experience poor reliability because of some subtle design issues.

Speake & Co FGM-2 dual magnetic field sensor



Basic digital compass using Speake & Co SCL004 self-calibrating compass integrated circuit with FGM-2 (Photo and diagram courtesy Speake & Co)

OUTLINE DESIGN



For correct operation, the magnetic field sensor must always be held horizontally. This is achieved by (1) having an external "hook" mechanism to allow the compass to level itself across the direction of the line, and (2) placing the field sensor on a pivot inside the compass housing to allow back to front levelling. The hooks should have a detent mechanism to hold them either fully extended when in use, or flat against the compass face when not in use. In the water, operation is by shining a light at the light sensor, to turn the compass unit on for a preset time (e.g. 1 to 5 minutes). Out of the water, the compass may be calibrated by shining a light beam from a simple "remote control" onto the sensor (the unit is then simply rotated slowly several times while being held level when in calibration mode).

Principal component	**Function**
Line hooks	Enable entire device to swing perpendicular to line. Fold flat when not in use. Should have detent arrangement to hold in horizontal and vertical positions.
Magnetic field sensor - Speake & Co FGM-2	Mounted internally in compass unit on pivot to allow swing along direction of line. Between this and the line hooks, FGM-2 will always be horizontal.
Compass chip - Speake & Co SCL004A	Complete logic to turn sensor reading into compass azimuth in serial BCD format ("A" variant is calibrate-on-demand).
Digital display - Three-Five systems TSM6755 or Lascar Electronics DDM4	Display azimuth reading from serial BCD signal from SCL004A.
EEPROM - 24LC01B	Stores calibration data
Light sensor	Underwater, compass turned on for preset time (e.g. 1-5 minutes) when illuminated. On surface, illuminated by simple remote control device (modulated light signal) to enter calibration mode
Batteries	?6 AAA cells giving 7.2V for regulation to 5V.

ANNEX C - FURTHER READING

Title	Author	Link	Comment
Applications of Magnetic Sensors for Low Cost Compass Systems	Michael J. Caruso, Honeywell SSEC	www.ssec.honeywell.com/magnetic/datasheets/lowcost.pdf	Operating principles for tilt-compensated compasses
HMC1055 3-Axis Compass Sensor Set	Honeywell Sensor Products	www.ssec.honeywell.com/magnetic/datasheets/hmc1055.pdf	"Advance information" on HMC1051Z single axis sensor, HMC 1052 dual-axis sensor and MEMSIC MXS3334UL dual axis accelerometer
Application note #AN-00MX-001 - Accelerometer fundamentals	MEMSIC, Inc	www.memsic.com/memsic/pdfs/an-00mx-001.pdf	Operation of tilt sensors
AN996 - Designing a Digital Compass Using the PIC18F2520	Chris Valenti, Microchip Technology Inc	ww1.microchip.com/downloads/en/AppNotes/00996a.pdf ww1.microchip.com/downloads/en/AppNotes/COMPASS_071505.zip	Link to applications note and source code
C8051F350 50 MIPS, 8 kB Flas 24-bit ADC, 32-Pin Mixed Signal MCU	Silicon Laboratories, Inc	www2.silabs.com/public/documents/tpub_doc/dshort/Microcontrollers/Precision_Mixed-Signal/en/C8051F350_Short.pdf	Data "short"
Digital Compass Reference Design Kit User's Guide	Silicon Laboratories, Inc	www.silabs.com/public/documents/tpub_doc/evbdsheet/Microcontrollers/Precision_Mixed-Signal/en/DIGITAL-COMPASS-RD.pdf	-
C8051F350DK Development Kit	Silicon Laboratories, Inc	www.silabs.com/tgwWebApp/public/web_content/products/Microcontrollers/Precision_Mixed-Signal/en/C8051F350DK.htm	-
FGM-series Magnetic Field Sensors	Speake & Co Llanfapley	www.speakesensors.com/PDF/detail.pdf	Overview of FGM series fluxgate sensors
SCL004 Integrated Circuit - Self Calibrating Compass	Speake & Co Llanfapley	www.speakesensors.com/PDF/scl0041.pdf	Use of SCL004 to build 1 degree accuracy self-calibrating compass
Autocalibration algorithms for FGM type sensors	Speake & Co Llanfapley	www.fatquarterssoftware.com/downloads/AUTOCAL.pdf	Autocalibration algorithms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