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Issue 37

Compass Points

March 2007

BCRA

Calibrating an electronic compass/clinometer

An electronic compass for cave divers

Web-based survey viewer

The Journal of the BCRA Cave Surveying Group

COMPASS POINTS INFORMATION

Compass Points is published three times yearly in March, July and November. The Cave Surveying Group is a Special Interest Group of the British Cave Research Association. Information sheets about the CSG are available by post or by e-mail. Please send an SAE or Post Office International Reply Coupon.

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courtesy of Doug Dotson, Speleotechnologies.

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The journal of the BCRA Cave Surveying Group

Cover image: The "Shetland Attack Pony" combined electronic compass/clinometer unit, designed by Phil Underwood.

Editorial

Welcome to what has turned out to be something of an "electronic instruments special edition" of Compass Points. Much of the material concerns aspects of various projects to build electronic compasses and clinometers that are accurate enough to replace existing instruments and robust enough to survive in cave environments. It is encouraging to see that progress continues to be made – it seems that the day when we no-longer need to squint through misted-up sighting instruments whilst half immersed in muddy water draws ever closer.

Forthcoming Events

Field meet

The CSG Spring field meet has been timed to coincide with the BCRA Cave Technology Symposium on the weekend 14-15 April 2007. The current plan is to hold presentations on Saturday covering electronic instruments and computer drawing. Sunday will be set aside for practical work, particularly practice with electronic instruments and comparison with conventional instruments. It is possible to arrange training in general surveying or computer drawing if there is sufficient demand – please contact the meet organiser in good time if you are interested. Accommodation will be arranged at the Orpheus Caving Club headquarters. If you would like to attend or need further information, please contact Allan Richardson (`csg-meetings@bcra.org.uk`).

BCRA Cave Technology Symposium

David Gibson

Members of BCRA's Cave Surveying Group and Cave Radio and Electronics Group are joining forces to organise a one-day "classroom" symposium to be held on Saturday 14 April 2007 near Ashbourne in Derbyshire starting at 08:30. The idea is to provide a forum for discussion of cave technology topics, with a particular emphasis on cave surveying, computing and electronics. It is hoped that papers based on the lectures will be available for publication by BCRA or one of its SIGs. Offers of presentations (with varying degrees of commitment) have so far been made as follows. In some cases (marked *) the author may not be able to be present his work in person, but someone will give a report on his behalf.

- Rapid and Solo Surveys of Short Caves – Trevor Faulker
- Data Management of Large Cave Surveying Projects – Wookey
- Digital Compass & Clino – Two project reports from Phil Underwood* and Mike McCombe*
- Cave Hydrology: Reviving the BCRA Special Interest Group – Keith Plumb
- A Data-logger for Monitoring CO2 in Caves – Les Williams
- Digital Photography – What the Books do Not Tell You – David Gibson
- Extending the Scope of a Flashgun Slave Unit – David Gibson
- Digital SSB Generator for a New Digital Cave Radio – Graham Naylor*
- Battery Technology in New Equipment Design – David Gibson
- Extending the Range of Your Mobile Phone – Rob Gill
- Electro-Fracture: Using Electrical Discharges to Fracture Rock – David Gibson

We will be showing the winning entry from the BCRA Video Media Salon at Hidden Earth 2006 – "Fourpence a Day" by John Robinson, and the HE 2006 Closing Film, "Voyage" by Martin Baines. John Robinson's AV used the PicturesToExe software, and it would be good to find a volunteer to talk about this software!

The deadline for submission of abstracts was 1 March 2007. However, if you wish to contribute, it may be possible to accommodate late submissions by arrangement with the lecture secretary, David Gibson (`d.gibson@bcra.org.uk`) – though only up until the end of March at the absolute latest. The latest details, including directions to the venue, can be found on the BCRA website at `http://bcra.org.uk/detail/tech2007.html`

Snippets

Electronic compass/clino update

Mike McCombe

This note describes the latest developments in my project to build an electronic compass/clinometer, previously discussed in issues 34 and 35 of Compass Points. At a high level, it seems that what I've done is similar to others but I suspect there are significant differences in the detail.

This has been very much a "home construction" project - Veroboard construction and a DVM as the only test equipment. I'm reasonably proud of the software and DSP, but less confident of the analogue circuitry as without an oscilloscope I just can't see whether it's good or bad. On the assumption that the magnetic sensor amps are a bit noisy, I've tried to turn this into an advantage by using averaging to to improve signal:noise and at the same time enhance the digital resolution. It may seem counter-intuitive, but a little analogue Gaussian noise can be helpful because it allows you to filter out the quantisation noise.

Another thing that I've done that others may not have has been to start averaging the H_x, H_y and H_z magnetic sensor values once the accelerometers in the clino determine that the instrument is stable. The final bearing calculation is then done once using the average of a batch of samples (64?) and the display illuminated and frozen so that you can move the instrument to copy the measurements into the survey book. The only problem experienced with this has been when the surveyor can't hold the instrument still enough - but then is a poor reading better than no reading at all?

A feature awaiting development is to flag the effects of stray magnetic fields by checking the overall magnitude of the H vector. Having experienced the effects of the steel railings whilst surveying in the showcave at Dan Yr Ogof, I can see circumstances where this would be useful in identifying errors in the field, rather than afterwards when the loops won't close properly.

I spent a very long time trying to work out how to calibrate the compass (the clino was easy). The main issue is that each of the three H channels have unknown gains and offsets, plus the absolute orientation of the sensor is unknown. Others had talked of having their instrument self-calibrate by taking samples with the compass in different (random?) orientations and then solving the simultaneous equations to establish the unknown coefficients. I was never particularly happy with this idea as the inevitable small errors in the original observation set produce unpredictably large errors in the coefficients and, in turn, bigger errors in the resulting bearings. My proposal to overcome this was to try taking as many samples as possible of the observed H field values with the instrument in many different orientations and then to use a least-squares algorithm to "best-fit" an ellipsoid to the samples. As I'd already included a serial port in the instrument to help debug the software, it was easy to get it to stream the H values to a PC and do the calibration number-crunching there, rather than have to write the whole thing in MicroPIC assembler.

After many months of struggling with the algebra and, literally, thousands of samples I seemed to be getting nowhere. I then hit upon a much more obvious and straightforward approach:

- Stream the 3 H sensor outputs to a big display on the PC.
- Adjust the orientation of the instrument to maximise one of the sensor values and write it down.
- Turn the instrument around and tweak orientation to get the minimum sensor output. Write this down.
- Simple addition and subtraction gives the gain and offset values for this channel.
- Repeat for the other two channels.

This led, at last, to reasonably convincing results. Calibrating the angular offset between the laser pointer and the sensor axes had to be done by direct comparison with a conventional compass. If my Suunto is 10 degrees out, so is my digital instrument. Other errors, such as the three sensors not being truly orthogonal, were ignored on the basis that they are small and would only have the effect of introducing a small octantal error in the result.

Used underground, the instrument seems to work OK but I haven't done much closed-loop work to assess the accuracy. I really need to find the time to do this so that I can use it with confidence as it's certainly a lot quicker than squinting at a Suunto with steamed-up glasses!

A web-based survey viewer

Martin Green

The internet is producing an ever increasing number of interactive on-line maps, with custom images and points of interest. This has included several caving clubs such as the Bristol Exploration Club and the Bracknell District Caving Club. I have put together a little website for displaying caves using Googles javascript map viewer, although I intend to also produce a WMS map server, such that openlayers can also be used as a viewer. The main aim of this project is to allow clubs with hand-drawn surveys, to be easily displayed onthe web, rather than continuing to hide away in draws, attics and basements.

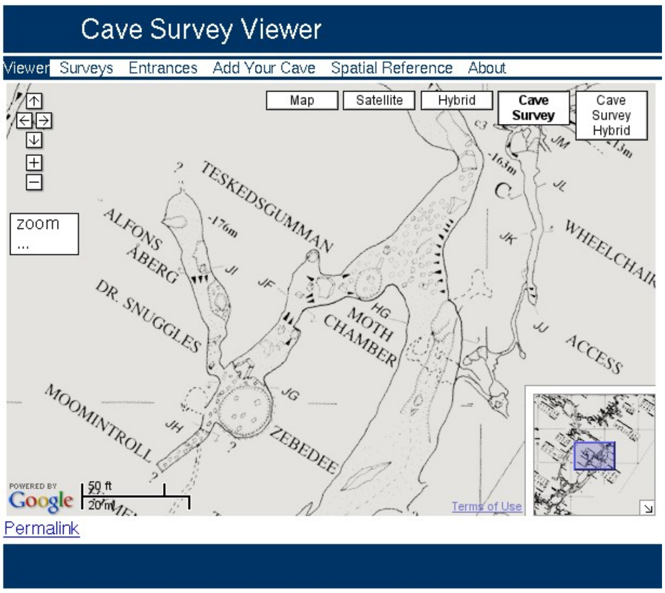
The website is currently located at:

`http://seagrass.goatchurch.org.uk/~mjg/cgi-bin/map.py`

At present, it contains surveys from only two areas: the Loser Plateau in Austria, and Houping in China (see example below). If anyone has any surveys, that they would like displayed on the website, please let me know.

The site has not been in development for long, so much of it does not work and is still up in the air. However, there is little point in finalising all the details if people are not going to like the results and thus not use it. Ultimately I envisage a web interface for specifying the locations of points of interest and the locations, orientations and scaling of user surveys. So far there is the ability to specify Transverse Mercator grids of a ellipsoidal datum, or alternatively specifying latitude and longitude. Once these spatial references are specified there is functionality to allow coordinate transformations. Currently maps can be uploaded to the site, but I would still need to manually orientated them.

Significant progress has been made in terms of the tile cutting, which is the process of making small images, for the viewer to load and display from the large uploaded surveys. Displaying cave surveys nicely, at low resolutions, is a problem that was hard to solve. They either become pixelated, or become very faint due to aliasing. This was solved by downscaling the original bitmap, taking the maximum pixel value to all the prescaled pixels to make the zoomed out pixel. This obviously produces a very blocky image, but after suitable rotation and zooming out by a further factor of four using antialiasing, the result seems pretty good.



Example of part of a survey from Austria shown in viewer.

Rotating and scaling images to the tile is a rather costly operation, whilst merging tiles together is relatively cheap. Thus each tile is made individually for each cave, giving the flexibility to easily add and remove cave surveys. The making of the tiles is performed lazily, hence the slowness, that can be observed if you are the first person to look at a particular bit of cave at a particular zoom level.

If the site is to be successful it needs to be fairly easy to contribute data, otherwise people will be discouraged. One possibility is to solely use information published in wikipedia/wikicommons/wikisource, which avoids some licensing pitfalls. This could be done without loading the wikiprojects servers too much by only downloading files when necessary. However that may not work too well for clubs that have large repositories of data who may want to use a script to transfer across data. Other people may want to simply upload material directly to the website itself.

I would welcome ideas on any of these issues, offers of any surveys to be put up or volunteers to do some coding on this site. Finally I would like to thank Julian Todd for hosting the site free of charge.

Surveying software updates

A new version of **Compass** [1] was released on 10th March 2007, and includes several new features. The software will now calculate the travel distance through the cave from the entrance to each survey station. This information may be shown next to each station, or used to colour code the survey by travel distance, thus giving an indication of the relative difficulty of reaching different parts of the cave. Information about each survey shot, such as length, azimuth and inclination, can now be displayed next to the legs. The viewer also has a “fit cave to screen” facility which will automatically scale the cave to the current window size – a useful option if you have just resized the viewer window. On the data entry side, there is a new “Block Modify” option which allows the user to make changes to large numbers of survey shots or surveys simultaneously, for example correcting errors in cave names, adding a prefix or postfix to station names, or setting and clearing shot flags.

Caving drawing packages have also seen some recent updates. The latest version of **Therion** [2], 0.5.0, was released on 2nd February 2007 and includes several new features in addition to minor enhancements and bug fixes. These include: support for geodetic co-ordinate systems including transformations between; a geomagnetic model that allows automatic calculation of magnetic declination based on date and location; export of maps in ESRI shapefiles or Google Earth KML format; and morphing of original survey sketches. **Tunnel** [3] now has an installer for Windows XP. It has also become more closely integrated with Survex (which is the file format for imported centre-line data): the program for creating the station co-ordinate files that are necessary for morphing the sketches can now be called directly from within Tunnel.

[1] Compass: `http://www.fountainware.com/compass`
[2] Therion: `http://therion.speleo.sk/`
[3] Tunnel: `http://www.freesteel.co.uk/wiki/index.php/Tunnel`

Calibrating a combined electronic compass/clinometer

Phil Underwood

There are currently many projects targeted towards building an electronic compass/clinometer unit for use in cave surveying. This article concerns Phil Underwood's attempt, which is expected to go on sale shortly for around £250. The article covers the method for calibrating the unit, and presents data from a recent underground field trial.

Introduction

Current standard cave surveying techniques use a tape measure and a sighting compass and clinometer. (Where access is easy, a theodolite is sometimes used). To use both of these instruments accurately, it is necessary to get ones eye and the instrument all on a line connecting adjacent survey stations. This can be difficult if not impossible in small or awkward passages, leading to errors in the readings. Also, the requirement for the compass to be held level can cause significant errors on steeply inclined legs, as one has to sight to an imagined point above or below the survey station. It is also easy to misread the scale on these devices, as they usually go in a different direction to that expected. Most surveyors will have experienced the difficulties of using these instruments while wallowing in a pool of mud and trying to contort their bodies so that they can get a reliable instrument reading. I have often dreamed of a digital compass/clino, that would allow me to just place the instrument against the station, shine a laser beam on the next station, and record the readings directly into memory, to be downloaded later on a computer. So I built one and, thanks to the high alcohol content of Austrian beer, called it the *Shetland Attack Pony*. The unit is accurate to 1°, and measures 28x65x140 mm (see cover image). It comes complete with laser pointer, digital display, and USB interface, through which the Li-polymer battery is recharged. Up to 1000 data points can be recorded.

Physical principles

I have dealt with the electronic aspects of this device in an article in the Cave Radio and Electronics Group Journal [1]. The hardware produces a set of 6 numbers, which correspond to the readings from 3 magnetic sensors roughly at right angles to each other, and 3 accelerometers, also at right angles to each other. The laser pointer is also roughly aligned with the first sensor of each group.

The sensors determine the vectors of two forces, gravity (**g**) and the magnetic field vector (**m**) in "device" co-ordinates. The direction of east (**e**) (bearing 90°, clinometer 0°) can be determined by taking the cross-product of **m** and **g**. North (**n**) (bearing 0°, clinometer 0°) can then be determined by taking the cross-product of **g** and **e**.

$$\mathbf{e} = \mathbf{g} \times \mathbf{m}$$
$$\mathbf{n} = \mathbf{e} \times \mathbf{g}$$

If these vectors are scaled to unit length, then the resulting vectors $\hat{\mathbf{n}}$, $\hat{\mathbf{e}}$ and $-\hat{\mathbf{g}}$ form an orthonormal basis (each vector has a unit length, and they are mutually perpendicular). They can be used to transform a vector from device co-ordinates into "real" co-ordinates, i.e. the components in the north, east and downward directions. This is achieved by pre-multiplying the vector by a 3×3 matrix whose rows are formed from the components of the new basis vectors. In our case we wish to find the components of the vector along the line of the laser. Given that this vector has components (1,0,0) in device coordinates, the components in "real" co-ordinates are given by the following expression:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \hat{\mathbf{n}}^{\mathrm{T}} \\ \hat{\mathbf{e}}^{\mathrm{T}} \\ -\hat{\mathbf{g}}^{\mathrm{T}} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

From these we can work out the bearing and inclination (atan2 is the C library function of that name – it is essentially identical to the arctangent, but uses the sign of each argument to correctly identify the quadrant. The factor of 180/π converts from radians to degrees).

$$bearing = \operatorname{atan2}(y, x) \cdot \left(\frac{180}{\pi}\right)$$
$$inclination = \operatorname{atan2}\left(z, \sqrt{x^2 + y^2}\right) \cdot \left(\frac{180}{\pi}\right)$$

If we wanted, we could also find the translation of (0,1,0), which would enable us to determine how far the instrument is rotated along the axis of the laser.

Sources of error

There are several potential sources of error within this application. Each sensor has its own unique scale and offset. There is also no guarantee with normal assembly methods that each chip will be precisely aligned with the PCB, giving two possible rotational errors for each sensor. There is no guarantee that the laser is aligned with the long axis of the PCB, again giving another two rotational errors. Finally there are cross-axis effects of up to 4% Full Scale (FS) within the accelerometer and 2% within the magnetic sensor. This gives a total of 33 factors that need to be accounted for. This can be simplified somewhat. We can consider the scale (s_i) and offset(c_i) for each sensor i as an affine transform.

$$\begin{pmatrix} m'_x \\ m'_y \\ m'_z \\ 1 \end{pmatrix} = \begin{pmatrix} s_x & 0 & 0 & c_x \\ 0 & s_y & 0 & c_y \\ 0 & 0 & s_z & c_z \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} m_x \\ m_y \\ m_z \\ 1 \end{pmatrix}$$

This approach can be generalised to all of the mentioned distortions – any rotation and inter-sensor cross-reactivity can be represented as an affine transform. These can all be combined together to form a single calibration matrix for each set of sensors, giving just 24 variables to be determined. I have used separate calibration matrices for the gravity and magnetic sensors as there should be no cross-reaction between the two.

$$\begin{pmatrix} m'_x \\ m'_y \\ m'_z \\ 1 \end{pmatrix} = \begin{pmatrix} a_{00} & a_{01} & a_{02} & a_{03} \\ a_{10} & a_{11} & a_{12} & a_{13} \\ a_{20} & a_{21} & a_{22} & a_{23} \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} m_x \\ m_y \\ m_z \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} g'_x \\ g'_y \\ g'_z \\ 1 \end{pmatrix} = \begin{pmatrix} b_{00} & b_{01} & b_{02} & b_{03} \\ b_{10} & b_{11} & b_{12} & b_{13} \\ b_{20} & b_{21} & b_{22} & b_{23} \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} g_x \\ g_y \\ g_z \\ 1 \end{pmatrix}$$

or

$$\mathbf{m}' = \mathbf{M_c} \mathbf{m}$$
$$\mathbf{g}' = \mathbf{G_c} \mathbf{g}$$

Where **m** and **g** are the raw magnetic and gravity sensor data, **m'** and **g'** are the calibrated sensor data, *a* and *b* are calibration coefficients, and $\mathbf{M_c}$ and $\mathbf{G_c}$ are the calibration matrices.

Calibration routine

I mounted a wooden pole on a table in the centre of a largish room. I held the device with the brass eye-ring against the tip of the pole, and the laser beam on the point chosen. I then selected various points around the room. For each point, I recorded the sensor readings with the device in 4 different orientations (display pointing up, left, right, and down respectively). I then used a Suunto sighting compass and clino set to measure the "true" bearing and inclination for that point. This was repeated for a total of 12 points, each separated by about 30 degrees. All of the points were at different heights, giving a range of inclinations.

Calibration algorithm

The calibration data is downloaded into a PC, where it is converted into floating point numbers, where 1.0 nominally represents the full reading of a sensor. I have used an iterative solution to find the optimal calibration matrices – this requires an assessment function, to grade how good a particular matrix is. Roughly speaking, this subtracts the vector that the device should be reading from the actual vector calculated, and then calculates the square of the length of the resulting vector. Obviously, the smaller this is, the better. The errors are summed for each reading, giving a total error.

$$\mathbf{n} = \mathbf{e} \times \mathbf{G_c}\,\mathbf{g}$$

$$\mathbf{e} = \mathbf{G_c}\,\mathbf{g} \times \mathbf{M_c}\,\mathbf{m}$$

$$\mathbf{v_{calc}} = \begin{pmatrix} \hat{\mathbf{n}}^{\mathrm{T}} \\ \hat{\mathbf{e}}^{\mathrm{T}} \\ -\hat{\mathbf{g}}^{\mathrm{T}} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

$$\mathbf{v_{real}} = \begin{pmatrix} \cos(bearing)\cdot\cos(inclination) \\ \sin(bearing)\cdot\cos(inclination) \\ \sin(inclination) \end{pmatrix}$$

$$\mathbf{v_{offset}} = \mathbf{v_{real}} - \mathbf{v_{calc}}$$

$$error = \|\mathbf{v_{offset}}\|^2$$

The ideal calibration matrix is found by an iterative approach, aiming to find the lowest possible total error. The starting position is where each calibration matrix is equivalent to the identity (i.e. no changes are made to the raw sensor data). Then each co-efficient is varied by ±1, and the total error is recorded. The single move that creates the biggest improvement is used as the starting point for the next iteration. If there is no move that improves the error, then the iteration is repeated, but this time, the change is ±0.5. The whole process is repeated until the change is $\pm 1/2^{18}$. Unfortunately, this process can be unstable and find false minima. To avoid this the above heuristic is first used only on the scale and offset coefficients down to $\pm 1/2^{12}$, to find the approximate area for searching for the true minimum value. It is then repeated on all coefficients, but starting with a step of ±0.1, going down to $\pm 1/2^{18}$.

Leave-one-out analysis

The above approach will tend to over-estimate the accuracy of the device, as the calibration matrices will be tailored precisely for the data used, and will likely be less accurate for data that was not used in the calibration process. The fewer the data points, the more severe the problem is.

It is possible to check the robustness and accuracy of the heuristic using a leave-one-out technique. Here the calibration matrices are determined using all of the data except for one reading. The error is then calculated for that reading using the calibration matrices. This can then be repeated for each reading. This not only allows the algorithm to be checked for robustness, it also gives an indication of the accuracy of the instrument, and can identify any readings where the standard compass/clino reading may have been incorrect. It will, however, slightly under-estimate the accuracy of the device (as not all possible calibration data have been used).

Practical considerations

I attempted to calibrate the device several times, each time getting unsatisfactory readings. If you are attempting to perform a calibration, consider the following.

- Tripods that appear to be made of plastic, may well have iron screws in them. If in doubt, test it by bringing it near a compass resting on a wooden table.
- Some wooden tables have screws in them as well. Also some have iron legs.
- House walls often have metal studs and wiring in them. Don't do backsights from a wall to your sighting point.
- If you have a battery in your device, make sure it is firmly anchored within the device, and is reasonably far away from the sensors. (Even though it does have a significant magnetic field, provided it is constant, its effects will be eliminated in the calibration process).
- Wearing a big heavy metal watch while doing the calibration can cause problems, and also substantial hair loss when you finally work it out...

Experimental results

Using the above methods, I have performed a calibration on one of my devices, and obtained the results shown in Table 1. Using a leave-one-out analysis, it looked like two of my compass readings were suspect, so I have also presented data with these readings removed. All numbers are quoted in degrees.

	All data		**Suspect data removed**	
	Inclusive	**Leave-one-out**	**Inclusive**	**Leave-one-out**
Compass reading error: mean (s.d.)	-0.21 (0.60)	-0.31 (0.87)	-0.21 (0.58)	-0.30 (0.85)
Clino reading error: mean (s.d.)	-0.002 (0.44)	0.004 (0.50)	-0.004 (0.32)	0.0017 (0.36)

Table 1: Compass and clino reading errors.

As can be seen, there is no systematic offset in the clino readings. The spread in the clino readings would be roughly what is expected given that the standard I am comparing against has an accuracy of ±0.5°. There is a small systematic offset in the compass readings, and the compass readings are more spread out; this may be due to small movements in the battery in the device, noise in the magnetic sensors, or alternatively due to problems with my sighting compass. Another potential source of error would be physiological tremor (a small tremor of about 5-6Hz).

Field trials

I took two unsuspecting volunteers (AU and DL), neither of whom had much previous experience, on a circular surveying trip down Bull Pot of the Witches. We used a Leica Disto to record distances, a *Shetland Attack Pony*, and a pair of Suunto's. AU operated the Disto and the *Pony*, while I and DL took their own readings from the compass/clino pair. I gave both AU and DL instructions in how to use the relevant instruments. We all used the same stations, and used the same Disto reading for each leg. We used a leapfrog system to reduce systematic errors. The survey was circular in nature, and was 180m long. So, in summary we were comparing the *Shetland Attack Pony* (used by a novice surveyor), against standard instruments as used by both an experienced surveyor and a novice surveyor. The raw survey data is shown in Table 2.

From	To	Leg length (m)	Compass (°)			Clinometer (°)		
			SAP	Suunto		SAP	Suunto	
			AU (novice)	DL (novice)	PU (experienced)	AU (novice)	DL (novice)	PU (experienced)
1	2	4.76	009	009	008	-2	-1	0
3	2	6.66	197	196.5	198	+02	+4	+1
3	4	5.95	318	319.5	331	-13	-13	-12
5	4	14.52	187	193	190	+19	+19	+20
5	6	4.06	342	347.5	344	-36	-36	-38
7	6	9.49	183	184.4	188	+16	+16.5	+6
7	8	12.08	352	346.5	352	-21	-21	-22
9	8	3.88	174	174	176	+8	+9	+8
9	10	6.55	226	227	227	-5	-7	-6
11	10	3.79	173 (R)	001	351	+9 (R)	-11	-10
11	12	10.51	22 (R)	201	201	-2 (R)	+2	+2
13	12	8.36	213 (R)	033.5	033.5	+5 (R)	-6.5	-6
13	14	4.83	349 (R)	149	170	+23 (R)	-23	-24
15	14	9.87	191 (R)	013	015	+4 (R)	-4.5	-6
15	16	10.09	034 (R)	201.5	211.5	-12 (R)	+12	+13
17	16	11.43	181 (R)	350	000	-1 (R)	+2.5	+1
17	18	4.68	302 (R)	124	125	+05 (R)	-6	-7
19	18	2.85	134 (R)	311.5	317	+24 (R)	-24.5	-27
20	19	7.03	164 (R)	345.5	046	+22 (R)	-22	-22
20	21	3.34	292 (R)	121	121	-61 (R)	+57	+60
22	21	6.16	144 (R)	322	343	+54 (R)	-53	-52
23	22	6.25	274	281	278	-42	-42	-42
23	24	8.07	209 (R)	029.5	030	+1 (R)	-2	-2
25	24	8.93	014 (R)	193.5	193	-1 (R)	+0.5	+1
2	25	5.46	169	169	170	-5	-5	-6

Table 2: Raw data from the field trial. Some legs were recorded in the opposite direction when using the SAP compared to the Suunto – these are marked (R).

The loop closure errors are summarised in Table 3. The horizontal and vertical offsets show the loop closure error. I noticed from comparing my notes with the others, that I had inadvertently recorded a reading of 346° as 046° so results are shown with this corrected later (although this may have been missed, if I had not been able to compare with other results). Comparing the written data from AU with that recorded by the *SAP* showed no transcription errors.

	AU (*SAP*), novice	DL (Suunto), novice	PU (Suunto), experienced	
			Uncorrected	Corrected
Horizontal Offset	0.43m	4.67m	6.17m	1.25m
Vertical Offset	1.3m	0.52m	2.89m	2.89m
Percentage Error	1.08%	2.69%	3.90%	1.80%

Table 3: Summary of loop closure statistics.

Discussion

I have shown that a digital compass/clino can produce a survey of similar accuracy to that of a moderately experienced surveyor. It is worth noting that both PU and DL have on occasions disagreed either about the compass or clino - but the digital compass has been close to one of the readings. I think we can fairly assume that these errors have been due either to a gross misreading of the instrument, or due to a transcription error. There are no readings where both analogue readings are similar and the digital reading is substantially different. I intend to attempt to calibrate the device more accurately, using a theodolite or differential GPS, which may improve the accuracy further. For those interested in testing or purchasing one of my devices, please contact me on `phil@furbrain.org.uk`.

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A prototype digital underwater line compass for underwater cave surveying

Simon Richards

This article describes the result of a project to design and build a digital compass for cave divers that is easy to use and will reduce the frequency of gross errors. It is an abridged version of a paper on the cave-exploration.com website [1] which includes further details of the construction of the device.

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 "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 article.

The principal objective of this project was 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. 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. Also, 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.

Design options

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° 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.

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 motivation, not pursuit of extreme accuracy. 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.

Our initial approach was to use an existing commercial underwater digital compass 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. This worked as a proof of concept. However, a major problem was that the resolution of the compass in question is only 5°, and its accuracy is not known. One or two degrees accuracy would be required, with say 1° or better resolution. There are at present few digital underwater compasses of any type available which have the required accuracy, which meant that there was little benefit in taking a crude two-sensor underwater compass with low accuracy and gimballing it. Because of this and other considerations, we decided to develop a prototype using an electronically tilt-compensated compass with no gimbal mechanism.

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 [2]. 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. Since the use of magnetic switches might interfere with the operation of the compass, we considered using light sensitive switches, but ultimately chose to modify the software to cope with these issues instead. We also added an LED and some driver circuitry to an unused output from the microcontroller to allow the compass to signal to the user. The electrical, mechanical and software design are outlined in the following sections.

Electrical 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. 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 [3]. 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. The sensitivity ratio of the X and Y sensors within the HMC1052 is +- 5% and their orthogonality is 0.01° [4]. 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 [5].

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.

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. An amber LED was chosen in hope of achieving maximum brightness underwater.

The compass board is shown in Figure 1.

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. 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. However, for a variety of reasons, this proved difficult for the prototype, so the unit is currently powered by alkaline cells.

Mechanical design

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).

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. 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). 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. 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. Two prototype housings were built by RGM Machining, who produced some first class results within just a couple of days, for a few hundred dollars per set.

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. 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. Figure 2 shows detail of the magnetic switches.

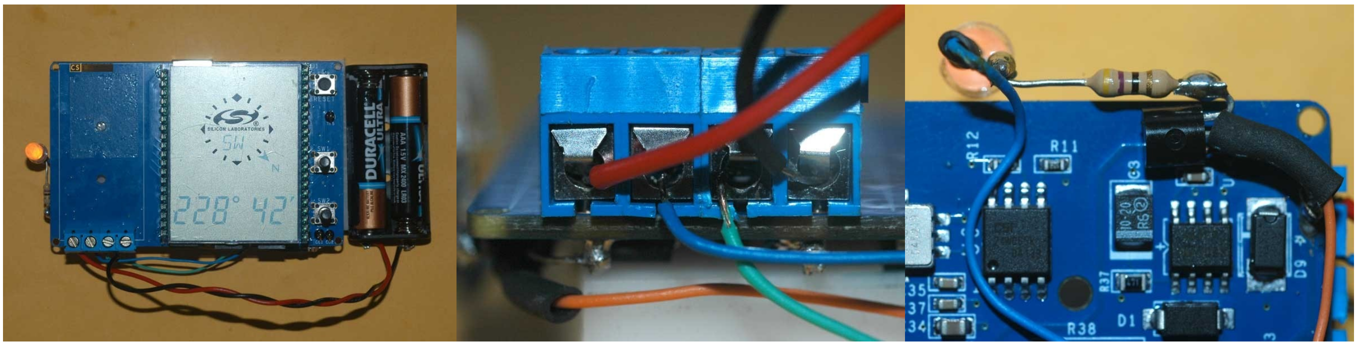

Figure 1: Views of the compass board: off-board battery holder, connector block, and LED (left); connector block (middle); LED and emitter follower circuitry (right).

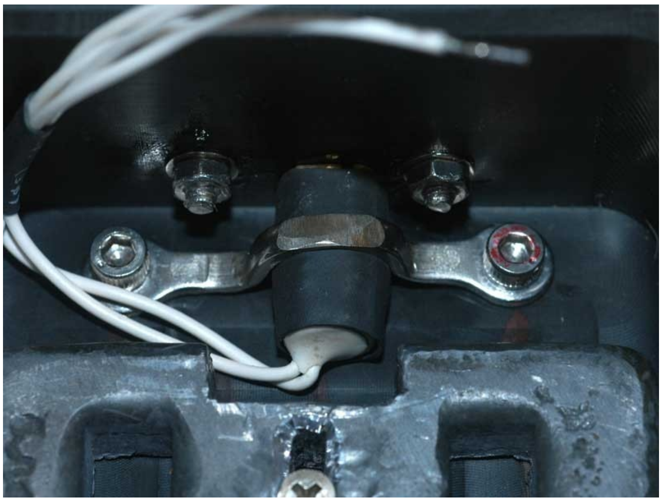

Figure 2: Magnetic switches. Plastic or brass retainers would have been better from a magnetisation perspective. Note screws penetrating from outside the housing - the original plan was to use these for battery charging. The threads are sealed with silicone.

The line hangers a 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 (see Figure 3). The hangers for the prototype were hand-made from 3/8 inch white delrin and hinged in the centre around two stainless steel half shafts. In order to provide some adjustment for alignment, the half shafts are located within the fixed part using small stainless steel set screws.

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 (see Figure 4). Another pair of SPG O-rings is used either side of the PCB to provide additional flexibility.

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.

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).

Figure 3: Compass suspended on line hangers (top). When not in use, hangers fold flat against compass body for stowing in pocket (bottom).

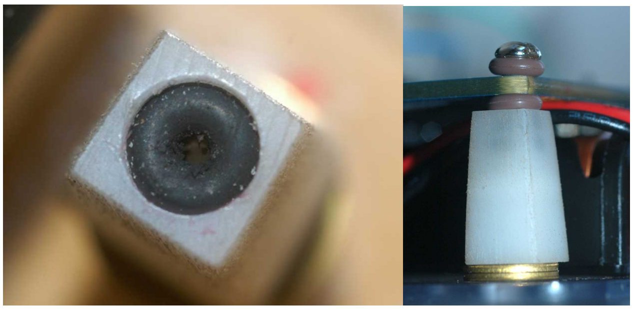

Figure 4: Two SPG O rings are recessed into the mount (one is below the visible one), and the PCB mounting screw "self taps" into these.

Software

The software for the Silicon Labs design was written by Sytron Technologies Overseas, and 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 1° for up to about 30 to 40° tilt, which is more than adequate for our application.

The following changes to the reference design 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. 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.

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, and 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. This option will be useful in poor visibility conditions, as it will allow the user to swim to clearer water to read the azimuth and record it in the notebook, and also 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 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).

Accuracy

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° error for 30° 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° 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. The results are shown as the solid curve in Figure 5. We did not measure long term repeatability, sensitivity to supply voltage or temperature, or calibration repeatability.

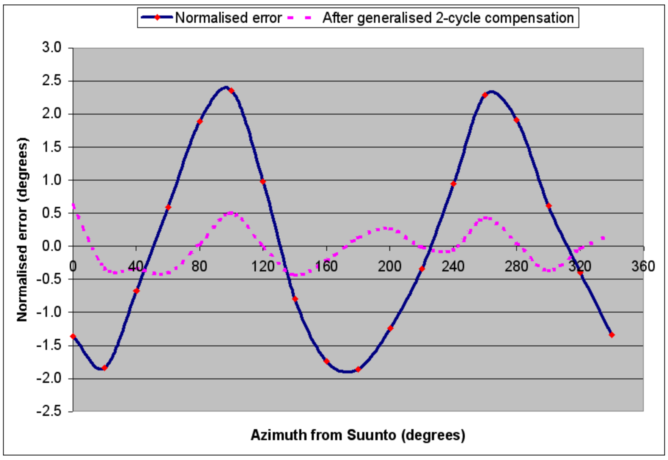

Figure 5: Azimuth Error (DULCE-Suunto) Normalised to Zero Mean (dashed line shows residual error after eliminating two-cycle error).

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 Figure 6 shows the consequence of a 5% mismatch. Other sources of error could have a similar 2-cycle effect.

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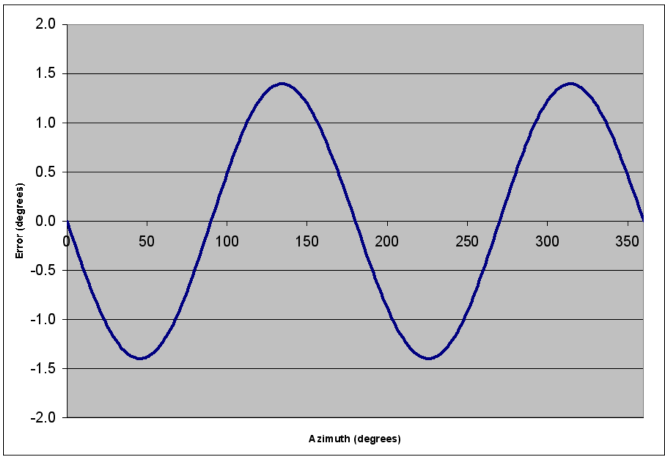

Figure 6: Azimuth Error from 5% Effective Sensor Gain Error.

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° 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 used in the software.

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.

For cave survey purposes, the most useful measure of accuracy is probably the mean absolute or RMS errors, which appear to be 1.25° and 1.4° 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° mean absolute error, 0.3 ° RMS error, and 0.5° maximum absolute error. Honeywell suggest that it should be feasible to achieve 1° accuracy [6], and this seems entirely plausible given our results. 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.

Conclusions

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 magnetic sensors and a 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 [2], 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.

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.

Although this article 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.

Acknowledgements

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. We are grateful to Fred Devos for suggesting the option to "freeze" readings. Aude & Maurico Domenge kindly modelled for photos with the prototype. Donna Richards fed the monkey.

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