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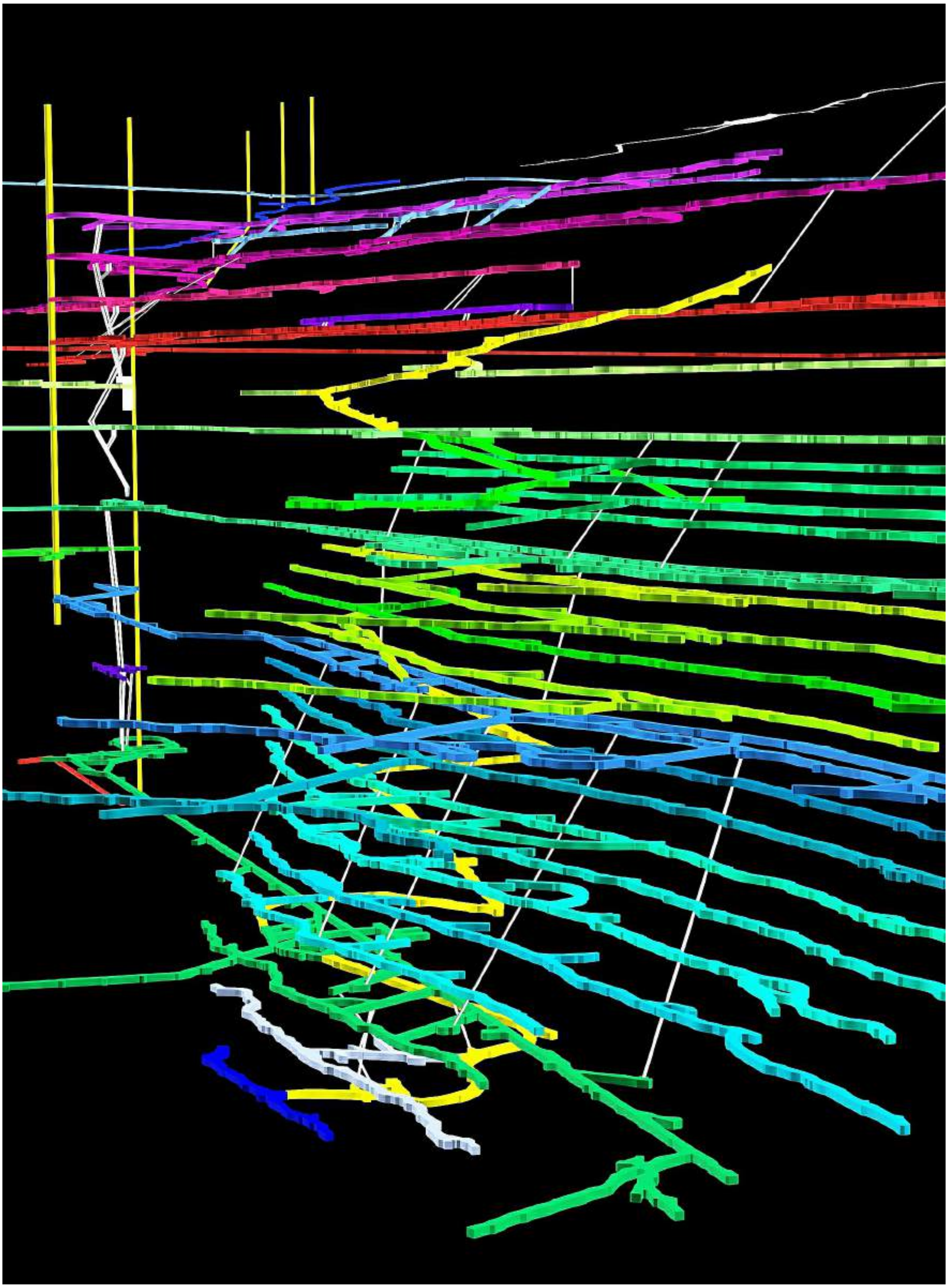

Image: Keith Russ

Modelling Historic Mines in 3D

Poor Man's Laser Scanner, Cave Thermal Imaging with a Smartphone, An Electromechanical VLF Transmitter, CREG Field Meeting Report, We Hear, Wet & Dry, Web Watch, Letters & Announcements

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Stuart Cadge of GeoSLAM at the November Field Meeting

***Front Cover:** An extract from the model of the Wheal Jane mine, showing the extent and complexity of these old mine workings.*

***Image:** Keith Russ*

The Mines of Cornwall and West Devon: A Three-dimensional Model

***Keith Russ** describes the creation of a three-dimensional underground world that covers the mining world heritage site of Cornwall and West Devon. The paper outlines the reasoning behind the creation of such a model, the processes and software used during model creation, the availability of historical data and the production of animations show-casing the dataset. Finally, the paper will give links to online content where some of the dataset and videos can be seen.*

Introduction

In 2006, the legacy of mining in the West Country (England's south-west peninsular), and Cornwall and West Devon in particular, was recognised by its inception as a world heritage site. This designation covered the mining landscape, the engine houses, fields, smallholdings, estates, foundries and other related structures, which are monuments to the scale of metal mining.

There is a huge archive of material which relates to mining in this part of the UK which can be found in books, papers, plans and photographs. However, the facts and figures do not, in themselves, give any real understanding of what the geometry of the underground workings looks like and the relationship between mines.

The story of the model starts back in 1989/1990 when the author was a student at the Camborne School of Mines. It is at this point that an interest in surveying of old workings began. The first project was an old lead mine in Derbyshire called Old Millclose. A rudimentary 3D computer model was created as part of the author's final year project. This simple model became the starting point for what followed. In 1995, the author was granted his PhD (Russ, 1994) for work on the visualisation of complex underground workings.

As part of this research work, data relating to South Crofty Mine was obtained and this was the first Cornish mine to be modelled in 3D. True there is a physical three-dimensional model of the mine workings, which still exists, but this pioneering work was paving the way for the creation of probably the largest computer model of mine workings certainly in the UK, if not elsewhere.

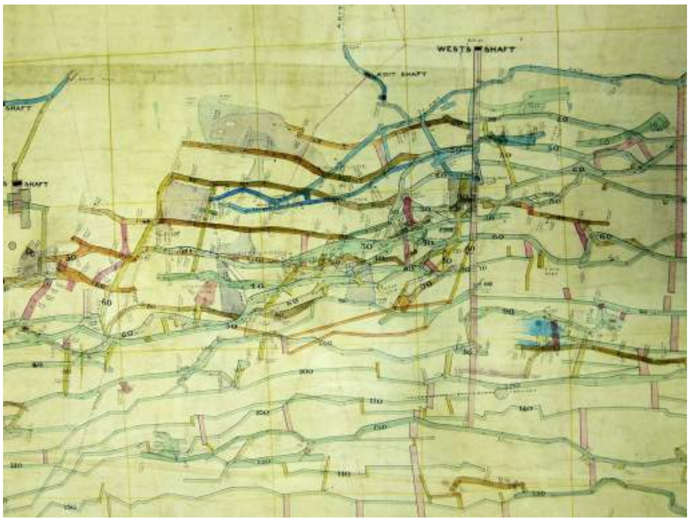
After leaving CSM in 2001, the author joined the staff of what has become Western United Mines, a company trying to restart mining in Cornwall. Part of the work was to digitise and create computer models for planning purposes.

Slowly, the number of models increased over the years as did the areas that were modelled. Initially, the modelling was concentrated on the Camborne / Redruth district centred around South Crofty, but gradually spread to cover the whole of the county of Cornwall, plus mines in West Devon.

Why?

It's pertinent to address the question of why the model was created. It would be flippant to say, because there wasn't one, but that is part of the reasoning, another reason was that the author had an interest in what some of the more famous mines actually looked like in 3D. An important reason for creating those in the Camborne / Redruth district was from a mine planning point of view with significance being placed upon the health and safety aspects of unwanted intersection with old workings.

H.G. Dines (1956) published a book called *The Metalliferous Mining Region of South West England* which was a description of the abandoned mine plans that were held by law. In 1998, a friend of the author joked that what he was creating was going to be a virtual Dines. Little did my friend know that nearly 18 years later this is exactly what has been created.



Hand-drawn plans, like this one of Phoenix United Mine, created in the 1890s, were the source material for the 3D model.

J C Burrow's historic photographs from the early 1890s provide a graphic illustration of the mines represented by these plans.

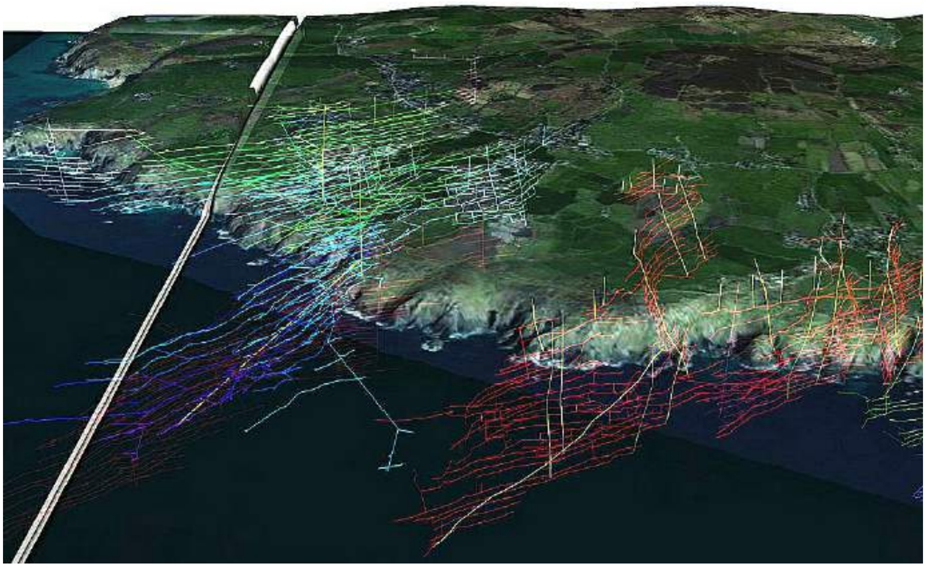
	Mine	Length	
		Miles	km
1	South Crofty	98.7	154.0
2	Geevor	79.2	127.6
3	Dolcoath	66.3	98.7
4	Fowey Consols	60.9	98.1
5	Carn Brea Mines	53.4	86.0
6	Botallack	36.1	50.2
7	South Caradon	30.0	48.3
8	Consolidated Mines	28.3	40.8
9	Wheal Jane	28.2	40.7
10	Devon Great Consols	24.7	39.9

Top Ten Mines Included in the Model

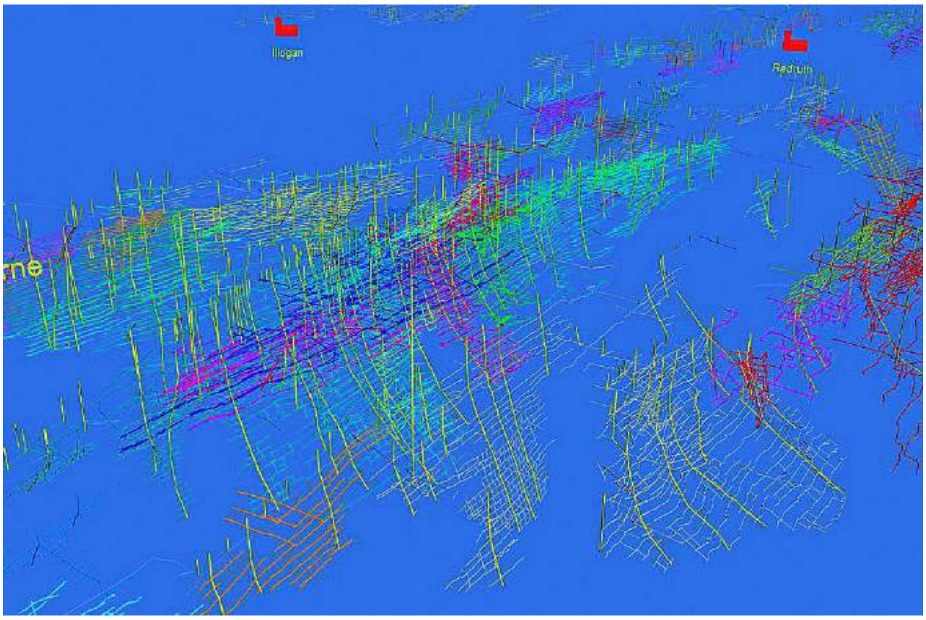
Creating the Underground World

The creation of any digital model relies on data and, in this case, lots of it. All the models of the mines, and there are currently 340 individual mines within the model, have been constructed from plans either held in the local record offices in Cornwall and Devon or in private archives to which access has been granted. So most of the data is in a paper or film format and has to be digitised. Some mines like South Crofty were already in a digital format as the surveys to this mine were obtained from the surveyors when the mine closed in 1998. The plans to Wheal Jane, drawn at a scale of 1:250 exist on over 70 A1 sheets. Geevor mine, on the other hand, exists on 12 sheets drawn at 1:1000.

The process of model creation is simple – starting with the plans of the mine, these are either scanned or photographed or both so that there is a high resolution digital version of the plans. Some of these date back to the early 1800's, whereas others are modern and date from the 1990s. In the case of the modern plans, each one was traced in AutoCAD, thus an accurate digital plan was created in which each level was based upon a modern survey with surveyed walls. These levels were then elevated, based upon actual surveyed elevations, as the author had access to the survey peg databases in many cases. This was done for the five modern mines comprising South Crofty, Wheal Jane/Mount Wellington, Pendarves, Geevor and Wheal Concord.



The St. Just Mining Region with Surface Features



The Camborne/Redruth Area Showing the Staggering Density of Mine Workings

In the case of the pre-war abandoned mines, which covers everything else, the following procedure was employed. Like the modern mines, the photographic representation of the plan was traced in AutoCAD to create a digital centreline model. This model was then scaled and transformed so that it fitted the Ordnance Survey National Grid. By building all the mines in OS, each one could be constructed individually and then added to the growing model. Using specialist mining software (Surpac), solid models were created from the centrelines and these were then exported into an animation package (3ds Max) where the fly-bys were created.

The length of time taken to create a single model of a mine is dependent upon the information that is available and the size and complexity of the geometry of the workings. Some notable examples include South Crofty, which took nearly a year, with re-workings as more information within the company archives were located. Wheal Jane took about six months, as did Geevor and Fowey Consols. Other smaller mines could be constructed in a day, whereas the majority took a couple of days to a month to produce.

The model was created district by district, which allowed all the mines in one area to be modelled, for example those found in the St Just, Gwinear, St Austell or Caradon mining districts. By modelling in this way, once an area was completed, the author knew that there were no other mines to add, rather than building on a more *ad hoc* basis. Also, the mines are conveniently divided into districts, which certainly aided model construction when searching for information.

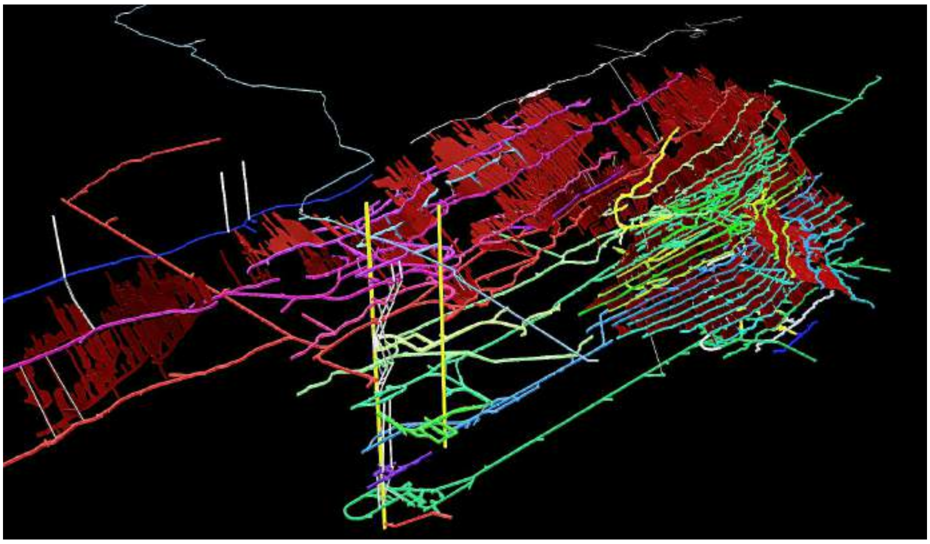
It became obvious after a while that it would be possible to create a model which comprised all the mines within the world heritage site, a virtual Dines. However, it also became apparent that in order to do this, plans to Geevor mine would be required and, for several years, locating a suitable set of plans from which to build a model was proving difficult. Luck played its part in the discovery of a suitable set and the associated survey information, which was required in order to construct a model.

The Resulting Model

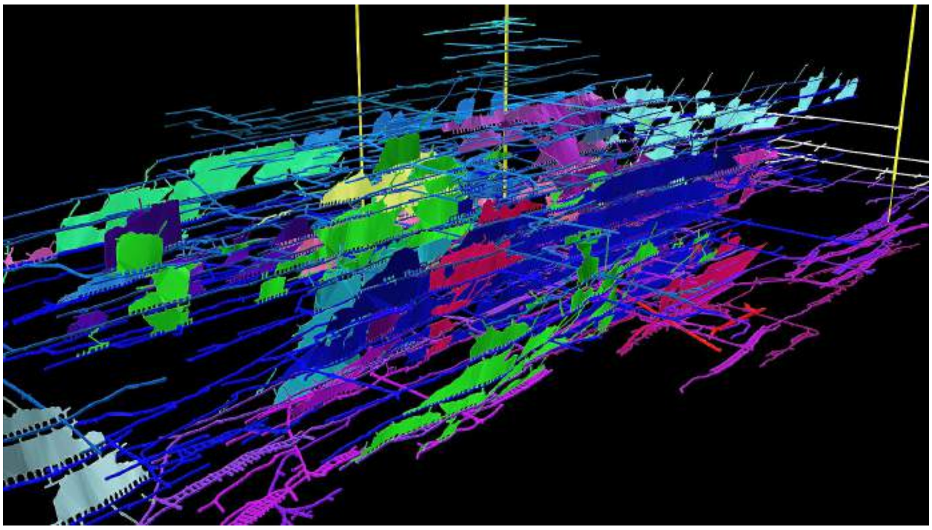
By the early part of 2015, the model was nearly complete. As stated, the model contains 340 individual mines which have a combined total length of over 1,500 miles (2,400km) of workings and several thousand shafts and winzes. The length of the model is some 80 miles (130km) from Land's End to Tavistock.

The top ten mines, in terms of total linear distance of levels, is given in the table on this page. It may not come as a surprise that South Crofty Mine is the largest, but the fact that it is followed closely by Geevor may be a surprise to many. It should be noted that in these totals, that for South Crofty does not include any of the old mines that it is holed into, such as North Tincroft and East Pool and neither does Geevor include the total for Levant which it is connected to.

The deepest shaft is Williams Shaft on Dolcoath Mine at 920m. It would be difficult to say exactly which mine has the most shafts, but Dolcoath has at least 50.



Wheal Jane with Stoping shown in Red



South Crofty Mine with Stoping – Individual Lodes Coloured Separately

The Illustrations

Several parts of the model are reproduced here.

While the model as a whole covers all of Cornwall plus the western area of Devon, the two sections reproduced on the previous page represent two of the regions with the highest density of mining operations. Both images show the shafts and levels and, for those familiar with coal mining, one of the main differences is the large number of shafts and the fact that the shafts aren't always perfectly vertical. Instead, the shafts follow the lodes, i.e. the mining term for the mineral-bearing veins which, in some area, are at an angle of 60 to 90° to the horizontal.

The top image shows the St. Just mining district near Land's End, a prominent feature being that much of the mining took place below the sea floor. This can be clearly seen as this image shows surface features.

The bottom image is of the Camborne / Redruth mining area, where the density of mine workings is staggering.

On this page, the two images both show stoping which contrasts to the images on the previous page which show only the shafts and levels that were dug to provide access to the ore. Stoping is the area of ground removed during the production phase which contains the ore-bearing rock. This rock is then hoisted to surface for processing. Whereas plans show the location of the various levels within the mine, sections showing the extent of stoping are usually shown on longitudinal sections. It is these stoping sections which have been used in the construction of the models.

Online

At present there is no dedicated website, although one is in the planning stage and a rudimentary one should be online sometime early in 2017. The website will eventually have an interactive map through which users will be able to select the mine models that they wish to view. Currently, the author is experimenting with various 3D games engines which it is hoped will provide the ability for the user to interact with the mine models and navigate their own way around inside the 3D world. Early results indicate that this is possible as the author has successfully loaded all the mine data into such a game engine and is able to navigate around.

The Facebook page 'Abandoned mine models' is currently the best location for announcements regarding new developments.

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Dines, H. G. (1956) *The Metalliferous Mining Region of South-West England, Volumes I and II*, Memoirs of the Geological Survey of Great Britain: England and Wales, HMSO, London

Russ, Keith (1994) *An Investigation into the Application of Computers for the Processing of Survey and Planning Data for 2D and 3D Interpretation,* PhD Thesis, Mining Engineering Dept., Camborne School of Mines, University of Exeter, UK.

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Keith Russ

After graduating from the Camborne School of Mines (CSM) in 1990 with a degree in Mining Engineering, and completing his PhD in 1994, Keith taught surveying and computer packages at CSM. In 2001, he departed from CSM to work for firstly Baseresult Holdings, and then Western United Mines at South Crofty Mine as part of the technical team trying to restart deep mining in Cornwall. Here Keith is employed as a mining engineer / surveyor with a keen interest in mining history and computer graphics.

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The Intriguing Tale of the Electromechanical VLF Transmitter

***John Rabson** investigates SAQ, a 17.2kHz transmitting station at Grimeton in Sweden, which uses an electromechanical transmitter, and which is still operational today. While it seems unlikely that this old technology will ever play a part in cave communication, there has been speculation that there may be benefit in another form of mechanical VLF transmitter for caving use.*

Non-Electronic Radio

In the early days of radio, before the advent of valves, it was difficult to achieve great distances. The principal way of generating a useful amount of radio frequency power was to use a spark-gap transmitter. This was fairly straightforward to construct but amongst its disadvantages were the high bandwidth of the transmitted signal and the lack of frequency stability. These drawbacks made it difficult to share the radio frequency spectrum with other stations.

A number of engineers and scientists investigated the possibility of building an electro-mechanical AC generator (i.e. an alternator) which could be run at a sufficiently high speed to generate radio waves. Among those who demonstrated that this was possible were Elihu Thomson, Nikola Tesla, Rudolph Goldschmidt and Ernst Alexanderson (Clawson, 1924). The latter collaborated with Reginald Fessenden to produce a 100kHz speech transmission system based on such a generator. Transmitted frequencies were typically in the range 20 to 100kHz with powers of up to 500kW using on-off modulation in Morse Code, i.e. CW or Continuous Wave.

Such systems, particularly those of Goldschmidt and Alexanderson, were used world-wide for point-to-point long distance communications at LF and VLF. They were very largely superseded in the 1920s by vacuum tube-based systems, but a few Alexanderson systems remained in use for specialised purposes until well into the 20th century.

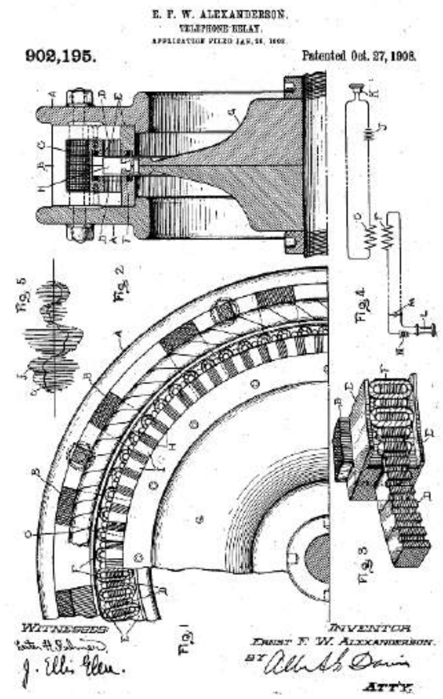
Station SAQ

The only remaining Alexanderson transmitter in working order has the callsign SAQ. It was still in service until 1996, transmitting orders to submarines in the Swedish Navy. It is now a heritage installation and is demonstrated two or three times a year on a frequency of 17.2kHz as part of the Varberg Radio Station Museum at Grimeton, Sweden. In its original application, reception was by ear or Morse inker at up to 25 words per minute at the companion receiving station at Kunsbacka, 20km from Gothenburg, but that installation no longer exists.

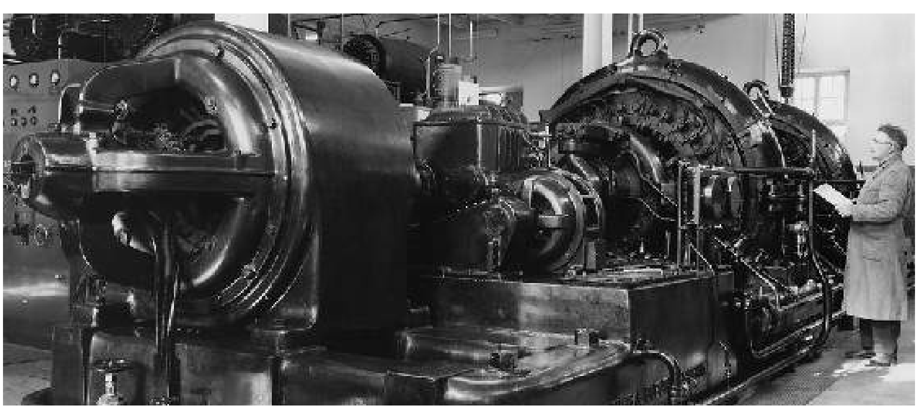
The transmitter consists of a 440kW induction motor, a 1:3 step-up gearbox, a magnetic amplifier, and a high frequency alternator which nowadays produces 17.2kHz.

According to the SAQ website (**alexander.n.se**), "The rotor of the high frequency generator is a steel disc, 1.6m in diameter and 7.5cm thick at the periphery. The steel disc has no winding. Instead, 488 slots are milled at the periphery. The slots are filled with non-magnetic material (brass), in order to reduce the air friction. The magnetic flux is generated by a field coil, situated outside the stator."

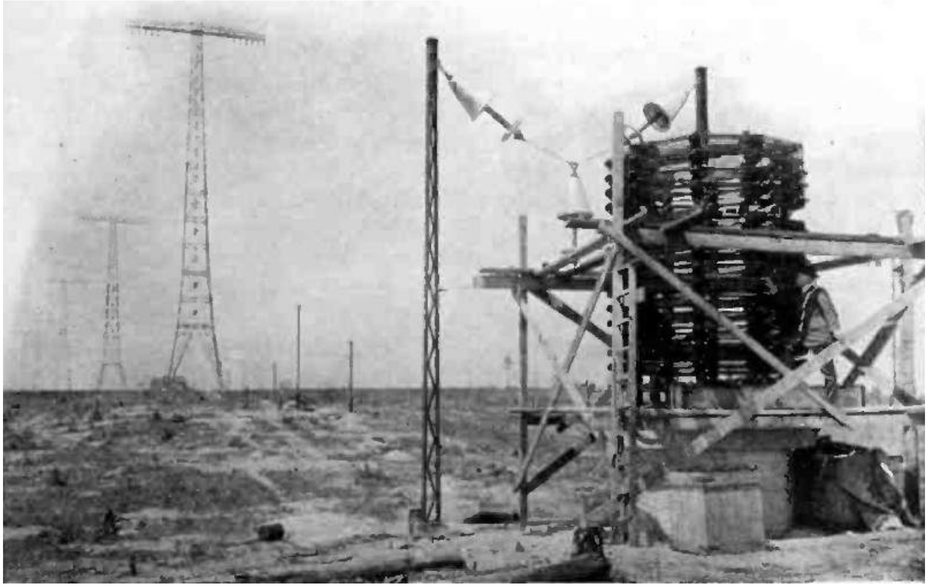
"The stator is designed to encircle the periphery of the rotor. The magnetic flux is conducted through the periphery of the rotor via the stator. The air gaps between the rotor disc and the stator are less than 1mm wide. On the stator, there are 64 armature windings that collect the variations of the magnetic flux. The variations arise when magnetic steel and non-magnetic material passes through the magnetic flux. Each armature winding produces 100V and 30A, which is conducted to the output transformers."... "The speed of the high frequency generator is 2,115 rpm"



Detail of the Rotor in Alexanderson's 1904 Patent Application for his Transmitter



Ernst Alexanderson's Electromechanical Alternator at the Varberg Transmitting Station at Grimeton in Sweden



Antenna and Tuning Coil at the Varberg Transmitting Station

Ernst Alexanderson – Radio and Television Pioneer

Most stations which transmit Morse turn the transmitted signal on and off (or modify its frequency) at some point in the transmit chain. The Alexanderson system, by contrast, is keyed using a magnetic amplifier based on a saturable reactor to reduce the drive power very considerably, leaving the master generator still running.

In practice a small ‘space’ or ‘back’ wave may still be audible. Another effect of using this method of keying is that the load on the master generator changes and this produces a slight variation of transmitted frequency, known colloquially as ‘chirp’.

This transmitter is capable of delivering 200kW of radio frequency power but, today, for demonstration purposes, it is limited to 80kW. Nevertheless, reception reports of SAQ’s occasional transmissions are commonly received from listeners worldwide.

More details of the transmitter can be found in (Blake, 1921).

Ernst Alexanderson

EFW Alexanderson was born at Uppsala, Sweden and educated in Sweden and Germany. He emigrated to the USA in 1902 and spent much of his life working for General Electric and RCA. He designed the alternator which is named after him. As well as the long-distance VLF communications application for which the alternator is known, it was subsequently used by the Canadian engineer Fessenden in 1906 to transmit speech and music.

Alexanderson also worked on the development of television. The first TV broadcast in the US took place from his home in Schenectady, NY during 1927.

Over his lifetime, Alexanderson received 345 US patents, including ones on RFI suppression, directional antennas, the magnetic amplifier (or magamp – which was used for keying, control and modulation of Alexanderson generators) and the amplidyne (an electromechanical amplifier). Students were still being taught about magamps in the 1960s and some PC power supplies use them for regulation of auxiliary voltages.

Alexanderson received his last patent when he was 89.

Mechanical Cave Radios?

The Alexanderson alternator might seem unbelievably quaint by today’s standards but it’s worthwhile considering whether there are any lessons to be learned for cave radio. After all, this technology is entirely possible at LF, VLF and below, the very areas that have application to through-rock radio.

A hundred years ago this method of generating radio signals was chosen out of necessity since valve technology was in its infancy. But with the maturation of valves and their eventual replacement by solid state devices, it seems hard to believe that we’d ever want a cave radio containing an electric motor. Surprisingly, though, it has been suggested that there might just be some benefit in using a quite different type of electromechanical transmitter. That design takes the form of a spinning bar magnet and could, perhaps, provide an efficient form of VLF or ULF transmitter for radiolocation applications.

An Electromechanical Receiver

By today’s standards, the thought of an electromechanical transmitter might seem strange, but radio amateur **Jim Moritz** has gone one further in designing and building an electromechanical receiver and has used it to receive broadcasts from SAQ.

It is a direct conversion receiver with a 2-pole passive pre-selector which also impedance matches the antenna to the mixer. The mixer uses saturating ferrite cores and is driven by a local oscillator (LO) which saturates the cores at both positive and negative peaks of its waveform, so the core windings present an inductance that varies at twice the LO frequency, in series with the signal path.

The LO signal is produced by a 200 steps/revolution stepper motor which, when driven as a generator, produces two signals in phase quadrature – with 100 cycles for each revolution. Driven at 4800 RPM by a DC servo motor, it generates a couple of Watts at 8kHz. The frequency doubling action of the mixer gives a 16kHz LO. Because of the mechanical noise it produces, the oscillator is connected to the rest of the circuit with long cables.

The main defect of the electro-mechanical receiver is poor frequency stability – the motor currently has no feedback speed control, and so the oscillator frequency varies by about ±1% – not a problem as far as copying goes but, reportedly, the received audio does sound a bit wobbly! This is probably the only receiver of its type in existence, and perhaps the only entirely electromechanical radio transmission/reception arrangement since the 1920s.

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Clawson, Harvery (1924) *A Radio System Built of Air-Castle Dreams*, Wireless Age, August 1924, pp. 26-29. Available: **www.americanradiohistory.com/Wireless-Age_Master_Page.htm**

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The Poor Man's Laser Scanner: A Simple Method of 3D Cave Surveying

Attila Gáti, Nikolett Rehány, Balázs Holl, Zsombor Fekete, and Péter Sűrű
describe how a Disto X with modified firmware has been used to provide a 3D laser scanning facility at a fraction of the price of a conventional commercial laser scanner.

Introduction

The most widely used measuring devices for cave surveying are Beat Heeb's DistoX (Heeb, 2009) and DistoX2 (Heeb, 2014), which are a laser distance meter equipped with compass and inclinometer. Using these devices, one can take several hundreds of splay shots from a station in a few minutes. Doing this systematically, we can make a sparse 3D survey of a cave. However, we can measure only about ten or twenty thousand points in a day with a single DistoX, which is very few compared to point clouds obtained from Terrestrial Laser Scanners (TLS) (Bedford, 2003), or GeoSlam's ZEB1/ZEB REVO handheld laser scanners (Williams, 2014). In addition, the distribution of the sampled points can be extremely uneven. The question then arises: is it possible to acquire a 3D model of a cave based on such few and unevenly distributed measurements? Considering the price of TLS and ZEB devices and the fact that it is very complicated or even impossible to use TLS in narrow places, this problem is of great importance.

In this paper we give a first report on the Poor Man's Laser Scanner (PMLS), which is a new cave surveying technique and associated software based on splay shots performed with the DistoX or Disto X2. We have developed a simple yet robust and reliable surface reconstruction algorithm that interpolates the measured points with a watertight surface of good quality, free of self-intersections. Recent advances in 3D software technology significantly improved the possibility of such software development. Nowadays, many software libraries and programs are available for manipulating and viewing 3D data effectively. These pieces of software come from the field of 3D scanning, 3D medical imaging, and 3D animation. Building upon these tools, we created a software solution for acquiring good quality, realistic 3D cave models from DistoX measurements with modest software development efforts. We have surveyed Hungary's deepest cave, the Bányász Cave (273m), which is about one kilometre long, and we think that the required on-site work is also reasonable. In one day, we could survey 50-100m long sections with a single DistoX. We compared one of our models with a dense point cloud resulting from a thorough TLS survey. The vast majority of the TLS's points were closer to our model than 300mm.

Related Work

Let us take a look at the already existing methods that can provide 3D cave models. By conventional cave surveying, it is common to take splay shots in four directions with DistoX: left, right, up, and down (LRUD) in addition to the leg shots. Some widely used cave mapping programs – Compass (Fish, undated), WinKarst, Therion (Budaj & Mudrák, (2008) – are capable of producing rough 3D models from centreline and LRUD measurements. LRUD models are very inaccurate and not very realistic, but the survey is fast and cheap. Therion can also produce 3D models by combining passage outlines from digitized 2D maps and height data. In Hungary, Joe Mészáros created some 3D models based on cross-sections and centrelines (Mészáros, 2011). Both of these techniques result in unrealistic models. The problem with these approaches is that they try to recover the 3D layout from separate 2D and 1D information. This kind of divide and conquer strategy leads to poorly distributed sampling of 3D reality, because we can only build upon data points lying on specific cross section planes or some projection planes. In the case of Therion, the information is furthermore distorted by the projection. Proper 3D reconstruction methods must use 3D data directly and treat all the three dimensions together.

Besides the techniques based on traditional cave mapping, there are solutions that can provide detailed, high quality models based on dense and accurate point clouds. Unfortunately, the equipment has a price that definitely cannot be afforded by caving clubs. The terrestrial laser scanner is the equipment of professional 3D surveying (Bedford, 2003). TLS scanners are usually very accurate, even at a range of several hundred meters. On the other hand, it is impractical to use TLS in tight caves due to their size and fragility (Holenstein *et al*., 2011). Since these devices must be mounted on a tripod, large cave chambers and wide passages are most suitable for surveying, where data can be captured from a modest number of stations (Rüther *et al*., 2009; Lerma *et al*., 2010); Strange-Walker, 2013; Berenguer-Sempere *et al*., 2014; Milius & Petters, 2012; Roncat, 2011; Gede *et al*., 2013; Gede *et al*., 2015; Gallay *et al*., 2015). In extremely large chambers, TLS is the only possibility (Walters, 2016). A rather new piece of equipment is the ZEB1 (Williams, 2014) and its enhanced version, the ZEB REVO (Dewez *et al*., 2016). These are handheld laser scanners utilizing the so-called Simultaneous Localisation and Mapping (SLAM) technology (Bosse & Zlot, 2009, 2010; Holenstein *et al*., 2011). Neglecting the price, this is probably the best tool for 3D cave mapping in general. It is easy to carry, easy to use, and the survey is extremely fast. It is not as accurate as TLS, but its accuracy is good enough for our needs, meeting grade XD according to the BCRA survey grading system, although it can be difficult to use in tight places. In (Dewez *et al*., 2016) the authors tested accuracy on a planar wall and noticed 25-32mm of deviation, operating at a range of 30m. The ZEB REVO weighs about 4kg so it is heavier than a DistoX and has only an IP64 rating, but the main problem is its price. In Hungary, we can buy a ZEB1 for €20,000, while a ZEB REVO is sold for €30,000. The SLAM software costs another €13,000, but you can also choose cloud processing on GeoSlam's servers and pay for each of your surveys.

Our new method, the Poor Man's Laser Scanner (PMLS), is a technique that makes it possible to acquire detailed and realistic models, almost like those obtained with tripod-based or handheld laser scanners, but using the surveying equipment that we

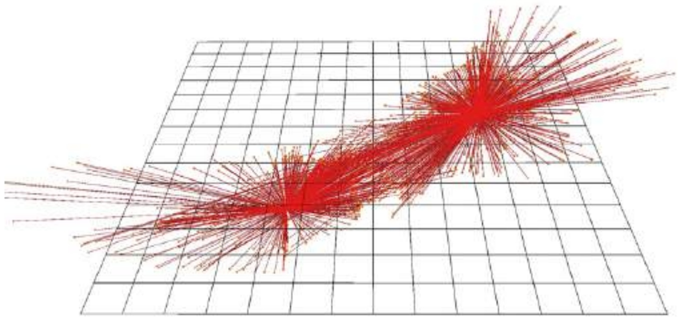

Figure 1 – Extended hedgehogs (Balázs Holl's survey)

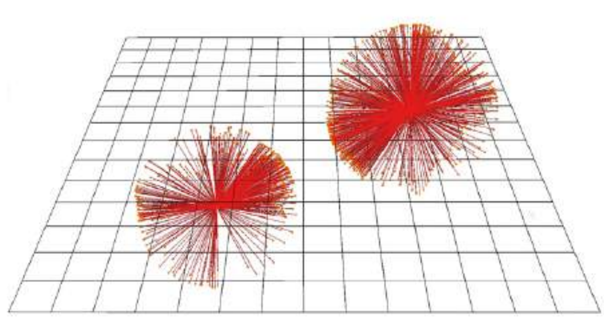

Figure 2 – Extended hedgehogs with unit length splay shots

already have, since most caving groups own, and are familiar with, the DistoX or similar devices. A PMLS model can also piece together disconnected 3D surveys created from other sources.

The Proposed Method

Our main contribution is a surface reconstruction method and associated software that applies the method. In our case, we would like to create a realistic 3D model of a cave that corresponds to our measurements. If our measurements capture enough information about the geometric layout of the cave, then our model will correspond to reality. Our algorithm solves the problem of surface reconstruction reliably and it can be assembled from pieces of software already implemented by others, so we can realize the method with minimum software development effort.

From our point of view, a cave is a connected cavity. We try to approximately reconstruct the boundary surface of this cavity from rather sparsely-sampled points in the form of a triangular mesh. As cavities are physical objects, the boundary of a cavity is a watertight surface. Watertight means that there are no holes in it. Such surfaces divide the 3D space into two parts: the interior and the exterior of the surface. The surface's interior is a solid – the cavity itself.

We have rather few samples of a complicated surface, so we must be able to use all the information that our measurements capture. In addition to the location of the splay shots, there is also a relation between them. We know which shots were taken from the same station and the coordinates of all the stations are also known. We call a given station, together with the splay shots measured from that station, a *hedgehog*. So, we are looking for a watertight surface that satisfies two constraints:

Constraint 1

The splay shots lie on the surface.

Constraint 2

The segments connecting the splay shots to their stations are in the interior of the surface.

Unfortunately, for a finite number of splay shots, there are infinitely many feasible surfaces, i.e. that satisfy the constraints, and most of them are very unrealistic. For instance, the surface that resulted from replacing the segments in the hedgehogs with poles satisfies the constraints but cannot be accepted as a cave model. It is clear that we must select the best, or at least a rather good surface from the feasible solutions. We thus face a constraint optimization problem. In such problems, the solutions that satisfy the constraints are called *feasible* solutions. The goal is to find a feasible solution with optimal value of a function called the *objective function*.

The criterion by which we choose a good surface, i.e. the objective function, will be the bending energy (Germain, 1821; Wardetzky *et al*., 2007), which is defined for the surface S as:

$$E_b(S) = \frac{1}{2}\int_S H^2 dA \qquad (1)$$

where H is the mean curvature (Perdigão do Carmo, 1976), i.e. the sum of the principal curvatures, and dA is the differential area. A feasible surface with low bending energy will likely be free of unnecessary and undesirable 'bending' and 'wrinkles'. Our algorithm consists of four steps. In the first three steps, we construct an acceptable surface that satisfies the above constraints, at least for the vast majority of the splay shots. In the last step, we deform this surface to find a feasible solution with low bending energy.

Algorithms processing signals or measurements about real world phenomena usually have to incorporate the ability of detecting and removing outliers, i.e. anomalous measurements. Our algorithm also applies outlier detection. We remove the outliers, and do not require the constraints to be satisfied with respect to the outliers. An outlying splay shot can be the result of erroneous measurement with extremely long or short distance reading. If the laser beam accidentally hits a drop of water, the distance reading can be excessively long. On the other hand, short outliers usually result from shots on the surveyor's own body or objects that should be skipped over, like ropes or other artificial equipment in the cave. Unfortunately, outliers can also be caused by insufficient sampling (as described under 'Reconstructing Surfaces for the Extended Hedgehogs Separately'), so sometimes outlier detection can make bad decisions and remove accurate measurements, which leads to useful information being lost.

Extending the Hedgehogs

In the first step for each station we try to find all such points that are likely to be visible from the given station, but were measured from some other station. In other words, for each splay shot, we determine all the stations that it is visible from, and we add the point to the hedgehogs of these stations. We call the resulting hedgehogs the *extended hedgehogs*. In *Figure 1* we can see the extended hedgehogs of 1275 splay shots measured from two stations. The survey took place in the Mátyás-hegyi Cave under Budapest.

Reconstructing Surfaces for the Extended Hedgehogs Separately

In this step we create a watertight surface for each extended hedgehog separately. All surfaces will be watertight and will satisfy our two constraints with respect to their own extended hedgehog.

First, we cut back the splay shots to unit length, centred on the station (*Figure 2*).

Second, we take the convex hull of the endpoints of the unit length shots. If the points are in a general position, i.e. any four points are not coplanar, then the convex hulls will be a polyhedron with triangular faces – *Figure 3* (Na *et al*., 2002; Davies, undated).

Third, we keep the triangulation, i.e. the connectivity among the points, but put them back to their original positions (*Figure 4*). The resulting triangular surface is called *the turtle* of the given extended hedgehog.

Note that turtles are watertight triangular surfaces, that are free of self-intersections, so they are polyhedrons and encapsulate three-dimensional solids. Each turtle estimates the

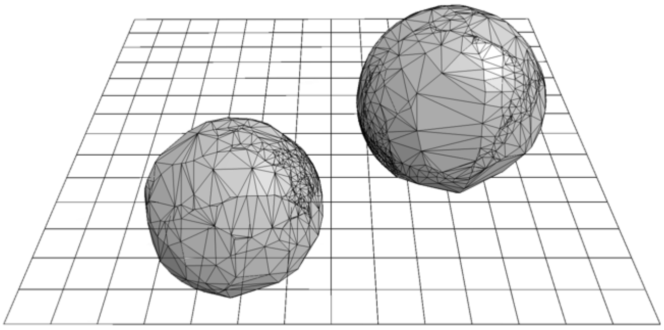

Figure 3 – Convex hull of the endpoints

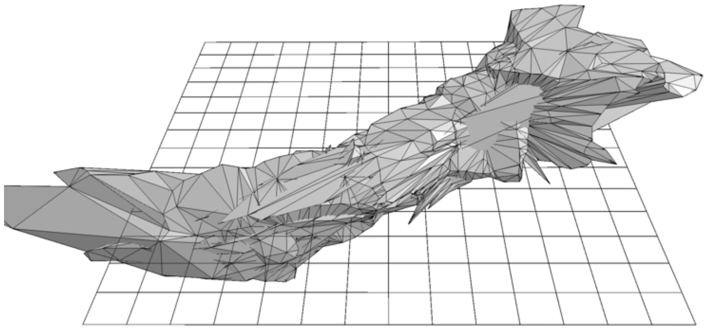

Figure 4 – Overlapping turtles

part of the cave that is visible from its station with an interpolation of the distance readings in the spherical coordinate system centred on the given station.

We propose here two conditions on the samples that are necessary for the correctness of our algorithm.

Condition 3

Neighbouring turtles are overlapping.

Condition 4

Splay shots that do not lie on the boundary of the volumetric union of the turtles, but in the interior of the union, come from erroneous measurements and they can be safely considered as outliers.

We assume that neighbouring turtles are overlapping. This can easily be guaranteed by taking overlapping measurements from the corresponding stations. *Condition 3* implies that neighbouring turtles are not disjoint and the resulting model will not be disconnected.

Condition 4 is necessary for correct outlier detection. The process of extending the hedgehogs ensures that splay shots lying in the interior of any turtle do not exist. Turtles are star-shaped objects, i.e. there exists a point, the station, from which all the points lying in the interior or on the boundary of the turtle are visible. So, the extending procedure has to result in turtles that do not contain any splay shots in their interior. Otherwise the given point should be considered visible from the station and added to the hedgehog of the station. In that case, the given point becomes a vertex of the turtle. Unfortunately, such boundary vertices may still lie in the interior of the union. To fulfil *Condition 4* volumetric objects inside the cave, that are large enough to survey, like large stalactites or the bridge in *Figure 7*, have to be surveyed from at least two opposite sides.

Creating the Union of Extended Turtles Based on Voxelisation

The union of the separate turtles are prepared by a robust method based on voxelisation. Voxels are 3-dimensional pixels. Voxelisation means that we divide the space into many small cubes, just like digital images are built up from pixels. In this step, we create a 3-dimensional binary image where each voxel represents the centre of a small cube. We set the value of a voxel to 1 if the centre-point is in the inside of any turtle, otherwise we set it to 0. We re-mesh (triangulate) the boundary of the volume made up of voxels with a value of 1. In *Figure 5*, we can see the resulting surface. The black dots show the splay shots.

By re-meshing, we make the mesh rather dense, so it will have much more vertices than the number of splay shots. We proceed in this way, because we will deform this mesh by moving its vertices while maintaining the connections, i.e. the triangles, among the vertices.

Under *Condition 4* the theoretical union of the turtles satisfies *Constraints 1* and *2*, neglecting some erroneous measurements. The voxelised union is only an estimation of the true union and may lead to additional splay shots that dissatisfy the constraints. Voxelisation is robust because it introduces a simple form of *regularisation* since volumetric features with extremely small volume, like needles or blades, will likely disappear. The corresponding samples will not satisfy the constraints, but usually they can be safely regarded as outliers resulting from measurement errors.

Optimization

During this step we shall deform the union in order to minimize the bending energy of the surface and conform to the constraints with as few 'wrinkles' as possible. In a continuous model, deformation is a function p defined on the points of the surface to deform. For all points, we assign its new position: p: $S \rightarrow S'$, where S and S' are sets of coordinate vectors. We assume that p is a regular parametrisation of the new surface with the old one, i.e. the mapping is one to one and continuously differentiable at least two times. Regular means that linearly-independent directions remain independent during the mapping. We apply the method described in (Jacobson *et al*., 2010) to minimize the bending energy. For the sake of efficient computing we apply an approximation:

$$E_b(S') \approx \frac{1}{2} \int_S \langle \Delta p, \Delta p \rangle dA \qquad (2)$$

where Δ is the Laplace-Beltrami operator on the reference surface and ⟨ , ⟩ denotes the

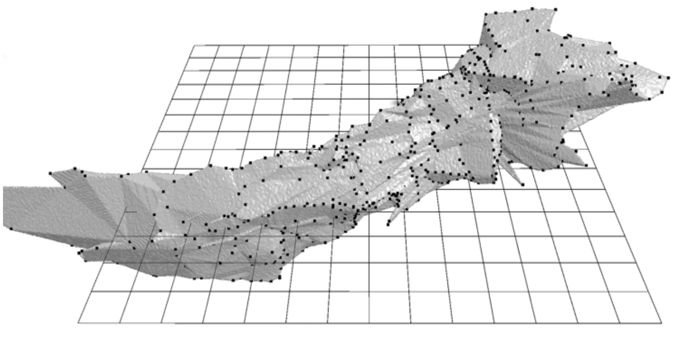

Figure 5 – Voxelized union of turtles

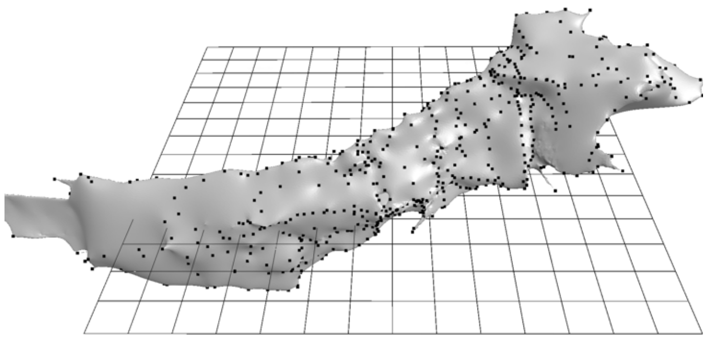

Figure 6 – Final biharmonic surface

Figure 7 The interior of the result (left), photo of the same place by András Hegedűs (right)

inner product in $\mathbb{R}^3$. The related Euler-Lagrange equation is the biharmonic equation with the unknown function *p*:

$$\Delta^2 p = 0 \qquad (3)$$

The approximation in Equation (2) requires that *p* be closely isometric, which likely does not hold for large deformations. The integral in Equation (2) is sometimes called the Laplacian energy. In addition to minimising Equation (2), we have to ensure that our constraints are satisfied. Constraints can be incorporated into our framework as boundary values of the unknown function *p* in the biharmonic differential equation. For some points on the reference surface, i.e. the union, we can prescribe new positions by boundary values of the form:

$$p(x_i) = c_i \qquad (4)$$

where x_i will be some selected vertices of the reference mesh and c_i will be the new coordinates of these vertices.

We choose x_i and c_i as follows. For all vertices v_i of the reference mesh we assign the closest splay shot:

$$f(v_i) = \underset{c \in C}{\arg\min}\, d(v_i, c)$$

where *C* is the set of sample points (splay shots) and *d* is the Euclidean distance in the 3-dimensional space. For each c_i from the range of *f* let

$$x_i = \underset{v \in f^{-1}(c_i)}{\arg\min}\, d(v, c_i)$$

where $f^{-1}(c_i) = \{v: f(v) = c_i\}$. The splay shots that were not assigned to any vertex by *f* are considered outliers (erroneous measurements) and removed.

Solving the above boundary value problem and evaluating the resulting function *p* in every vertex of the reference mesh gives the vertices of the deformed mesh. While moving the vertices to their new positions, we maintain the same triangulation. The deformation assures that *Constraint 1* will be satisfied with respect to the measurements that have not been regarded as outliers. Satisfying *Constraint 2*, namely keeping the segments of the hedgehogs in the interior, is achieved in a less elegant way. We detect the segments that have some interval outside the new surface. We sample these intervals equidistantly. For these new points, we assign vertices from the original mesh in the same way as for the splay shots, and we add a further boundary value condition, but we keep the assigned vertices in their rest positions, i.e.

$$p(x_i) = x_i \qquad (5)$$

We solve this extended boundary value problem again on the original union mesh. *Figure 6* shows this solution in the case of our example.

In *Figure 7* we can see the same mesh from the inside (left) and a photo of the real cave from nearly the same point of view.

Note that our algorithm estimates cave geometry by interpolating instead of approximating the splay shots. This implies that we do not apply any error model in order to eliminate the effects of errors in the measurements that have not been removed by outlier detection. The algorithm is designed to work on extremely sparse samples, so interpolation seemed to be a more appropriate approach than approximation. In the case of having a large number of splay shots, it is worth to apply smoothing on the resulting mesh as a post-processing step and achieve a suitable smooth approximation.

Implementation

As PMLS is a project done by hobby-cavers, we did not have much time for software development. It was critical to find an algorithm that can be assembled from already existing software tools with moderate programming efforts. Most of the tools we have applied are free and open source. The only commercial program that we used is Matlab (Mathworks, 2015). Matlab is ideal for fast implementation of concepts and algorithms to verify, and to create a software prototype that can even be handed to the users for testing.

To solve the surface reconstruction problem, we used several free and open source software in addition to Matlab. Considering the details of our algorithm, the step of creating the turtles from hedgehogs is done by Matlab functions. For extending the hedgehogs with points measured from other stations we used the fast ray casting software opcode (Terdiman, 2001), through a modified Matlab wrapper (Vijayan, 2013). The voxelized union is performed by Iso2mesh (Fang & Boas, 2009), which is a package containing many mesh-processing tools originating from the field of 3D medical imaging. The optimization of the bending energy is performed by the biharmonic deformation function of LibIgl (Jacobson & Panozzo, 2016).

In order to effectively try out a concept, the developer needs a tool for visualizing the results. The program that we used for that purpose was Blender (Blender Online Community, 2016). Blender is a software package for creating 3D animations. Its coolest feature is that we can make a fly-through of the models. During my talk at the EuroSpeleo conference, I demonstrated the potential of PMLS by performing a fly-through inside one of our cave models (Editorial Team, 2016). Blender is excellent for viewing every tiny detail of 3D models. In addition, Blender's functionalities can be extended with add-ons written in the Python programming language. On the other hand, Matlab has a Python interface, i.e. Matlab functions can be called from Python. It was straightforward to create a graphical user interface for our method in the form of a Blender add-on.

We can load the input data from CSV files, then we can view and edit the hedgehogs in Blender. For instance, we can delete erroneous measurements. The steps of the surface reconstruction process can be triggered by pushing buttons. At the end we can view the resulting mesh, and we can

Figure 8 – Tripod Head for DistoX2

Figure 9 – Surveying in Bányász Cave

export it in many kinds of file formats. Our software will soon be available for download at **cave3d.org**.

Guidelines for On-site Work

The geometric layout of caves can be very complicated with features at all scales. So, do not try to make a perfect job, because it’s impossible. Note that the DistoX can have an error of 1-2 degrees in the horizontal angle, and try to capture details at a reasonable scale. The ‘take it easy’ approach is more effective than being a perfectionist.

Typically, we take about 50 to 500 splay shots from one station. Stations can be on the walls, as in conventional centreline survey, or a station can also be on a tripod. The only strict rule that the surveyor must satisfy is to make sure that the measurements performed from neighbouring stations are heavily overlapping. You should take splay shots at least until the neighbouring stations, i.e. each turtle, contains its neighbouring stations.

On the other hand, it is wise to avoid long range shots if the given section can be surveyed from a closer station, because angle errors cause displacement of points proportional to the distance. Try to think a bit in spherical coordinates. All your measurements assign a distance to a pair of angles. The first step of surface reconstruction will be an interpolation of the distance function, which should well estimate the cave section that is surveyed from a given station. The most important thing is to make measurements on corners and peaks, and to survey edge-like features with some detail. Flat surfaces can be surveyed with a small number of shots. Avoid shots where small changes in the direction can cause large errors in the distance. This is especially the case at some edges where a hidden surface becomes visible (discontinuities of the distance function), or by measuring walls nearly parallel to the laser beam. Discontinuities should be surveyed on both the near and the far sides, so do not skip such edges, but keep off a bit from the true edge.

If a volumetric object inside a cave is surveyed, there should be enough samples on its opposite sides to fulfil *Condition 4*.

We found that it is convenient to use a tripod wherever possible. Balázs Holl built us a special 3-axis, non-magnetic tripod head as shown in *Figure 8* and in use in *Figure 9*.

Tripod-based stations provide points of view in the interior of passages and chambers, which are usually much better than on-the-wall stations.

An upgrade to the DistoX firmware by Beat Heeb accelerates the measuring process. It makes a scan mode available, so it is not necessary to push the button for each shot, but the device samples automatically as fast as it can. A shot requires one or two seconds, depending on the reflectivity of the wall.

Results

Validation Against a TLS Survey

We needed to validate the results to see how realistic the PMLS cave surveying technique is. For the validation, we picked up an easily-accessible place in the Mátyás-hegyi Cave where complex and internal surfaces are also found (see *Figure 7*). We scanned this location with a Faro Focus 3D S 120 TLS (ranging error is ±2mm at 10m) to validate the surface whose creation was shown in the section entitled ‘The Proposed Method’. As our models are very inaccurate at their endings, where the walls are visible only from a single station, so we cut off the two ends, and kept only a 16.5m section around the bridge in *Figure 7*.

We scanned the place with TLS from six positions, which resulted in a really high density pointcloud, therefore it was necessary to resample the points in a 1cm grid. The surface model was then transformed (only translation and rotation, without scaling) into the coordinate system of the TLS point cloud using the Iterative Closest Point (ICP) algorithm.

We measured the distances of all the 24.5 million samples in the mentioned grid points from the surface with the CloudCompare software.

Figure 10 shows the orthogonal projection of the point cloud viewed from above and coloured according to its deviation from the model. Every point is closer to the model than one metre. 92% of the samples are closer than 300mm and 85% of the points are closer than 200mm.

In *Figure 9* we can see that errors larger than 500mm are due to small features that were not surveyed or were not even visible from the two stations of the PMLS survey. The cumulative histogram of the distances can be found in *Figure 11*.

The mean of the distances is 113mm. Since the largest errors are caused by not surveying some narrow cracks, the median is a more appropriate descriptive measure, which is only 74mm. Considering that the 860 splay shots that lie on the analysed surface have a 52mm mean deviation from the TLS point cloud, these results are very impressive, and show that our interpolation technique is rather effective.

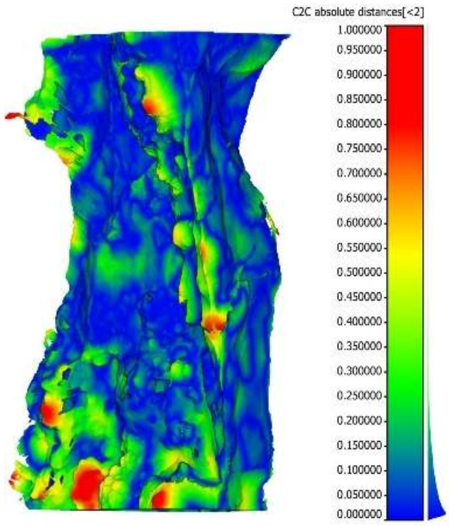

Figure 10 – Deviation of point cloud samples

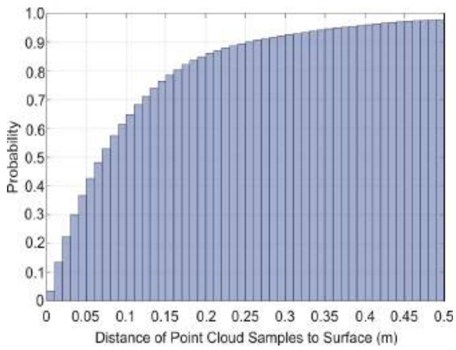

Figure 11 – Histogram of point cloud deviation

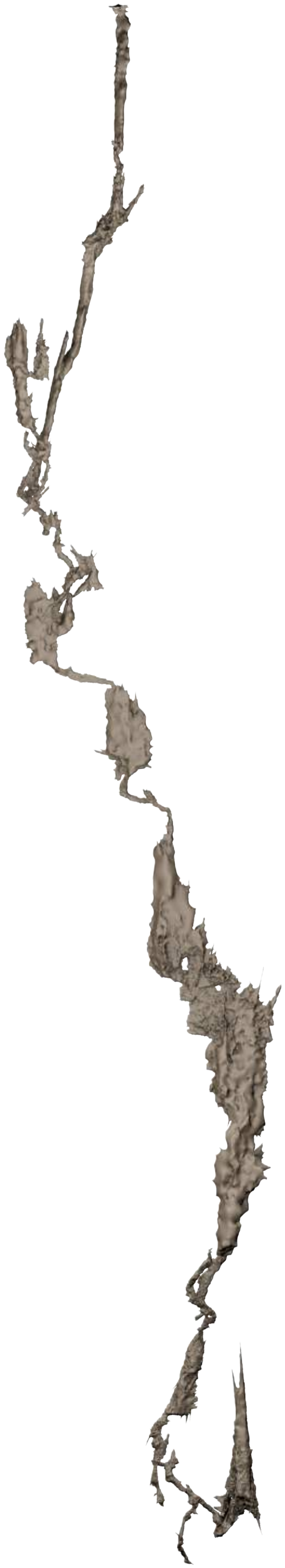

Figure 12 – Bányász Cave

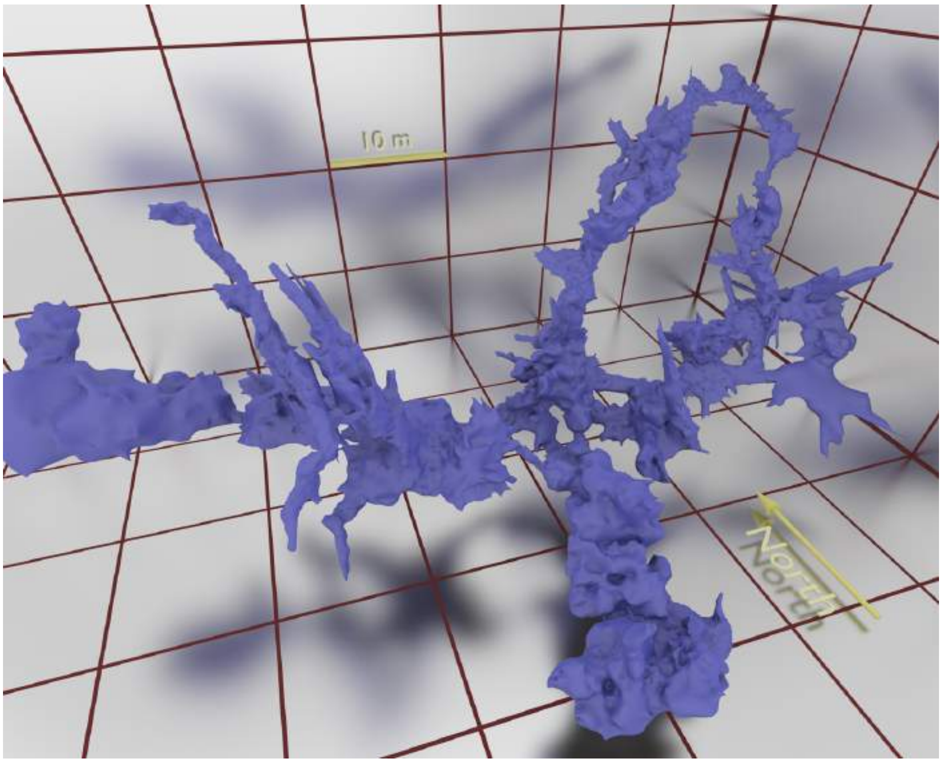

Figure 13 – Legény Cave

Bányász Cave

Our main project is surveying the Bányász cave, the deepest cave in Hungary (273m). The cave is a true pothole, which requires heavy use of SRT. The entire cave is 830m long, from which we have surveyed 810m. *Figure 12* shows the orthogonal projection of the result. The on-site work took 15 days. One surveying team worked 4-8 hours each day. Usually we have worked with a single DistoX, but there were four days when we could use two DistoXs. We measured about 61,000 splay shots from 197 stations.

Legény Cave

The surveyed section of Legény cave is not so long as in the case of Bányász cave. It is only 390m, but the cave has a rather complicated geometric layout – see *Figure 13*.

The surveying took three days. On the first two days, we used a single DistoX, while on the last day we were able to use two DistoXs. We measured more than 24,000 points from 112 stations.

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The Authors *(see cave3d.org)*

Attila Gáti graduated in Computer Science from the University of Miskolc in 2003. He was a PhD student and a scientific co-worker in the Institute of Mathematics at the University of Miskolc from 2003 to 2008. Since 2008 he has been with the R&D division of ARH corporation (**arh.hu**) as an algorithm developer working in the field of image processing and computer vision. He earned his PhD in Informatics from the Óbuda University in 2013. He began caving in the same year as a member of FTSK (**ftsk.hu**) and MLBE caving clubs (**mlbe.hu**).

The idea of using the DistoX for 'scanning' many points on the wall of the cave and to gain a 3D model seems obvious. Probably many cavers had been experimenting on this, among them a Hungarian group of cavers, the authors of the current paper. Péter Sűrű, Imre Balogh and Zsombor Fekete (members of MLBE and OBTE caving clubs) after the first experimental measurements turned to Attila Gáti for help in data processing, who developed a method of surface reconstruction for the current application.

At the same time Balázs Holl from the Papp Ferenc Speleologic Club (**pfbke.hu**) also contributed with testing and with many good ideas (like the tripod head).

Balázs Holl has been dealing with cave surveying and spatial modelling for 30 years. Currently he is experimenting with photogrammetric mapping of caves.

Nikolett Rehány (member of FTSK caving club) joined the team as an expert in static and mobile laser scanning. She is pursuing her PhD at the Budapest University of Technology and Economics.

Zsombor Fekete is a Hydrogeologist Engineer and currently a PhD student at the University of Miskolc. His main caving activities include exploration and hydrological studies.

Péter Sűrű works as an Environmental Engineer. He is an experienced cave explorer, who has been caving for 15 years.

We Hear...

News and events – Mike Bedford brings us the latest to impact the world of cave radio and electronics.

Batteries to Last Longer

Although recharging a battery is, in theory, the reverse electrochemical process to discharging it, in practice it isn't totally reversible. The end result is that batteries don't last forever. Today's lithium-ion batteries, as used in smartphones, tablets and laptops, can lose as much as 25% of their capacity after 250 full discharge-recharge cycles, although the degradation isn't quite as bad with shallower discharge cycles.

Given that this loss of capacity can, therefore, start to become noticeable after a year of constant use, scientists at University of California, Irvine have developed a nanowire-based battery material that can be recharged hundreds of thousands of times, moving us closer to a battery that would never require replacement.

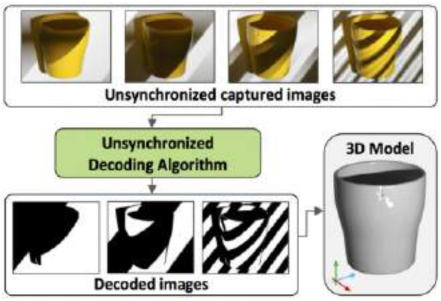
The use of nanowires is common in battery research because they're highly conductive and feature a large surface area for the storage and transfer of electrons. However, these filaments are extremely fragile and don't hold up well to repeated discharging and recharging, or cycling. In a typical lithium-ion battery, they expand and grow brittle, which leads to cracking. UC Irvine researchers have solved this problem by coating a gold nanowire in a manganese dioxide shell and encasing the assembly in an electrolyte made of a clear gel. The combination is reliable and resistant to failure and has been tested through 200,000 cycles with no loss of capacity.

3D Scanning Becoming Affordable?

Although most cavers can't afford a 3D laser scanner, the use of multiple still images to build up three-dimensional models of cave formations is an option that has been reported in *CREGJ*. However, taking the necessary sequence of photographs from multiple viewpoints is a lengthy process. An alternative technique referred to as structured light scanning simplifies the process but requires sophisticated hardware comprising a structured light projector that is accurately synchronised to a camera.

In the structured light technique, a projector casts a series of light patterns on an object, while a camera captures images of the object. The ways in which those patterns deform over and around an object can be used to render a 3D image. But for the technique to work, the pattern projector and the camera have to be precisely synchronized, which requires specialized and expensive hardware.

Now, an algorithm developed by Brown University researchers could help turn smartphones and off-the-shelf digital cameras into structured light 3D scanners. All that is required is a camera that can capture images in burst mode at several frames per second and the software is able to match the images with the projected pattern without the usual synchronisation.



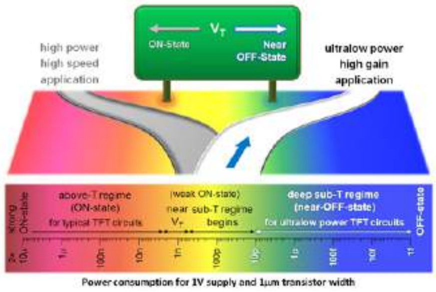
Ultra Low-power Transistors

Extracted from 'Research News' on the Cambridge University website, this could revolutionise 'fit and forget' cave sensors.

A newly-developed form of transistor opens up a range of new electronic applications including wearable or implantable devices by drastically reducing the amount of power used. Devices based on this type of ultralow power transistor, developed by engineers at the University of Cambridge, could function for months or even years without a battery by 'scavenging' energy from their environment.

Using a similar principle to a computer in sleep mode, the new transistor harnesses a tiny 'leakage' of electrical current, known as a near-off-state current, for its operations. This leak, like water dripping from a faulty tap, is a characteristic of all transistors, but this is the first time that it has been effectively captured and used functionally.

The new design gets around one of the main issues preventing the development of ultralow power transistors, namely the ability to produce them at very small sizes. As transistors get smaller, their two electrodes start to influence the behaviour of one another, and the voltages spread, meaning that below a certain size, transistors fail to function as desired. By changing the design of the transistors, the Cambridge researchers were able to use Schottky barriers to keep the electrodes independent from one another, so that the transistors can be scaled down to very small geometries.



The design also achieves a very high level of gain, or signal amplification. The transistor's operating voltage is less than a volt, with power consumption below a billionth of a watt. This ultralow power consumption makes them most suitable for applications where function is more important than speed, which is the essence of the Internet of Things.

"If we were to draw energy from a typical AA battery based on this design, it would last for a billion years," said Dr Sungsik Lee of the Department of Engineering.

Isolated Current Measurement

LEM has introduced a new series of small integrated-circuit transducers for AC and DC isolated current measurement which are potentially useful for monitoring earth arrays. These new parts offer complete isolation despite their tiny dimensions (SO8 package). They have an integrated primary conductor for nominal current measurements up to 20A and with a measuring range of 2.5 times the nominal current. They can handle large current surges up to 200A for a short time (1ms).

Your Reports are Invaluable

It's encouraging that several of you send me snippets for this column but I'd welcome more to make its content more varied. So, if you see a news item that you think would interest other *CREGJ* readers, please forward them to me.

Please send your input to me, Mike Bedford, at **BedfordMD@aol.com**.

Cave Thermal Imaging with a Smartphone?

The FLIR® ONE mobile phone accessory transforms a smartphone into a thermal imaging camera. ***Andy Lillington*** *has been evaluating the device in the caving environment, looking for thermal anomalies that may be related to underground features. His evaluation included both UK limestone and Icelandic lava tube areas.*

This article describes a series of cave-related trials using the FLIR® ONE, a miniaturised next-generation mobile phone accessory device which turns a smartphone into a fully-fledged thermal imaging camera.

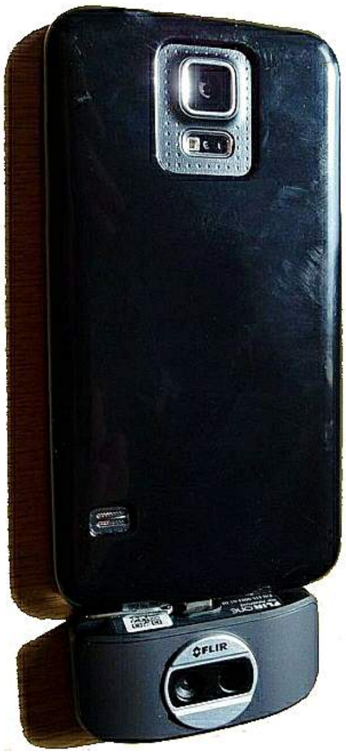


Figure 1 – Android Phone and FLIR ONE

It was considered that a thermal imaging device connected and recording to a smartphone could form a practical tool in the detection of caves by allowing the terrain to be remotely and quickly scanned for temperature anomalies which may be related to underground features.

The use of thermal imaging for cave detection has been covered in this Journal before, principally by John Lyles [1a,b] in CREGJ65 and 66. However, this was nearly ten years ago and, as John suggested it would, the cost of such equipment has come down and capabilities have improved, making it a more practical proposition.

Trials

For the experimentation undertaken during Summer 2016, two different types of caves were selected. A limestone cave entrance and resurgence was recorded in the UK, followed by lava tube entrances (or skylights) in Iceland. The results from the testing appeared fairly positive. It was thus considered that emerging devices of this nature may, in some circumstances, provide some assistance to a cave explorer.

Technology

The FLIR® ONE for Android® was released in August 2015, and includes a 160×120 resolution LEPTON® thermal imaging sensor which takes a rolling reading of the longwave infrared spectrum, with a temperature detection range of -20°C to +120°C and a resolution of 0.1°C. The

Figure 2 – A Domestic Infrared Source

Figure 3 – Otter Hole Cavers' Entrance

The thermal signature of the cave entrance is clear. Note the edge detail contributed by the VGA camera and superimposed on the thermal image.

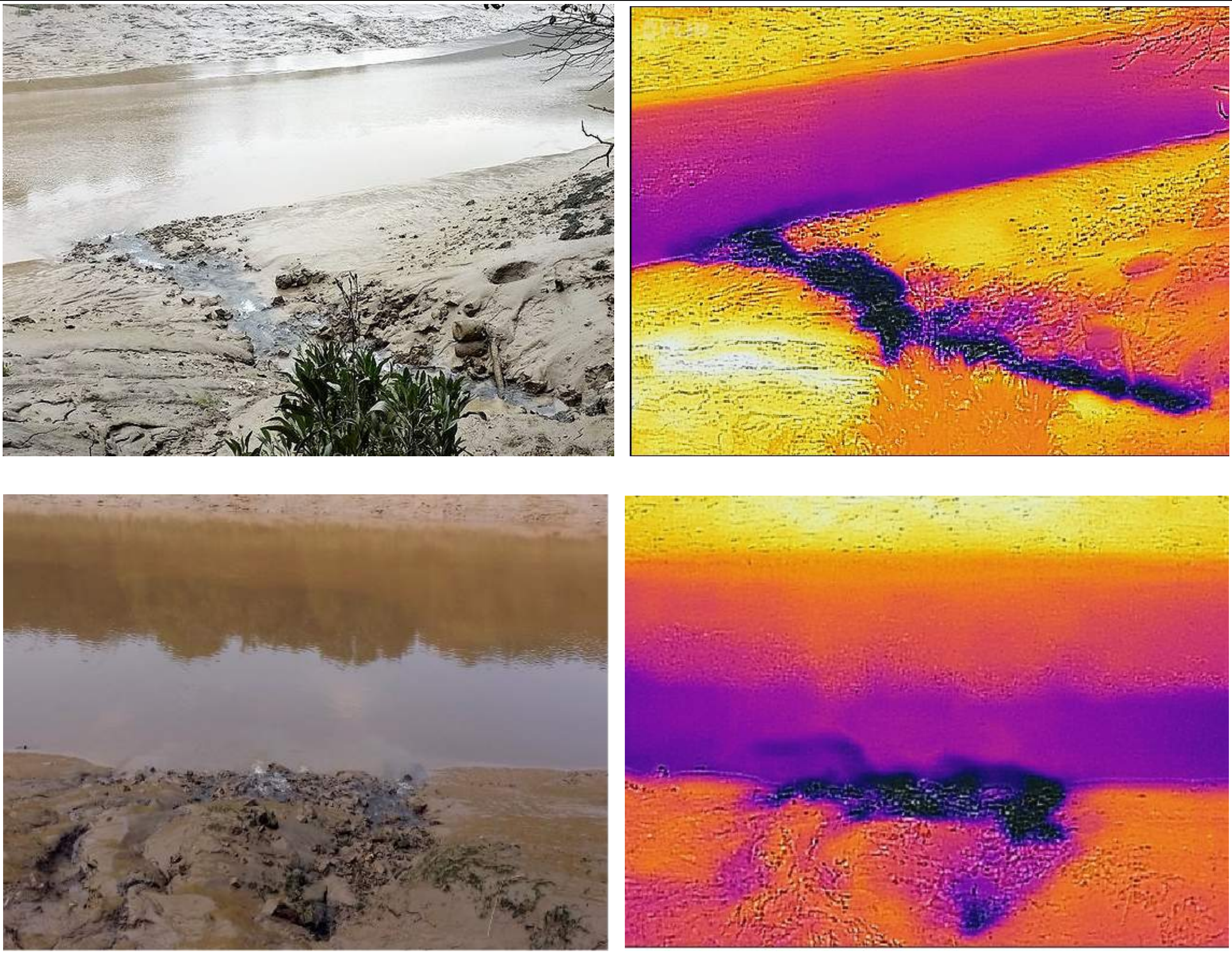


Figure 5 – Otter Hole Resurgence (top) and Ban-yr-Gore Rising (bottom)
Good examples of the temperature difference between the river and water emerging from underground

thermal imaging information is then combined with a standard picture taken with an on-board 640×480 pixel VGA camera and blended together using multi-spectral MSX® technology to provide greater physical detail to the thermal reading. This is undertaken using an app downloaded from the Google Play store [2].

Using the phone app, it is possible to change the palette, use a spot temperature meter and post-process the imagery to obtain further spectral detail using a separate app tool. Recording modes include basic still images, close-up images, video, panorama shots and thermal time lapse. The images are updated at 8.9 frames per second and the unit is auto-calibrated every 30 seconds. An illustration of a Galaxy S5 phone connected to the FLIR® ONE is given in *Figure 1*, together with a typical image as viewed on the screen in *Figure 2*.

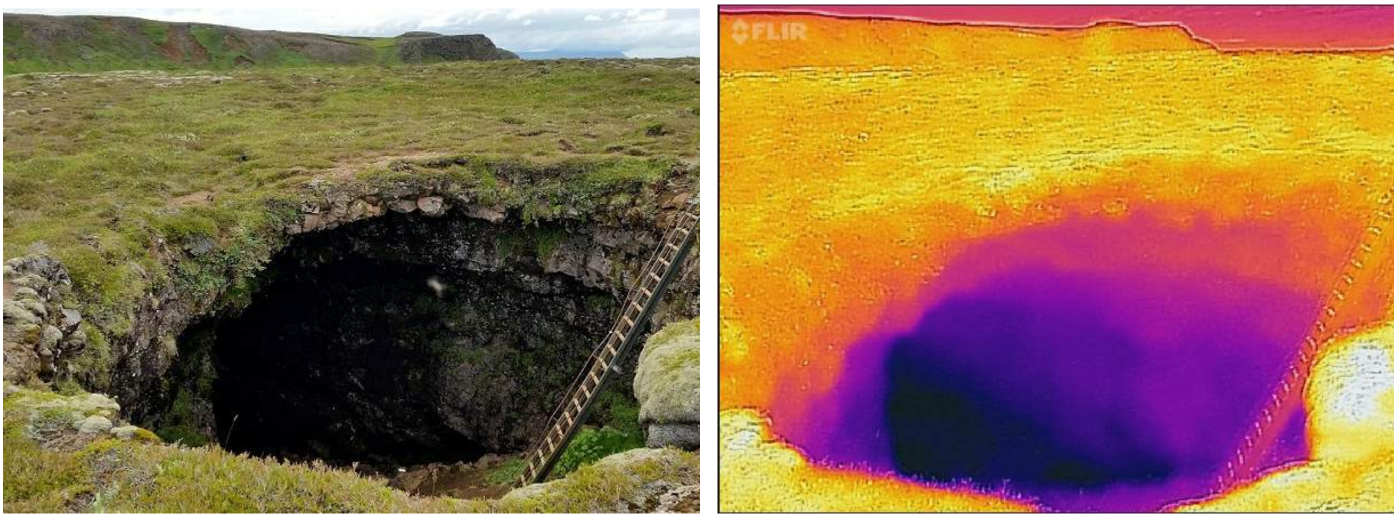


Figure 6 – Arnarker Lava Tube
The lower temperature of the lower section of this 15m diameter entrance is clear.

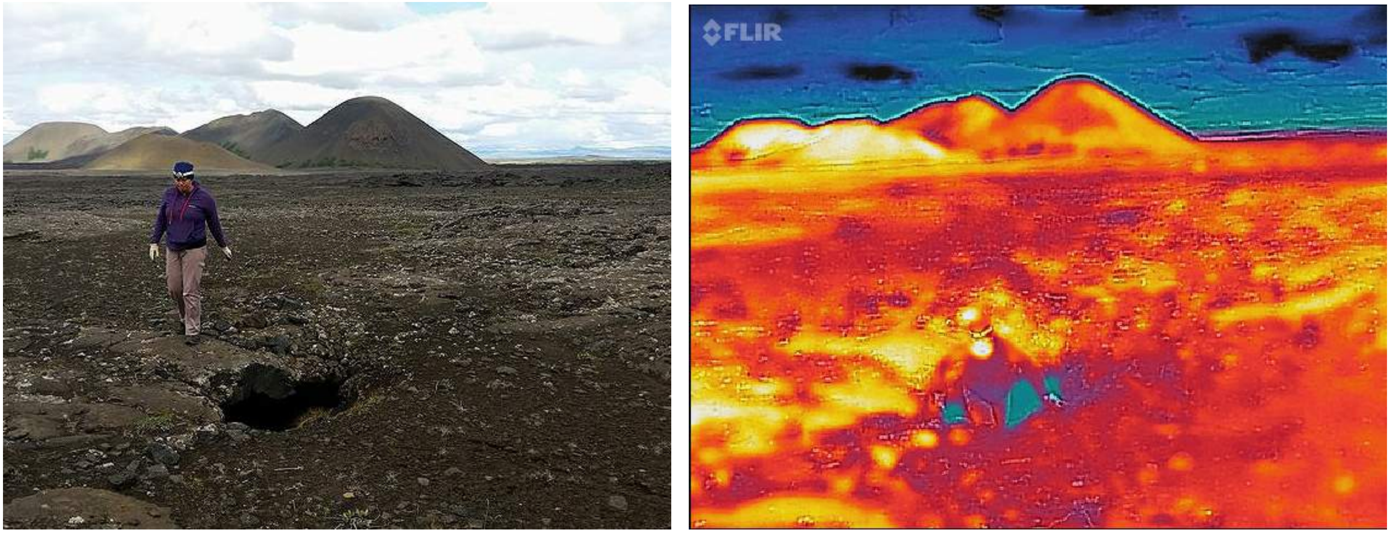


Figure 7 – Unnamed Lava Tube
A test to determine if a very small entrance can be detected in a relatively featureless area.

The dimensions of the device are 72mm × 26mm × 18mm and it weighs 78g. The miniature size of the device lends it to easy transporting over long distances when exploring on foot.

The FLIR device includes an on-board 350mAh battery powering the device for 45 minutes between charges and the device is charged separately from the phone. The current lowest retail price (as of September 2016) is £165.

Some research into the possible practical use of this thermal imaging technology to locate caves has been undertaken by others. A video [3] was produced in 2013 comparing the infrared signature of cave entrances. It indicated caves without a draught are not very visible at all and emerging cave water produces the greatest thermal signature.

A trial has been undertaken with thermal imaging cameras by Irish cavers who attached an early model of the FLIR ONE / iPhone combination onto a drone to try and find cave entrances from the air, and although the drone crashed due to the combined weight, the video [4] indicated some encouraging handheld images of the entrance to Ireland's Poulnagree cave.

Other similar devices exist such as the Seek Compact4 which includes a 206 × 156-pixel thermal sensor which is also attached via the micro USB connector. The Compact uses the phone battery and doesn't use blending technology to add lines and definition to the image.

Testing in the U.K.

A series of trials were undertaken on limestone caves in the U.K. to see what kind of thermal signature could be expected. The first trial was undertaken at the entrance to Otter Hole in Monmouthshire, both at the cavers' entrance and at the river resurgence.

The trial was undertaken when the River Wye was at low tide such that the tidal sump was open and the air draught was in evidence at the cavers' entrance. *Figure 3* illustrates the thermal images obtained.

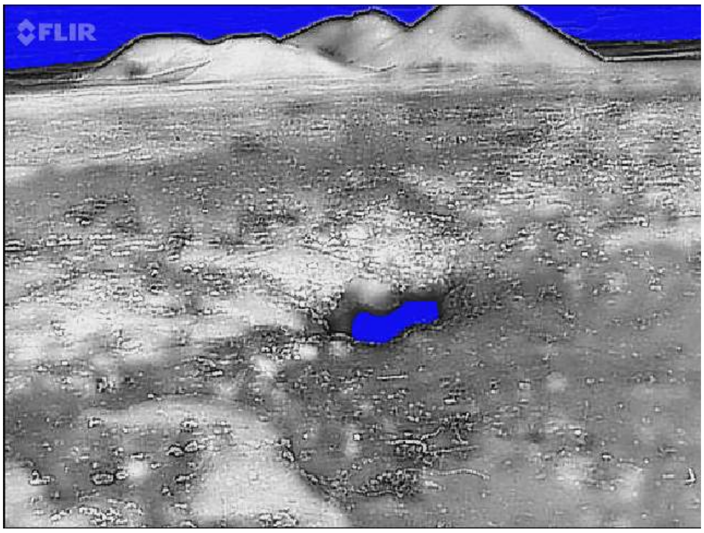


Figure 8 – Coolest Readings
By manipulating the colour pallet of the device, only the coolest area is shown. This show promise for rapid scanning and detection.

The effect of the colder air draught can be seen on the rocks surrounding the entrance, which seems to lower the temperature by approximately 7°C, given the ambient outside summer air temperature was about 22°C.

The thermal imagery of the river resurgences of Otter Hole and at Ban-yr-Gore are shown in *Figure 5* The water emerging from the cave is much colder than the surroundings and the river water, and contrasts strongly against the estuarine mud. The mixing of the cave water into the river can also be observed.

Testing in Iceland

A number of tests on post-glacial lava fields were undertaken in Iceland during Summer 2016. The experimentation aimed to observe how the device functioned near cave entrances (or skylights) in a lava flow.

Given lava rock forms a good insulator, the summer daytime ground surface temperature readily increase in comparison to the lava tubes beneath, which remain cool and in some cases close to freezing all year around with ice formations present. This significant temperature gradient was already known and thus thought to lead to potential detection by a thermal imaging camera.

Arnarker forms a large diameter 516m long lava tube located in the Leitahraun lava flow, located 30km to the south-east of Reykjavík. The entrance skylight to this cave is fairly large at about 15m diameter. *Figure 6* illustrates the thermal image recorded of this cave.

The thermal image of the cave is strong and contrasts with the vegetated surface-covered lava, however the temperature gradient was restricted to below the entrance skylight. This may be a function of the large size of the skylight.

A further test was therefore undertaken at another, unnamed, lava tube, located elsewhere in Iceland, which includes much smaller entrances that are known to strongly air draught given they are linked to an extensive 2km series of passages and other entrances.

The thinking behind this test was to determine whether the camera could detect (at a reasonable scanning distance) any entrance against the lava field backdrop, given Icelandic pahoehoe lava fields can be fairly featureless.

The picture shows the cave entrance in the centre of the image; however, the high solar irradiance on the day seems to have reduced any localised cooling effects of the exiting air draught from the very small entrance onto the surrounding rocks.

However, the colour pallette option in the FLIR app can also be set to show just the coolest or warmest part of the image. *Figure 8* illustrates what is shown on the screen of the phone using this setting.

This setting proved to be a much more useful tool in quickly detecting hitherto unknown cave passages in a vast and featureless lava field. It forms a more prominent image than the graduated thermal display and allows fairly quick detection of temperature anomalies on the surface, even at some distance.

Summary and Conclusions

The main findings from the smartphone testing can be summarised as follows:

- The FLIR® ONE smartphone device would appear to be a fairly capable miniaturised thermal imaging device which can be easily transported into the field.
- The device can record images and video onto a smartphone for immediate viewing and analysis, email attachment or uploading to the cloud.
- The device is capable of detecting ground temperature anomalies up to a practical distance of about 40-50m which is probably a function of the limited resolution of the LEPTON® thermal imaging sensor.
- Water emerging from a cave or a spring produces a very strong thermal signature against the surroundings and a colder temperature may help determine whether a cave may be present.
- The presence of an air draught from a cave entrance can enhance the temperature anomalies in the vicinity of a cave entrance, but only if the solar irradiance of the surrounding surface does not offset the effects of the air draught.
- Use of the available software palette options can readily enhance the ability and usefulness of the thermal imaging camera when in the field.

The testing of the FLIR® ONE thermal imaging camera smartphone attachment has therefore revealed that, under some circumstances, it may be able to provide some practical assistance to a cave or mine explorer by allowing the surrounding terrain to be remotely and quickly scanned for temperature anomalies which may be related to underground features.

The limitations of the device are however apparent, which is perhaps not surprising given the product cost is low. More capable thermal imaging cameras typically cost between 5 and 10 times as much and are generally much larger.

USB OTG

It is worth noting that this thermal imaging accessory will only work with devices that are OTG-enabled. OTG (On-the-Go) is a standard that enables devices to connect directly to each other. This allows external USB drives, keyboards and other peripheral devices to be connected.

The Samsung Galaxy S5 smartphone used here is OTG-enabled; however, many mobile devices are not. Beware of this requirement if tempted to obtain one of these units.

An alternative approach may be to use a Raspberry Pi or similar device in place of the smartphone. At least one individual has reported success, **twitter.com/TheRealMike**, and further details may become available over time.

Future Work

It has been speculated that this technology may be useful for underground draught detection. Success would depend on the persistence of the draught and the thermal properties of the rock surrounding the draught, for a sufficiently detectable temperature difference to be established. However, solar effects will obviously not compromise detection. Trials will be reported in due course.

Acknowledgment

We are grateful for the opportunity to publish this article, which is based on material submitted for publication in the Journal of the Shepton Mallet Caving Club.

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[2] **play.google.com/store/apps/details?id=com.flir.flirone&hl=en_GB**

[3] **cavingnews.com/20130302-video-compares-cave-features-in-infrared-and-visible-light**

[4] **cavingnews.com/20150128-watch-cavers-test-thermal-imaging-infrared-camera-finding-caves** and **http://cavingnews.com/20150530-watch-cavers-use-drone-to-locate-cave**

[5] **www.thermal.com/products/compact**

CREG

Articles for the CREG Journal

We sense that much work in cave radio and electronics goes either unreported or, at best, is reported only in local caving club magazines.

We are keen to make such material available to a wider audience.

If you write something on a suitable topic for your club magazine, please consider forwarding a copy to us for possible publication. We are happy to let your club publish first and, of course, will credit the club with giving permission to publish.

And as a reader there is also a role for you to play; please act as a scout and let us know if you come across a project or anything published in the UK, or further afield, that might be suitable for the CREG Journal. Layout and presentation is unimportant, as we will handle that. All we ask is that we are put in touch with authors who might like to present their work to readers of the Journal.

And if you are thinking of providing something for publication, it makes life easier if photographs of equipment are taken against a plain background and that pictures and diagrams are also provided as separate files, if at all possible – though we can generally cope if not!

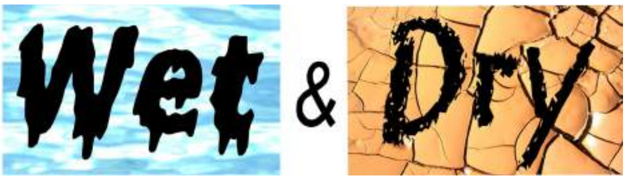
So, please consider the CREG Journal when writing up a project or when you spot something that you think might interest fellow readers!

Many thanks,

Rob Gill
creg-editor@bcra.org.uk

Print Subscribers

We try hard to ensure that readers of the printed Journal are not disadvantaged by our being limited to printing internal pages in monochrome. However, attempts at monochrome compatibility inevitably fall short when the illustrations must rely on colour for interpretation. Full colour PDFs are available online to all subscribers.



Ruggedisation, waterproofing & construction techniques – a roundup by Tony Haigh.

Keeping that case waterproof!

Continuing with the theme from the last edition, this time focusing on keeping the water out!

So we purchase an expensive IP67-rated case for our new project, and the first thing we do is to drill holes in it for all the various switches, sockets etc, potentially degrading the IP67 rating in the process! Eliminating or at least minimising the number of holes in the case is therefore an attractive option.

In general most devices will need one or more of the following, each potentially requiring a hole in the case:

- On/off switch
- Switches to control the functionality of the device
- Visual display
- Input/output connections
- Connection to allow internal battery to be charged.

There are a number of options to minimise the number of holes in the case, as follows:

- Magnetic reed switch operated by an external magnet
- Resistive switch senses the change in resistance when a finger bridges two contacts – but discounted for caving use because they're susceptible to false triggering by airborne water droplets
- 'Capacitive' switch that senses the close proximity of the operators finger through the case wall of the device
- Membrane switches that operate by applying pressure to an outer membrane
- A touch screen that uses either resistive or capacitive coupling to detect the presence of the operator's finger
- Remote control using Bluetooth to provide a wireless link between the sealed device and an external waterproof user interface device
- Battery charging through the case using inductive coupling between the charger and the internal battery.

Apart from the reed switch, all these require the sensing circuitry to be live for them to function, even as an off/on switch, this means a small current drain still occurs in the standby mode. Furthermore, this functionality adds complexity to the core circuit design.

Magnetic reed switches

The reed switch is relatively old technology, but still provides an extremely robust solution for simple switching application. The reed, comprising of two metal strips that make contact when drawn together by an externally-applied magnetic field, that are housed in a sealed glass envelope. A reed switch mounted close to the inside wall of a case can be operated by the presence of an external permanent magnet. The magnet can be retained using some sort of slider mechanism – simple, robust and effective!

Capacitive switches

These comprise of an active circuit that will detect the presence of the operator's finger in close proximity to the sensing electrode. The finger effectively provides a capacitive path to a high impedance earth via the body. This can be implemented as a single switch or a multiple array such as a keypad. The Nicola 3, for instance, uses an array of four pads to control the functions of the radio.

A useful description of touch sensing technology by Texas Instruments may be found at **www.ti.com/lit/an/slaa576a/slaa576a.pdf**

There are several methods of implementing this in hardware. The first example is shown in *Figure 1,* where the capacitance to earth via the finger causes a detectable shift in frequency.

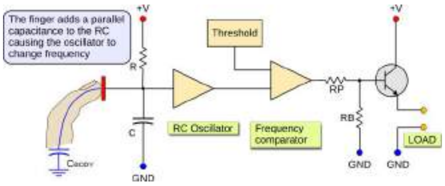


Figure 1 – Frequency shift touch switch
(source: **www.pcbheaven.com/wikipages/How_a_Touch_Button_works/?p=1**)

This is rather complex for a simple switch operation. An alternative, if a microprocessor is used for the main circuit operation, is to use an analogue-to-digital converter (ADC) to sense a small voltage change caused by the introduction of the additional capacitance of the operator's finger.

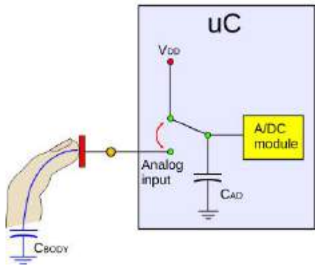


Figure 2 – Small voltage change detected by ADC
(Source as Figure 1)

An example of a small keypad with up to 16 keys is shown in *Figure 3*, this includes on-board ADC and multiplexing circuitry, and is particularly useful for controlling Arduino-based devices, or similar, as the code for the keypad can reside on the same processor board. Note only two digital inputs are required in this example.

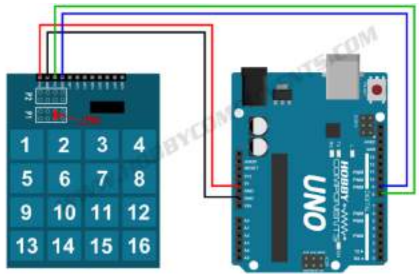


Figure 3 – Example of keypad interface for an Arduino
(source: **hobbycomponents.com/sensors/585-ttp229-16-key-capacitive-keypad)**

Alternatively, a range of industrial grade capacitive keypads/boards are readily available (see **goo.gl/ABYNiC** for some good examples).

Such keyboards often have a range of outputs, including USB, and they are particularly useful if a QWERTY type is required, for example.

This theme gets to one of the core purposes of *Wet & Dry*, so I plan to continue this topic in the next edition of this column.

Contributions to *Wet & Dry* are always most welcome, so why not share your ideas and experiences, or even a problem that can't be resolved!

I can be contacted at **tony_haigh@yahoo.co.uk**.

CREG

Letters and Notes

Please send contributions to the editor at ***creg-editor@bcra.org.uk***

CREG Journal on YouTube

Thank you for the invitation to the CREG Autumn Field Meeting. I'm sorry that I was unable to attend.

Readers might be interested in viewing a short video on radiolocation in Sweden's longest underwater cave. This can be found at **youtu.be/I3XTSVp4_Uk** (or search for 'signal seeker' on YouTube).

Bo Lenander SM5CJW

Rob Gill writes:

This fascinating video talks of Bo's lifetime involvement with cave diving and exploration. The CREG Journal makes a cameo appearance, though that's not the main reason for watching!

Surveying Articles

In the early days, CREG had a good smattering of cave surveyors among its subscribers and articles about cave surveying were commonly published in CREGJ. Then, in September 1993, Compass Points was launched as a sister publication to CREGJ, to cater specifically to cave surveyors. Eventually, following the formation of CSG, the Cave Surveying Group, editorial responsibility for Compass Points transferred to CSG. With the launch of Compass Points, and especially following the creation of CSG, we have avoided publishing general surveying-related articles in CREGJ, although we have continued to cover the application of electronic devices to caving, as illustrated by the inclusion of an article on the ZEB-REVO laser scanner in this issue. This policy resulted in two high-quality publications, each with their own well-defined subject areas, a situation that continued for many years.

While initially a quarterly publication like CREGJ, Compass Points hasn't been published in its original form since issue 39 in March 2008. Instead, CSG now provides a forum for discussion and publishing of short articles on its website at **cp.cavesurveying.org.uk**, but we are conscious of the fact that the opportunity for cave surveyors to publish their work in a more conventional format with archival value has been lost.

With this in mind, we've decided that it's appropriate to invite articles on cave surveying, once again.

Initially, we think that it's probably appropriate to focus our coverage on articles with some electronic or software content – after all, this is CREG's main emphasis – but we're willing to readdress this if it becomes apparent that there's a desire to cover more general surveying topics.

We'd welcome some feedback from our readership on this move and, if you have a desire to write something on a surveying topic, please feel free to start the ball rolling.

Editorial Team

Diary Dates

19-21 MAY 2017 – PORT EYNON, GOWER PENINSULAR, SOUTH WALES
BCRA Field Meeting

The first BCRA field meeting for 2017 will be held at Port Eynon on the Gower Peninsula, over the weekend of 19-21 May. The meeting aims to provide a full weekend of walks, caves and talks about the geology, geomorphology, archaeology and speleogenesis of the caves of Gower.
For any other query about travel, bookings and the meeting's program please contact Kostas Trimmis at **pktrimmis@gmail.com**

LATE MAY 2017 – MENDIPS
CREG Field Meeting

Subscribe to **CREG-Announce** to keep in touch with preparations or contact Mike Bedford, **BedfordMD@aol.com**. Please let Mike know if you are planning to attend and to book accommodation, if required. Confirmation of the date and further details will appear through the usual channels shortly.

9-11 JUNE 2017 – CASTLETON
BCA Party Weekend & AGM

23-26 JUNE 2017 – GODSTONE, SURREY
NAMHO Conference

Caving diaries and further information about events can be found in the BCA Newsletter, Speleology and Descent magazines and on the web at **bcra.org.uk/forum** and **wildplaces.co.uk**.
For CREG events, subscribe to **CREG-announce@lists.bcra.org.uk** or visit the discussion forum at **bcra.org.uk/cregf**

Web Watch

Peter Ludwig *serves up another batch of interesting links from ferrites to quantum communications via energy harvesting oversuits and battery technology…*

A smart fabric, harvesting energy from both mechanical movement and solar radiation. But it seems like a long way to go before your caving oversuit is powering your lamp and cave radio: **nature.com/articles/nenergy2016138**

Body cooling by nanoporous polyethylene textile. Maybe it can be combined with the energy harvesting properties of the previous material to make to ultimate caving suit?: **science.sciencemag.org/ content/353/6303/1019.full**

A wealth of information about the practical application of ferrites. This site includes a mass of practical information:

people.zeelandnet.nl/wgeeraert/ferrietUK.htm

A promising technique for extending the lifespan of rechargeable batteries:

news.uci.edu/research/all-powered-up

also at: **good.is/articles/nanobatteries-last-forever**

A promising approach to using magnesium in place of lithium in batteries, though the researchers hint at a very long development time before that can be realised: **gizmag.com/toyota-magnesium-battery/43204**/

And the last battery story for this issue: **onlinelibrary.wiley.com/doi/10.1002/ange.201608607/abstract**

How about tiny drones to check passages: **aerixdrones.com/products/aerix-vidius-hd-the-worlds-smallest-live-streaming-hd-video-drone**.

Finally, I wonder if this type of communications also will work through rock:

qz.com/760804/chinas-new-quantum-satellite-will-try-to-teleport-data-outside-the-bounds-of-space-and-time-and-create-an-unbreakable-code

Greetings from Austria!

CREG

CREG Field Meeting: Autumn 2016

At our recent field meeting in the Yorkshire Dales, demonstrations and experiments covered cave surveying, rescue communications and HF cave radio. ***Mike Bedford*** *reports on the weekend's activities with additional photographs by* ***Gregory Collins****,* ***Robin Gape*** *and* ***Chris Trayner****.*

After a break for EuroSpeleo 2016, CREG's programme of field meetings returned in the Yorkshire Dales over the weekend of 5th and 6th November. Despite the bitterly cold weather – a marked change from the unseasonably good weather just two weeks earlier – about a dozen people got together to continue their experiments in the presence of people with similar interests and to witness demonstrations of the latest technological gear to impact caving. Articles are planned to look at some of the themes in more detail but here we provide an overview of the weekend and give brief details of the various activities.

If you haven't been to a CREG field meeting, we trust that this report will provide the inspiration to join us in the future. As well as the practical underground activities during the days that you can read about here, the evenings also provide ample opportunity for technical discussions and plans for future work. While the evenings are usually informal sessions in a local pub, there is also the opportunity, if there's sufficient interest, as there has been previously, to organise more formal presentations, perhaps during the early part of the Saturday evening.

The next field meeting will take place in late May or early June 2017 in the Mendip area. Details and further announcements and updates will be provided on the *CREG Forum* (**bcra.org.uk/cregf/**). We hope that you'd like to join us at a future field meeting and look forward to meeting some new people and, perhaps, welcoming back some of the people who, previously, were familiar faces at these events.

ZEB-REVO

At a previous CREG Field Meeting, Emily Williams of GeoSLAM demonstrated the ZEB1, a handheld laser scanner able to survey a cave in three-dimensions purely by walking along the passages. The ZEB1 has now been joined by the ZEB-REVO which offers advantages in several scenarios. ZEB-REVO will operate even without the walking motion that is required by ZEB1 to cause the scan head to bounce on its spring, thereby achieving random scanning. Of potential interest to cavers, this means that scanning can be achieved if the ZEB-REVO is lowered into a pitch on a rope. GeoSLAM's Stuart Cadge joined us to try out the new scanner in a natural cave for the first time.

Because these caves have previously been scanned using ZEB1, Yordas Cave and Kingsdale Valley Entrance were chosen to provide comparisons. The Main Chamber of Yordas was scanned first, as was the short loop passage near the Main Entrance and the tight sloping passage to the Back Door. Also, the bottom part of the outdoor gulley from the Main Entrance up to Yordas Pot was surveyed.

Perhaps the most interesting, though, was the surveying of Yordas Pot from the surface. This involved the use of a special bracket that GeoSLAM had produced for securing ZEB-REVO and its associated control box which would normally be carried in a backpack. In practice, we found that an unusually large amount of water was flowing into Yordas Pot and it was difficult to see clearly more than a few metres to judge how close the unit was from becoming drenched. Given its IP64 rating for waterproofing (protected from splashing water but not jets or immersion), scanning was carried out only to around seven metres into the shaft but the exercise was considered useful, nevertheless. In future, it is recommended that a bright light is also lowered with the ZEB-REVO to assist in water or obstacle detection.

Below you can see the ZEB-REVO in action in Yordas Cave; a more detailed article is planned for the near future.

Cave-Link

Cave-Link is a text-based cave radio that several of the UK's rescue teams have recently obtained. Following his demonstration of Cave-Link at the CREG Field Trip during EuroSpeleo 2016, Paul Taylor, Chairman of the Gloucestershire Cave Rescue Group (GCRC), joined us to show more of its capabilities. In particular, his aim was to showcase the optional GSM Modem which allows a Cave-Link on the surface to interface

Stuart Cadge with the ZEB-REVO in Yordas Cave

Mike Bedford Lowering the ZEB-REVO Down Yordas Pot

Rob Gill and Tony Haigh Experimenting with 7MHz Cave Radio

Fred Rattray Operating from his 'Communications Van'

with the cellular phone network, thereby permitting an underground station to exchange text messages with mobile phones worldwide.

Rescue applications of this feature are not hard to appreciate. We can envisage, for example, an underground team caring for an injured casualty exchanging messages with medical professionals. While real-world applications are not nearly as obvious, as an impressive demonstration of the GSM Modem, it was planned to exchange messages between Short Drop Cave in the Yorkshire Dales and Ogof Ffynnon Ddu in South Wales.

Therefore, as an impressive example of inter-rescue team collaboration, GCRC's Cave-Link units were used in conjunction with a GSM Modem provided by the Cave Rescue Organisation of Clapham, and the South Wales Cave Rescue Organisation provided equipment for and operated the other end of the link.

The bottom line was that, although the aim of sending messages between two underground locations wasn't achieved, the GSM link proved itself in allowing a message to be sent from underground in Short Drop to a mobile phone. It seems very likely that the problem was one of configuring the Cave-Link units and it's planned to repeat this exercise in the near future.

Equipment Co-existence

After trying out radio-controlled photo flash slave units (433MHz) at previous field meetings, Gregory Collins used the more familiar Firefly 3 slaves on this occasion. It's interesting to note that the slaves were triggered prematurely be the ZEB-REVO, hardly surprising given that it uses an infrared beam and its rapidly rotating head would cause this to be seen as the short pulse that causes the Firefly the fire.

In fact, this was just one of two incidents over the weekend in which one piece of equipment affected another. The other incident was the Nicola 3 cave radio on 87kHz causing interference to HF radio transceivers on 7MHz. This suggests that more attention should be given to inter-operability of cave electronics equipment. Indeed, there are reports of LED caving lamps causing interference to LF cave radios and even vice versa.

LORAN Filtering

LORAN, the terrestrial navigation system that provides a backup to GPS in some parts of the world, is well-known for causing interference to voice-based cave radios that operate on 87kHz. Audio filtering is one possible means of combating the 'galloping horses' and, with this in mind, BHI loaned one of their latest DSP-based noise filters for trialling with a HeyPhone.

Unfortunately, one of the pair of HeyPhones used for this exercise failed to operate correctly. This provided a timely reminder – not that one should have been necessary – of the importance of maintaining equipment that is used in the cave environment, and of testing it before expecting it to work in the field.

Although the failure of a HeyPhone curtailed an assessment of the filter at the field meeting, tests will still be carried out and the results reported in *CREGJ*.

HF Cave Radio

With a proliferation of radio amateurs at the Field Meeting, further work was carried out to understand the operation of HF through-rock radio.

Trials focussed on gaining further understanding of HF antennas on the surface and underground. Once again, the venue was KMC Valley Entrance. Focussing on the 40m (7MHz) amateur band, the surface dipole antenna was rotated whilst monitoring the underground station. The plan had been to arrive at a polar plot of antenna radiation pattern, but high noise and interference levels meant that meaningful measurements were not possible, though 'by ear', the maximum signal was received with the dipole end-on towards the cave transmitter. This confirmed previous experience and might be related to the steeply-rising hillside very close to the surface antenna.

The 1m diameter underground loop antenna was then rotated whilst monitoring the surface transmitter. The antenna, held with its plane vertical, showed a very broad maximum with a fairly sharp minimum when the plane of the loop was broadside to the direction of the surface station. A sharp minimum was also found when the loop was held horizontally, reflecting the fact that at this location, the surface and cave stations were at almost exactly the same elevation.

Comparative trials were also conducted between different underground 7MHz antennas. The loop, a full-size 40m dipole and a 6m span earth current antenna were monitored in turn at the main surface station and a second surface station located nearer the overhead point. All antennas were received at the surface at similar strengths. Once again, precise measurements were not possible, though, by ear, the earth current antenna was of poorer performance. The principal lesson to take away was that unless we can overcome interference and make repeatable measurements, it is going to be difficult to make further progress.

WSPR

Although experiments with WSPR involved the use of HF radio, these tests had a very different aim. WSPR (pronounced "whisper") stands for Weak Signal Propagation Reporter Network, which was set up by radio amateurs for use in researching radio propagation of potentially low-strength signals. Stations alternately spend periods sending and receiving low-speed, low-bandwidth text messages, which include their callsign and location. Details of those stations received are uploaded to a database with Web access, thereby allowing stations to monitor how far their signals were propagating.

Since one of the perceived benefits of HF cave radio is that it might be possible to transmit signals over a longer path than between a cave and the closest point on the surface, Rob Gill used WSPR in two cave locations to put this to the test. Because of the lack of a local Internet connection, the tests involved operating a WSPR station underground for a period and checking for any reports of reception later.

To cut a long story short, we can report that although no reports were received from KMC Valley Entrance, a shorter session at Short Drop Cave on Leck Fell on 7MHz resulted in signals being received in Liverpool, London and Southampton, the latter representing a range of about 370km. The reported signal strengths indicated that there was some signal 'in hand', suggesting that signals could have been received in deeper caves and/or over longer distances. Further tests are planned.

Further information about WSPR can be found at **wsprnet.org.**

CREG

THE ADVENTURES OF GREG

Illustration: Adrian Higgins
Words: Mike Bedford

Greg was impressed by those handheld laser scanners that can survey a cave in full 3D just by walking along the passages. But timing to pico-second accuracy isn't a job for Greg, in fact, to be perfectly honest, anything less than a couple of minutes would be taxing. But necessity is the mother of invention and so a new idea was born. Instead of laser beams, telescopic arms with extensometers would be used to sense the cave walls, floor and ceiling.

Greg was suitably impressed by his creation – the spider's web – in fact it was sometimes accurate to within less than a metre – yes, really. But other cavers weren't quite so impressed. Squirming their way through this contraption at the end of a long and hard caving trip was usually the last thing they needed, even though Greg insisted they should thank him for the extra challenge if offered.