Laser scanning, used in Ogof Ffynnon Ddu in Wales has revolutionised the surveying on large cave chambers.

DEEP DIVE INTO CAVE SURVEYING

Mike Bedford reveals how high-tech equipment and Linux-based software is assisting cavers in exploring the astonishing world beneath our feet.

Caving, potholing, spelunking, or whatever you want to call it, the exploration of caves is often thought of as an exercise in which human explorers pit themselves against nature. Certainly, it's true that venturing into some of the more challenging caves requires a high level of fitness, stamina and agility, and expertise in descending and ascending vertical shafts using ropes, but more technical skills are also important with electronics and software increasingly coming to the fore.

While there are now few places on the surface of the Earth that remain unexplored, the same cannot be said about the world beneath our feet. Indeed, much of it still waiting to be discovered. Conventionally, in exploring remote parts of the Earth's surface, one of the first jobs in documenting a new discovery has been to map it. The same is true in the subterranean realm and with good reason.

Accurate maps – or surveys as cavers tend to call them – are vital to many aspects of caving. They are invaluable in helping others venture into the same caves, they are essential to making further discoveries, and they find application in areas of research including hydrology, volcanology, cave archaeology and cave biology. Here we look at the process of cave surveying, concentrating specifically on the latest electronic surveying instruments, and the software – much of it running under Linux – that's used to generate maps, 3D navigable on-screen images or fly-throughs, and even 3D printed cave models.

We anticipate that this introduction to cave surveying will provide a glimpse into an unusual yet impressive application of technology. If you feel inspired to get involved, though, this is most definitely an area where you could make a contribution, thanks to the open source nature of many cave-surveying packages.

Mapping has undergone massive changes in recent years, with GPS and satellite imaging now playing an important role alongside more conventional methods. In the world of cave surveying, though, things are very different. GPS signals don't penetrate the ground, imaging satellites can't see into caves, and even traditional surveying instruments such as theodolites and total stations are too bulky and fragile to be man-handled into tight cave passages for everyday surveying. Here we'll start by looking at the tried and tested methods of cave surveying so we can use this as a foundation on which to build a discussion of modern electronic techniques.

Conventionally, cave surveying is an iterative process of taking readings from one so-called station to another along the length of a cave passage. Stations are generally placed at the limit of visibility from the previous station, the separation usually being limited by the often twisty nature of cave passages. Three readings are taken at each station, namely a distance using a tape measure, a horizontal bearing using a compass, and a vertical bearing or inclination, using an instrument known as an inclinometer or clino. Needless to say, if the location of the cave entrance is known, these three readings per station enable the location of the stations to calculated and hence the centre-line of the passages to be plotted. At each station it's also common to measure the width and height of the passage and sketch a cross-section.

Underground stations

While the station-to-station approach still forms the mainstay of cave surveying, the tape, compass and clino are now being phased out in favour of all-in-one electronic instruments, most of which have been engineered by cavers. The DistoX2, by Swiss caver Heeb Beat, illustrates the principle of these units. It's based on the Leica Disto X310, which is a low-cost, moderately rugged and waterproof, hand-held surveying instrument incorporating a laser range-finder and an electronic compass. Heeb Beat's enhancement, which involves replacing one of the circuit boards and changing the firmware, adds the inclinometer functionality as required for cave surveying.

CAVE SURVEYING EVOLVES

> "The tape, compass and clino are now being phased out in favour of all-in-one electronic instruments"

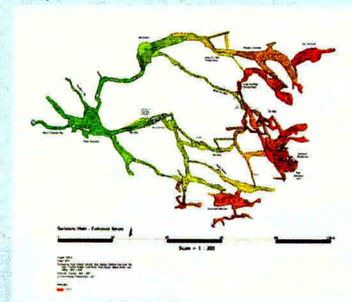
It communicates with a hand-held device such as a rugged Android smartphone so that the survey can be viewed as it's built up. Compared to the tape/compass/clino approach, the process is much quicker, potentially unintelligible figures in a notepad are eliminated, and erroneous readings will often be spotted immediately on the associated display. It also makes it practical to take several measurements from a point in the centre of a passage to points on the wall so that more accurate cross-sections can be produced. Back on the surface, the error-prone process of entering the hand-written data from a muddy notepad into the cave surveying software is also a thing of the past.

Major Lazer

Cave surveying was revolutionised a few years ago with the introduction of laser scanners, even though these instruments weren't created with cave surveying in mind. »

» RADIO LOCATION

SWILDONS HOLE – ENTRANCE SERIES



The step-by-step nature of the conventional cave surveying process means that errors steadily accumulate. As such, the calculated position of the end of a long cave passage could be subject to significant errors. One way of overcoming this problem is to use radio-location to determine the absolute location of the cave extremities and thereby double the number of fixed points.

Normal radio is heavily attenuated as it passes through rock and earth. However, if a sufficiently low frequency is used, signals can penetrate the earth to a depth of a few hundred metres.

This is a technology that's used by cave rescue teams to coordinate their operations. It's also the key factor of radio location. The process involves setting up underground transmitter and its associated loop antenna that generates well-defined magnetic field lines. Now, using a receiver and loop antenna on the surface, "ground zero" – in other words, the point directly above the underground transmitter – can readily be identified.

A GPS receiver then makes it possible for the absolute position to be determined. Taking measurements of the angle of the field lines some distance away from ground zero also enables the depth of the transmitter to be calculated.

This radio location receiver is able to pinpoint an underground transmitter to provide a fixed point on the surface.

» KEEPING A CAVE HANDY

A printed map is surely the most common way in which cave survey data is presented, although it's impressive to see an on-screen 3D model that you can rotate, zoom and pan. However, there's something rather special about having a physical 3D model of a cave in your hands, something that has become possible with the advent of 3D printing.

It's by no means mainstream but cavers have demonstrated the production of 3D solid cave models with impressive results. This exercise demonstrated a diverse range of 3D cave surveying techniques. One model was generated from a 3D laser-scanning exercise carried out in the historic Caves of Nottingham, which strictly speaking are archaeological man-made cavities in the soft sandstone as opposed to natural caves of the type found in limestone. The second is a model of the complicated array of passages in Cueva de Riaño, Matienzo, Spain, and used the output of a conventional surveying exercise. The third is a model of a calcified bear skeleton, also found in a Matienzo cave, the 3D model having been generated using a technique called photogrammetry, which uses a sequence of ordinary photographs to work out the three-dimensional geometry.

The first laser scanners, and still the most commonly used, are large instruments that are mounted on a tripod and are hugely expensive. These instruments fire an infrared laser beam and measure the time taken for the pulse of light to be returned, following reflection off a solid surface. Because the speed of light is known, this time is readily converted into a distance.

The laser is motor driven so it can be fired at any horizontal angle around the scanner and through a range of vertical angles. This enables thousands of points to be collected each second so, in a matter of minutes, a full 3D point cloud (x,y,z coordinates of points in space) of the immediate environment can be built up. This type of instrument isn't suitable for surveying cave passages because it's not adequately manoeuvrable, but it's commonly used to create 3D models of cave chambers or rooms. Caver Roo Walters, for example, has set himself the task of surveying the world's largest cave chambers using a laser scanner and has made some startling discoveries. Sarawak Chamber in Malaysia, for example, is the world's largest by floor area, being big enough for 47 Boeing 747 jumbo jets to be parked on its floor. This sort of exercise can be hugely time-consuming though. Large chambers can rarely be surveyed from a single position because some parts will always be obscured so they have to be scanned from several positions and the data stitched together afterwards. Sarawak Chamber is a good example. Roo surveyed it from 101 separate positions, a task that took four days, and generated 137GB of data which then took 20 hours of processing to stitch together.

Although a conventional tripod-mounted laser scanner isn't suitable as a replacement for the tape/compass/clino combination, or even electronic instruments like the DistoX2, more recently introduced hand-held laser scanners are ideal. The original hand-held scanner, the ZEB1 from GeoSlam, had a rotating laser mounted on a large spring that bounced randomly as the user walked around. The more recent ZEB-REVO has a more controlled motion, having two motor-driven mechanisms, rotating at right angles.

Either way, a complicated 3D point cloud is built up that needs correcting to take into account the motion of the user and the nodding and/or rotational movement of the scanner head. This is achieved using positional data from built-in inertial sensors, and complicated pattern-matching techniques that are able recognise features between successive streams of data. This is a computer-intensive process. GeoSlam offers two processing options: pay per use on their cloud-based Linux servers or locally, with a more conventional licensing arrangement, with the software currently being available only under Windows.

A hand-held laser scanner, while much more expensive that the alternatives, offers major advantages compared to more manual methods of surveying. The first is speed. One of the first demonstrations of the ZEB1 underground took place in Skirwith Cave in the Yorkshire Dales national park in the UK. The first 168m of passage – to a climb that had become impassable due to the volume of water following heavy rain – was surveyed in both directions in 36 minutes. The scan in the reverse direction provided "closure", in other words the outward scan started at the known fixed position of the cave entrance while the return scan finished at this same position.

The presence of two known points enables the software to minimise cumulative errors. By way of contrast, conventional surveying would have taken an estimated 4.5 hours, in one direction only, and perhaps twice as long in the same length of low crawling passages. Electronic surveying instruments such as the DistoX2 would improve on these times but still not come close to laser scanning. The second main benefit is that, instead of just the occasional sparse cross-sections that are captured in traditional surveying, the passage is recorded as a fully three-dimensional model.

Surveying software

For most purposes, cave survey data needs to be presented in a format that resembles a map, and cave-surveying software has made huge advances here in recent years. Most of the software has been produced by cavers for cavers and, for this reason, it tends to be freely available. Generally it's released to run under a variety of operating systems, including Linux, and open source projects are common.

A process originally done by hand, the most fundamental requirement of cave surveying software is to

Hand-held laser scanners enable a full 3D representation of a cave passage to be obtained just by walking (or crawling) along it.

CREDIT: Paul 'Footleg' Fretwell

» GETTING INVOLVED

If this introduction to cave surveying has inspired you to get involved in this unusual but rewarding combination of exploration, physical activity, technical gizmos and coding, we must stress that you shouldn't be tempted to get a feel for caves by wandering into them yourselves. The only sensible option is to make contact with a caving club, which can provide you with a safe introduction. There are dozens of clubs in the main caving areas and you can find details of caving clubs at **newtocaving.com/contact-us.php** in the UK or **www.nssio.org/Find_Grotto.cfm** in the US.

As a technophile, though, you'll probably be interested in the technical aspects of caving and here we'd point you toward the British Cave Research Association (BCRA) and its Cave Surveying special interest (**cavesurveying.org.uk**) group. Also of particular interest is the Cave Radio & Electronics Group (CREG) at **bcra.org.uk/creg**, which published a quarterly journal and organises twice-yearly field meetings.

Despite the name, CREG promotes technology across a range of caving applications, including communication, photography, data logging, lighting and surveying. Indeed, if your interest in caving is more technical than sporting, attending a CREG field meeting will provide you with a gentle introduction to caving while, at the same time, giving you the opportunity to see some of the latest developments in cave technology.

calculate the positions of each survey station from the raw survey data. These positions would enable the centre line of each of the passages to be drawn but, normally, by using the measured passage cross-section at each station, the passage walls can be shown instead, thereby providing an impression of the variations in passage width. Hand-drawn passage cross-sections are usually added too, at selected points along each passage. Surveys of complicated caves, in which passages cross other passages at different depths, are notoriously difficult to read. A fairly recent trend in outputting survey data is to allow different parts of a cave, or perhaps different depths, to be plotted in different colours, something that very much improves interpretation.

What we've seen so far are just the fundamentals and you could probably write some software to do this quite easily. However, to suggest that this is the limit would do a great disservice to many cave surveying packages. We're just scratching the surface but, to give you an idea of what's on offer, additional features you're likely to find include erroneous data detection, provision for multiple surveyors to contribute data to a project, overlaying cave passages on conventional surface maps or satellite imagery, generating 3D models in WRL or similar for on-screen manipulation, and so the list goes on.

However, with advances in Graphical Information Systems (GIS), some cave surveyors are considering whether it might make more sense to concentrate on this type of mainstream software, some of which is also open source (for example, **qgis.org**). If you'd like to delve more into this subject, read up on the main Linux open source cave surveying packages which are **survex.com** and Therion (**therion.speleo.sk**), plus the Java cave drawing program *Tunnel* (**https://bitbucket.org/goatchurch/tunnelx**).

While this is by no means a run-of-the-mill application of technology, we trust you've found this introduction fascinating, nevertheless. It's an area where cavers don't yet have all the answers which also means there's potential for you to get involved and make a real contribution. If this unusual application appeals to you, therefore, be sure to take a look at the Getting Involved box (*above*). LXF

Hand-held laser scanning data can be represented as a 3D internal view of a cave passage like this one of Skirwith Cave in the Yorkshire Dales.