ADVANCES IN GROUND MONITORING TECHNIQUES
– A SURVEYORS PERSPECTIVE

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ABSTRACT

In essence ‘Surveying’ is simply the science of measuring positions on Earth. Surveying has been a key element in the development of the human environment since we stepped out of the caves. The relationship between surveying and geotechnical engineering principles arguably dates back just as far. There is a real synergy between these disciplines / professions that, in the main, is often not fully appreciated.

The core mathematical foundations upon which surveying is based are essentially unchanged. What has changed enormously over the centuries and dramatically over the past decade or two are the technologies available to Surveyors to aid them in measuring the ‘Earth’, and anything built on / in it.

This paper touches on a range of current survey measurement methodologies, some of which may be considered ‘tried and true’ traditional techniques along with a number of exciting newer technologies such as LiDAR (Light Distance and Ranging), DInSAR (Differential Interferometric Synthetic Aperture Radar), GNSS* (Global Navigation Satellite System) based real-time 3D measurements, with particular attention given to drone (Unmanned Aerial Vehicle - UAV) based digital photogrammetry.

Like many measurement techniques, digital photogrammetry is a technological evolution of a well understood and developed traditional analogue approach. With the advent of laser scanning (LiDAR) measurement technologies in the late 1990’s, analogue photogrammetry rapidly fell out of favour for all but a few niche measurement applications. However, over the past few years there has been a dramatic shift back to ‘digital’ photogrammetry. This re-emergence has been facilitated by advances in digital photogrammetry autocorrelation algorithms, increases in computing power, relatively affordable PC based software solutions, digital SLR cameras and most recently, the development of commercially available drone (UAV) based digital camera systems. Modern digital photogrammetry solutions are now capable of very quickly capturing high resolution, high accuracy and generally high quality measurements with flexible outputs ideally suited to 3D surface modelling and measurement problems. These technical attributes in tandem with affordable digital cameras and modern UAV platforms has opened up a wide range of applications, many of which are in mining, engineering and monitoring fields.

More important than any particular measurement technology, effective survey monitoring, or any type of monitoring, starts with clearly understanding: what has to be measured (critical parameter(s)), how accurately it needs to be measured, and at what frequency are the measurements required? Only once these factors are crystal clear should we start to consider which technology or combination of measurement techniques is most suitable for the project. In many cases, an integrated approach utilizing a blend of ‘surveying’ and ‘geotechnical’ measurements will deliver the optimal monitoring strategy.

1 INTRODUCTION

Surveying now takes many forms. We’ve probably all heard the claims that the latest piece of technology or instrument is revolutionising practises…*throw out all your conventional gear; Total stations, Global Positioning Systems (GPS), Laser scanners, drones, etcetera, can do everything better, you don’t need anything else!* These various technologies are indeed marvellous but to suggest that any one of them is the best tool for every job is simply not correct.

All too often we see examples where instrument manufacturers, clients, or consultants push a particular technology solution or instrument rather than focussing first on really understanding and defining what needs to be measured. Knowing what needs to be measured sounds relatively straightforward, and in many cases it is. However, in some instances, especially the more challenging projects, gaining a clear understanding of exactly what and how accurately something needs to be measured can be half the battle. Understanding deformation / failure mechanisms is the key to developing an appropriate measurement / monitoring strategy.

This paper aims to provide Geotechnical Engineers and associated professionals with a greater understanding of the various surveying factors to consider. In many cases, these same fundamental considerations transfer equally to other disciplines. In addition to providing general information on some fundamental measurement concepts the paper gives an overview of the current status of drone (UAV) based digital photogrammetry, as well as autonomous GNSS based real-time three dimensional (3D) movement monitors.

2 DEVELOPING A MEASUREMENT / MONITORING STRATEGY

We should not focus on how measurements will be made or what technology to use. Only once the answers to the questions below are completely understood should consideration be given to 'how'!

2.1 WHAT TO MEASURE?

Irrespective of whether a feature is natural or man-made one of the first steps in developing an appropriate monitoring strategy is gaining an understanding of the possible failure mechanism(s) of the feature. For example tension cracks is an earth wall dam have the potential to lead to a piping failure, differential leg movement of a steel truss high voltage (HV) transmission tower leads to change in stress distribution in structure members which could readily lead to a collapse of the structure, compression of a rock bar or bound highway pavement can lead to a sudden step failure.

The engineering characteristics, and likely behaviour of man-made features is generally easier to define than natural features. Civil and geotechnical engineers often play critical roles in determining failure modes. The determination of failure mechanisms leads to the definition of the key parameter(s) that need to be measured. Referring to previous examples: change in length along the dam wall, differential settlement of HV transmission tower legs, change in stress within rock / pavement. From a surveying perspective, we are often simply looking for relative movement between one structural element and another.

2.2 HOW ACCURATELY TO MEASURE?

How much movement is too much? The answer to this question informs how accurately something needs to be measured. There is no point measuring something to an accuracy of ± 5mm if a 1mm change could cause a failure. Similarly, a feature that is not sensitive to change at the ± 100mm level does not need the effort and (enormous) expense of a ± 1mm monitoring system. As a general rule, as survey monitoring accuracy requirements increase the cost increases exponentially.

2.3 HOW FREQUENTLY TO MEASURE?

How quickly can movements occur? The answer to this question leads to understanding what sort of measurement frequency is required. If the measured parameters can go from safe levels to dangerous levels quickly them high frequency monitoring is required to allow time to respond. However, if changes are slow and /or the risks are low then lower frequency monitoring may be more appropriate. A great example of this involves the measurement of underground longwall induced mine subsidence in the southern coalfield of NSW. The actual ground movement (subsidence) occurs relatively slowly, generally < 20mm / day. However, the Hume Freeway which has been undermined by longwall mining operations has the very real potential to experience a compressive stress 'build-up' within the pavement in response to the slow ground movements acting on the pavement structure to a point where a sudden brittle failure could occur. To aid in the management of a 'sudden' failure, pavement stress is monitored continuously by a real-time system whereas the ground movements only need to be monitored weekly.

2.4 ACCURACY, PRECISION, RESOLUTION – KNOW THE DIFFERENCE

Accuracy can be most simply defined as: how close a measurement / observation is to its true value.

Precision refers to how consistent results are when measurements / observations are repeated. It is entirely possible that measurements / observations can be precise but inaccurate.

Resolution is often defined as the minimum distance existing between two objects when those objects can still be observed as separate entities i.e the level of detail that can be detected – 'resolved'. With respect to photogrammetry, resolution is perhaps best thought of as: the pixel size of imagery or 3D renders produced, and / or the density (and precision) of the 3D point clouds generated.

2.4.1 Precision is the key

Survey monitoring aims to detect change. For this reason, precision is the key not accuracy. How precisely (or repeatable) a series of measurements can be made essentially quantifies of how accurately differences (change) can be defined. For survey monitoring, 'differences' is usually in terms of change in length, height or spatial position.

Using a real world example of this concept: a line of discrete fixed survey prisms installed to monitor ground deformations caused by mine subsidence can be repeatedly measured with only very small variations in the measured values, say ± 2mm, the measurements are very precise. However, the line of survey prisms may have only been approximately connected to the National Map Grid Australia (MGA) / Australian Height Datum (AHD) coordinate systems, say ± 1m. The reported MGA / AHD coordinate values for each prism are not very accurate i.e. close to their true spatial position. As mining related ground movements begin the survey repeatability remains the same and ground movements are calculated by comparing the initial (base) values for each prism location verses subsequent measurements of the prism location. The precision and accuracy of the reported movements (differences) is nominally < ± 5mm i.e. the true magnitude of the movement (change in coordinate values) is equal to the combination of the measurement precisions.

2.4.2 Absolute vs Relative Accuracy

Expanding on the definitions of accuracy, precision and resolution presented above, another key concept is the notion of absolute accuracy and relative accuracy. In typical deformation surveying applications, absolute and relative accuracy can be thought of in a very similar vein as the accuracy and precision discussion in section 2.4.1 above. Absolute Accuracy is defined as how close the data is to its true value. In the surveying context absolute, or global accuracy as it is sometimes known, generally refers to how close a reported 3D coordinate is to its true position with respect to a recognised coordinate framework, for example MGA / AHD. Relative accuracy refers to how true the spatial relationship (geometry) of the data is relative to other elements in the same dataset. Alternatively, more specifically, how accurate the reported 3D coordinates of one survey point are relative to other points reported within the same survey / monitoring network.

Differential movements of one piece of ground or one structural component relative to adjacent components effectively equate to 'deformation'. Deformation often leads to an increase in risk of failures. By way of example, continental tectonic movements might see might see a dam on the Australian continent moving 40mm North per year. This global (absolute) movement poses no risk to the integrity of the dam. However, if the dam wall moves 40mm relative to the adjoining abutment this most certainly would raise concerns about structural integrity.

For deformation monitoring surveys relative accuracy and survey precision are far more important than absolute accuracy as they directly influence the ability to detect change.

2.5 DISCRETE POINTS VS CONTINUOUS DATA

Traditionally surveying has involved the measurement of particular 'points of interest' – discrete points in space. Such discrete points can include: survey pegs on property boundaries, buildings, fence intersections and so on. The common element is the discrete points are always tangible physical features. In the survey-monitoring context, discrete points can take many forms: fixed survey prisms, pins or threads in rock / concrete, photography / scanner targets, permanently mounted GNSS receiver hardware to name just a few. The central idea being that the same point can be remeasured time and time again (i.e. multiple epochs in time) allowing a direct comparison of the measured data for each point. Discrete point measurements usually have simple well-defined accuracy and precision estimates. Total station measurements to fixed monitoring prisms and GNSS measurements to monitoring pins are two common examples of discrete point monitoring methodologies.

Within the surveying, mapping and remote sensing context 'continuous' data or non-discrete data as it is sometimes known, are datasets that are comprised of many, often millions, of individual arbitrary (blind) observations that are examined / viewed together as a surface(s). While the surveyor may have some control over the point distribution or density they typically have no ability to control exactly where individual points within the cloud will fall (i.e. the exact opposite of discrete point measurements where the surveyor knows precisely the point where each individual observation will be made). Many 'raster' datasets are effectively continuous. Perhaps the most prevalent current example of continuous surveying data would be 3D point clouds generated by LiDAR or digital photogrammetry and the Triangulated Irregular Network (TIN) meshes computed from point cloud datasets.

The accuracy and precision of continuous data is often more difficult to define and / or understand in practical terms. To date remote sensing derived raster datasets often have their quality described in terms of resolution or a mathematical computation of accuracy based on specific instrumentation, measurement parameters and processing methodologies. Mathematical computation based accuracy / precision / resolution statements are particularly common with interferometry based technologies such as Differential Interferometric Synthetic Aperture Radar (DInSAR). In the author's experience the practical (real world) accuracy / precision of these data is often significantly lower than the mathematical computation statements suggest.

LiDAR or digital photogrammetry derived continuous point cloud datasets often have their accuracies defined by the nominal quality of each individual data point within the cloud. The problem with this approach is that at the individual data point level the stated accuracy does not necessarily provide a fair indication of the accuracy of the continuous dataset as a whole. High density point clouds are capable of yielding extremely accurate shape / surface definitions. The key is that high point data density (usually millions) combined with high relative accuracy can often more than compensate for lower absolute accuracy of individual points in the cloud. A great way to illustrate this is to consider two measurement scenarios for a complicated, say 1 km² area of interest.

a. The first measurement method involves extremely high accuracy (say ± 3mm) total station observations, but in a full day of fieldwork, the surveyor can only measure 500 points to define the surface. Even though the surveyed points have been carefully selected by the surveyor and measured very accurately the overall accuracy of the surface shape of the landform is not likely to be great as there are simply not enough measured points to yield anything other than a very generalised definition of the 1 km² topographic surface.
b. The second measurement technique involves using digital photogrammetry from drone-based imagery. The same surveyor could comfortably survey the same area in a single day. The vertical accuracy of the individual points that make up the photogrammetry derived point cloud may only be accurate to ± 30mm however the data density would be nominally 30 points / m². Thus the 1 km² topographic surface would be defined by 30 million points at ± 30mm, rather than 500 points at ± 3mm.

Given the very high density of typical point cloud datasets the ‘continuous surface’ derived from the data points is far more accurately defined than official accuracy statements may suggest. The more complex the surface / shape to be surveyed the more influential data density is rather than individual point measurement accuracy.

3 GNSS BASED REAL-TIME 3D MOVEMENT MONITORS

GNSS based 3D monitoring systems as described below are a great example of discrete point measurement.

Real-time 3D movement monitoring systems come in many forms and can be based on a variety of measurement technologies such as: GNSS, Total Station, Radar, LiDAR and many others. In addition to these surveying based 3D movement monitoring systems there’s an equally wide range of geotechnical sensors such as extensometers, inclinometers and so on that are also highly effective at detecting movement.

This section will focus on GNSS based 3D monitoring systems with particular emphasis on the latest low cost options. GPS (Global Positioning System) based technology has been widely used in monitoring applications for over 30 years. Some of the earliest applications in the late 1980’s involved monitoring ground movements associated with active volcanoes. By studying the rate of change of key points around the volcano, volcanologists were able to develop predictions as to when eruptions were imminent. More recently, fixed real-time GNSS stations played a critical role in providing up to the minute survey control data during the construction of the world’s tallest building, the Burji Dubai Tower completed in 2008.

The technical capabilities of such systems are well understood and have been successfully applied to a broad range of surveying and monitoring applications. However, up until very recently GNSS based systems have been relatively costly as the unit cost for the hardware was quite high and each point to be measured requires its own hardware. On this basis such systems have been largely out of reach for all but the highest priority / value projects.

The rapid proliferation, particularly over the past decade, of consumer grade GPS and GNSS receivers for integration in mainstream devices such as mobile phones, watches, cameras and so on has led to enormous development and a dramatic reduction in cost of GNSS receivers, associated peripherals and software. These developments, together with powerful, compact computer hardware and simple telemetry options have facilitated the development of very low cost GNSS based 3D monitoring systems. As the cost of such systems has reduced the number of potential applications has expanded proportionally. One such arrangement that the author has extensive experience with is a completely autonomous system with each monitoring unit consisting of: GNSS receiver, computer board, telemetry module and solar / battery power supply. As shown in Figure 1 below, the entire stand-alone unit is not much larger than a shoebox with a dedicated solar panel. The measurement unit and solar panel are typically mounted on fixed posts in the ground or directly to structures.

Figure 1: Low-cost Autonomous GNSS Monitoring Installation

The key site constraints are that the mounting point is free of large amplitude vibrations and has a reasonably clear 'sky window' (i.e. view of the sky). This later point is the biggest limitation of any GNSS based measurement / navigation solution as a compromised sky window can have a significant impact on the quality / accuracy of 3D positioning, with the height coordinate being the most affected. When these systems are installed in suitable locations the daily 3D survey accuracies achieved are in the order of ±3 – 5mm. Each unit sends data back to a central computer multiple times per day with results uploaded to an internet site where they can be viewed and downloaded by clients, consultants, regulators and any other authorised parties (internet sites are all password protected). Figure 2 below illustrates some simple graphical representations of deformation data taken directly from a project internet site. In addition to the internet based data, the system is also able to be programmed to send automated SMS or email alerts in the event predefined movement triggers are reached.

As noted above, GNSS based monitoring systems with the functionality and measurement accuracy described are not new. However, with the latest systems now costing 5 to 10 times less the more traditional brand name systems this methodology now represents a very cost effective option for many applications. Another very appealing aspect of these newer systems is that additional sensors can be readily integrated into the same 3D position monitoring unit. To date tilt meters have been added to these systems and the latest work is looking at integrating a range of geotechnical sensors, such as piezometers, inclinometers and extensometers. In the very near future, we will see affordable fully integrated monitoring units capable of measuring, logging and uploading to an internet site, a whole range of surveying and geotechnical data.

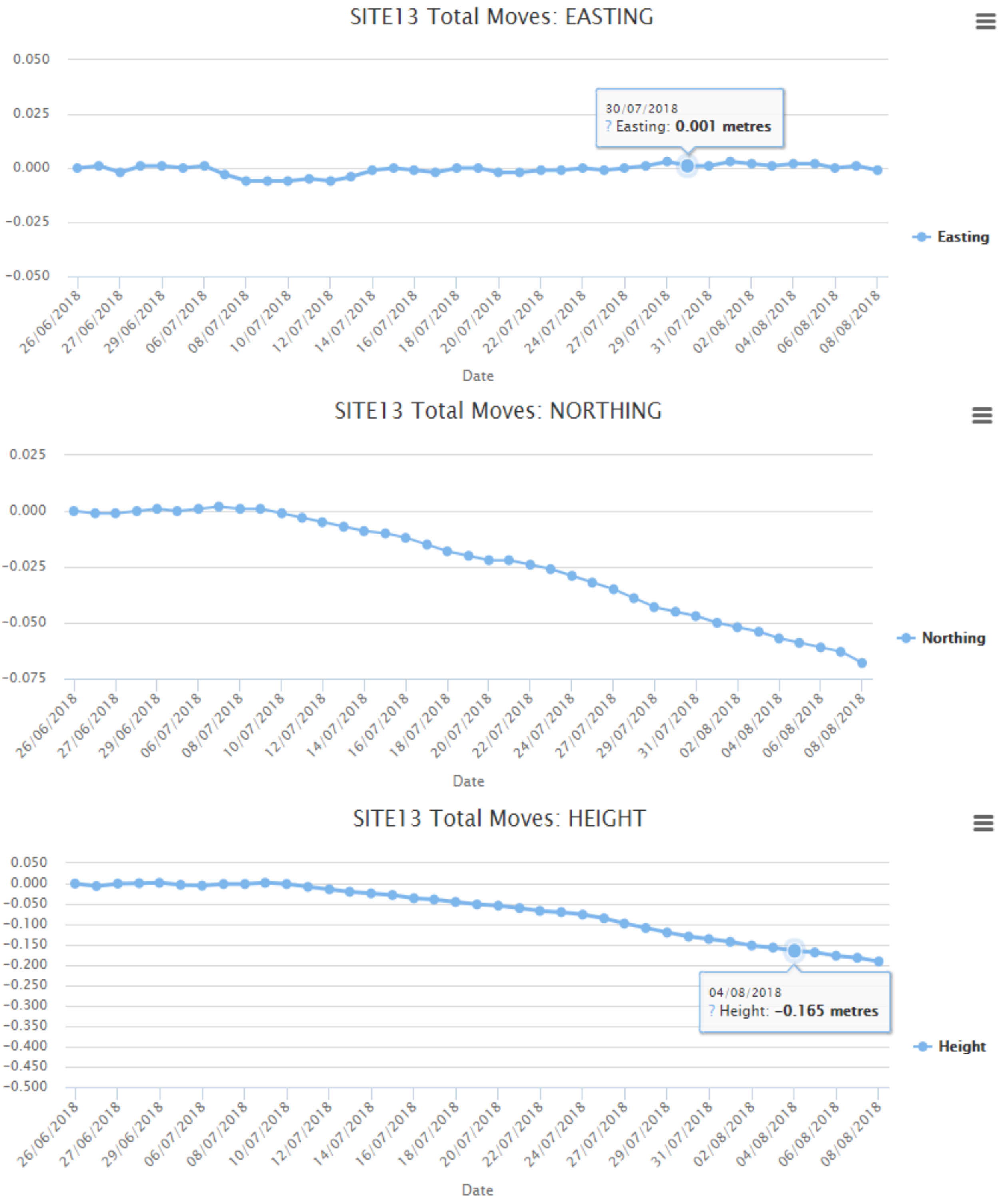

Figure 2: Typical Internet based deformation data represented in graphical form

4 DIGITAL PHOTOGRAMMETRY

Digital photogrammetry as described below is a great example of a technology that yields continuous data. However it should also be noted that discrete point measurements are also readily achievable using photogrammetric techniques.

4.1 BACKGROUND

Photogrammetry is most simply defined as: *the science of making measurements from photographs*. The key concepts and mathematical principles photogrammetry is based on date back hundreds of years. However, photogrammetry really emerged shortly after the advent of photography in the mid-19th century. Like many technologies before and since, photogrammetry developed quickly on the back of military investment. By the 1990's photogrammetry and photogrammetric principles were at the height of their powers, not only being well established as the primary mapping and remote sensing technology but also increasingly used for a wide range of terrestrial surveying applications.

The mainstream emergence of laser scanning, now referred to almost universally as LiDAR (Light Detection And Ranging), around the turn of the millennium resulted in a rapid shift away from photogrammetry for many applications. This shift was most notable in surveying where LiDAR and other alternate technologies very quickly replaced photogrammetry for all but a small number of specific applications. After almost fifteen years of relatively little use, photogrammetry has come back in to favour. This re-emergence has been facilitated by advances in digital photogrammetry autocorrelation algorithms, increases in computing power, relatively affordable personal computer (PC) based software solutions and most recently, the development of commercially available drone (UAV) based digital camera systems.

It is beyond the scope of this paper to focus on the hard, dry mathematics that is at the heart of digital photogrammetry technology. However, for context it should be noted that computer based image matching or 'autocorrelation' as it is now commonly known, is a term, which refers to automated raster-based identification of common points in two or more overlapping images. Digital photogrammetry projects generally adopt much higher photography overlaps than traditional film based analogue conventions. High overlaps together with rigorous autocorrelation based image matching protocols lead to high levels of redundancy such that sub-pixel accuracy is readily achievable.

So, with foundations in basic mathematical principles over 100 years old, along with modern day advances in digital techniques and computing power what is photogrammetry capable of today? Somewhat paradoxically, it is still a rapidly evolving technology. The rise in consumer level drones / UAVs has not only provided the obvious advancement in affordable image acquisition, but even more importantly, stimulated significant further software development.

The latest digital photogrammetry hardware and software is still advancing rapidly. As such, it is difficult at this stage to put bounds on what is possible in terms of both resolution and accuracy. Sub 10 millimetre (<10mm) resolution and accuracies are certainly possible for small localised sites / objects while many square kilometres can be covered at sub 50mm (<50mm) resolution and accuracy. The accuracy of control networks is often the limiting factor, particularly in terms of absolute accuracy. Like the resolution and accuracy parameters, there is a broad range of vertical and oblique (or combinations of both) methodologies available. The various techniques can cover almost any size / shape object, from kilometres of pancake flat desert through to small (<1m), highly complex natural or manmade shapes.
There is an equally broad range of outputs possible including (but certainly not limited to):

- 3D point clouds
- Triangulated Irregular Network (TIN) mesh surfaces
- Contours
- 3D rendered animations
- Ortho-photos
- Deformation models
- Cross sections
- Tabular data
- 3D virtual reality

4.2 APPLICATIONS

Applications for digital photogrammetry based methodologies are many and varied, ranging from traditional topographic mapping through to the creation of spatially and geometrically correct photographically rendered 3D CAD models.

4.2.1 Traditional Applications

Fundamentally, for most of the past 100+ years photogrammetry has been primarily used to create topographic maps. The native photographs were also often useful – particularly when viewed stereoscopically, but really it was all about making maps. Topographic mapping techniques were then applied to mapping open cut mining operations and large earthworks projects to quantify material movements, measure stockpile volumes and so on. The good news is that these traditional applications have all benefitted from the transition to, and ongoing refinement of, digital photogrammetry. Even stereoscopic viewing is still accommodated in some digital photogrammetry workflows.

4.2.2 Cliff Mapping

As per section 4.2.1 above, most traditional photogrammetric applications involved taking overlapping photographs looking vertically down in order to digitize a 3D model of the earth's surface – a topographic map. In analogue photogrammetry it was exponentially more difficult to effectively 'tip' the entire methodology on its side and use oblique photography to map vertical, or near vertical surfaces such as cliffs, mine batters or building facades. Digital photogrammetry and very recently, drone based camera systems have made this once extremely challenging application very doable and highly effective.

There have now been several cliff mapping projects aimed at quantifying and generating accurate 3D models of many kilometres of difficult to access cliff lines. In most cases these models are used to accurately, and in high resolution, quantify the baseline (pre-mining) status of these natural features. Follow-up mapping surveys can be undertaken at any time with any changes (geometric or aesthetic), disturbances or deformations measured, quantified and documented. Figure 3 is a still image of an extensive and complex 3D rendered cliff line model in the Western Coalfield of NSW. Over twenty similar cliffs were mapped during this project. Figure 4 is a similar 3D rendered model of a cliff collapse on the Illawarra escarpment.

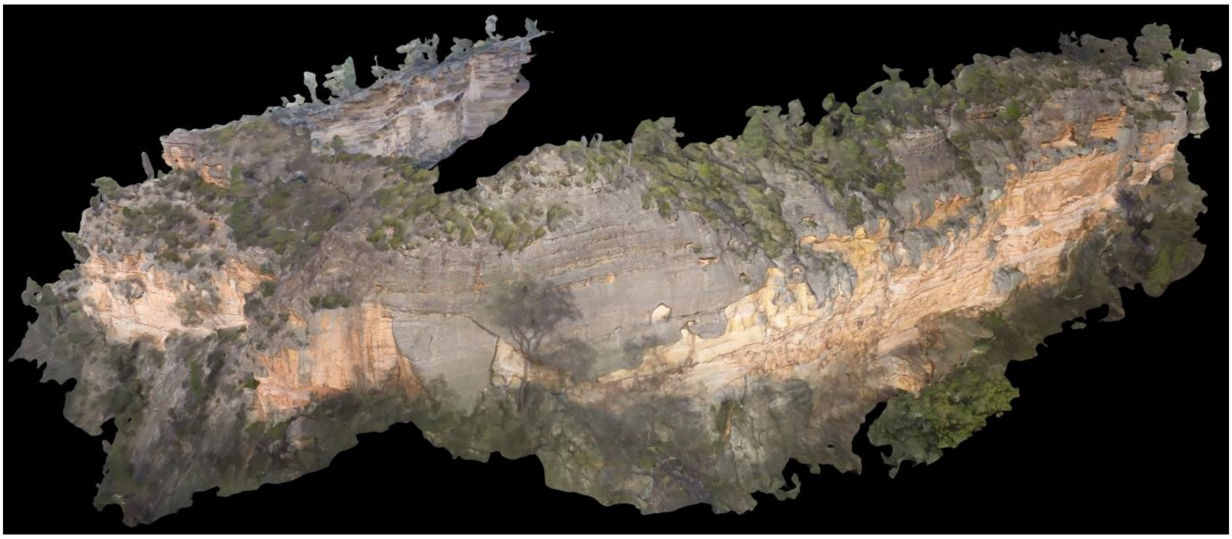

Figure 3: Cliff line model

Figure 4: Modelled cliff collapse on Illawarra escarpment

4.2.3 Highwall Mapping and Batter Monitoring

Using essentially the same methodology as that used for cliff mapping, mine highwalls and batters can also be mapped. Generally highwall and batter mapping is much simpler than cliffs as they are usually clear of vegetation and other obstructions which can often complicate cliff mapping. One of the key advantages of using photogrammetry for detailed highwall and batter mapping is the ability for geologists and geotechnical engineers to use both the 3D point clouds and the photographically rendered models to accurately define measure and map geological features such as joints, faults, lineaments etc., along with areas of potential or previous instability. Figure 5 is a very high resolution (<10mm) 3D rendered point cloud of a section of batter in a Victorian brown coal mine before and after the controlled failure of a small section of clay in the coal seam.

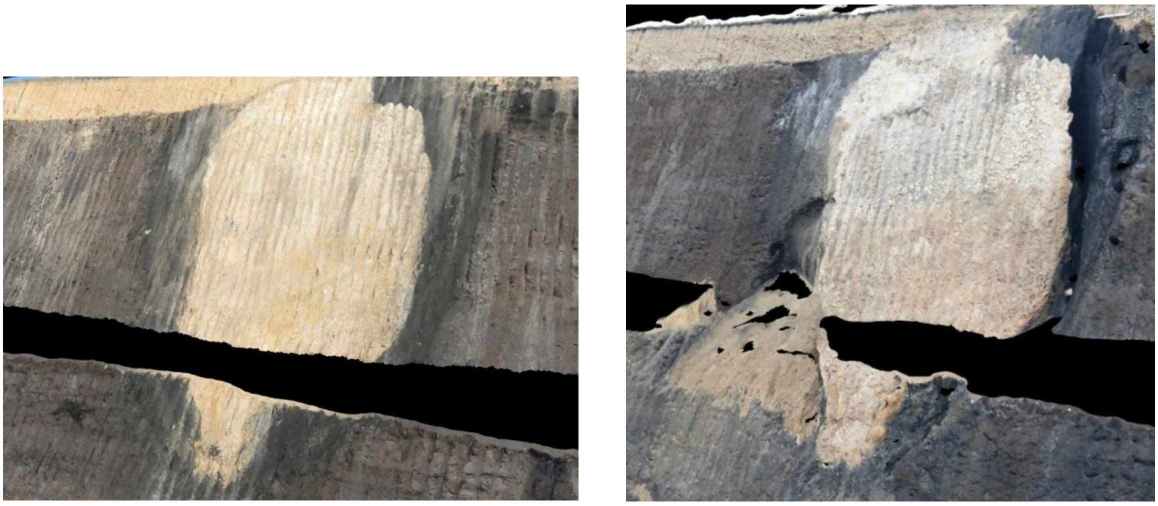

Figure 5: Before and after models of batter deformation

In benchmark trials against more conventional, discrete point prism monitoring, 3D drone based mapping of batters has proven to be effective in identifying areas of batter movement and deformation. On the basis of these extremely encouraging results, further trials are planned with a view to drone based photogrammetric mapping playing a significant role in future Ground Control Management for this site.

4.2.4 High Resolution Orthoimagery

It's only fair to note that orthophotos were routinely produced well before digital photogrammetry emerged. However, these 'analogue' orthophotos were really only available as hardcopies and were relatively expensive and difficult to produce.

An orthophoto or orthoimagery, as it is now often referred to, can be defined as an orthogonally rectified photographic image (either digital or hardcopy). The perspective projection of the raw photographs has been removed resulting in orthogonal, map accurate imagery. In almost all cases, the orthoimagery is made up of a large number of raw images where only the optimal central portion of each individual image is used in the production of the final overall product.

Digital photogrammetry together with GNSS positioning of airborne sensors (cameras etc.) has meant that the once very difficult task of orthophoto production is now just another step in the same digital workflow.

4.2.5 3D Modelling of Man-made Structures

Photogrammetric techniques can be applied to man-made structures such as viaducts, buildings, bridges, statues, as readily as natural features. It should be noted however that in many cases man-made features such as the examples given, represent more challenging photogrammetry projects as they are often no longer fundamentally planar, as is the case with traditional applications or cliff lines and highwalls. Rather, man-made features often involve full 360 degree complex photography networks which can be considerably more difficult, and require much more photography than simpler, nominally planar projects. Having said that, and perhaps because of the added complexity, the 3D models that are created of man-made features can be among the most visually impressive, whilst also retaining the backbone of a fully spatially and geometrically correct 3D survey.

Objects / structures that can be particularly difficult to model are those of long, slender proportions. Generally the more 'massive' the object the easier it will be to model. For example, an old sandstone railway viaduct would be much easier than say the Sydney Harbour Bridge.

Figures 6a and 6b are an old gold smelting stack of considerable historical significance. Figure 6a shows the underlying, photogrammetry derived 3D point cloud framework, while Figure 6b provides an overview with photography based 3D render applied to the frame.

Figure 6a: Underlying point cloud

Figure 6b: Photographically rendered historic stack model

4.2.6 Rock Shelter / Rock Bar Modelling

As with the man-made features discussed in section 4.2.5 above, rock bars and rock shelters are ideal applications for digital photogrammetry based 3D modelling. These features are generally quite complex in geometry, lighting and accessibility, making them very difficult to accurately record / survey using more conventions methods. These sensitive features are regularly the focus of mining companies and related stakeholders as their sensitivity means they may be more susceptible to impact resulting from ground movements.

The benefits to all parties of accurate, high resolution 3D modelling of such sites is twofold: firstly a baseline condition record, both geometric and visual (photographic), can prove extremely valuable for both qualitative and quantitative assessment of any impacts which may occur; secondly, in the event the features are damaged or even destroyed the 3D models can facilitate the accurate restoration of the site, and / or provide a permanent high quality record of what the site was like prior to being damaged. Figure 7 shows a recently completed 3D model of a combined rock bar and rock shelter site in the NSW Southern Coalfield.

4.2.7 Archaeology & Heritage Recording

Photogrammetry based modelling has been used for a range of environment and heritage features. In the rock bar model in Figure 7 there are numerous Aboriginal grinding grooves which have been modelled. Likewise, rock art has been recorded in shelters where the real benefit is that not only does the photogrammetric model yield a photographic quality record of the art / grinding etc., but the 3D model provides a complete geometric and spatial context of the site. Similarly, man-made features of historical significance such as the previously referenced stack or abandoned buildings, entire facilities, ruins can be readily modelled and recorded.

Unfortunately, time is often the enemy of both Indigenous and built heritage sites. In many cases, full 3D rendered computer aided design (CAD) models of these sites may become the only record available. One of the really exciting aspects of this application, will be the ability of the 3D rendered models to be experienced in a virtual reality environment (refer section 4.3.2).

Figure 7: Combined rock bar and rock shelter 3D Model

4.3 FUTURE DIRECTIONS

4.3.1 Deformation Monitoring without control

Like virtually all survey and mapping activities, control points are required to provide an accurate framework for photogrammetric mapping and modelling surveys. The most accurate, versatile and reliable way of controlling photogrammetry networks is by adding targeted control points at / around the site that are visible in the photography. Typically, control points are surveyed in using either total station instruments, GNSS receivers or a combination of both. In many cases, especially inaccessible areas such as cliffs, rock shelters and creek lines, the provision of survey control points is substantially more difficult, time consuming and costly than the rest of the digital photogrammetric modelling process.

It should be stressed that 'control' in the context discussed above refers to absolute control. Controlling models in a relative sense is far simpler and can also include an approximate (± 3m) absolute location without imposing too much additional expense on the project.

An exciting advancement in drone technology is the integration of full differential real-time kinematic (RTK) or post-processed kinematic (PPK) GNSS sensor positioning and rotation determination. The addition of this accurate positioning technology onto relatively affordability drones (from ~ $30K) means that 3D models with an absolute 3D accuracy of better than ±50mm is now possible with little to no ground control.

Even more interesting is using a form of autocorrelation on two (or more) 3D point clouds that have no absolute control at all, to determine and quantify areas of difference – deformation. A large open cut coal mine is currently trialling and benchmarking the effectiveness of using uncontrolled drone derived 3D point clouds for deformation monitoring of mine batters. Initial results have been extremely encouraging. Figure 8 provides a visualisation of two auto-correlated point clouds on a section of open cut coal mine, where white / light grey shows areas where point cloud correlation agrees to better than 50mm whilst coloured regions identify areas where the point clouds diverge indicating change in the shape of the surface. These deviations between surfaces can be represented and quantified in a range formats including: colour coded images such as Figures 8a and 8b, contours of deformation, cross sections, right through to simple tabular data.

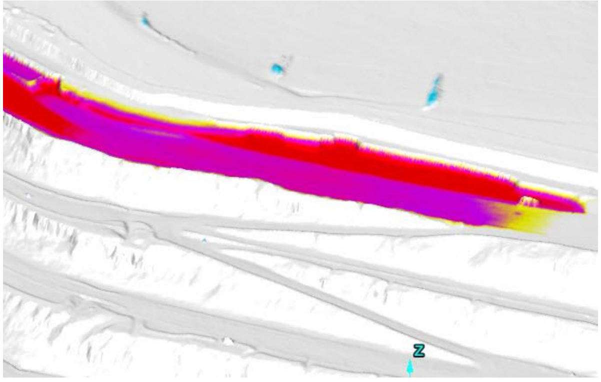

Figure 8a: Point cloud autocorrelation – civil site

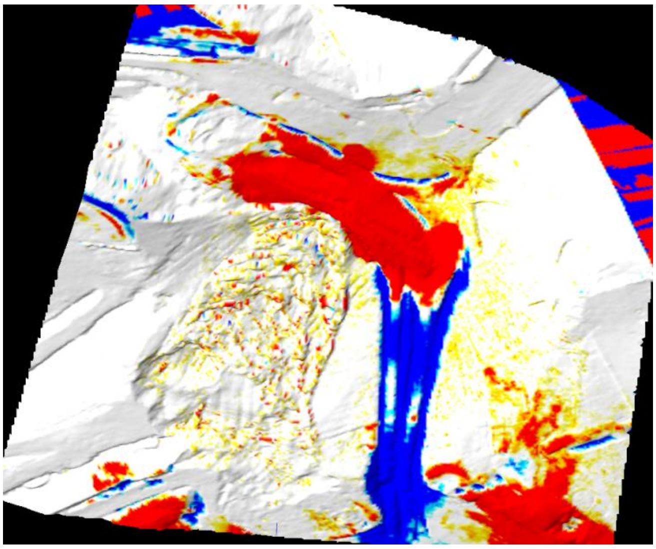

Figure 8b: Point cloud autocorrelation – deformation site

The same auto-correlated point cloud principle has great potential to yield extremely accurate (<±5mm) deformations from a given baseline surface. To this end, trials are ongoing to gain a greater understanding of the full potential and limitations of this very promising methodology.

In addition to using the continuous point cloud data, trials are also under way to automatically extract discrete point monitoring information from the same raw overlapping photography.

4.3.2 Virtual Reality

Currently, hi-resolution 3D rendered animations are routinely produced and only really limited by our imagination (and file size). These animations are visually spectacular and it is easy to forget they are actually built from survey quality, geometrically accurate datasets. These datasets have all the functionality of traditional survey data, but with the added bonus of being able to yield such high-resolution qualitative data formats that are easily accessible to everybody, not just surveyors and engineers.

It is a relatively small step to move from the current predefined video animations to a fully immersive 3D virtual reality experience. Perhaps the most exciting aspect of the virtual reality solution is that users can experience sites in a way that is second only to being there in real life. When we consider that many of the best Indigenous rock art sites for example are, quite rightly, off limits to the general public, virtual reality allows people to still engage with, and hopefully appreciate such sites in ways that are simply not possible from more conventional imagery. Taking one-step further, many culturally significant sites have a finite lifespan and may well be lost to the future. 3D survey quality rendered models such as those produced by modern digital photogrammetry provide us with a way of ‘digitally preserving’ these sites indefinitely.

Please note that some elements of this section: **Digital Photogrammetry** have been taken directly from the author’s 2017 paper - *Re-emergence of Photogrammetry for Hi-Resolution 3D Surface Modelling and Measurement*.

5 CONCLUSIONS

With the seemingly ever-increasing rate of technological advancement, it is interesting to note that two of the most exciting areas of development in survey monitoring involve the evolution of older technologies. GNSS (formerly GPS) position monitoring solutions have very recently become dramatically more cost effective and can now incorporate a range of additional sensors such that they are an integrated hub reporting a variety of measured data autonomously to a central internet site. Digital photogrammetry is an extremely powerful measurement / monitoring technique capable of simultaneously yielding continuous point cloud datasets and the numerous derivatives along with accurate discrete point data. Stand-alone GNSS + monitoring units and digital photogrammetry are just two areas of recent development, there are many more across the surveying, mapping and remote sensing disciplines. Irrespective of the measurement technologies available, it needs to be reinforced that carefully defining what has to be measured, how accurate the measurements need to be and how frequently measurements need to be taken is by far the most important step in any measurement / monitoring task. Only once these parameters are clearly understood should specific measurement methodologies be considered.

* GNSS stands for ***Global Navigation Satellite System*** and is the new naming convention for what was previously referred to as GPS. The reason for the change in terminology was that GPS referred directly to the United States Global Positioning System (Satellites) whereas GNSS refers to the combined satellite positioning systems (e.g. GloNass (Russia), BeiDou (China), Galileo (Europe)).

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