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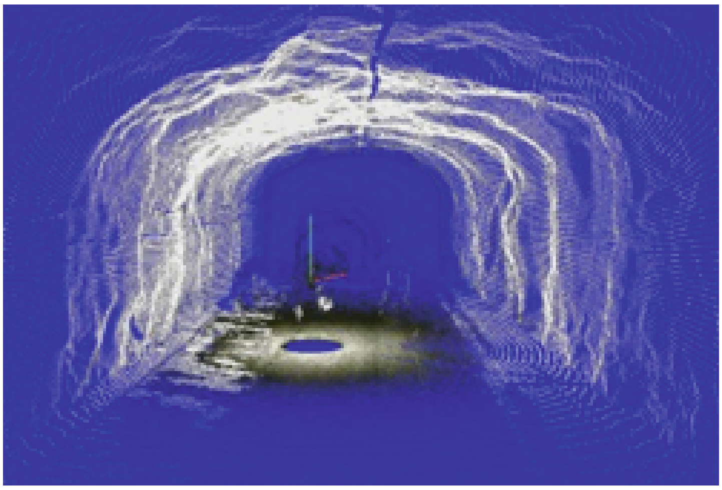

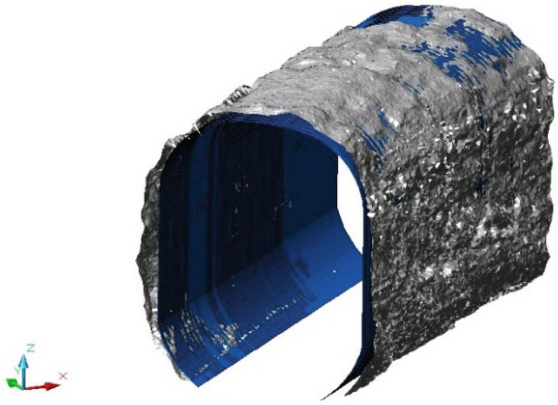

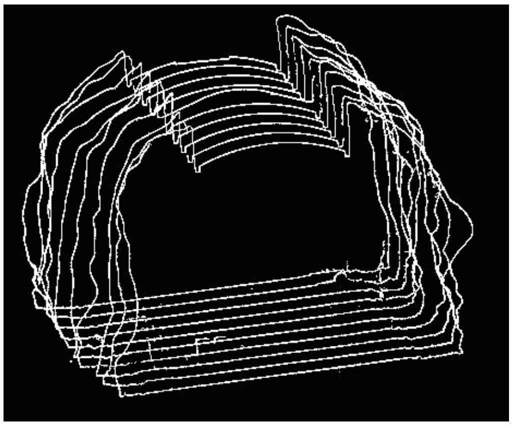

PRACTICAL APPLICATION OF 3D LASER SCANNING TECHNIQUES TO UNDERGROUND PROJECTS

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BeFo Rapport 114

ROCK ENGINEERING RESEARCH FOUNDATION
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PRACTICAL APPLICATION OF 3D LASER SCANNING TECHNIQUES TO UNDERGROUND PROJECTS, PHASE 2-3

A part of ISRM-Swedish national task: "A survey of 3D laser scanning techniques for application to rock mechanics"

Praktiska tillämpningsområden av 3D laserskanningstekniken i undermarksprojekt, fas 2-3

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Preface

The work resulting in this report "A survey of 3D laser scanning techniques for application to rock mechanics" commenced in 2007 and was conducted during the 2007–2011 ISRM Presidential period. The motivation for the work was to produce a comprehensive report explaining the techniques and advantages of laser scanning for rock mechanics/rock engineering use. 3-D laser techniques have been used in many engineering fields over the last twenty years and show great promise for characterizing rock surfaces. Thus, it was considered that a report concentrating on a description of the laser scanning capabilities plus the actual and potential rock mechanics applications would be of great benefit to the ISRM members and the rock engineering community at large.

The project began as an ISRM-Swedish National Group project, stimulated by Professor John A Hudson (the then ISRM President), with the work being undertaken by Dr Quanhong Feng of the MultiInfo 3D Laser Scan Solution AB company. The work was funded by BeFo, the Swedish Rock Engineering Foundation in three different stages. The first stage was in 2008 for the pre-study of both laser scanning and photogrammetry, the second stage in 2010 for the further pre-study of laser scanning, and then the third stage in 2011 for the case study and this final report. BeFo's aim is to support research which will have broad support among takers in industry, academia and society in general and that the results should be useful in practical applications. Thus, the overview of laser scanning techniques fitted well within this objective. For the 2011 latter stage of the project, BeFo set up a reference group, comprised of the following: John Hudson (ISRM), Mikael Hellsten (BeFo), Ulf Håkansson (Skanska), Anders Boberg (Tyréns), Peter Lund (The Swedish Transport Administration) and Peter Hultgren (SKB, Swedish Nuclear Fuel and Waste Management Co).

We are pleased to report that the project has been brought to a successful conclusion with Dr. Feng's production of a document published in the 'Orange Book' of the ISRM. The following document is a little more extensive compared to the version in the ISRM Orange Book. Our aim is that this report will provide extended information useful for practical industrial decisions concerning site characterization. Readers will find that the successive main report sections (of Introduction, Current Development, Special Features, Capturing Procedure, Application Examples, and Rock Exposure Characterization) are both comprehensive and lucid. The report does exactly what was originally intended: to alert readers to the significant potential of laser scanning capabilities and to illustrate its use with examples.

We are grateful to Dr Feng for his commitment to the project throughout the four-year period and congratulate him on its most satisfactory outcome. We hope that readers will be as impressed by the report as we are.

Stockholm February 2012

Mikael Hellsten

SAMMANFATTNING

3D-laserscanning har utvecklats sedan slutet av 1990-talet för 3D digital mätning, dokumentation och visualisering inom flera områden, inklusive 3D-design inom processindustrin, dokumentation och kartläggning i arkitektur och infrastruktur. Genom att använda en 3D laserscanner kan en tunnel eller ett undermarksbygge digitaliseras i 3D med högskanning hastighet och upplösning på mm nivå. Data från skanningen består av inte bara XYZ-koordinater utan även högupplösta bilder, antingen i grå-skala eller färg (med RGB-data) som för översikt kan omvandlas till ett globalt koordinatsystem. Varje bergtekniskt objekt kan med sina relationshandlingar snabbt registreras i digitalt 3D och visuellt format i ett riktig koordinatsystem. Det innebär en potentiell tillämpning för 3D-mätning, dokumentation och visualisering med hög upplösning och noggrannhet avseende bergmekaniska tillämpningar.

För att undersöka den nuvarande utvecklingen av state-of-the-art avseende laser scanning tekniker och dessas potential för tillämpning inom bergmekaniken, har ISRM i samband med kongressen i Lissabon 2007genom Svenska Bergmekanikgruppen administrerad av BeFo definierat en Svensk Nationell ISRM- uppgift. Uppgiften fokuserar på tre delar: 1) Undersöka state-of-the-art rörande nuvarande utveckling av laserskanning tekniker, 2) Sammanfatta applikationsexemplen genom att använda laserskanning tekniker i bergmekaniska projekt, 3) Utvärdera gränser och behov för vidare utveckling.

I denna rapport beskrivs inledningsvis syftet med rapporten, och därefter sammanfattas nuvarande utveckling av laserskanning tekniker av så¨väl hård- som mjukvara. Baserat på litteraturstudier och några fallstudier, presenteras aktuell status avseende laserskanning tekniker för bergmekaniska tillämpningar.. Slutligen diskuteras gränserna för nuvarande utveckling och behovet av vidare utveckling.

Nyckelord: 3D laserskanning, undermarksbyggande, bergmekanik, bergteknik, byggresultat, kontroll mätning, 3D mätning, Dokumentation.

SUMMARY

3D laser scanning techniques have been developed since the end of 1990s for 3D digital measurement, documentation and visualization in several fields including 3D design in processing industry, documentation and surveying in architecture and infrastructure. By using a 3D laser scanner, a tunnel or underground construction can be digitized in 3D with a fast scanning speed and high resolution up to mm level. The scanning data consists of not only X-Y-Z co-ordinates but also high resolution images, either gray-scale (with reflex intensity data) or color (with RGB data), and then can be transformed into a global co-ordinate system by control survey. Therefore, any rock engineering objects with its as-built situation can be quickly recorded as the 3D digital and visual format in a real co-ordinate system. In this case, it provides a potential application for 3D measurement, documentation and visualization with high resolution and accuracy.

In order to investigate the current development of the state-of-the-art on laser scanning techniques and its potential application to rock mechanics, ISRM therefore set up the ISRM-Swedish National task in 2007 during ISRM congress in Lisbon through Swedish Rock Mechanics group (BeFo). The task focuses on three parts: 1) Investigate the state-of-the-art on current development of laser scanning techniques; 2) Summarize the application examples by using laser scanning techniques to rock mechanics projects; 3) Evaluate the limits and needs for further development.

In this report, the purpose of this study will be described first; and then summarize the current development of laser scanning techniques on both hardware and software. Based upon the literature review and some case studies, current status on application of laser scanning techniques to rock mechanics are presented. Finally, the limits of current development and the needs for further development are discussed.

Key Words: 3D Laser scanning, Underground construction, Rock mechanics, Rock engineering, As-built, Control survey, 3D measurement, Documentation.

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1. Introduction

1.1. Background

In rock mechanics, on-site characterisation of a rock exposure for a project is one of the important steps, which is required to collect the input data for further rock mechanics analysis, rock engineering design and numerical modelling. The quality and quantity of the on-site mapping data play an important role for the results of the following steps. However, traditional methods have some drawbacks in capturing enough data for further analysis, which then affects the results for the whole project. Therefore, efforts to improve on-site mapping data with new techniques have continued, and different techniques have been tested in order to make on-site mapping successful.

A typical set of parameters often suggested for capturing in practice include fracture orientation, spacing, trace length and aperture etc. [1, 2, 3]. However, in current practice, much of these data is still obtained by hand, including using compass and inclinometer for fracture mapping, measurement with a ruler, and documentation by recording information in a notebook and photographing with a camera. These so-called traditional methods are now still used in most of rock engineering projects, so the quality and quantity of the data are sometimes unable to meet the necessary requirements for rock engineering projects. The most well-known drawback in traditional methods is that too much personal work is involved in the *in situ* data acquisition procedure, which is time-consuming, not accurate enough, sometimes difficult and can be dangerous when reaching the rock faces physically. In addition, the method of data recording and storing cannot make full use of modern IT and computer technology to speed up the data processing, and then provide the input data in a required format for further analysis and designing. Therefore, the quality and quantity of the drawbacks inherent in the traditional method have great impact on the quantity and quality of mapping data, and will inevitably affect our understanding of the rock mass behaviour.

In this case, it has been recently realised that applying a new method for *in situ* data acquisition is the key point in solving the bottleneck problem for improving rock face mapping data, in terms of both quality and quantity. Especially with the development of IT technology, the digital data must be used as the input for computer-aided work. Therefore, interest in new methods for acquisition of digital data has greatly increased in recent years.

To avoid these problems, a new method should have the following benefits:

- quickly capturing the data in the field;

- digitally collecting the data in order to utilise modern computer resources to speed up the procedure of data capturing and processing;
- having the access to visually operate the data so that the operator's background knowledge and experiences can be fully utilised to observe any complicated phenomena observed in the jointed rock mass, and then obtain the required information for rock engineering applications;
- keeping the necessary level of accuracy for different rock engineering applications; and
- having the possibility to capture the data in 3D without physically contacting rock faces at a range of distances.

Through the literature review for this project, it has been found that different digital techniques have been tested, including the following

1) Digital image analysis

Several research groups have tested the utility of image processing techniques for automatic measurement of fracture geometry on rock surfaces. The research work done by Reid and Harrison [4], Hadjigeorgiou *et al.* [5], Post and Kemeny [6] have shown successfully applied different image segmentation techniques for automatically extracting and recognising trace lines of fractures. Roughness measurement was also performed using image processing techniques [7]. To perform the automatic 3-D mapping, automatic image matching is another important step. Due to the complexity of the features in the rock face images, it seems difficult now to successfully achieve 3-D fracture mapping by image processing techniques.

2) Geodetic total station

Total station (TS) is a geodetic method usually used for surveying and mapping. It also has been employed for determining the trace length of fractures on inaccessible rock slopes by Bulut and Tüdes [8]. With the TS method, discontinuity traces can be determined through the co-ordinates of a set of points, but the co-ordinates of the points must be captured by the help of a reflector. In addition, TS has also been tested by Feng *et al.* [9] for measurement of fracture orientation. However, it is time-consuming for a large amount of measurements.

3) Photogrammetry

There are different photogrammetry techniques. Analytical photogrammetry techniques have been already used before for measuring fracture geometry at exposed rock faces by Harrison [10], Ross-Brown *et al.*[8] and Coe [12]. With this method, each pair of photographic hard copies is used to create a stereoscopic view of target areas of the rock face using a stereoscopic plotter or stereocomparator. Geometrical parameters of fractures, such as orientation, spacing and trace length, can then be determined by capturing co-ordinates of several target points. With the latest development of digital photogrammetry technology, the rock surface is recorded as the images from a digital camera, and the procedure (similar to that of analytical photogrammetry) for capturing 3-D data can be conducted in a PC with suitable software by using a pair of digital images of the rock faces, instead of the hard copies of six photos. This method has been applied for fracture mapping in tunnelling by Beer *et al*. [13], and more applications have been continuously developed in recent years.

1.2. Purpose of this study

In addition to the items mentioned above, a new technique, 3D laser scanning, has become more and more popular in recent years for on-site mapping, and shows more potential as a digital method for on-site characterisation of a rock exposure in rock mechanics.

3D laser scanning techniques have developed since the late 1990s, and these enable us to capture 3D digital data and associated images with high speed and accuracy. It has also now become more and more popular for use in capturing 3D digital data for 3D documentation and measurement in the processing industry for 3D virtual design, documentation in architecture and archaeology, and also 3D surveying and mapping in civil and infrastructure fields. In addition, these techniques have also been tested in some rock engineering projects, such as 3D digital fracture mapping [14, 15, 16], detecting water leakage via laser images [17], identifying rock types based upon image analysis [18, 19], input data for numerical modelling [20], deformation monitoring [21, 22] and 3D roughness analysis [23]— which shows the potential benefits for rock mechanics and rock engineering applications.

In order to investigate the practical possibility, the 2007–2011 ISRM (International Society of Rock Mechanics) President, Professor John A. Hudson, established a ‘National Task’ with the Swedish National Group in 2007. The purposes of this study were:

- Investigate the current development for hardware and software for 3D laser scanning,
- Summarise the existing applications to rock mechanics,
- Evaluate the laser scanning benefits for rock mechanics, compared to other methods, and
- Identify the limits and needs for further development.

In this report, the purpose of this study will be further described first; and then the current development of laser scanning techniques, both hardware and software, will be summarised. Based on the literature review and some case studies, the current status of the application of laser scanning techniques to rock mechanics will be presented. Finally, the limits of current development and the needs for further development are discussed.

2. Current development of 3D laser scanning techniques

2.1 State-of-the-art of 3D laser scanning hardware

Laser scanning, often also referred to as LiDAR (light detection and ranging), is a new technique to obtain the digital data of an object—rather than making a single measurement like a laser rangefinder, but capturing millions of measurements by rotating mirrors, so the unit can cover a large area of an object. The 3D scanner is a type of a device that records the as-built situation with the data on its shape and possibly its appearance (i.e. intensity or colour), by emitting light and detecting the reflection of the light in order to accurately determine the distance to the reflected object. This technique has been developed since the late 1990s, and has now been applied to different fields for 3D measurement, surveying, documentation and modelling.

There are different scanning systems used for capturing different sized objects (i.e. from a small tool to a large building), with a wide range of scales (i.e. from few mm up to tens of hundreds of metres), and so can be divided into different scanning systems according to range:

- Airborne Laser Scanning (ALS)
- Terrestrial Laser Scanning (TLS)
- Micro-Laser scanning (MicroLS)

Airborne Laser Scanning (ALS) is the scanning system used on an aircraft to capture 3D data of large areas, such as agricultural or forestry sites, urban areas, industrial plants, etc. Micro-Laser scanning (MicroLS) are those 3D scanning devices used to scan an object over a short distance (from mm to a few metres), and mainly applied to reverse engineering and prototyping, quality control/inspection and documentation of cultural artifacts, etc. These two types of scanning systems are not typically applied to rock engineering. So, in this report, the focus is on Terrestrial Laser Scanning (TLS) which is now mostly applied to rock engineering projects in practice.

There are many different types of laser scanners on the market and they have different specifications for different applications. However, the specifications of different scanners are designed with different scanning principles. Almost all of these scanners are designed according to three different scanning principles: 1) Pulse-based; 2) Phase-based; and 3) Triangulation-based. Most of the hand-held and short-range scanners or MicroLS are designed with triangulation-based techniques, but all TLS scanners are designed with either pulse-based or phase-based techniques, and the scanning principles can be described simply as the following:

1) Pulse-based scanner

The pulse-based scanner is also called the time-of-flight (TOF) scanner, which is an active scanner that uses laser light to probe the subject. At the heart of this type of scanner is a time-of-flight laser rangefinder. The laser rangefinder finds the distance of a surface by timing the round-trip time of a pulse of light, see Figure 2-1 [24]. A laser is used to emit a pulse of light and the amount of time before the reflected light is seen by a detector is timed. Since the speed of light *c* is a known quantity, the round-trip time determines the travel distance of the light, which is twice the distance between the scanner and the surface. When *t*, the round-trip time, is recorded, then the distance can be calculated with the following equation:

$$\text{Distance} = (\text{Speed of Light} * \text{Time of Flight})/2$$

Clearly the accuracy of a time-of-flight 3D laser scanner depends on how precisely we can measure the *t* time. The laser rangefinder only detects the distance of one point in its direction of view. Thus, the scanner scans its entire field of view one point at a time by changing the range finder's direction of view to scan different points. The view direction of the laser rangefinder can be changed by either rotating the range finder itself, or by using a system of rotating mirrors. The latter method is commonly used because mirrors are much lighter and can thus be rotated much faster and with greater accuracy. The typical time-of-flight 3D laser scanners can measure is the distance of 1,000–150,000 points every second [25].

2) Phase-based scanner

Compared to the TOF scanner, this type of scanner has a high speed scanning rate and better accuracy, but a short distance in the range of tens of metres. In this case, the transmitted beam is modulated by a harmonic wave and the distance is calculated using the phase difference between the transmitted and received wave. The Phase-based scanner has a higher precision, in the domain of millimetres, and higher measurement rates up to one million points per second, can be obtained applying the phase shift measurement principle. A c/w (continuous wave) laser is used as the carrier for a signal modulated onto it, typically using amplitude modulation. The phase of the emitted and the received signal are compared. The relation between phase differences, $\Delta\varphi$, given in radians, and the one-way range is:

$$\gamma = \Delta\varphi/(2*\pi)*\lambda/2 + \lambda/2*n$$

where λ is the wavelength in metres, and *n* is the unknown number of full wavelengths between the sensor system and the reflecting object surface. Choosing, e.g., λ =100 m, means that there is a unique measurement range of 50 m. All measurements to objects further away will be folded into the first 50 m interval. The precision of the measurement is in the order of one per cent of the phase and can even be better. With the values from above, this would result in a measurement precision of ±50 cm. This problem can be solved by using more than one modulation wavelength, i.e. two or three wavelengths (Figure 2-2). Then, the longest wavelength defines the uniqueness range and the shortest wavelength defines the precision that can be obtained.

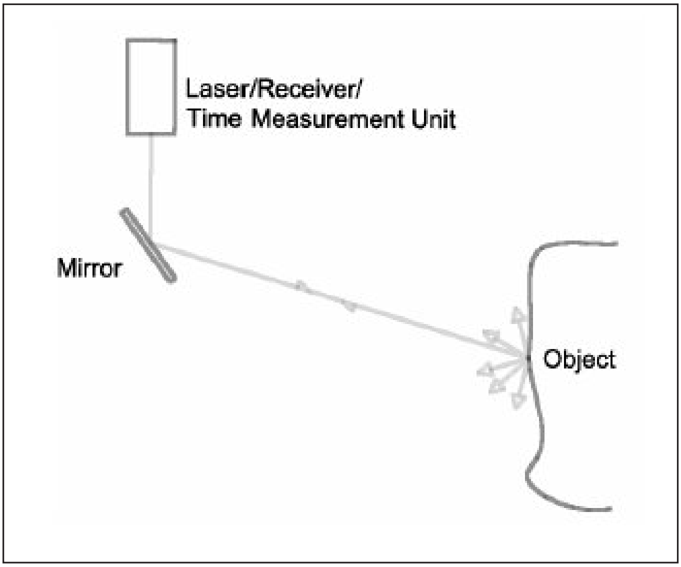


Figure 2-1. Principle of time-of-flight laser scanner [25].

Comparing these two different types of scanners, their main features can be presented as follows.

1) The TOF scanner is a long-range scanner. It has a large range of scanning field, up to several hundreds of metres, but lower accuracy and scanning speed compared to the phase-based scanner. The maximum scanning range is now about 6000 m;
2) The phase-based scanner is a middle-range scanner, up to the maximum of 187 m. Its accuracy is between the TOF and Triangulation scanners, but it has a high scanning speed and wide field of scanning view by rotation in both the vertical and horizontal through 360 degrees.

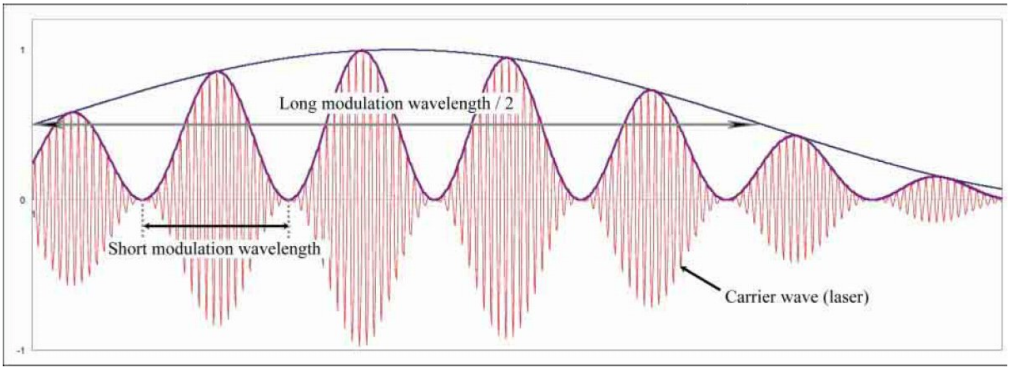


Figure 2-2 Schematic drawing of two modulation wavelength and carrier wave for phase-based laser ranging [25].

Table 2-1 shows the most of the TLS scanners on the current market, and Figure 2-3 shows some pictures of the TLS scanners.

Table 2-1. Terrestrial Laser Scanner existing on the current market.

TLS scanner	Company	Date of introduction	Scanning principle
DeltaSphere-3000IR	3rdTech	2005	Phase-based
Surphaser 25HSX	Basis Software	2006	Phase-based
Surphaser 25HS	Basis Software	2005	Phase-based
LS 420	Faro	2005	Phase-based
LS 840	Faro	2005	Phase-based
LS 880	Faro	2005	Phase-based
Imager 5006/ HDS6000	Z+F/Leica	2006	Phase-based
Imager 5010/HDS7000	Z+F/Leica	2010	Phase-based
Faro Focus 3D	Faro	2010	Phase-based
CPW 8000	Callidus	2007	TOF / Phase-based
CP 3200	Callidus	1997-2006	TOF
4400-LR	I-Site	2006	TOF
4400-CR	I-Site	2006	TOF
ScanStation 2	Leica Geosystem	2007	TOF
ILRIS-3DER	Optech	2006	TOF
ILRIS-3D	Optech	2000	TOF
LMS-Z420i/LMS-Z390i	Riegl	2003/2007	TOF
LPM-321	Riegl	2007	TOF
GX	Trimble	2005	TOF
VX	Trimble	2007	TOF

Figure 2-3 Examples of TLS scanners on the current market (updated to Sept, 2011, and [29]).

2.2 Current development of software

Software for terrestrial laser scanning actually comprises several software modules of different types. Considering the whole procedure of a scanning project from data collection to the final model, a rough division may be made as follows:

- Software for scanning control
- Software for registration of individual scans together or into the global co-ordinate system
- Software for point cloud treatment
- Software for CAD modelling
- Software for texture and image mapping
- Software for data and project management
- Software to integrate scanning data to another existing program, e.g. CAD and GIS systems

The software described above is more general for scanning and modelling. Some special software is needed as follows:

- Software for converting between scanning data and CAD or other software; and
- Software for special applications, i.e. architecture documentation, rock surface mapping.

The development of the software is advancing rapidly, and becoming more and more studied by the users—because the quality of these software modules has a considerable influence on the quality of the final modelling results, and also on the time needed to achieve the results. Thus, a smoothly performing software product is the basic requirement for the acceptance of 3D laser scanning techniques.

For laser scanning data, the most important software is the one for point cloud processing, and indeed most of the scanner manufacturers have developed their own point cloud processing software. In addition, several other companies have developed point cloud processing software. By exporting the point clouds in the xyz file format, point clouds from any scanner can be analysed with any of the software packages. Point cloud processing software includes:

1) Cyclone and Cyclone Cloudworx (Leica)
2) Polyworks (Innovmetric)
3) Riscan Pro (Riegl)
4) Isite Studio (Isite)

5) LFM Software (Zoller+Fröhlich)
6) Luposcan (Lupos3D)
7) Split FX (Split Engineering)
8) RealWorks Survey (Trimble)
9) Pointools (Pointools)

Furthermore, much research work has also focused on development and improvement of the algorithms in order to provide good quality software, including:
- Error analysis and control of the whole scanning procedure from scanner calibration to modelling; and
- Matching and segmentation of 3D point clouds in order to make the modelling more effective and automatic.

2.3 New trend for further development

Through more than ten years of development, hardware and software have been greatly improved for their basic functions as a new technique for 3D surveying, such as scanning speed, range and resolution. However, compared to other surveying techniques, laser scanning has its own special features, and therefore cannot only be taken as a surveying tool, but also as a new 3D technique for documentation, design and visualisation. Some of its new features, such as too much data flow (in the unit of MB and GB), all the information being in 3D (3D image, point clouds and model), inevitably there are some problems in its applications: for example, incompatibility with existing software, difficulties in processing so much data, and transformation between 2D and 3D. So, laser scanning provides us with much more information than any other surveying techniques, but at the same time introduces difficulties in use if no good solutions for the afore-mentioned problems are found. Fortunately, the recent developments in both hardware and software are focused more on practical applications. The development focus can be summarised as described in the following text.

2.3.1 Developing a unique system for special applications

In order to make the whole procedure simple, new development is focusing now on the key-door solution, which develops a system, including both scanning hardware and software for data processing, and also the data formats, for the results to be compatible for exchange with the existing software. Such systems have their own special applications, and both hardware and software are developed for special application situations and standards.

A typical example is the tunnel scanning system, TMS, developed by Amberg AG, and it is specially applied to tunnelling projects in order to control the geometry of a tunnel. In this package, the hardware consists of ,not only a phase-based scanner, but also associated tools for positioning of each scan, and the software is also specially designed for scanning control in the tunnel situation. It enables the creation of standard products, such as cross-section and difference models for tunnel dimension measurement and documentation. The export results have a standard format for input to other software, such as AutoCAD.

Another example is the cavity scanning system, which has been developed by Optech (www.optech.com) and MDL (www.mdl.com).

2.3.2 Much more development has taken place with the associated tools and scanners

As the scanner is applied to many different projects, it is not enough only to use the scanner, but some associated tools are needed to perform the scanning tasks. Scanning examples are scanning a shaft or borehole by running the scanner up and down, or inserting the scanning system into an enclosed building through a small hole (e.g. 200 mm diameter) due to the high radiation, or mobile-scanning on the railway or on the road surface. Therefore, the scanner is also developed by being associated with some tools to load and run the scanning, so as to make the scanning more effective and applicable.

A typical example of recent developments is to use remote-control for the scanning in order to run the scanning in an area where it is dangerous or inaccessible. Figure 2-4 illustrates a remote-control scanning system developed by Faro [26]. A special scanning system which can run on the railway has beendeveloped by Amberg and is shown in Figure 2-5 [27].

Figure 2-4. A prototype of remote-control scanning system developed by Faro [26].

Figure 2-5. Amberg GRP scanning system developed for railway scanning [27].

2.3.3 Integration of colour photography

In addition, and compared to photogrammetry, the greatest disadvantage is that the laser scanner cannot provide a colour image. It is not easy to develop a true colour 3D laser scanner with high scanning speed and accuracy, so one of the alternatives, which is now often used, is to integrate colour photography with the laser scanning. Much more development has been undertaken by different vendors, and can make scanning systems semi- and fully-automatic through both scanning and photographing. A ‘semi-automatic’ system means that the scanning is made automatically first, and then the scanner is replaced by a digital camera at the same position (i.e. on a tripod) for taking a series of colour photos manually. But, the ‘fully-automatic’ system has both scanning and photographing automatically controlled by the software, and there is no need to replace the scanner by the camera because they are installed together. Figure 2-6 shows the integrated system from both Faro [53] and Z+F [28].

2.3.4 Mobile scanning system

In recent years, mobile scanning systems have been significantly developed. These mobile scanning systems are grouped as follows:

1) car-borne mobile scanning systems, see Figure 2-7;
2) small-vehicle-borne mobile scanning systems, see Figure 2-9; and
3) train-borne mobile scanning systems, see Figure 2-8.

Compared to a normal TLS scanning system, the mobile scanning system consists of several units with integration of the different techniques, including:

1) GPS positioning system
2) Profile laser scanning system
3) Video camera
4) Associated tools for anti-vibration and data transferring etc.

Faro system [26]. Z+F system [28]

Figure 2-6. Integration of laser scanner and digital camera.

Figure 2-7. Topcon mobile scanning system (www.topcon.com).

Figure 2-8. Z+F Railway mobile scanning system (www.zf-laser.com).

Figure 2-9. S+H trolley mobile scanning system (www.intergeo.com).

2.3.5 Hand-held scanner

This type of scanner is based on the triangulation scanning principle and is often used for scanning a small object a short distance away, e.g. few metres. Compared to both pulse-based and phase-based scanners, it has higher resolution and high accuracy, but normally a lower scanning-speed. So, it is not recommended for application to scanning large objects.

However, the updated developments show potential for scanning large objects. A new hand-held scanning system, called Mantis Vision, can quickly scan an object with high resolution up to less than 1mm, see Figure 2-10.

Figure 2-10. Hand-held scanner of Mantis Vision.

Compared to other hand-held scanners, it has some advantages:

- Longer scanning range: 0.3–5m with a resolution of 0.5 mm
- Large scanning view field: 38–40º
- Higher scanning speed: few seconds per scan
- No need for reference targets

2.3.6 Software suitable for multiple data format

Software has been developed for more compatibility in exchanging the scanning data with other existing software, and it is now focusing on:

- Scanning raw data to be directly imported to different software or converted as the standard format (e.g. ASCII) to be processed in other software;

- Developing interface programs to exchange the scanning data with the existing software; now it is much more developed in CAD software.

2.3.7 Development for 3D analysis

In recent years, laser scanning has not been only limited to 3D surveying and documentation, but also has been combined with other parameters (e.g. stress, temperature and radioactivity) to make 3D analyses of some physical features in 3D. As laser scanning can provide an accurate as-built 3D model, 3D modelling of physical parameters become more realistic. For example, stress distribution and deformation monitoring in rock masses can be modelled in a more realistic environment; also 3D analysis of radioactivity distribution has been used for nuclear decommissioning through a combination of the 3D as-built mode from laser scanning and the 3D distribution model from radioactivity measurements.

3. Special features from 3D laser scanning data

Compared to traditional methods for rock mass characterisation, laser scanning has more advantages, with the following features:

- Capturing a large coverage of a rock surface with high resolution (up to mm) in a short time (in a few minutes depending on the resolution selection)

- All the data are digital and in 3D, both image and co-ordinates

- After reference surveying, all scanning data are registered in a global co-ordinate system, and the rock mass is referenced to its real position in space

- The rock mass can be recorded by remote control and so there are no adverse personal safety issues

- No need for illumination for a high resolution digital image

- By combining scanning and photographing in the software, a rock mass can be recorded in real colour.

Through these advantages, laser scanning can avoid the drawbacks of the traditional method, and improve the quality and quantity of the data for rock mass mapping. So, via the laser scanning, a rock mass can be quickly recorded and the following useful information obtained.

- Position of a rock mass with 3D co-ordinates in a global co-ordinate system

- Geometrical features, e.g. length between points, orientation of a fracture, etc.

- Visual information, e.g. 2D and 3D digital image, 3D virtual model

- Physical features, e.g. water leakage and different rock type by different intensity

Those features have great potential for rock mass characterisation in a rock mechanics project.

4. Procedure for capturing 3D digital data by 3D laser scanning

A typical scanning procedure and the associated data can be described as the following. For a typical scanning job in the field, both reference surveying and scanning are needed.

4.1 Control surveying

Reference surveying is often carried out by using a total station to set up a local co-ordinate system around the scanning area, and link the local co-ordinate system to a global co-ordinate system, and then the surveying data are applied for positioning of each scanning set into the global reference co-ordinate system.

4.2 Scanning

The operation of each different scanning systems is different—because it depends upon the requirements of scanning software and reference surveying. But some basic parameters must be correctly selected for different applications: 1) Scanning resolution; 2) Scanning range; 3) Position of each scanning; 4) Number and location of reference targets. In addition, some scanning systems are also sensitive to the environment, such as temperature, moisture, density of particles in the air, and even the reflectivity of the object. These parameters and factors must be carefully considered in order to obtain good quality scanning data.

The typical raw data from laser scanning is the so-called point cloud, which is a set of vertices in a 3D co-ordinate system. These vertices are usually defined by x-y-z co-ordinates, and typically intended to be digitally representative of the external surface of the rock mass.

For most of the phase-based scanners, the raw scanning data is combined as both point and intensity, so the corresponding intensity image in both 2D and 3D can be obtained, which is useful for documentation and identification of objects in detail. Figure 4-1 shows the raw scanning data typically captured from a phase-based scanner.

The true colour scanner is still under development, and it is only possible now to scan some small objects, but not possible in practice to scan the rock mass over a large area. However, another alternative, through combining scanning data with colour photos in software, is now possible. When scanning at the location, the colour photos are captured by a digital camera at the same time, and then the colour photos are registered to the scanning data in the software; the true colour 3D model of a rock mass can be obtained, see Figure 4-2.

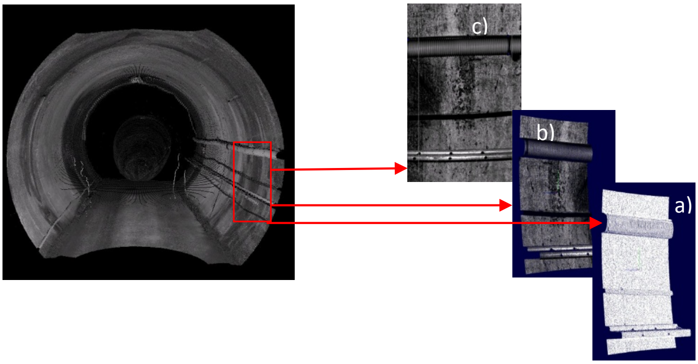


Figure 4-1. Presentation of raw scanning data from scanning of the same object [40]

a) Point cloud; b) 3D laser image; c) 2D laser image.

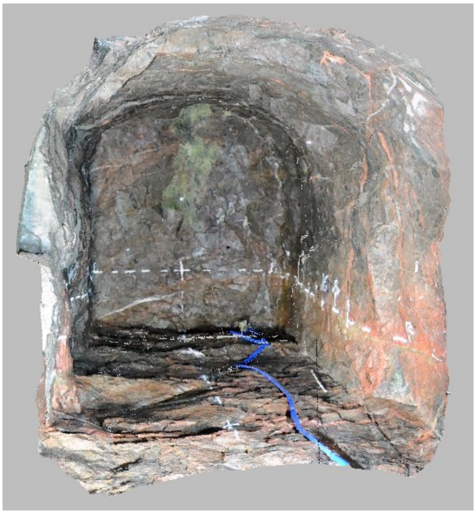


Figure 4-2. 3D colour model of scanning in a tunnel [40].

4.3 Pre-processing data

The on-site captured scanning data, also termed raw scanning data, are necessary to make pre-processing before any further modelling and calculation. The reasons are:

1) Each individual scan obtains the scanning data in the local co-ordinate system, and mostly several scans are needed to cover the whole object. Therefore, each individual scan needs to be registered into a common co-ordinate system; and
2) Not all points in the raw scanning data can be used because there are always some noise points captured, especially there are more noise points from the phase-based scanner. So, these noise points need to be filtered out from the raw scanning data.

In this case, the raw scanning data need to be pre-processed mostly by two steps:

Step 1. Register each individual scan into a common co-ordinate system; and

Step 2. Filter out noise points from the raw scanning data.

In addition, there are different data formats for the raw scanning data from different scanner producers, so it is sometimes necessary to convert the raw scanning data into another format, depending upon which modelling software is used for the post-processing.

4.4 Post-processing data

After pre-processing of the raw scanning data, the point clouds are positioned and oriented in a certain co-ordinate system, and all scanning points are correctly located in a known co-ordinate system, so the post-processing can be performed. The post-processing is done by two different situations or software, as follows.

1) By special developed software

As the scanning data are quite substantial, compared to other data, and also have a special data format, special software has been developed. These software methods can process large amounts of scanning data, and create different results, including support for a CAD model, mesh-model, cross-section, etc. And then, the results can be exported into other existing systems, such as CAD, GIS or other user-familiar systems for different applications.

2) Input into existing software

This was difficult in the earlier period of the development, but now many types of so-called ‘plug-in’ software have been developed, and this plug-in software makes it possible to import a large scanning data file into user-familiar software, such as CAD, GIS and so on.

In addition, many hardware producers will now attract more users, so they allow their special data formats to be converted into a neutral format, the ascii format, to be available for post-processing in many different software programs.

5 Application examples to rock mechanics

To evaluate the potential application of laser scanning to rock face mapping, it is important to establish what is the typical procedure for site mapping in a rock engineering project, and then find out if laser scanning can help to improve or solve the problems of the traditional methods.

For a site mapping project, a typical procedure is:

1) Collect the raw data in the field

The raw data consist of different types, which depends upon the different projects, but all projects must collect some data, such as location, geometry (of fracture, rock surface etc.), through measurement, photographs, taking notes of the observations, etc. Digital methods can make this step much faster and accurate than the traditional approaches. More detailed description in relation to this subject will be presented in the later sections.

2) Calculate and analyse the raw data

After the field data collection, the raw data must be processed for different purposes, such as calculation of fracture orientation and plotting on a stereogram for fracture analysis and stability analysis, importing the fracture parameters for numerical modelling, and also for the design of a dam or tunnel. All of the data processing is now computer-aided, so the raw data must be digitised, which is time-consuming with the traditional recording method.

3) Present and transform the processed data

The processed data and results, either in table or in graphical form, should be presented in a way, or exported to other software, to enable further analysis, modelling or design, which might be in digital form and computer-aided.

4) Store and archive the raw data and results

With the development of computer science, the data and results are now mostly stored and archived in a digital way on CD/DVD, band or external/internal hard disk, so it is important to convert all the data to digital form.

So, in order to avoid the drawbacks of the traditional methods, a new method must have the following important features: i) quickly capturing the data in the field; ii) digitally collecting the data in order to utilise the computer resources to speed up the procedure of data capturing and processing; iii) having the ability to visually operate the data so that the operator's background knowledge and experiences can be fully utilised to observe the complicated phenomena related to a jointed rock mass, and then obtain the required information for rock engineering applications; vi) keeping a certain level of accuracy for different rock engineering applications; v) possibility to capture the data in 3D without physically contacting rock faces—over a range of distances.

As 3D laser scanning has many advantages for 3D measurement and documentation, it shows great potential for application to different projects in rock engineering and rock mechanics. Some typical examples are summarised in this Section.

5.1 Site characterisation of a rock exposure

The most typical application for 3D laser scanning is applied to site characterisation of a rock exposure. Currently, rock surface mapping is still mainly performed by traditional methods, which is well known as by a geological compass with inclinometer to measure dip and strike, and taking notes in a notebook, and also taking some photos for documentation etc. Obviously, the traditional methods have some drawbacks, including:

- Physical contact with the rock face, which inevitably leads to some problems, such as danger in reaching the rock face in some cases, and the impossibility or difficulty in obtaining the mapping data;
- Uncertainty and inaccuracy. Mapping results are very dependent upon personal experience, and the related difficult in making sure or checking out whether the mapping data are reliable, and, if not, why not;
- Time-consuming—not only for the field work but also in transferring data into the computer for further modelling and analysis.

But with 3D laser scanning, there is a great potential to avoid some drawbacks of the traditional methods, and also to improve the quantity and quality of the raw data and the results.

Based upon the literature review and our project experiences, the potential application of laser scanning to rock surface mapping can be summarised as the following:

1) Laser scanning is a non-contact technique, so it is not necessary to reach the rock surface, and there is thus no risk to the person in this regard;
2) It can capture the rock surface with its geometry and position much more quickly and accurately than traditional methods;
3) It collects the data in digital form and in 3D, so 3D digital mapping is possible, and the raw data can be directly processed by a computer, and so possible to

utilise computer-aided resources to speed up the data processing. Both semi-automatic [17] and fully-automatic methods [15] are possible and have been tested for fracture mapping;

4) All the data, from the raw data to the processed results, can be stored and archived within a digital medium, and also transferred (i.e. input and output) between different software;
5) In particular, the data and the results can be checked because the raw data and the processing methods are retrievable, which make the data quality more reliable and controllable.

To characterise the features of exposed rock faces, the International Society for Rock Mechanics (ISRM) proposed ten parameters [1], namely: orientation, spacing, persistence (or trace length), roughness, aperture, wall strength, filling, seepage, number of fractures sets, and block size (as shown in Figure 5-1), to describe the geometrical, mechanical and hydraulic features of fractures.

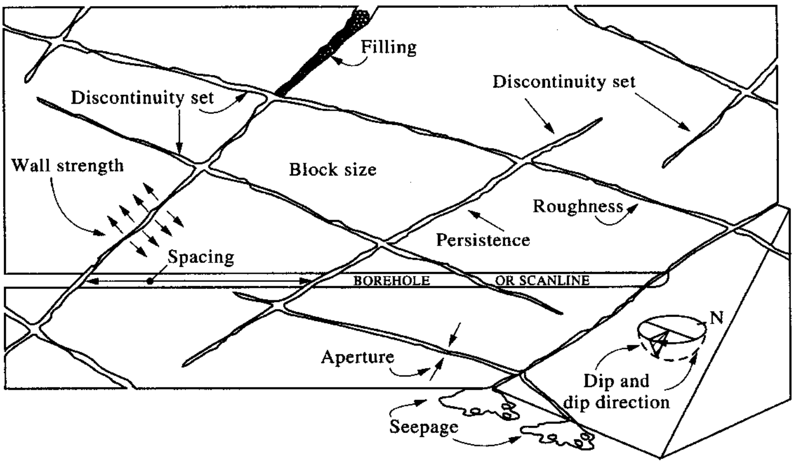


Figure 5-1. Primary geometrical properties of discontinuities in rock (from Hudson [2]).

To be able to characterise the features of a rock surface, the methods must provide the enough information in order to replace the personal observation and measurement obtained by the traditional methods, and be even better in some ways. In general, this information is as follows.

1) Geometrical information

This is necessary for obtaining relevant geometrical parameters, i.e. fracture orientation (dip and strike), block size, spacing, roughness and aperture. Digital methods are able to capture 3D digital data, and can provide 3D geometrical information for rock face mapping.

2) Physical information

Rock face mapping also needs to obtain particular information, such as rock types, mechanical properties of a rock, wall strength, mineral fillings, etc. It is possible to identify the rock types, perhaps also the mineral fillings from the colour photos and laser intensity images, but has limited value for estimating the mechanical properties, e.g. wall strength.

3) Visual information

Visual information, like photo and images, are needed for a mapping mission in order to identify the rock types, discontinuity sets and water leakage (seepage). The colour photos and laser intensity images make this possible.

4) Spatial information

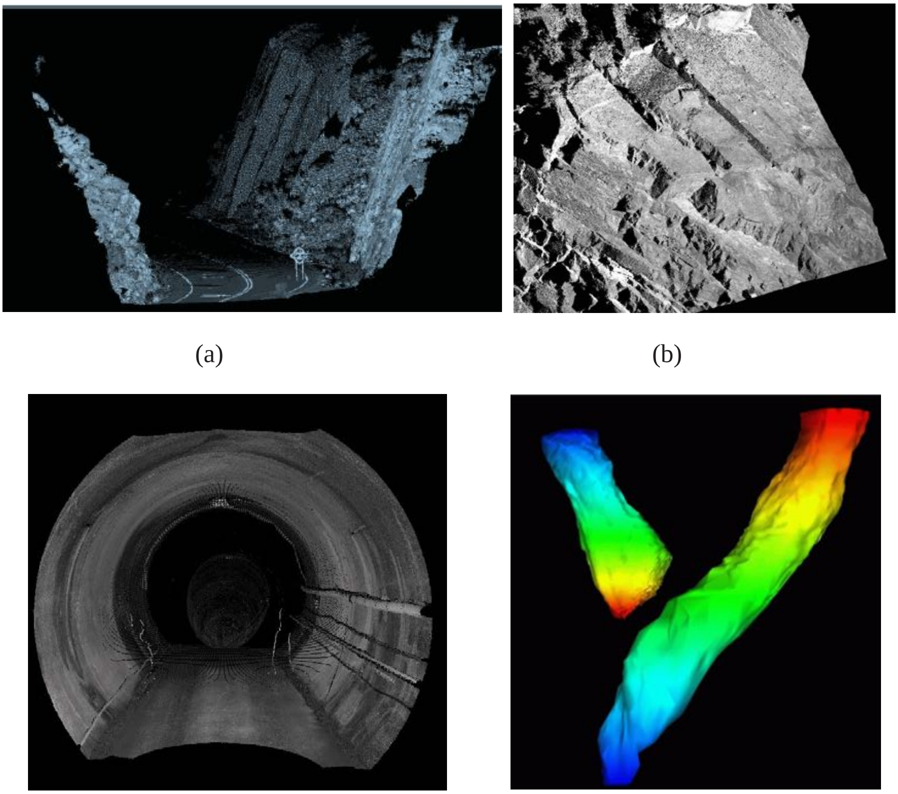
Spatial information can provide the location and orientation of a rock surface in space, which can also be captured by the digital methods through measurement of some reference points, and then transformed into a global co-ordinate system.

As in the description of laser scanning features in Section 3, laser scanning can be applied to obtain significant information for a rock exposure characterisation. From the literature review, laser scanning techniques have been applied to different situations at rock exposures, from road-cuts, open-pits, tunnels and even boreholes, see Figure 5-2a, b , c, d [29].

For site mapping of a rock exposure, it is possible to apply laser scanning for different purposes, and here we present some application examples.

- Fracture orientation

The orientation of a fracture plane is traditionally measured by a compass and inclinometer. By using laser scanning, the fracture orientation can be measured semi-automatically or full-automatically. Both semi-automatic [17] and full-automatic [15] methods have been tested. By using the semi-automatic method, the orientation of a fracture plane (e.g. dip and strike) can be determined interactively or semi-automatically from the 3D laser scanning data. The presented method aims to not only make use of the advantages of modern computer techniques, but also enables the operators to utilise their geological background knowledge to control the mapping results.



(c) (d)

Figure 5-2. Scanning of different types of rock exposures.

A typical mapping procedure by this method is not only taken by computer software as a virtual mapping platform, but is also interactively performed between the computer and the operator: 1) select a part of rock surface from the whole 3D scanning model by the operator; 2) choose a fracture exposed on the scanned rock surface, and mark the exposed fracture surface interactively by the operator; 3) automatically calculate the best-fit fracture plane by the computer program, and then calculate the fracture orientation. Figure 5-3 shows an example for fracture mapping based on 3D laser scanning data from an exposed rock face.

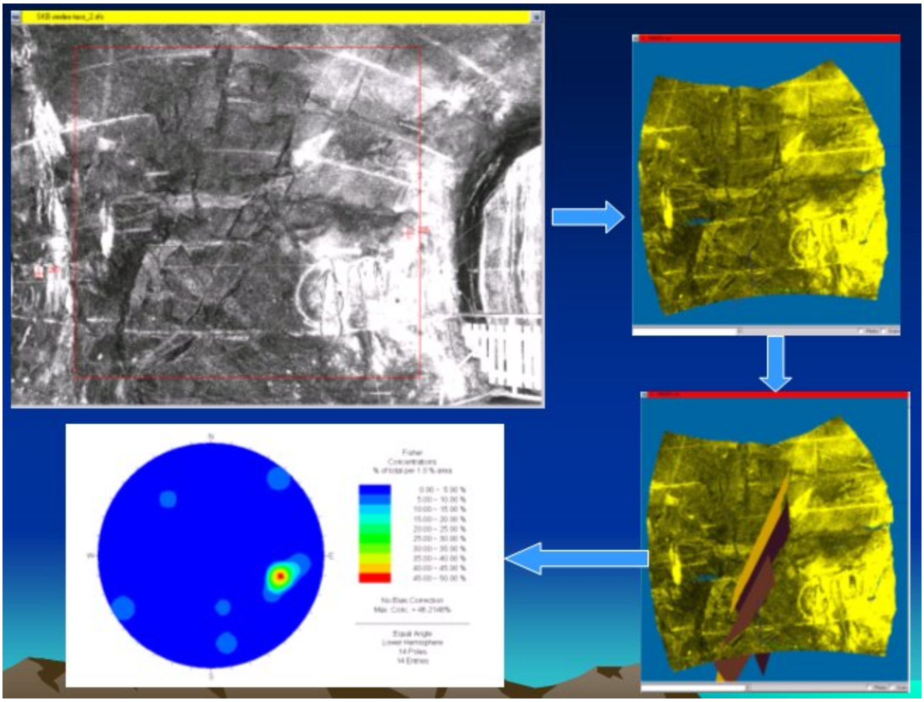


Figure 5-3 Semi-automatic fracture mapping [40].

The automatic method [15] is based upon some segmentation approaches for processing of the scanning point clouds, and then the best-fit plane of fracture surfaces can be automatically calculated, so the fracture orientation can be determined, see Figure 5--4.

- Roughness

Fracture roughness is mostly characterised in the laboratory on small specimens of a natural fracture surface. *In situ* determination of fracture roughness at the large-scale is important for understanding the scale effect of fracture roughness, large-scale deformation of rock masses, and hydro-mechanical behaviour of fractured rocks. By using laser scanning, fracture roughness can be quantitatively described in several different ways, and show more advantages.

1) Using a triangulated mesh created from scanning point clouds

The first technique is to use a triangulated mesh of a fracture, as illustrated in Figure 5-5 [29]. If the orientation of each triangle is plotted on a stereonet, then the scatter about the mean orientation of the fracture gives information on the dilatation angle. In the classic saw-toothed fracture analyzed by Patton [30], the dilatation angle is defined as the rise angle of the saw teeth compared with the mean orientation, as shown in Figure

5-5. The dilatation angle is directly related to the additional friction angle due to roughness [31], and on a stereonet, the dilatation angle can be directly determined by the angle between the mesh triangle orientation and the mean orientation of the fracture. The example in Figure 5-5 shows a scatter of triangle orientations, with the mean fracture orientation at the centre of the scatter. The stereonet in Figure 5-5 is marked off in degree increments of 10 degrees, and indicates dilatation angles ranging from a few degrees to over 30 degrees. Also the shape of the scatter in the stereonet is elliptical, indicating roughness anisotropy (dilatation angle varies with direction). By varying the triangle size of the mesh, scale-dependent roughness can be determined. As an important note, the triangle size needs to be greater than the scanner error, or else roughness due to measurement error will be calculated.

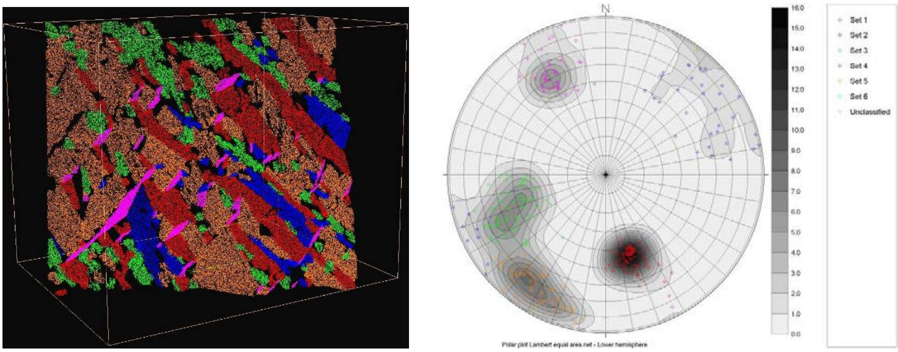


Figure 5-4. Full-automatic fracture mapping [15].

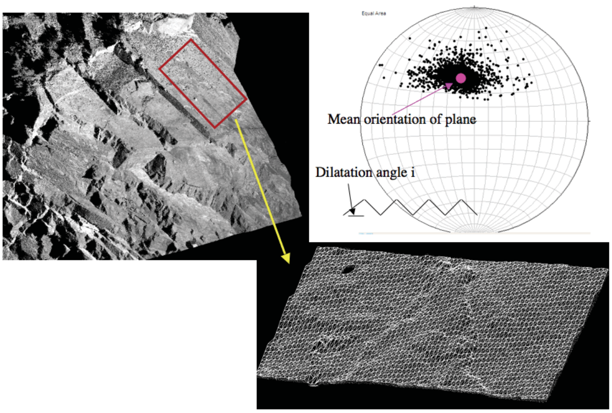


Figure 5-5. Schematics from one method of analysing fracture roughness using scanning data, by a triangulated mesh of a fracture and plotting the pole for each triangle on a stereonet [29].

2) Cross-sectional profile with a direction

The second way [29] to obtain information about roughness is to make cross-sections through a fracture at different angles (a cross-section in the direction of the dip vector, for instance, would be relevant for slope stability purposes). Figure 5-6 illustrates the procedure.

Compared to traditional methods, laser scanning can not only describe the fracture roughness quantitatively, but also give its orientation in a known direction when the scanning area is registered in a known co-ordinate system. This is important for rock mechanics, not only to calculate the shear strength, but also to determine the slipping direction.

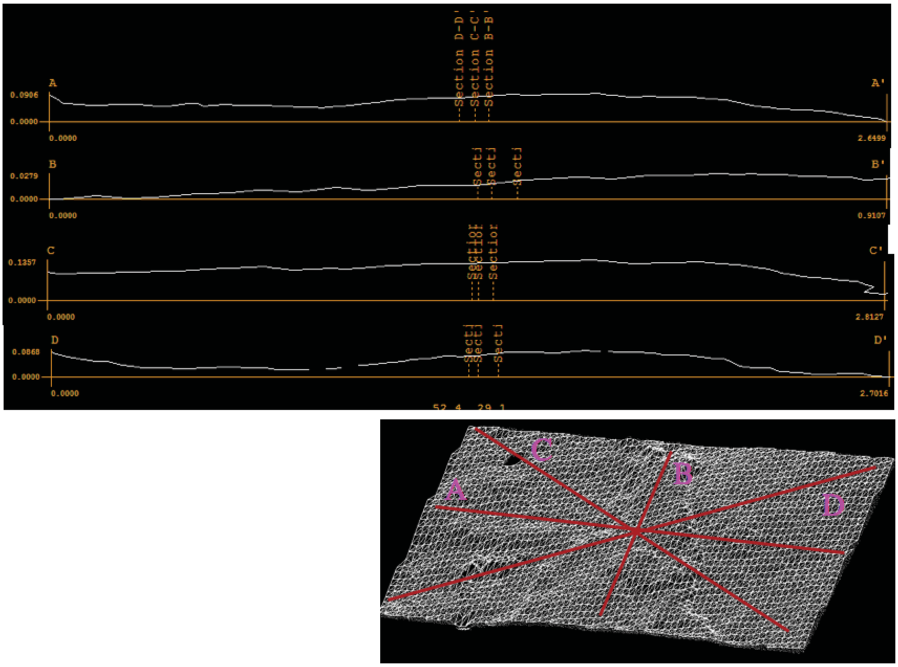


Figure 5-6. Schematic. A second method of analysing fracture roughness, by making topographic profiles of the fracture in different directions, and processing the roughness profile to extract roughness parameters such as JRC [29].

- Length and spacing

Fracture exposure length and spacing between different fracture sets can also be measured, either in the laser image or in 3D point clouds, see Figure 5-7.

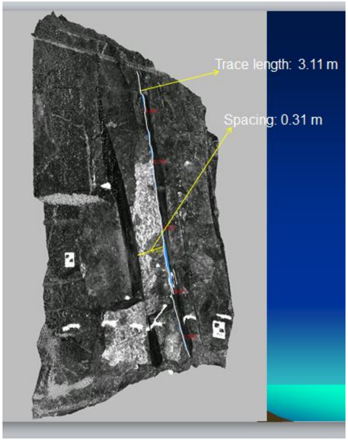


Figure 5-7. Measuring fracture length and spacing in 3D scanning point clouds.

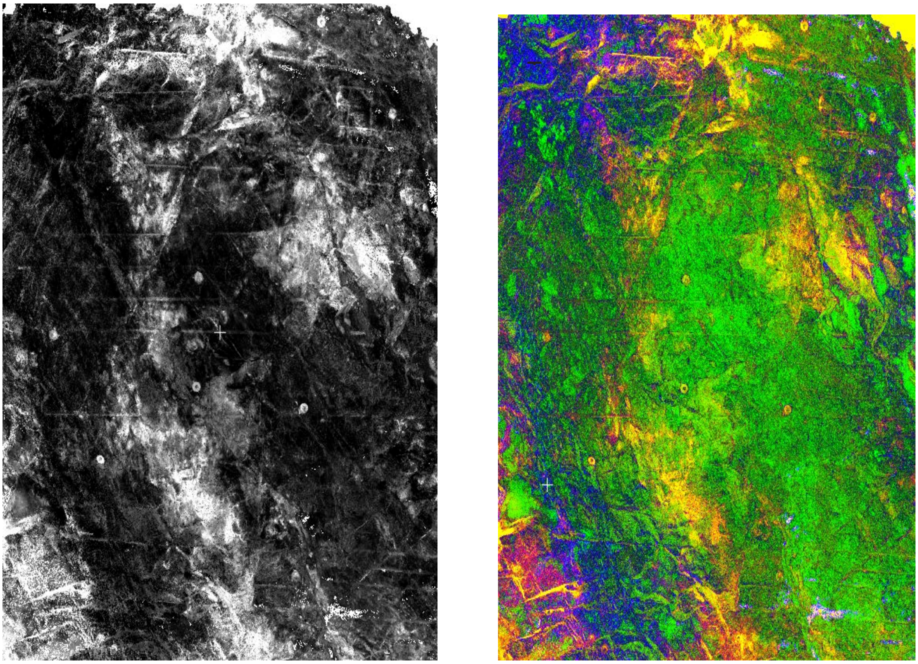


Figure 5-8 Rock type comparison between laser image (left) and pseudo colour image (right) [18].

- Rock type

Laser scanning can not only measure the position but also the reflex intensity at every point, so the laser image is created based upon the intensity difference of different objects. As different rocks have different intensities, the intensity of the laser image has been tested to identify different rock types. In this study, several image processing methods have been tested, such as texture analysis, image classification. Figure 5-8 shows different rock types in the pseudo-colour laser image by image processing methods.

- Identify water leakage

Water leakage is an important hydrological parameter in site characterisation. Based upon the reflex intensity difference between water leakage and the dry rocks, the laser image can be used, not only to detect the position and area of the water leakage, but also to quantify the amount of the water leakage, see Figure 5-9

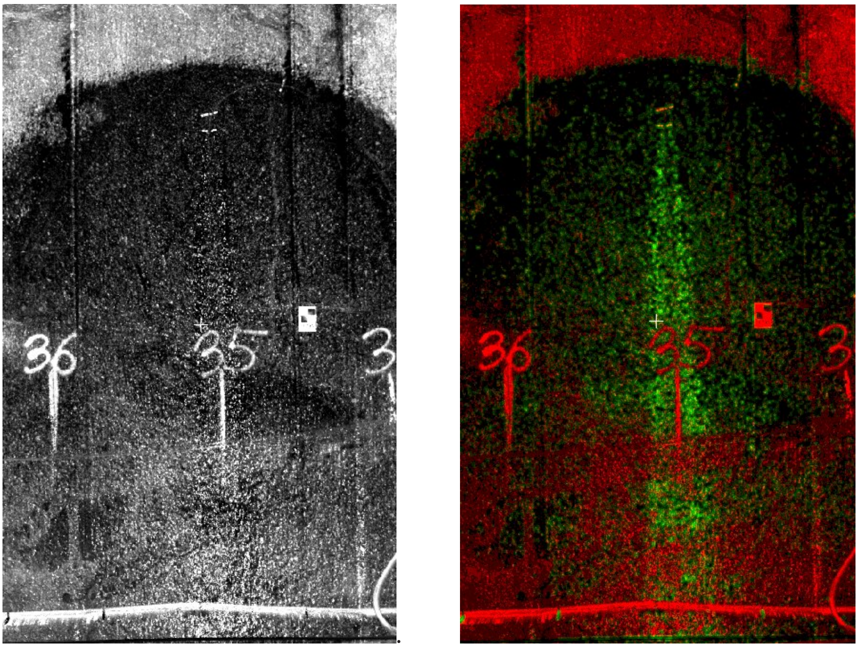


Figure 5-9. Identifying water leakage from laser images by image processing analysis [18].

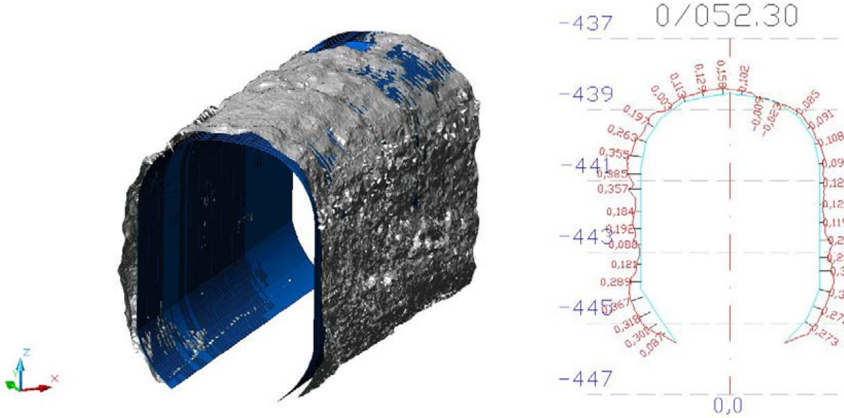


Figure 5-10. Difference model for profile comparisons between designed and blasted tunnel.

5.2 Quality control of tunnel blasting

1) Controlling the quality of tunnel blasting

For a new tunnel and during the construction period, it is important to control the over- or under-break as compared to the theoretical design. By using the full-coverage laser scanning data, the quality of the blasting can be accurately presented, by either a 3D model, a cross-section or an unfolded difference model, see Figure 5-10.

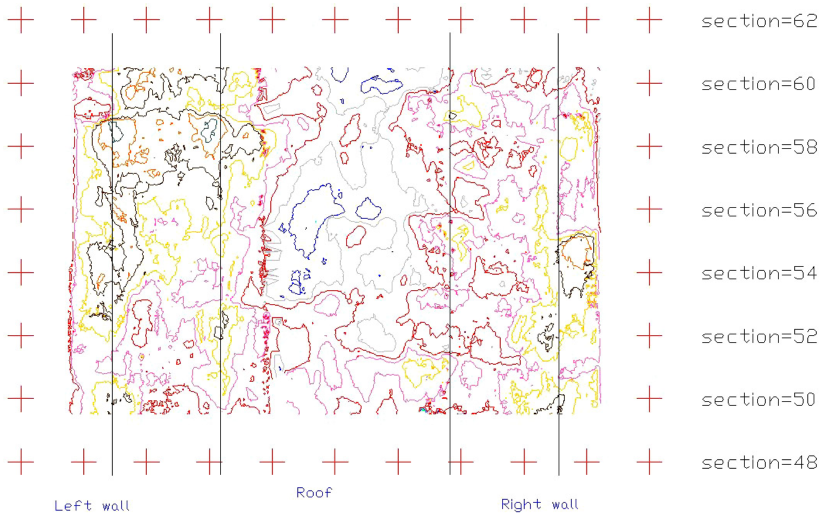
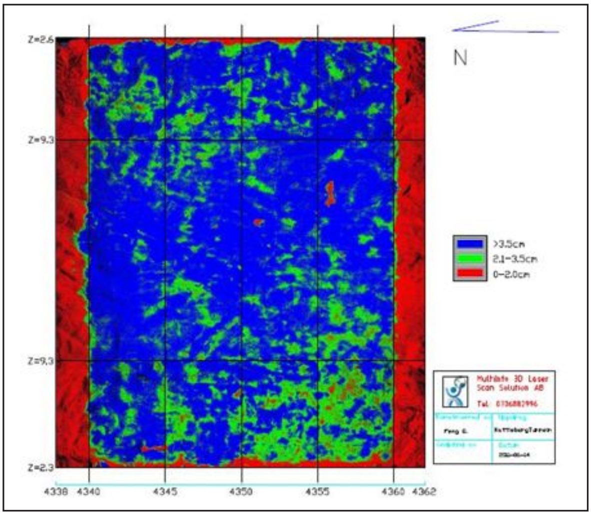


Figure 5-11. Control of tunnel blasting by laser scanning data.

2) Controlling the thickness of sprayed-concrete

The thickness of sprayed concrete is important for tunnel enforcement. Traditionally, it is just checked by a stick at randomly selecting some points. Using the full-coverage laser scanning data, the thickness of the spayed concrete can be accurately calculated and presented in the unfolded tunnel map and even in the 3D model, see Figure 5-12.



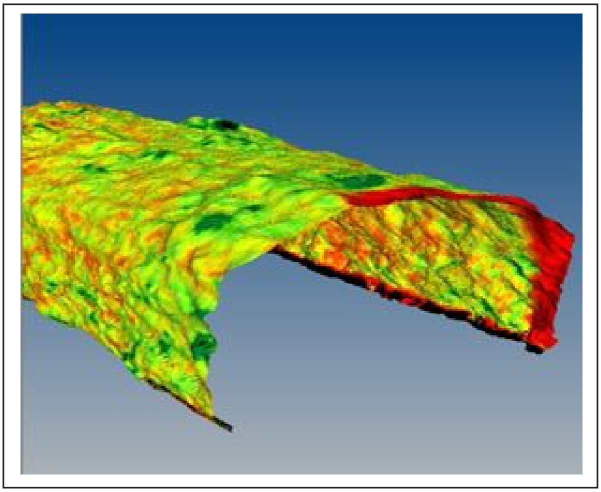


Figure 5-12. Thickness of the sprayed concrete created from scanning data in an unfolded tunnel map (upper) and 3D model (lower).

5.3 Deformation monitoring

A rock mass can be deformed by both artificial and natural forces, such as in tunnelling, mining and earthquakes, which may result in a disaster for both human beings and facilities. Therefore, one of the important concerns for rock mechanics is to monitor the deformation of a rock mass, e.g. a tunnel, underground storage facility, or road slope.
Traditionally, the rock mass is monitored by measuring the displacement of several points at some defined positions, so the monitoring is limited to those selected parts, with no control of the rock mass as a whole. Therefore, it is risky because of missing some unstable parts.

With laser scanning, the surface of a rock mass can be scanned at a full coverage with a high density of scanning points at the millimetre level, so the rock mass can be monitored as a whole, and it is possible to control the deformation of the whole surface. Compared to the traditional methods, the laser scanning has some advantages for deformation monitoring:

1) Full coverage of the complete monitored part, not only limited to some selected points

Traditionally, the deformation is monitored by the relative displacement between some selected points, which are limited to some points, so this is risky because of missing the unstable parts due to the points being selected subjectively or randomly. By laser scanning, the disturbed parts can be fully covered and quickly scanned at high resolution up to few millimetres, so there is much less risk of missing unstable portions, and it is possible to monitor the complete area of interest. Figure 5-13 shows the deformation at a section of a tunnel by scanning before and after blasting, and the deformation variation at different parts is shown in different colours, so the deformation can be monitored and displayed across the whole area.

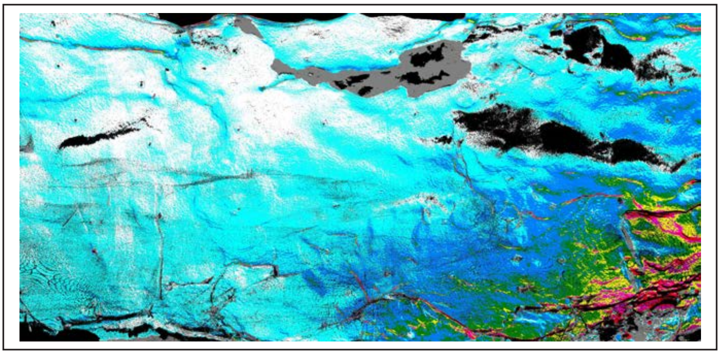


Figure 5-13. Deformation of a section of a tunnel by laser scanning analysis [40].

2) By using the laser image, the deformation can be visualised in 3D and recognised in the laser image.

As mentioned before, the scanning data consists of both point clouds and an intensity laser image so, if some particular objects are of interest, then the deformation and its corresponding objects can be visualised in both 3D and laser image; see Figure 5-14, which shows the location of a special object and its deformation after blasting.

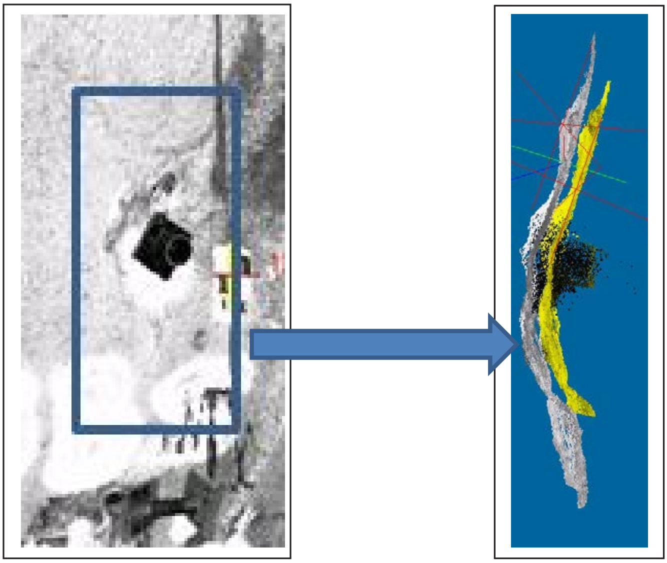


Figure 5-14. Identifying the deformation of an object in both the laser image and 3D model.

3) Deformation of a rock mass can be evaluated by more parameters

As the rock mass can be fully scanned, so its deformation can be evaluated in different ways, not just the relative displacement between points. For example, if a section of a tunnel is deformed due to blasting, by scanning before and after blasting, the deformation can be investigated by the difference of the volume and the surface area. In addition, by creating some profiles from scanning point clouds, the deformation can be identified by the length of the profile, or easily recognised by comparing two profiles—before and after blasting.

In addition, a case study by Monserrat and Crosetto has applied a long-range scanner to land deformation [32]. In this study, several parameters are tested to show the potential application by laser scanning for 3D deformation measurement, including 3D displacement vectors, 3D rotations. Moreover, the least squares 3D surface matching was used to check the quality of the estimated deformation parameters.

Although laser scanning techniques show the potential for deformation monitoring, it is still difficult to monitor small deformations, and the system is limited to a few millimetres for both long-range and short-range scanners. There are some problems and uncertainty concerning deformation monitoring, so we must pay more attentions to them as follows.

- Accuracy of control surveying related to the real deformation

In order to monitor the absolute movement of a rock mass, control surveying is important, which is linking the deformed part to the stable part, or transforming the deformed area to the global co-ordinate system. In this case, it is important to know the accuracy of the control surveying with respect to the real deformation. In many case studies and publications, the accuracy of control surveying is not mentioned. So it is uncertain if the displacement comes from the error of control surveying or the real deformation. This is very sensitive if the deformation is small, in the range of few millimetres, because the control survey often has an accuracy of just a few millimetres.

- Resolution of a scanner related to the accuracy of deformation measurement

In general, high resolution scanning is possible for identifying the minor deformation of an object. However, the object scanned by a high resolution scanner may not provide a high accuracy of deformation measurement. This often causes misunderstanding in practice. As mentioned before, a rock mass sometimes needs to be scanned from several positions, or a large area of a rock mass needs to be covered by several scans. In this case, all of the scans must be registered into the same co-ordinate system. Normally, the more scans to be registered, the more errors can be propagated in registration.

- Accuracy of the parameters created from scanning points

By laser scanning, the deformation can be evaluated through different parameters, e.g. changes of volume, surface area, rotation and length of a profiles, etc. However, it is also necessary to analyse the accuracy for creating those parameters from scanning points. If the error to create the parameters is larger than the deformation, no deformation is discovered.

5.4 Improve input data for numerical modelling

In rock mechanics, numerical modelling is often used to estimate and simulate the behaviour of a rock mass under certain conditions in geometrical, geological and hydrological boundaries. The results of numerical modelling with respect to the reality depend upon the parameters that represent the boundaries of the rock mass. Therefore, it is important for numerical modelling to input the parameters that closely describe the real conditions of a rock mass. By laser scanning, the input data can be improved, and then the results of numerical modelling can be closer to the rock reality. Some case studies have tested laser scanning techniques to create the input data for numerical modelling, and to show the potential applications.

A case study by D. Mas-Ivars *et al.* [33] applied the input data from laser scanning, e.g. the as-built 3D model and profile of a tunnel, to evaluate the factors that affect and control the EdZ/EDZ (Excavation Disturbed/Damaged Zone), and compare the results with the designed data, which are traditionally applied for the numerical modelling. By using the irregular as-built profile of the tunnel, the stress distribution around the tunnel shows interesting results, see Figure 5-15. It shows that the irregular shape of the tunnel walls in the as-built sections, as well as their bumpiness, generates asymmetry in the stress redistribution around the tunnel. “Bumpy” type irregularities (convex) tend to distress the area because of being able to generate high tension locally. On the contrary, cavity type irregularities (concave) tend to increase the compressive stress locally. The larger the irregularity of the tunnel contour, the larger such heterogeneity is found in the boundary stresses at the tunnel contour. The localised high stresses caused by the tunnel wall irregularity could induce local fracturing and asymmetry in the EdZ/EDZ.

In this study, it was also shown that the current developed software for numerical modelling has some limits for inputting the ‘heavy’ 3D model and profile with a high resolution up to few mm. However, it does show the potential application of laser scanning data to numerical modelling. With the further development of the numerical modelling software, more interesting results may develop which could not be obtained from the traditional methods.

Another case study example was undertaken by A. Abellan *et al.* [34], which applied a long-range terrestrial laser scanner for the detailed study of rockfall. In this study, the authors applied the laser scanning method to obtain some input data for rockfall analysis, such as orientation of joints, the slope, block geometry and volume. Accordingly, one of the most important input data for rockfall simulation is the slope itself [35]. But in the earlier studies [36], the slope was represented by a bi-dimensional profile. By using laser scanning, the topography can be described in a 3D model with a DEM (Digital Elevation Model), and the presence of 3D variations in slope morphology (e.g. ridges, convex talus cones and micro-topography) may exerts a considerable influence on rockfall trajectories [37, 38].

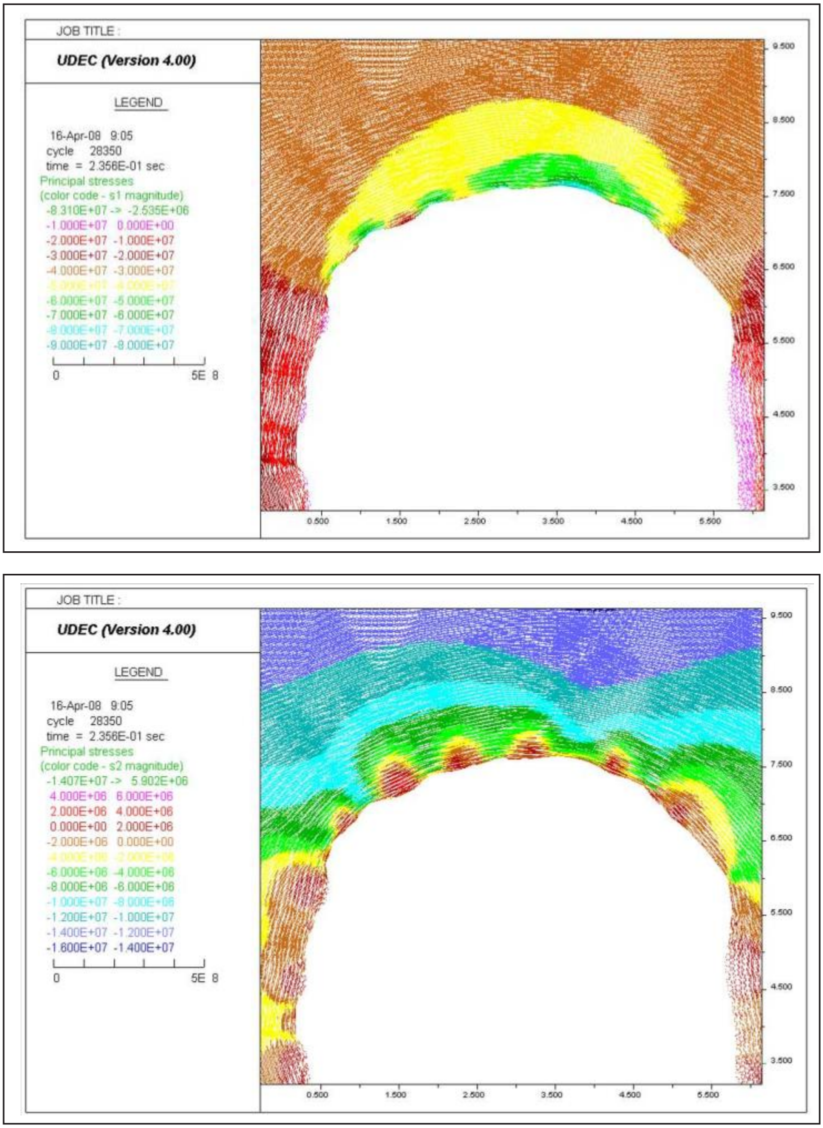


Figure 5-15. Stress tensor plots at section 47 with the borehole seismic data after excavating the heading; Model with E = 65 GPa. Upper: maximum compressive stress = 83 MPa, Lower: maximum tensile stress = 5.9 MPa [33].

If an accurate DEM can be generated by laser scanning data, the results of the rockfall simulation (e.g. trajectories, energy, rebound height) can bear a closer resemblance to the rock reality. The results of this study show that accurate input data are important for a rockfall hazard assessment. Laser scanning appears to have great potential in the characterisation and monitoring of landslides.

5.5 Documentation and visualisation

In rock engineering, the *in situ* documentation and visualisation is important for observing the situation around a rock exposure. Traditionally, a notebook with some numbers and drawings, together with a camera, is the common way for on-site documentation, which has some drawbacks, such as the following.

1) The notes and drawings made by the person can be wrong or subjective, and difficult to check;
2) Pictures taken by a camera need to have illumination, and have a small coverage;
3) Particularly, the pictures taken by a camera are only ‘visible’, not measurable. If using photogrammetry techniques, extra work is needed;
4) All the information is separately recorded, and it is difficult to combine them in terms of their location, so it is difficult to understand the relations between them.
5) Some of the data are not digital, so an extra job is needed if the information is required to be processed by a computer.

Compared to the traditional methods, laser scanning techniques have some advantages for on-site documentation, as follows.

1) A high resolution intensity image can be recorded by scanning without illumination

The best resolution of a high speed scanning can now be up to less than 1 mm with the intensity image. Figure 5-16 shows a part of an intensity laser image with high resolution, and the boundary line of the paper target is about 0.8mm, so it can be identified. , In addition, as the scanner utilises an infrared laser, so illumination is not necessary, which means a high resolution digital image can be quickly captured in the dark, so it is especially useful for underground rock engineering projects.

2) Integration of both visualisation and position

As in the above-mentioned, laser scanning data consists of both position information with the co-ordinates for each point and the visual information with the laser image or intensity image. So, an object in the laser scanning intensity image cannot only be visualized but also measured in 3D, see Figure 5-17 with the co-ordinates of the head of a rockbolt in an intensity laser image. This is a unique feature compared to the photos from a still camera or film from a video camera.

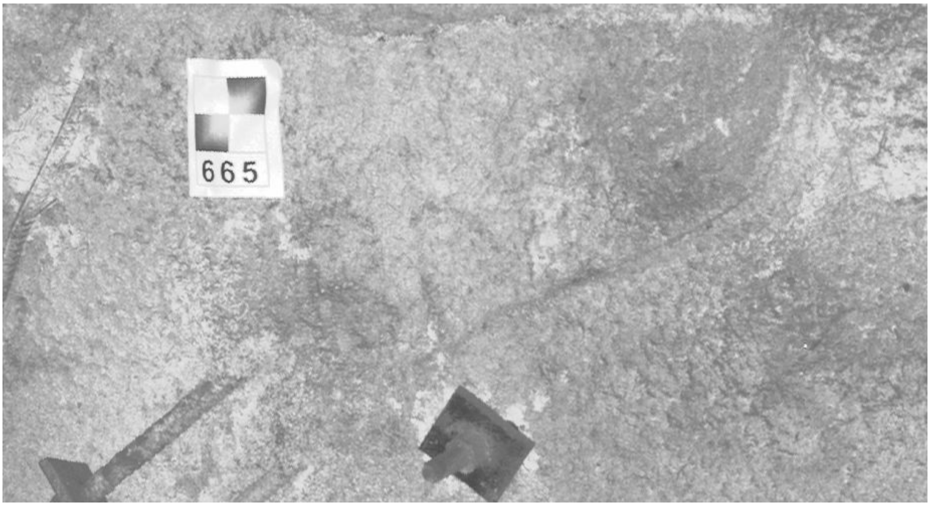


Figure 5-16. Intensity image from high resolution laser scanning.

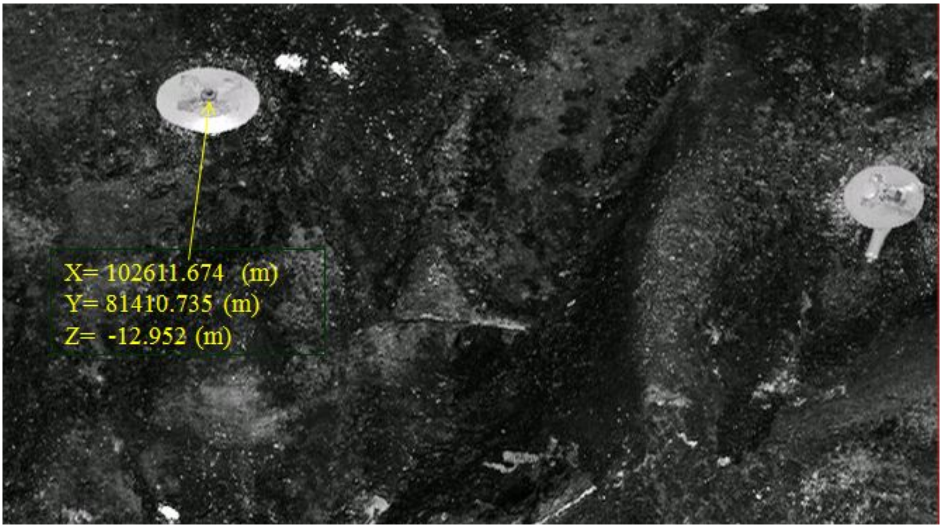


Figure 5-17. Co-ordinates of a rockbolt shown in the laser scanning intensity image.

3) Provide relational information

As we know, the on-site documentation by traditional methods, e.g. written notes and pictures from a camera, has no exact positional information, so it is difficult to inter-relate the data.. By laser scanning, the scanning data can be registered into the same co-ordinate system, so the laser scanning image has the exact location, and any objects shown on the image can be positioned in space, and the relationship between them can be obtained.

One of the examples is the trace map of fractures overlaid on the laser scanning image, see Figure 5-18 [39]. Compared to a traditional trace map, it is easy to see what is presented by the fracture trace line, and also each trace line can be tracked to its position in a 3D model. In addition, a 3D trace line is also possible to be obtained, and it will be interesting to see how to use such a 3D trace line in rock mechanics in the future.

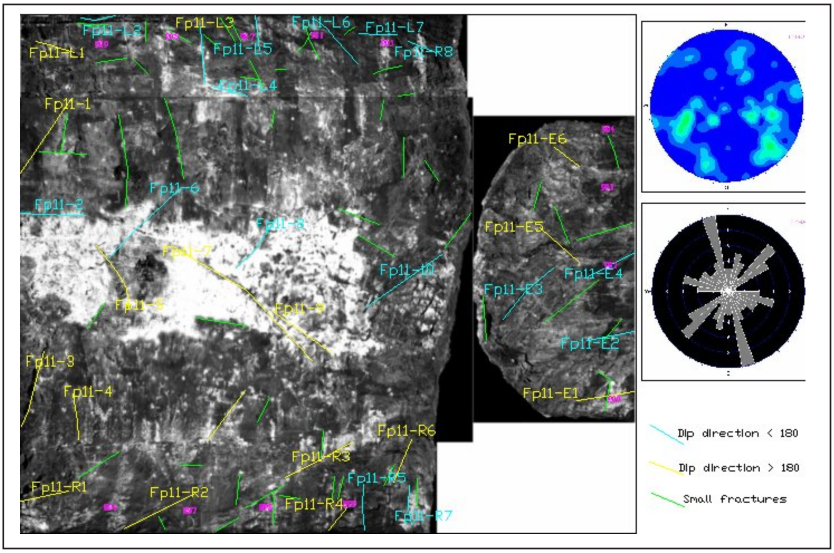


Figure 5-18. Fracture trace line map created from a laser scanning intensity image [39].

In addition, when a scanner is scanning, it can rotate through 360 degrees both horizontally and vertically. So, normally, a rock face is often recorded together with its surroundings. Moreover, even a whole tunnel, e.g. a 42 km long tunnel, can be scanned and registered in the same co-ordinate system, and each scan, together with the laser image, shown by its exact position in space. In this case, the relation between a rock face and its surroundings can also be obtained, which shows good potential application for design and project planning in both rock mechanics and rock engineering.

4) Retrievability

By laser scanning, a rock face or a tunnel can be accurately recorded in a certain co-ordinate system, and visible in laser scanning image, which means the rock mass can be virtually stored in a computer in 3D. This indicates potential applications to rock mechanics in at least two cases.

1) If something is uncertain or wrong, it is possible to be tracked back to the original virtual model, and one can find out the reasons. For example, if the measurements of the on-site mapping, e.g. fracture orientation and slope geometry, are uncertain, it is possible to check these out by the 3D scanning virtual model, and to establish the correction.

2) If some information is missing, this is also possible to be obtained from the virtual model, and there is no need to visit the site again. Even if the original rock face has disappeared, e.g. a tunnel section is blasted out or collapsed, the required data can be retrieved from the scanning model. This is useful for both quality control and accident investigation.

5) Large and wide coverage

Comparing to a camera, the laser scanning has a large and wide coverage, even in the dark. In particular, each scan can be registered into the same co-ordinate system, so a large 3D model, up to a tens of kilometres long tunnel, and a large laser scanning image (e.g. an unfolded tunnel image several hundred metres long) can be obtained, which is impossible by a camera. In addition, a high resolution laser image can be captured in difficult conditions, such as a vertical, small (about a half –metre in diameter) shaft.

6) Generate different types of ways for visualisation from the same data resources

Based upon the same scanning data, a rock surface or a tunnel can be visualised in several different ways by data processing with different software, including: 1) 2D unfolded laser image with the same format as the photos from a camera (e.g. jpg or tiff); 2) 3D panoramic image, which can 'see' all around in a tunnel; 3) A video film or movie with the usual format (e.g. *.avi) can also be created, so one can fly through or walk through a tunnel in a 3D virtual model; 4) The scanning data, e.g. point clouds, can also be converted as 3D model (e.g. CAD model, mesh model), and then be animated or be used for simulation in some software for further analysis.

6 Discussions

Laser scanning techniques have been developed for more than 10 years since the late 1990s. They show significant potential applications in rock mechanics and rock engineering. However, there are still some uncertainties for rock mechanics application for some reasons, including 1) there is usually no detailed description of the scanners from the scanner developers or manufactures in terms of all the information required by the rock mechanics user; 2) Scanning is carried out by surveyors, and the users in rock mechanics receive the scanning data from the surveyors, but the users have no detailed information how the scanning data are captured, and hence no idea about the quality of the scanning data. Therefore, it is important to clarify some points in order to apply this method correctly and effectively in practice.

6.1 How to select a suitable type of laser scanner for a certain application

On the market, there are many different types of 3D laser scanners, and about 90% of them utilise pulse-based scanning and about 9% of them by phase-based scanning. They are quite different in their specifications, such as scanning speed, maximum scanning range, resolution, accuracy, limit for working temperature, etc. Normally, the pulse-based scanner has a long scanning range, but the phase-based scanner has a short range. However, the pulse-based scanner has a slower scanning speed than the phase-based scanner. For different applications in rock mechanics, it is important to select the most suitable type of scanner in order to apply this technique in the best way.

6.2 How to use the specification parameters of the scanner

Each scanner has a list of its specification parameters, such as the resolution, accuracy, scanning speed and maximum scanning range etc. It is necessary to understand exactly what the real meaning is for each specification parameter—which is important for a user to use the scanner correctly. For example, the maximum scanning range is related to the reflex intensity. If the object has very low or very strong reflex, the scanner cannot receive the return signal, so the scanning data cannot be collected. So, it is not only important to know the maximum scanning range for a scanner, but also there is a need to confirm what the reflex limit of the scanner is. In addition, the maximum scanning range can be affected by some factors. For example, the scanning range of a pulse-based scanner can be affected by weather. If it is cloudy or sunny, there is no substantial difference, but there is a shorter range if the sun shines too strongly. Light rain or fog also affects the scanning range, depending on their intensity. Day and night conditions also affect the scanning range. When scanning at night, the noise is less, but the scanning spot is larger, and the scanning range is longer. For a phase-based scanner, it is difficult to obtain the return signal if the object has a reflex less than 5% or stronger than 95%.

6.3 Difference between resolution and accuracy

Although ‘accuracy’ is quite different from ‘resolution’ in terms of their definitions, it is easy to confuse the real meaning of these two terms in practice when laser scanning is applied to some practical projects. With the experience of the authors, there are two main problems in practice:

1) Misunderstanding the difference between resolution and accuracy

By using the scanning control software, the scanning resolution can be selected according to the requirement of a project. Different scanners have different maximum resolutions as well. However, the scanning resolution of an object not only depends upon the defined resolution parameters while scanning, but is also related to other factors, including the distance and incidental angle to the scanned object, the reflex intensity of the object or rock surface, etc., and even the transformation between different co-ordinate systems by a software can affect the final resolution. So, the effective resolution of the scanning data can be quite different to the defined resolution parameters in the scanner. On the other hand, even if the object cannot be scanned with a high resolution, this does not mean that one cannot achieve high accuracy of the final results. For example, the accuracy of deformation monitoring on a rock mass depends upon several factors, including the accuracy of control surveying from the stable area to the deformed area, the resolution of each individual scan, the registration accuracy of each scan into the same co-ordinate system, and also the calculation accuracy of parameters or models to monitor the deformation. So, there can be confusion by the users caused by the difference between resolution and accuracy, and it is not so easy to check out in practice.

2) Confusing the meaning of the accuracy between the scanner specification and the accuracy of the final results

The manufacturer often provides a specification of a scanner with different parameters, including the instrument accuracy. It is then a simple step for some users to use the instrument accuracy as the accuracy of their final results or the reference for their projects. This is quite dangerous in practice. The instrument accuracy is often carefully or simply illustrated by the manufacture under some specific and perhaps advantageous conditions, e.g. within a certain distance and incidental angle, or for some object surface, and with some working temperature, etc. Moreover, the instrument accuracy is often given separately by its linear and angular accuracy, which is quite different to the accuracy of the co-ordinates of a point, or a 3D model, etc. The accuracy of a final result for a project depends upon many factors, such as: 1) Control surveying; 2) Instrument accuracy and setting of scanning parameters; 3) Methods and procedures for registration of scanning point clouds with different software; 4) How to present the final results, e.g. the cross-section with a point line or a ‘polyline’, and a 3D model with a mesh or a solid model. Nowadays, it is difficult for the clients to check out the final accuracy; even some consultants may confuse the instrument accuracy with the final accuracy for a project. This must be improved in the future.

6.4 Data format

There are different data formats in the whole procedure of laser scanning, but these can be categorised in three main groups.

1) Raw scanning data from a scanner

There are several different formats for raw scanning data as captured by different scanners, e.g. FLS, FWS, ZFS, ZFC, IXF, 3DD, RSP, PTB, PTG, etc. At the beginning of the technique development, these raw data format could only be opened by some special software for each type of scanner, but now the situation is much better, and the data can be imported directly by the so-called third-party software for different applications.

2) Processed data from the raw data

The raw data can be processed by different software, and exported as point clouds, laser images, etc. For the point clouds, there are many different formats, e.g. XYZ, PTS, PTX, DXF, ASC, etc., and for a laser scanning image with formats including BMP, TIFF, JPG, PNG,COE, etc. These formats of the data are often more neutral than the raw data, which can be imported and processed in many application software types.

3) Final model or parameters for applications

The 3D model or parameters generated from the scanning data can be saved and then exported in some formats which are compatible to the application software for design and further analysis, e.g. SAT, DWG, DXF, STL, etc.

In practice, it is often required to convert among these different data formats during the whole procedure of a laser scanning project. The situation is now much improved compared to the beginning of the development of this technique. However, it is still not fully satisfactory. Information converted from one format to another can be lost, and not be mutually exchangeable. In addition, even the same format of the data can be displayed in different ways after importing into different software due to reasons such as the different structures of the layers in different CAD software, etc.

6.5 Data back-up and storage

The safety of the data back-up and storage is important for a laser scanning project because the data can be reused and retrieved, and sometimes it is impossible to go back to scan again, for example, a section of a tunnel can be removed by blasting, or the rock surface be covered by the shotcrete. Two questions on this subject are often asked: 1) which media type is the safest way to back up? 2) how long can the data be stored? Actually, this is the same challenge for back-up and storing the digital information in computer science as well. For laser scanning, it is special because of the large amount of data, from several GB up to several TB. However, thanks to the development of the hard disk techniques, this is now overcome. It was just a several GB hard disk ten years ago, but now an external hard disk can contain TBs. Just now, it is not 100% clear just how long the data can be stored, and which storage medium is the best for laser scanning data. But the scanning data stored on a CD for about ten years are still readable if the CD is kept carefully. Alternatively, extra work is necessary to check out the data regularly and to make several backup in different media. Also, the technology is changing rapidly, as we have experienced over recent years, and so it may be necessary to upload the data into new systems in a case where longevity is required, e.g. the scanned data of an historical building made of stone.

7 Conclusions

Traditional methods for site characterisation of rock exposures have several drawbacks which can affect further analysis, numerical modelling and design in rock mechanics. Many efforts have been made to improve the quality and quantity of site mapping and documentation. In this context, 3D laser scanning has been developed for more than 10 years since the late of 1990s, and shows potential application for site mapping and documentation in rock mechanics, and so has become an interesting subject in recent years.

By reviewing the state-of-the-art for 3D laser scanning techniques as described in this report, it is clear that there has been much development and improvement in both hardware and software since the late 1990s, and the new developmental trends are focusing on improving scanning quality (e.g. scanning speed, resolution and accuracy, and scanning with colour), easy and simple operation for the users' hardware, and data format and processing is becoming more compatible and standard. Especially, there has been more development on the interfacing to and integration with the existing application software—which make the data from laser scanning more compatible with other data and hence useable for more applications.

3D laser scanning has significant advantages compared to other characterisation methods because it enables quick capture of an object in 3D with large coverage and high resolution without illumination. The scanning data consist of different information, including geometrical, spatial, visible and physical information. In particular, the data can be retrievable and reusable, which make it possible to improve the quality control and reduce the cost for a site investigation. Comparing to the photos and videos from a camera or video camera, the laser scanning images in both 2D and 3D can not only be visualised but also measured, which indicates the potential application for site characterisation in rock mechanics and rock engineering.

Case studies show the potential applications in rock mechanics for using scanning data with both co-ordinates and images, which make it possible to measure and view the rock surface in 3D at high resolution and accuracy. In recent years, laser scanning techniques have been applied to different projects in rock mechanics and rock engineering, including site characterisation of rock exposures (e.g. fracture mapping, identifying water leakage and rock types from laser images), measurement of over- and under-break for tunnel blasting, quality control of sprayed shotcrete, deformation monitoring, improving input data for numerical modelling, documentation and visualisation, etc. These case studies show the potential application of laser scanning techniques to rock mechanics and rock engineering.

However, there are some issues while using laser scanning techniques in practice, such as selecting the most suitable scanner for the required application, not misunderstanding the specification parameters provided by the manufactures, establishing the difference between resolution and accuracy, etc. The user should pay attention to the function of each scanning system, and control the whole procedure from filed data capture to office data processing—in order to apply laser scanning data in the correct and effective way. In addition, there are still some limits with current development, such as the fact that colour scanning still, by definition, limited to circumstances with a good illumination, it is difficult to process a large amount of scanning data having a high resolution, and especially that there has not been so much development for specific application software to rock mechanics. These problems will be solved with further development underway.

8 Suggestions for further development

3D laser scanning techniques indicate the potential applications in rock mechanics and rock engineering. For better application to our field, the current development on both hardware and software should be continued. The following aspects are suggested, based upon the users' feedback and investigation of current developments.

1) Improvement in hardware

Up-to-date reviewing of the hardware development indicates the following improvement in hardware: 1) Scanning range extending longer for both pulse-based and phase-based scanners; 2) Scanning resolution is being improved, especially the phase-based scanner can reach up to less than 1mm, but this is taking a longer time and it is difficult to process the data by a normal computer; 3) Scanning speed is improved, but related to the resolution; 4) Scanning noise is a big problem, specially for the phase-based scanner, which is improved, but hopefully will be effectively solved by both hardware and software; 5) WiFi and Bluetooth are now used for remote control of the scanning, but limited to a short distance. The scanning needs to be remotely controlled, even for a considerable distance for some situations; 6) Hardware needs to be improved for some rock mechanics working conditions (e.g. working temperature) and for stability.

2) Integration of other sensors and associated tools with the laser scanning system

Control survey is one of the important steps in the whole scanning procedure, which determines the location of each individual scan, and then registers all the scans into the same co-ordinate system. There are different ways to stitch each scan together, but improvement is needed to make the registration more accurate and simple by integration of other sensors (e.g. GPS). In addition, other associated tools are necessary to be improved in order to make the field scanning safer and easier and to operate, such as built-in tilting and bearing measurement, on-board camera with high resolution, built-in motion compensators, etc.

3) Mobile scanning

Mobile scanning on a train, car or other terrestrial vehicles have been developed significantly in recent years, but the associated resolution and accuracy need to be improved for some rock mechanics applications.

4) Colour scanning

Scanning with the true colour is required for some projects, like rock type mapping, which can be solved by either using a real colour scanner or the texture mapping of colour pictures on the scanning point clouds. The former solution is difficult, but possible in the future. The latter is often used now in other fields such as architectural and archaeological documentation. However, illumination is necessary. A simple and easy way to provide sufficient illumination for a camera needs to be developed, and the software for texture mapping needs to be improved.

5) Registration of each scan into the common co-ordinate system

For further modelling and data processing, one of the important steps is to register each individual scan into the same co-ordinate system. The registration accuracy depends upon not only the control surveying but also on the software or algorithms to perform the registration. Different algorithms have been developed but a more accurate and robust solution is needed.

6) Development of software for rock mechanics applications

Special software used by laser scanning for rock mechanics applications is not well-developed. Existing software, e.g. software for numerical modelling, needs to be improved for compatibility, both for data format and for the limits of large amounts of data.

7) Standardisation of data formats

There are so many types of data formats in the whole procedure of a scanning project which need to be converted, involving extra work. So, standardisation of different data formats is important for better application.

8) Evaluation of the accuracy for rock mechanics applications

Laser scanning has potential applications in a variety of rock mechanics projects, e.g. site mapping, deformation monitoring, quality control of tunnelling, etc. It is often confusing for the users to distinguish between the instrument accuracy and the final result accuracy. Moreover, it is not so simple for the users to evaluate the actual accuracy and the associated influential factors. More case studies are needed to evaluate the influential factors for different applications in the future.

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