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Acquisition and assessment of geometric rock mass features by true 3D images

Gaich, A.
3G Software & Measurement GmbH, Graz, Austria
Pötsch, M.
Graz University of Technology, Graz, Austria
Schubert, W.
Graz University of Technology, Graz, Austria

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ABSTRACT: This contribution describes a mobile mapping system based on 3D images and its applications for determining geometric rock mass parameters. The contact-free measurement system allows determining the spatial condition of rock mass discontinuities by taking measurements directly from 3D images. Two different imaging sources are used: a calibrated off-the-shelf camera for highly flexible application and a panoramic line-scanner for capturing large areas at high resolution by images up 100 megapixel. Both systems are used freely without requiring the determination of the imaging locations. Stereoscopic image pairs are acquired and processed to a 3D image by special purpose software. Drawbacks of conventional mapping are overcome by the contact-free measuring principle leading to increased working safety, improved data quality and reliability, and reduced acquisition costs.

1. INTRODUCTION

The knowledge on the geometry of the rock mass is a basic requirement for any rock mechanical assessment. Without thorough knowledge on the geometry of the rock mass and especially its discontinuity network any geotechnical analysis is open for a greater extent of uncertainty. Though experience is an important factor for rock mechanics, improved data on the rock mass should also be taken into account, especially, as more data allow stronger statistics and therefore better knowledge on the rock mass and its behaviour.

Within this contribution a computer based system is presented that allows an easy and quick recording of the rock surface and provides the ability for measuring visible geometric features. Two different imaging systems are used enabling to adapt on different project and application needs.

The first imaging system is an off-the-shelf SLR camera that is calibrated and used to take at least two pictures of an arbitrary rock mass region (*stereoscopic image pair*). During imaging the camera can be used freehand without any prior or posterior knowledge on the camera locations which provides great flexibility in the field application. This becomes possible by observing a vertical range pole established somewhere in the imaging area and a strong camera calibration, as well as using computer vision principles.

The second imaging system is a panoramic line-scanner capable to take very large digital images up to 100 megapixel. This is especially useful for the acquisition of large areas as still fine details remain observable.

Both systems can be applied from distances below 1 m to more than 1.500 m and both systems are used to acquire a stereoscopic image pair, i.e. two images taken from different angles.

From the stereoscopic image pair a metric 3D surface model is computed and aligned with one of the pictures leading to a true 3D image. A true 3D image therefore consists of a real photograph combined with three-dimensional information on the imaged surface.

In contrast to traditional photogrammetry no surveying or reference points are required in advance to generate the metric 3D image. Reference points are used only if a relationship to an exterior co-ordinate system shall be established. If required, several 3D images are joined together. For that, only the visible structural information and image matching techniques in overlapping regions are used.

Once a 3D image is ready, geometric measurements can be extracted. A purpose built 3D software called JMX Analyst allows assigning visible rock mass features directly on the 3D image. Discontinuity orientations given by dip and dip direction can be measured without physical contact, i.e. with no restrictions due to time, access or weather conditions. Measurements can be grouped to structure sets and instantly inspected in a hemispherical projection. Also integrated is the determination of the spacing directly from the joint trace measurements.

The procedure of gaining geometric rock mass properties by 3D images is a strong support for current field mapping and, by the way, highly economical.

2. RELATED WORK

The classical approach for performing geological mapping includes the use of a compass-clinometre device, i.e. it requires physical access to all measurement locations. Several constraints arise from this procedure:

(i) Access is not always possible safely
(ii) Locations for orientation measurements are possibly not significant ones but rather those easier to reach.
(iii) A close view to structures of a large outcrop complicates determining where the significant measurement locations are (overview problem)
(iv) Mapping is strongly related to subjectivity (especially under time restrictions like in tunnelling)
(v) Access and time restrictions lead to incomplete information.
(vi) Mapping results are hard to reconsider/reproduce as original rock structure may have changed due to excavation or erosion.

Several approaches are known for determining geometric rock mass features contact-free. Besides aerial approaches, early terrestrial beginnings with photographs date back to the 1960’s [1, 2]. More recent approaches also showed the advances of contact-free measurements from images [3, 4].

Others used laser scanners for acquiring rock faces [5, 6] or combined the laser scanner with a digital image [7, 8, 9]. Laser scanning allows fast 3D measurement of rock faces by 3D point measurements. However, expensive and bulky hardware raised new constraints.

In order to provide a tool for practical use, reliable results and reasonable cost the concluding approach for geological mapping is to use digital cameras for taking high resolution images of the rock mass, generate a true 3D image, and provide a software for interactive mapping supported with certain automatism. Such systems would provide a true support to conventional mapping but can never replace field work completely. They rather supplement the field work for getting more objective, more complete, more reproducible results overcoming the current restrictions at reasonable costs.

3. WHAT IS A 3D IMAGE?

A 3D image is referred to as an image that covers additionally three-dimensional information on the objects/surfaces it shows.

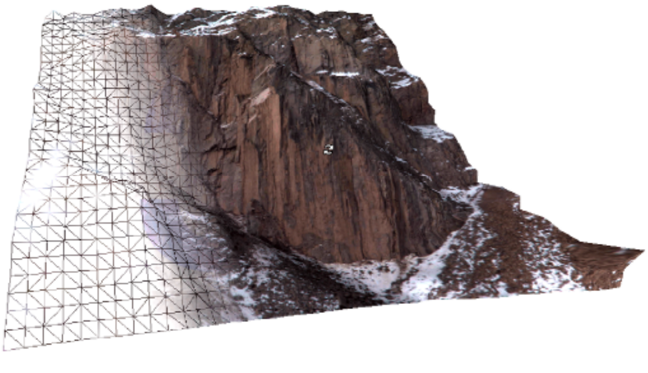


Fig. 1: A true 3D image combines topographic information with a (high resolution) digital image. The 3D image of the 150 m rock slope is about 100 megapixel containing 1.5 million surface measurements. Images were taken from about 800 m distance. Note that the displayed grid is coarsened in order to show the principle of a 3D image.

Fig. 1 shows an example of a 3D image taken at a hazardous rock slope in Italy. The central parts of the slope cannot be accessed safely so conventional mapping of geological features is impossible.

Due to the high resolution of the digital images (100 megapixel) and the dense three-dimensional surface measurements geological mapping could be done thoroughly over the whole critical area of about 10.000 m^2. Strong statistics based on a sufficient number of orientation measurements allowed a good report on the actually stability condition.

4. HOW TO GET A 3D IMAGE?

A conventional photograph always maps the three-dimensional world, e.g. a rock surface onto a two-dimensional image. This means an implicit loss of information making it impossible to gain three-dimensional information from a single picture. If a second picture taken from a different angle and showing the same rock surface is available then the third dimension can be recovered. Such two images are also known as stereoscopic image pair [10]. Fig. 2 shows the geometric arrangement when taking a stereoscopic image pair.

4.1. History

The beginning of measurement from images dates back to the 19th century to the beginning of photography and the 20th century with increased possibilities using airplanes.

Classical photogrammetry relies on knowing the positions and viewing directions of the two images (*exterior camera orientation*) as well as certain parameters describing the image formation process (*interior camera orientation*). However, reasonable efforts are required to determine the exterior camera orientations, e.g. a rigid setup relying on precise mechanics or a mechanism that determines the viewing direction of the cameras. Another way to determine the exterior orientation is to observe at least three so-called control points which means

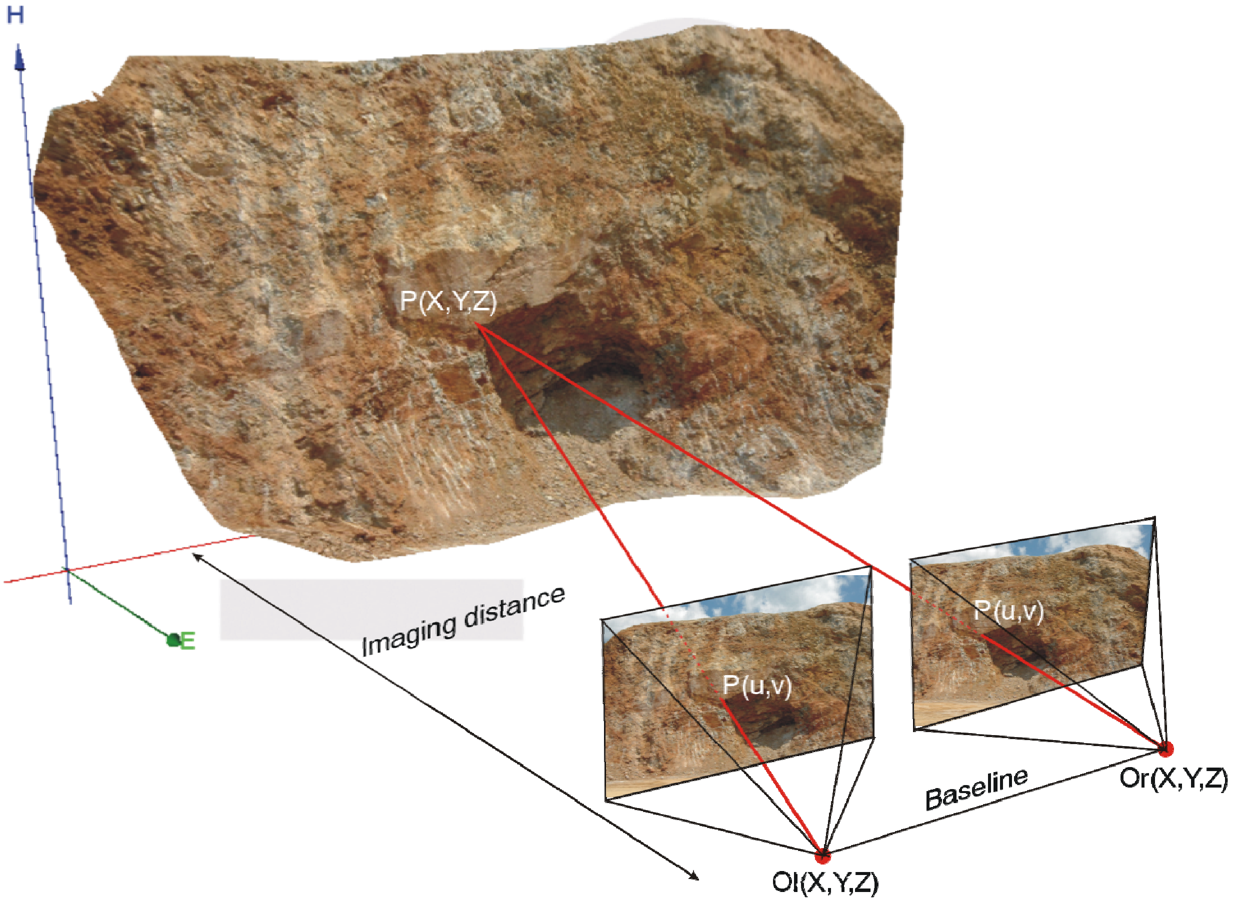


Fig. 2 Stereoscopic image pair. Two corresponding image points P(u,v) relate to one three-dimensional object point P(X,Y,Z). The distance between the imaging locations (baseline) is to be chosen approximately 1/10 the mean imaging distance. Note that modern algorithms do not require the baseline to be known.

points of known locations in a given co-ordinate system.

More recent extensions to classical photogrammetry are related with the term computer vision introduced in the early 1990's together with upcoming digital imaging. Using computer vision it was tried e.g. to use standard cameras for measurement purposes. Computer vision brought new mathematical formulations and algorithms to the well known problem of getting three-dimensional information from stereoscopic images [11]. Among others it was shown that the relative exterior orientation of two images can be recovered only by using the existing image information provided the interior camera orientations are known. The major consequences of this fact are:

(i) Pictures for the later measurement can be taken freehand allowing an increased flexibility in applications.
(ii) The 3D image needs to be scaled and referenced as no information on camera locations has to be acquired.

4.2. Actual procedure

The major steps are:

(i) Establish reference element(s) somewhere around the area to be measured; this could be a simple range pole (local co-ordinate measurements) or surveyed control points (geo-referenced measurements)
(ii) Find two locations for taking a stereoscopic image pair; rule of thumb: mean imaging distance to the rock surface is about 1/10 the distance between the imaging locations (see Fig. 2)
(iii) If the camera was not calibrated in beforehand: Preserve the actual image formation process of the camera by taking calibration images.
(iv) Generate a generic 3D image by means of a special software component
(v) Reference the image using the reference element(s) from step (i)
(vi) Take your measurements directly from the 3D image using a special 3D software component

5. WHAT CAN BE GAINED FROM A 3D IMAGE?

A 3D image represents an indirectly acquired geometric model of the physical rock surface. Therefore, different kind of geometric information can be determined directly from the 3D image by marking locations or regions of interest.

Besides the geometric measurements, the 3D image itself represents a good documentation of the actual rock mass conditions.

The following paragraphs provide am overview on information directly obtainable from a 3D image.

5.1. Navigation

Navigation "through" a 3D image means that the 3D image can be inspected from any designated view by changing the observing position. This can be done interactively by using the computer mouse. For assessments structural features of the rock mass can be investigated and marked by clicking the appropriate location directly on the 3D image. As the markers are set on a 3D image spatial measurements are instantly available.

Interaction with the 3D image alleviates rock mass assessments since structures can be inspected from different angles, and a quick zoom between a close-up view and an overview is possible which supports to identify where the geologically significant locations are.

5.2. Co-ordinates and distances

Basic magnitudes are related to surface point measurements (x,y,z co-ordinates) and the determination of the Euclidean distance between arbitrary surface points which correlates to a virtual tape measure. By clicking on the designated position the software instantly provides the metric information.

5.3. Singular orientations

Any location on the 3D image can be touched with a special kind of cursor. It follows the actual 3D shape of the reconstructed surface and changes its pointing direction according to the actual orientation of the surface (see Fig. 3). In this way orientation measurements are possible corresponding to the application of a compass-clinometre device on any particular location.

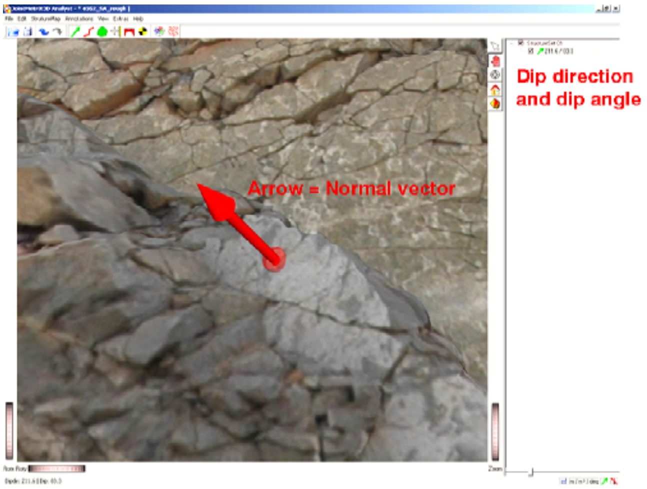


Fig. 3: Orientations can be measured at arbitrary locations on the 3D image. Dip angle and dip direction are provided instantly.

5.4. *Lineaments*

The measurement of linear rock mass features such as joints, lithological borders, or strata is also performed by marking the joint trace on the 3D image.

The result of these markings is a three-dimensional poly-line as it consists of 3D surface point measurements. If the 3D poly-line shows a significant change in depth, a plane can be fitted automatically to the set of surface points. The orientation of the fitted plane corresponds with the spatial orientation of the discontinuity that was marked thus the three-dimensional orientation is determined only by marking the joint trace (see Fig. 4)

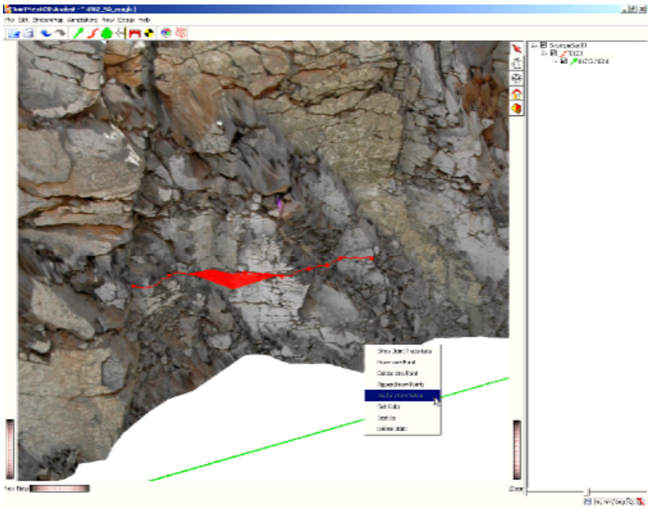


Fig. 4: A 3D poly-line marks a discontinuity trace. A plane is fitted to the poly-line. Its orientation corresponds with the orientation of the discontinuity.

5.5. *Areas*

With areas regions of similar geological attributes (e.g. lithology or same degree of fracturing) or joint surfaces are marked. When an area is marked, a closed 3D poly-line is defined. Without difficulty it is possible to determine that part of the 3D surface that is inside the marked area. From the marked part the mean orientation is computed and instantly provided as dip angle and dip direction.

Fig. 5 shows an example of a marked area and the resulting surface normal that indicates the spatial orientation of that area.

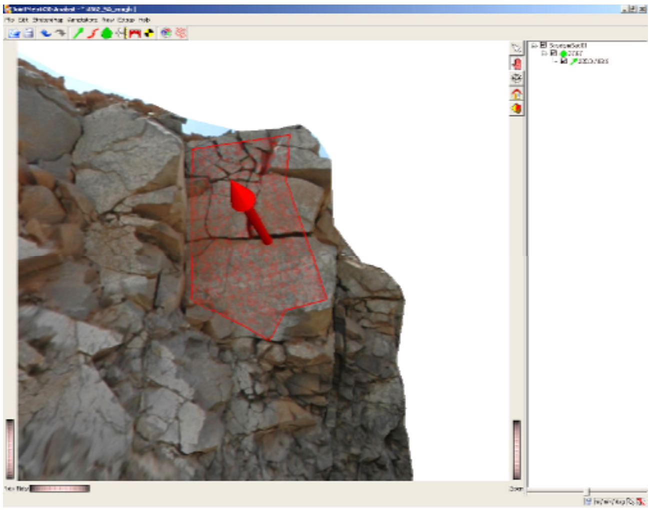


Fig. 5: Measurement of joint orientations at joint surfaces. By marking points on the 3D surface and calculating the mean orientation of the surface normal the orientation vector is determined.

5.6. *Structure maps*

Basic features, such as joints and areas, orientations, as well as co-ordinates, or distances are combined to structure maps that represent geological units, e.g. a discontinuity set. Structure sets enable to handle a various number of and various types of measurements. Fig. 6 shows an example of a 3D image with several structure sets marked.

5.7. *Hemispherical plots*

Once several structural measurements and especially orientations are present within a structure set, it becomes possible to visualize the orientations instantly in a hemispherical plot (see Fig. 7). This gives the geotechnical engineer the opportunity having a quick preview on the actual conditions.

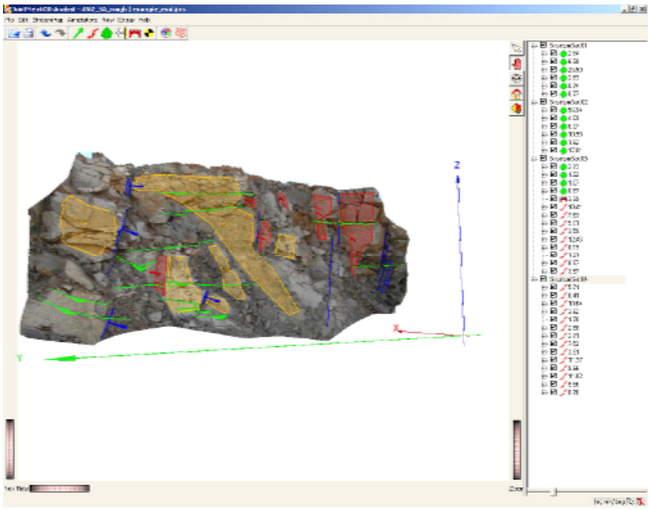
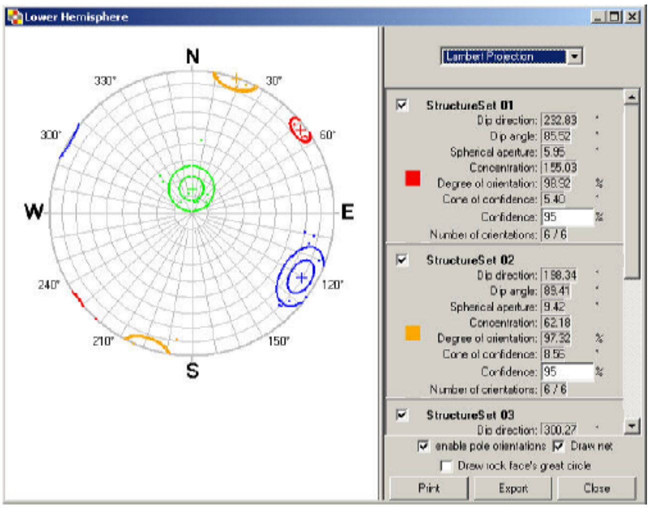


Fig. 6: Snapshot of the JMX Analyst software used for interactive assessment of 3D images and the determination of descriptive rock mass parameters.



☑ **StructureSet 01**
Dip direction: 232.83 °
Dip angle: 85.52 °
Spherical aperture: 5.95 °
Concentration: 155.03
🟥 Degree of orientation: 98.92 %
Cone of confidence: 5.40 °
Confidence: 95 %
Number of orientations: 6 / 6

☑ **StructureSet 02**
Dip direction: 198.34 °
Dip angle: 89.41 °
Spherical aperture: 9.42 °
Concentration: 62.18
🟧 Degree of orientation: 97.32 %
Cone of confidence: 8.56 °
Confidence: 95 %
Number of orientations: 6 / 6

☑ **StructureSet 03**
Dip direction: 300.27 °

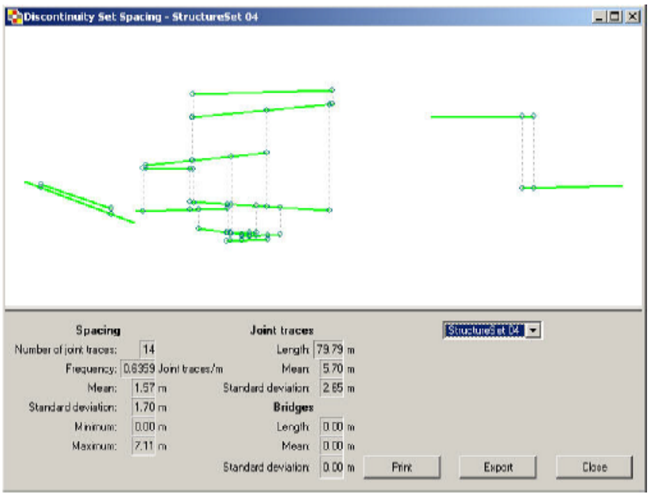
☑ enable pole orientations ☑ Draw net
☐ Draw rock face's great circle

Fig. 7: Lower hemisphere equal-area projection polar plot of identified discontinuity sets. Measured orientations are instantly displayed together with statistics on the distribution of the orientations.

5.8. *Spacing*

As orientation measurements are assigned to joints it is possible to determine the true normal spacing between joints traces within a structure set (see [12]). True spacing means to determine the real spatial distance between subsequent discontinuities of a set. Conventional scanline sampling or analysis of a single image normally leads just to the apparent spacing that depends on the orientation of the discontinuities and their intersection with the free surface.

Fig. 8 shows an example of an automatically generated sketch for visually checking the spacing calculation.



Spacing
Number of joint traces: 14
Frequency: 0.6359 Joint traces/m
Mean: 1.57 m
Standard deviation: 1.70 m
Minimum: 0.00 m
Maximum: 7.11 m

Joint traces
Length: 79.79 m
Mean: 5.70 m
Standard deviation: 2.65 m

Bridges
Length: 0.00 m
Mean: 0.00 m
Standard deviation: 0.00 m

Fig. 8: Computer generated sketch of a discontinuity network and statistics on the traces. The dashed lines indicate the scanline direction for determining the spacing and frequency.

5.9. *Profiles*

For certain analyses (e.g. roughness) a three-dimensional section through the surface is helpful. As a 3D image provides a dense grid of surface measurements over the whole image area, intersections can be chosen freely according to the requirements of the assessment leading to profiles ready for further analyses.

5.10. *Automatisms*

The automatic analysis of rock mass features was tried by several groups, e.g. [13, 14]. However, there seem to be limits for a fully automatic detection of rock mass properties that encounter during practical work, especially when facing on changing rock mass conditions. Observed problems so far include:

- **(i)** Artificial lineaments might be more representative than natural ones, e.g. excavator traces or traces from drilling in tunnelling or underground excavation which most probably confuses image processing automatisms and require reasonable efforts to check whether a structure was identified correctly or not.
- **(ii)** The automatic identification of joint sets based on topographic surface analysis (see [7, 9]) is only reasonable when a blocky rock mass is present.

A semi-automatic approach that supports the interactive assessment is therefore proposed for practical applications. Following automatisms are used:

(i) Accurate detection of lineaments by "guided" image processing: only a few sample points are marked on the 3D image and the points in-between are detected automatically based on image processing algorithms. This approach is also known under the term "live wire" [15].

(ii) Automatic detection of the extension of a joint surface and its orientation based on one single marked location on the joint surface.

(iii) Automatic discrimination of structure sets based on mean orientation values. As the orientation measurements from a 3D image provide the information on dip angle and dip direction instantly it is simple to define a new structure set containing the actual orientation measurement based on an (adjustable) angular discrimination.

The mentioned automatisms speed up interactive marking of geological features and concurrently let the decision on the geological relevance of a feature by the human operator.

6. A COMMERCIAL APPROACH

The possibilities for the contact free acquisition of rock mass parameters and especially their extensions to conventional field work naturally led to commercial systems. In the following two systems are highlighted:

6.1. The ShapeMetriX3D system

ShapeMetriX3D is a system for determining rock mass properties based on 3D images. For data acquisition a conventional SLR camera is used (see Fig. 9). In order to adapt on the actual size of the rock face zoom lens can be used which eases to find proper imaging locations.

The camera is calibrated before images in field are taken. Calibration means to determine parameters that describe the geometric image formation process inside the camera that changes with the camera settings, such as focal length, focus, or aperture. Calibration means in other words to determine the interior camera orientation.

Fig. 9: Picture of the ShapeMetriX3D calibrated camera together with reference elements and calibration target.

With the ShapeMetriX3D system a pre-calibrated camera is provided, thus it only requires noticing which lens and which camera was used for taking the pictures.

A special feature of the system is that the pictures from which measurements are taken later can be taken freehand without tripod or measurement of the distance between the two imaging locations (see Fig. 10). This is possible because reference elements are used consisting either of a vertically installed range pole or surveyed reference points.

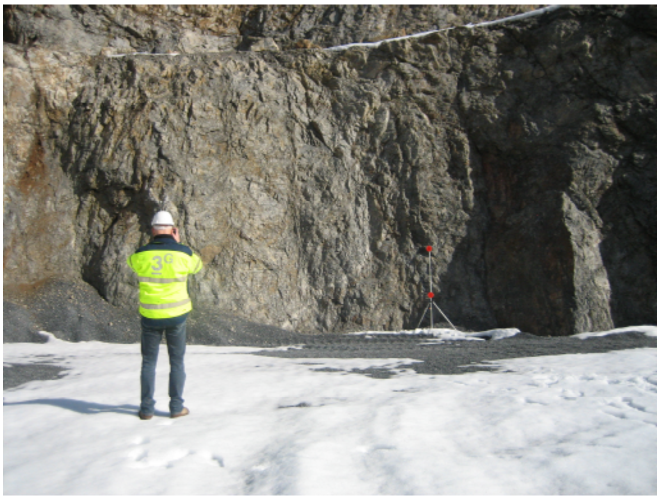


Fig. 10: Application of the ShapeMetriX3D system in a magnesite mine. Note the pictures are taken freehand.

Pictures taken with the calibrated camera are processed to a 3D image which can be done on a portable computer within some minutes. From the resulting 3D image geological analyses and geometric measurements can be taken instantly.

6.2. *The JointMetriX3D system*

The JointMetriX3D system works the same way as the ShapeMetriX3D system but using a special imaging source: a panoramic line scanner makes huge digital images up to 100 megapixel possible (see Fig. 11).

Such images are required when the rock outcrop to analyse is larger, e.g. more than 50 metres in height. Having a 100 megapixel 3D image large areas are captured at high resolution without the requirement to combine several partial images. This is especially advantageous when having control points spread over the area to acquire.

In order to adapt optimally on the size of the rock face the system can change the field of view individually for the vertical extension by changing the focal length and for the horizontal extension by changing the angle of rotation. Fig. 1 shows a 3D image resulting from the JointMetriX3D system used for geotechnical assessment of an inaccessible rock slope.

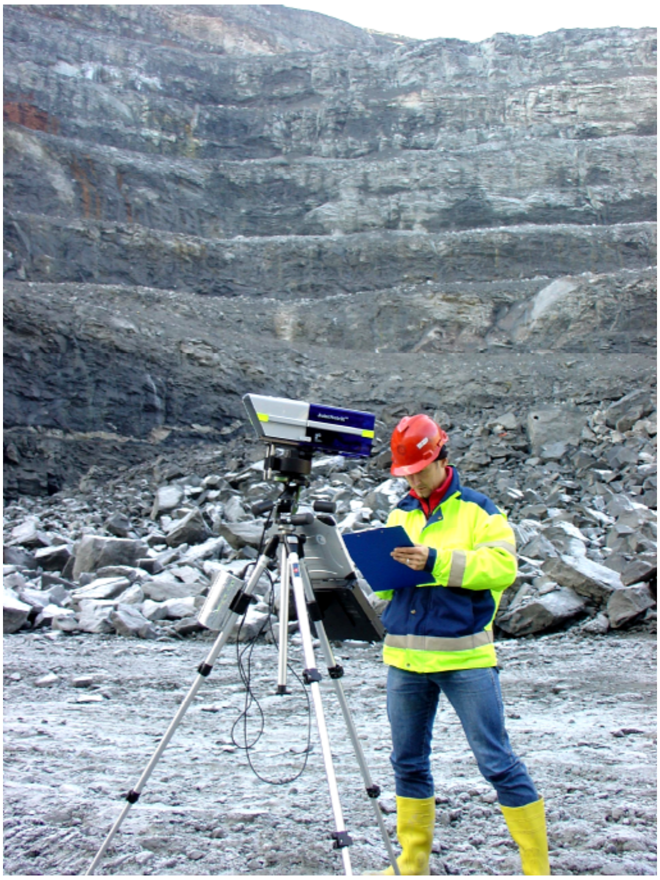


Fig. 11: Application of the JointMetriX3D system in a large open pit mine in Sweden.

6.3. *Image resolution*

For geological/geotechnical assessments of rock mass images resolution is a crucial issue. Depending on the image resolution different levels of detail in the analysis are possible. Therefore, one has to focus on the approximate size of the rock outcrop and the intended minimum size of structural features to be considered in the assessment.

However, not only linear features are affected by image resolution but rather also area based rock mass features: the higher the image resolution, the smaller the discontinuity surfaces and their orientations that can be measured.

Typical values for the image resolution are below one mm/pixel for close-up analyses, some mm/pixel in the case of tunnel faces up to some cm/pixel in the case of large outcrops, e.g. in open pit mines or quarries with wall heights of 150 m or more.

7. APPLICATIONS

Several applications for the assessment of differently sized rock mass are reasonable. Depending on the size of the acquired region the following list outlines investigations performed so far:

(i) Investigations on the shear behaviour of rock joints based on close range 3D images [16].
(ii) Determination of instable rock blocks [17, 18].
(iii) Geological face mapping in conventional tunnelling [19, 20, 21].
(iv) Tunnel face mapping and surveying of boreholes for optimizing blasting in underground mining [22].
(v) Bench face surveying and planning of blasts [22, 23]
(vi) Assessment of instable rock slopes.
(vii) Acquisition of the actual geometry of quarries and open pit mines combined with data for geotechnical assessment.

8. CONCLUSIONS

The contact-free measurement of rock surface geometries combined with high resolution digital images allows determining geometric rock mass parameters at a new quality. Different imaging systems are available to adapt on actual project requirements and 3D software components allow an intuitive assessment of the encountered rock mass conditions.

The use of zoom lens and the ability to choose the imaging locations freely without needing to survey brings high flexibility allowing a broad range of applications.

Besides the increase of *working safety* several advantages arise when using the described 3D imaging technology:

(i) Fast and easy-to-use data acquisition
(ii) Permanent documentation
(iii) Wide operational range from below 1 m to above 1.500 m due to changeable lens and free choice of imaging locations
(iv) Optimal cost/performance ratio due to relatively cheap hardware components; the measurement principle is covered within the software and not within hardware
(v) Ability to adapt to various sizes of rock outcrops and analyse also inaccessible parts
(vi) Ability to identify features that are otherwise not apparent when working too close to a rock face

Up to now, the systems were applied in different fields of rock engineering, tunnelling, mining, as well as in bench face surveying and blast planning.

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