Three-dimensional rock mass documentation in conventional tunnelling using JointMetriX3D

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ABSTRACT: JointMetriX3D is a novel system that generates reproducible records of tunnel faces based on metric 3D images. The photogrammetric approach allows measurements from the 3D images, such as positions, lengths, or areas, as well as orientations either by discontinuity surfaces or traces. From those data discontinuity spacing and frequency as well as stereograms are generated. The 3D images itself represent a reproducible record of the tunnel face preserving the information on the actual rock mass conditions allowing analyses also at a later time. Measurements can be taken at any required number and extent, even in regions that are not accessible. The improved data serve as proof of the actual conditions but also as substantial information for the decision making on site.

1 INTRODUCTION

Conventional tunnelling requires continuous adaptation of the excavation and support method to the actual ground conditions in order to get an economical and safe construction (Schubert et al., 2003). This observational approach requires among others the continuous collection of information on rock mass type, structure, and quality, as well as the system behaviour. Very important in this context are geometric properties of the rock mass and especially the discontinuity network as observed at every tunnel face and subsequently descriptive parameters which altogether supports to establish a plausible rock mass model.

Traditional methods of geological data acquisition are prone to errors (Fasching, 2001). First of all, there are sampling difficulties, human bias, and instrument errors. Secondly time restrictions lead to incomplete data and finally getting access to relevant locations is often difficult or hazardous. The resulting mapping usually do not allow to objectively reproduce the actual rock mass conditions. Data not recorded immediately are lost as excavation proceeds or support is applied.

The presented JointMetriX3D system overcomes those problems and opens new possibilities for optimisations on the tunnel site. JointMetriX3D bases on the generation of a high resolution metric 3D image of every tunnel face which is then analysed and assessed on a computer. This way the visible rock mass structures are completely recorded and geometric data on the rock surface and the discontinuity network are easily measured at an arbitrary number. There are no access restrictions and results are instantly available for further processing. The 3D image is an objective documentation of the rock mass conditions which makes analyses possible even if a specific rock face is does no longer exist.

2 WORKFLOW

Figure 1 outlines the required steps when applying the system.

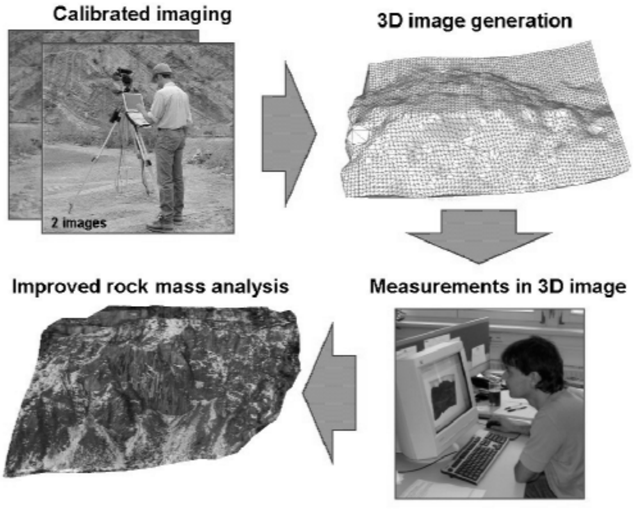


Figure 1: Data flow using the JointMetriX3D system.

Firstly, images using the high resolution panoramic image scanner are taken from two different angles (stereoscopic images). In order to enable measurements later, the imaging system should be calibrated, i.e. known deviations of the optical system from the ideal behaviour are determined and thus correctable.

Secondly the images are processed in order to get a 3D image using photogrammetric principles complemented by computer vision strategies. This step is done by a purpose-built software that can deal with panoramic images.

Then the 3D image is ready for taking measurements using another purpose-built software component that allows the quantification and management of geometric entities such as positions, lengths, areas, or spatial orientations given by dip and dip direction.

The results are structural maps, stereonets, descriptive and statistical rock mass parameters normally not determinable with reasonable efforts using traditional mapping.

3 IMAGING AT THE TUNNEL SITE

When taking images at a tunnel site one has to deal with several circumstances. Besides good visibility and *high resolution*, a sort of *referencing* mechanism is required in order to get a relationship between the data acquisition system and the surrounding which subsequently relates the derived measurements to the tunnel. A practical way to perform this relationship is to use reference points which means points of known positions in a superior co-ordinate system.

High resolution denotes that fine details are visible within the images which is crucial for documentation and analysis purposes. When doing conventional data acquisition the human observer also relies on the power of his/her visual capabilities. So it is obvious that any recording system must try to get as detailed information as possible when stating to be a documentation system. This is by the way a counting argument to use images instead of other sensors, such as lasers for example. If there are just intensities representing a rock face lacking of colour, lithological units and their borders as well as discontinuity traces might be misinterpreted or even not identifiable.

3.1 *The panoramic scanner*

A panoramic image is one that shows a full 360° field of view at least in one direction of the image. One approach to get a panoramic image is to move a camera along an rotation axis. When posing the rotation axis nearly vertically one gets an image that geometrically resides on a vertical cylinder, if an ideal rotation is assumed.

The actually used imaging system is a rotating line-scanner. It has three CCD arrays one for each of the colour channels red, green, and blue. Each of the arrays has more than 5300 sensor elements which is a determinant magnitude for the resulting resolution that is composed by the vertical field of view in meters divided by the number of sensor elements.

The scanner is mounted on a tripod and controlled by a field notebook computer that instantly stores the acquired image data. During imaging the scanner rotates along a defined axis taking the panoramic image column by column. This principle decouples the vertical field of view (then depending only on the used lens) from the horizontal one (depending on the rotational motion). Figure 2 shows the imaging principle when using a panoramic line-scanner.

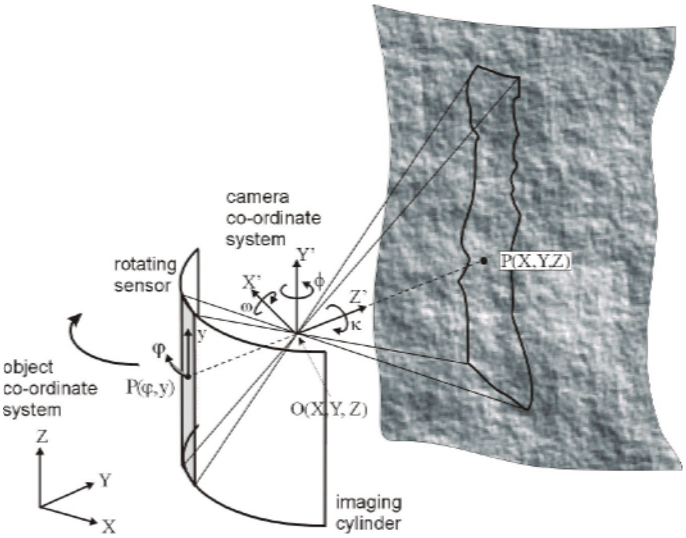


Figure 2: Geometry of panoramic line-scanning.

Since it is an imaging system there is of course a need for illumination. Usually one big flood light posed vaguely at the tunnel axis is sufficient to light the tunnel face up (see Figure 3).

Figure 3: Imaging at the tunnel site. Note that only one person is required to operate the scanner.

The panoramas taken at tunnel sites show typically a resolution in the mm-range The resulting panoramas have a size of about 100 million picture elements (megapixels) which is clearly beyond conventional digital cameras. A section of a panorama is given in Figure 4. It shows a part of a tunnel face and a detail zoomed out from it. The image was taken at a two-track railway tunnel site in Austria (top heading).

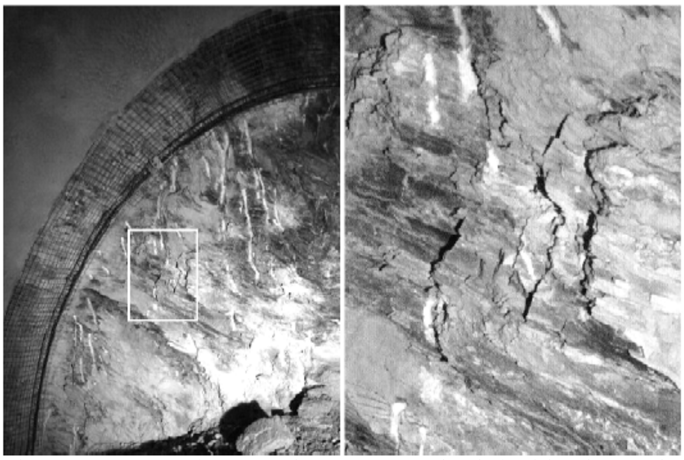


Figure 4: Parts of a tunnel panorama; the left side shows the tunnel face of a top heading excavation, the right side a detail taken from the same image. The geometric resolution is about 2mm/pixel

3.2 *Referencing*

In order to get a relationship between the images and the tunnel, points with known co-ordinates in the tunnel system are required to be visible within the images. These points, denoted as reference points, are often available at conventional tunnel sites anyway where they are used to monitor displacements (Schubert & Steindorfer, 1996). For that reason the points are gauged regularly, often on a daily base.

An arising question is how to use those points optimally? If a conventional camera is assumed and one takes an image farther away from the tunnel face in order to capture also the reference points, the tunnel face covers only a small area of the whole image, thus giving required resolution away. Getting a closer view of the tunnel face entails that reference points disappear from the field of view of the camera.

This problem can be solved if panoramic images are used which allow the combination of high resolution at the tunnel face and a large field of view, thus making also the reference points visible. Figure 5 shows the geometric arrangement for imaging at a tunnel face. Reference points, in photogrammetry also denoted as ground control points, are indicated as well as possible camera standpoints. Note that there is no need for setting up the imaging system specially. The actual scanner poses are determined right from the observation of the reference points. In order to get proper echoes from the reflective reference points visible in the back, small light sources are mounted directly on the panoramic scanner.

Once the relationship between the reference points and the acquired images is established, the results are referenced as well which means that derived measurements are related to the co-ordinate system of the reference points.

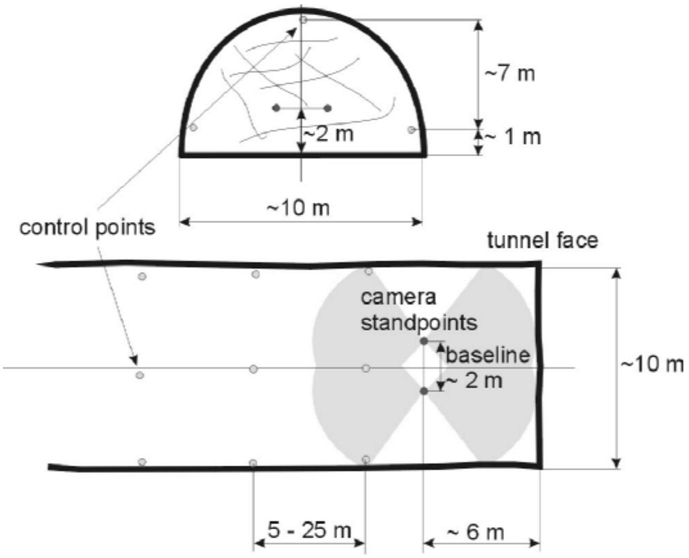


Figure 5. Schematic arrangement for imaging a tunnel face. The grey wedges indicate the useful parts from the 360° panoramas.

3.3 *Geometric arrangement*

As mentioned in section 2 there is a need for taking two images for getting measurements later. The two images can be taken simultaneously or subsequently. Each of the two panoramas contain the tunnel face and a view of the already excavated area as indicated with the grey wedges in Figure 5.

The time need in front of the tunnel face is some minutes typically. Within this time slot that is used usually before shotcreting all geometric data of rock surface and the discontinuity networks, as well as the referencing information is recorded.

4 3D IMAGE GENERATION

The generation of a 3D image uses principles of classical photogrammetry (Slama, 1980) complemented by more recent insights from computer vision where among others the calibration of off-the-shelf cameras was addressed (Faugeras, 1993). Having two images of the same region taken from different angles the so-called Shape from Stereo principle is applicable (Figure 6). Several tasks are required before a 3D image is ready (cf. Gaich, 2001):

- Calibration of the imaging system
- Determination of reference points
- Identification of corresponding image points
- Computation of 3D point cloud
- Connection of the 3D points to a surface mesh
- Geometric alignment of image and mesh

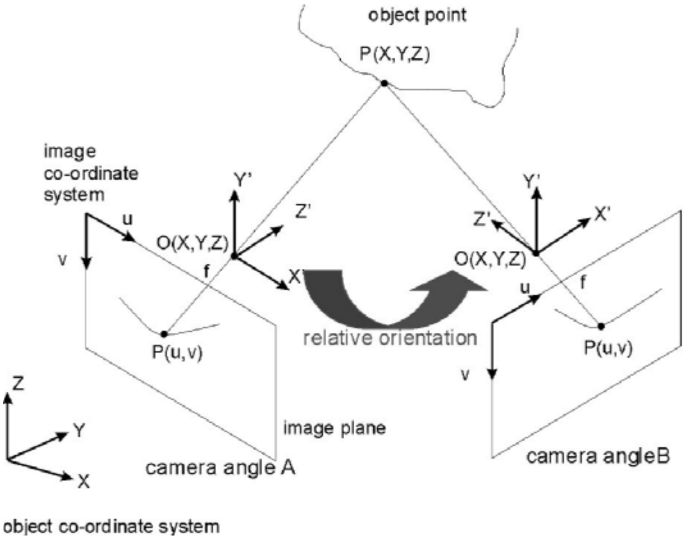


Figure 6: Shape from stereo principle.

5 ASSESSMENT OF 3D IMAGES

5.1 *3D Viewing*

Once a 3D image is ready, measurements can be taken from it. A purpose-built software is ready that allows to inspect a 3D image from any designated side. A turn and zoom mechanism brings any portion of the 3D image into any wanted pose. As additionally the 3D image is highly resolving, the human assessor gets this way a real impression on the rock mass conditions. Figure 7 shows a snapshot of the software with the 3D image of a tunnel face.

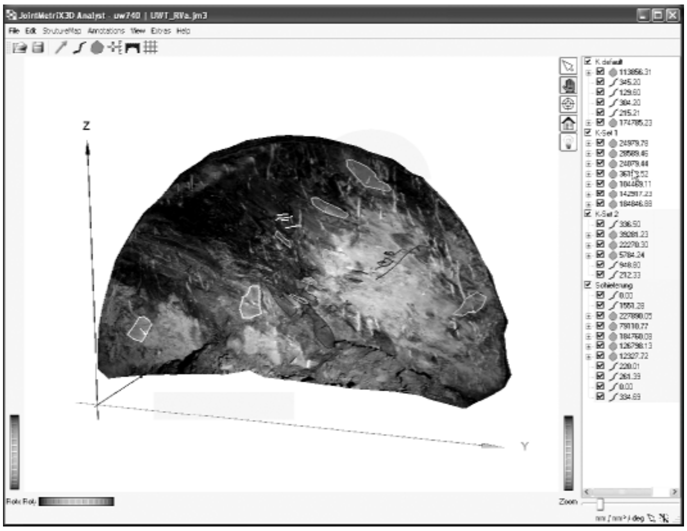


Figure 7: Snapshot showing the 3D image of a tunnel face and some measured structure data.

5.2 *Direct Measurements*

From the 3D image geometric measurements are taken. At any of the possible poses of the 3D image, graphical markers can be placed “onto” it using the computer mouse. These marks denote points or regions of interest, e.g. visible discontinuity traces or discontinuity surfaces. The graphical marks themselves consists of 3D sample points and each of the sample points is given in the used object co-ordinate system, thus all measurements taken from the 3D image are inherently three-dimensional and digital.

5.2.1 *3D measuring point*

Any visible location can be marked by a measuring point getting it in the 3D Cartesian co-ordinates of the superior co-ordinate system, thus the position of any wanted location can be measured.

5.2.2 *Linear elements*

Discontinuity traces as well as lithological borders or geological strata are marked by linear elements providing instantly the true lengths in meters. Linear elements are represented as polygonal lines that follow the surface in 3D.

5.2.3 *Area elements*

Any region within a 3D image can be annotated by an arbitrarily defined closed polygonal. The sample points of the polygonal are determined directly from the 3D surface which brings the marked region also into 3D. The area of the marked patch is instantly provided in square meters.

5.2.4 *Orientations by discontinuity surfaces*

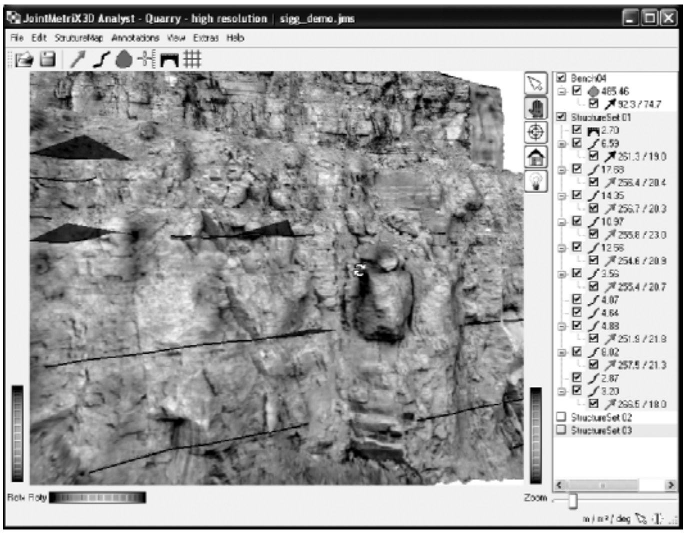
If a discontinuity surface is identified during the 3D analysis, it can be marked by an area element. The area element usually covers a number of smaller surface elements from which the 3D image is composed of. The software takes all affected surface elements and calculates a mean normal vector which represents a robust way to get an orientation measurement. Output is provided instantly by dip and dip direction and a graphical marker.

5.2.5 *Orientations by traces*

There is a second way to determine a discontinuity orientation mostly not possible during conventional field work. If a discontinuity trace is present that has a significant change in depth, i.e. the trace is not observed to be on a planar surface, the software calculates dip and dip direction from the trace alone by fitting a plane to the 3D polygonal. The plane is visualised as a spatial triangle that intersects the 3D surface as indicated in Figure 8.

5.3 *Derived Measurements*

As the system allows 3D measurements that lead to geometric magnitudes in a given co-ordinate system, all descriptive rock mass parameters that base on geometric information of a rock face and the discontinuity network can be derived from those measurements.



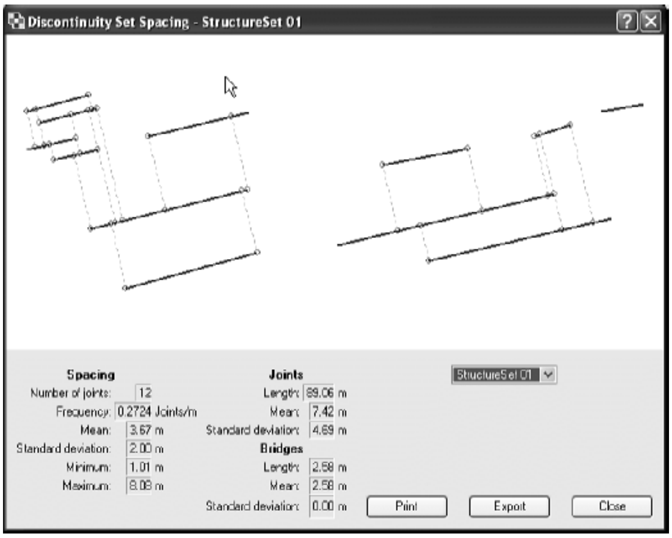
☑ Bench04
☑ 485.46
☑ 92.3 / 74.7
☑ StructureSet 01
☑ 2.70
☑ 6.59
☑ 261.3 / 19.0
☑ 17.68
☑ 256.4 / 20.4
☑ 14.35
☑ 256.7 / 20.3
☑ 10.97
☑ 255.8 / 23.0
☑ 12.56
☑ 254.6 / 20.9
☑ 3.56
☑ 255.4 / 20.7
☑ 4.07
☑ 4.64
☑ 4.88
☑ 251.9 / 21.9
☑ 6.02
☑ 257.5 / 21.3
☑ 2.87
☑ 3.20
☑ 266.5 / 18.0
☐ StructureSet 02
☐ StructureSet 03

Figure 8: Discontinuity traces and computed orientation measurements indicated by spatial triangles.

5.3.1 *Spacing*

Spacing in this context is referred to as normal spacing, according to definitions given in the textbook by Priest (1993). For each discontinuity set, a plane of projection perpendicular to the mean orientation value is determined automatically. The plane of projection ensures that not the apparent spacing that is dependent from the actual shape of the surface is determined as it would be if just a single two-dimensional image is used.

All discontinuity traces of a set are then intersected with the plane of projection. Now the distance between adjacent discontinuities is measured along scanlines. The direction of the scanlines is also determined automatically which happens to be perpendicular to the mean orientation. Using a plane-sweep algorithm it is determined which discontinuities are adjacent.



Spacing
Number of joints: 12
Frequency: 0.2724 Joints/m
Mean: 3.67 m
Standard deviation: 2.00 m
Minimum: 1.01 m
Maximum: 8.08 m

Joints
Length: 89.06 m
Mean: 7.42 m
Standard deviation: 4.69 m

Bridges
Length: 2.58 m
Mean: 2.58 m
Standard deviation: 0.00 m

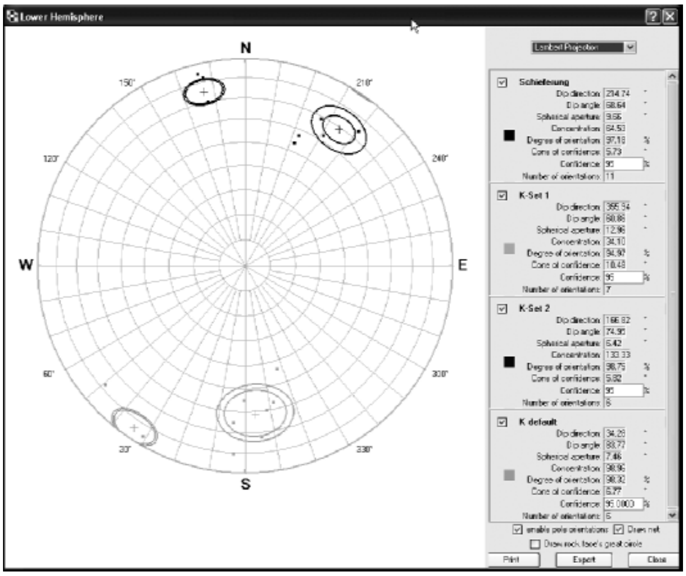
Figure 9: Computer generated sketch of the discontinuity network marked in Figure 8. The dashed lines indicate the scanline direction for determining the spacing.

Figure 9 shows the automatically generated sketch from the measurements shown in Figure 8. Continuous lines indicate the intersections of discontinuities and the plane of projection and dashed lines represent scanlines. This plot serves for visual inspection to verify a plausible spacing determination.

5.3.2 *Stereograms*

The measurements taken from the 3D image are grouped to sets by the user. Each set can be instantly visualized in polar nets in order to get an impression of the spatial distribution fastly where it is possible to choose between equal area or equal angle projections.

The stereograms deliver also some statistical figures, such as the spherical aperture or the cone of confidence for each discontinuity set. Figure 10 and Figure 11 outline such plots. The output is instantly updated when new orientation measurements are applied.



☑ **Schiefeung**
Dip direction: 214.74 °
Dip angle: 68.64 °
Spherical aperture: 9.66 °
Concentration: 64.53
Degree of orientation: 97.18 %
Cone of confidence: 5.73 °
Confidence: 95 %
Number of orientations: 11

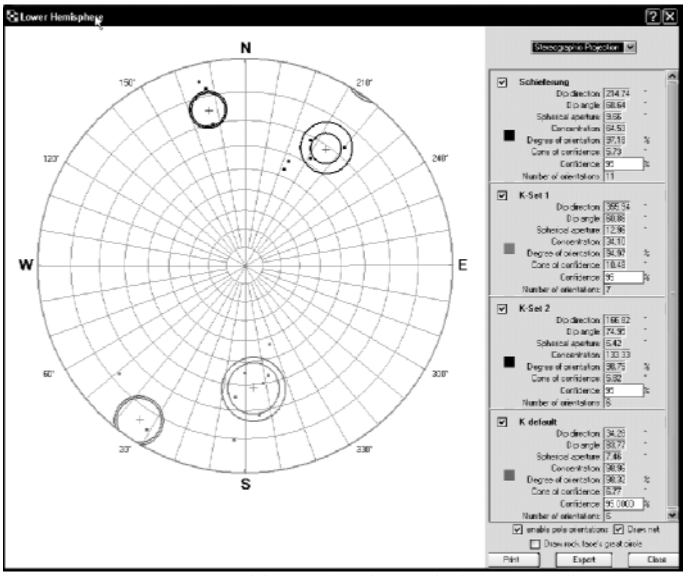
☑ **K-Set 1**
Dip direction: 355.54 °
Dip angle: 60.86 °
Spherical aperture: 12.96 °
Concentration: 34.10
Degree of orientation: 94.97 %
Cone of confidence: 10.48 °
Confidence: 95 %
Number of orientations: 7

☑ **K-Set 2**
Dip direction: 166.82 °
Dip angle: 74.95 °
Spherical aperture: 6.42 °
Concentration: 133.33
Degree of orientation: 98.75 %
Cone of confidence: 5.82 °
Confidence: 95 %
Number of orientations: 6

☑ **K default**
Dip direction: 34.28 °
Dip angle: 83.77 °
Spherical aperture: 7.46 °
Concentration: 98.96
Degree of orientation: 98.32 %
Cone of confidence: 6.77 °
Confidence: 95.0000 %
Number of orientations: 5

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

Figure 10: Lower hemisphere equal-area projection polar net of the identified discontinuity sets which is instantly available together with statistics on their distribution.



☑ **Schiefeung**
Dip direction: 214.74 °
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Spherical aperture: 9.66 °
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Degree of orientation: 97.18 %
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Degree of orientation: 98.32 %
Cone of confidence: 6.77 °
Confidence: 95.0000 %
Number of orientations: 5

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

Figure 11: Stereographic projection of the same data set as shown in Figure 10.

5.3.3 *Histograms*

Structural information that is annotated on the 3D image is stored as 3D information. Therefore true lengths of discontinuity traces are available. An export functionality allows to generate data files from which histograms as shown in Figure 12 are derived using external standard software.

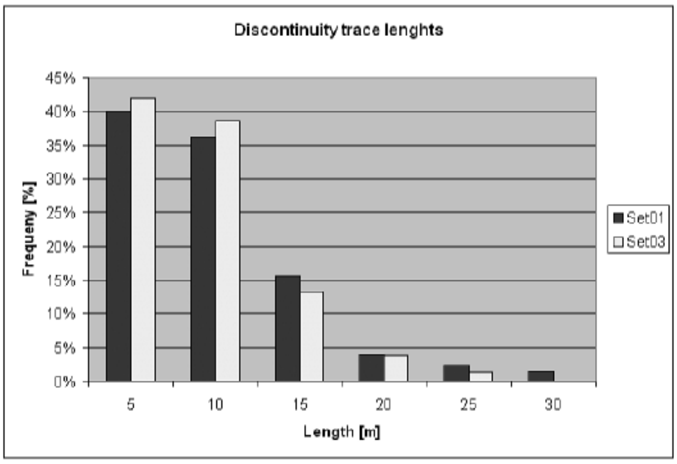

Figure 12: Discontinuity trace length distribution of two sets from a quarry assessment.

6 CONCLUDING REMARKS

The described system allows to record a tunnel face in a reproducible, objective way. Without needing knowledge on photogrammetry or computer vision one acquires relevant parameters of a rock wall quickly and preserves this way complete (visual) information of the actual rock mass conditions. Using this approach the data acquisition task is decoupled from the analysis task – the analysis can be performed even when the actual tunnel face does no longer exist.

Getting measurements from 3D images implies that this is an indirect measurement principle, therefore it is obvious that not all rock mass parameters can be determined by the system, for example discontinuity filling or strength parameters. However, indirect measurements increase safety as measurements can also be taken at inaccessible and possibly hazardous locations.

A 3D image resulting from the system represents an objective record of a tunnel face due to its high resolution, true colour, visual information and its three-dimensionality. It is no problem to do assessments at any later point in time or even support rock mass analyses from a distant location, as the data give a realistic impression to the observer.

Taking 3D images of a tunnel face in a regular manner, leads to an improved rock mass model that supports the understanding of the observed behaviour and serves as input for decisions on excavation and support on site. This specially bears the potential for saving construction cost since decisions on site are better if better information on the ground conditions is present.

An unbiased and reproduciberecord of the rock mass conditions can also a valuable asset in calim support and defence.

The JointMetriX3D system can also be applied on larger scale rock faces such as pit walls or quarries. Images of rock walls up to 300m high can be taken from a distance of several hundreds of meters which allows an assessment of even hardly accessible slopes.

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