Geotechnical data collection supported by computer vision

A. Gaich
Institute for Computer Graphics and Vision, Graz University of Technology, Austria

A. Fasching
3G Gruppe Geotechnik Graz, ZT GmbH, Austria

W. Schubert
Institute for Rock Mechanics and Tunnelling, Graz University of Technology, Austria

ABSTRACT: A computer vision approach is used to improve current geotechnical data collection for rock mechanics. High resolution digital images, photogrammetric principles, and image processing techniques allow an indirect three-dimensional observation of rock mass exposures. This allows to measure geometrical properties of the rock mass without working in hazardous environments, without restrictions in time. and without the need for manual access. This system gives a new tool into the hand of the geotechnical engineer supplementing his current field work.

1 STATEMENT OF PROBLEM

The collection and evaluation of geotechnical data is vital for any rock mechanical analysis. Present field work often relies on measurements using compass-clinometer devices and measuring tapes combined with manual sketches and eventually conventional photographs. This requires tactile access to the exposed rock mass which can be hazardous and time-consuming (Fasching 2000). Besides, this data acquisition process is strongly *subjective* and, what is even more problematic, it is not a comprehensive documentation of the rock mass. If for any reason the rock mass is altered, e.g. by erosion or excavation work, the original conditions are lost. However, the actual rock mass conditions are preserved, if *visual* data at a sufficient quality are acquired (Gaich 2000).

Generally, the results from current geotechnical data acquisition are incomplete, mostly incorrect (due they do not have metrics), and often inconsistent. Anyhow, further rock mass analyses rely on these data.

2 A COMPUTER VISION APPROACH

Computer vision can be understood as connecting a computer with (digital) cameras and processing the images on it. Three-dimensional computer vision (3d vision) is inspired by human perception and tries either to reconstruct objects from images or to understand the contents of a scene (Sonka et al. 1999).

Various approaches for 3d vision systems were introduced in the past and many algorithms were established (Faugeras 1993) and it showed to be no universal solution for the manifold applications which themselves are strongly liable for the configuration of a 3d vision system and the used principles. As one can imagine the *image quality* is an essential design criterion for a computer vision system. For geotechnical data acquisition the following basic needs are defined:

Specifications to the imaging system

- Instant image processing directly at the site which brings the need for digital images
- Image resolution of about 2-3 mm on the rock surface (object space) to identify smaller structures which requires image sizes beyond customary digital cameras
- Colour information to identify lithological borders
- Stereoscopic camera configuration which is the basis for metrics
- Metric measurements with an accuracy in the cm-range
- Determination of the camera orientations which allows measurements in relation to the surroundings
- Data acquisition within minutes, important e.g. at tunnel construction sites

These challenging specifications are not to fulfil using standard off-the-shelf cameras. In order to get a solution at reasonable cost the specifications led to the design and construction of a proprietary imaging system based on panoramic line-scan cameras.

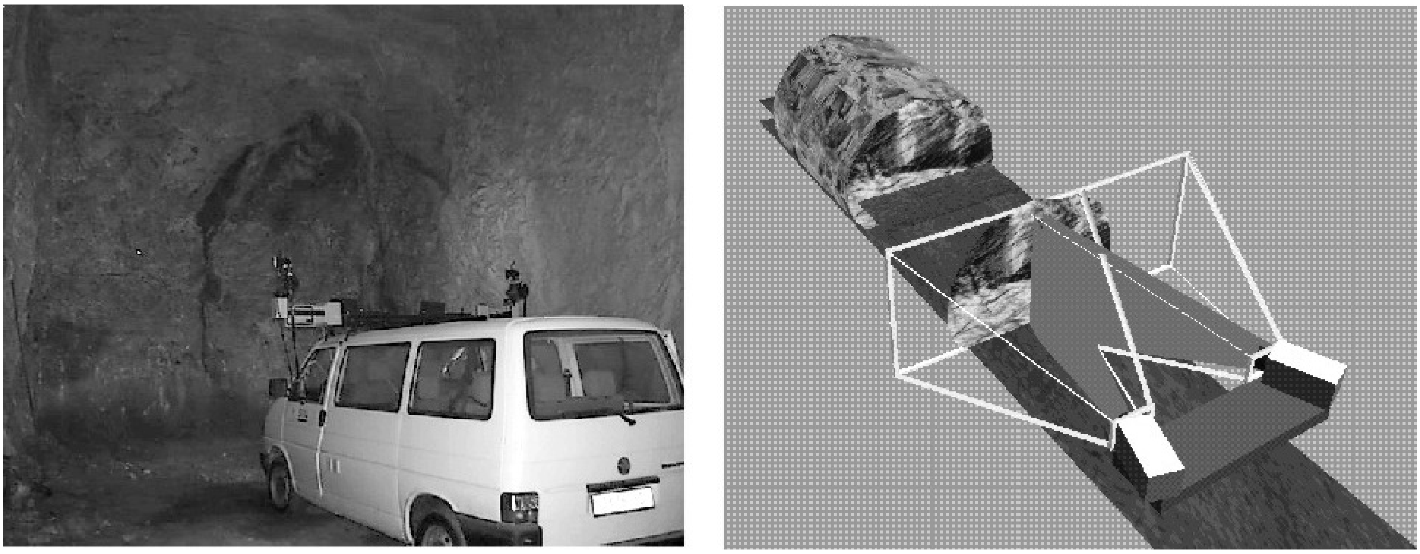


Figure 1: Proprietary imaging consisting of two rotating CCD line-scan cameras mounted on a vehicle (left). Basic configuration and line-scanning principle (right).

3 THE PANORAMIC IMAGING SYSTEM

3.1 *System description*

The imaging system is composed by two proprietary panoramic line-scan cameras with 6000x3 sensor elements each. The cameras are driven by stepper engines and mounted on top of a vehicle. By rotation of the line-scan cameras the object space is scanned, thus the scene has to be static (cf. Fig. 1).

Such panoramic cameras allow to solve a contradiction: they combine a *high resolution* in the object space which is achieved by using lenses with longer focal lengths with a *large field of view* which normally requires shorter focal lengths.

The cameras can take panoramic images up to 360° field of view (cf. Fig. 2). Such images have a size up to 27000x6000 pixel at full resolution which means a raw image size of 460 MB for one single colour image.

The system was already applied to record rock mass exposures in subsurface environments and in quarries delivering high resolution, stereoscopic images where measurements can be taken from.

3.2 *Measurement from images*

In order to measure from the images the perspective geometry of the cameras must be known. This so-called *internal orientation* of the cameras is determined using a test field containing targets with known co-ordinates. The internal orientation include the focal length, the geometric distortion of the used lens, and the position of the principal point (Slama, 1980). Once these parameters are known metric measurements can be taken within the scope of two different co-ordinate systems:

1 *Camera co-ordinate system*: The imaging system itself defines the co-ordinates, i.e. measurements do not relate to the surroundings. But relative measurements within a single image pair are valid and have physical reality. This is the simpler configuration which requires no other positioning

Figure 2: Panoramic image taken at a limestone quarry in Austria. The image shows a full 360 degree panoramic sweep and has a size of 27000x6000x3 pixels (uncompressed image: 460MB) at full resolution. The rock wall in the left is about 8 m high, but details in the sub-cm range can be identified.

system. But it is sufficient for many geotechnical analyses, like the evaluation of a single rock wall that uses measurements of structures only in relation to each other. Since the measurements base on panoramic images the field of view might be 120° without any problems, thus long drawn-out rock walls can be acquired.

2 *Object co-ordinate system*: Structures are measured in relation to a given (external) object co-ordinate system. To achieve this, the so-called exterior orientations of the cameras within the object space must be determined. The exterior orientation of a camera is defined by the location of the centre of projection and the pose of the optical axis. By observing at least three non co-planar control points (points with known co-ordinates in the object space) the exterior orientation can be determined (Slama 1980). This process was adapted for panoramic line-scan cameras (Case 1967, Gaich 2000). In the case of tunnel construction sites, control points are already existing. Since commonly applied reflection targets are used for displacement monitoring it is quite natural to use them to determine the camera orientation.

Using the parameters of the interior and exterior camera orientation the three-dimensional reconstruction of surface points becomes possible. The points are connected to a surface description and combined with geometrical structures originating from rock mass discontinuities which finally leads to three-dimensionally defined geotechnical parameters.

4 IMAGE ANALYSIS

This section shows exemplarily the different steps of rock mass image analysis and their combination in order to derive geotechnical measurements.

4.1 *Interactive structural analysis*

A single rock mass image from a stereoscopic pair is used to interactively annotate geotechnically relevant structures identified within the rock mass. This approach was plurally used in the past in order to digitise structural (2d) information from conventional photographs, e.g. by Hagan (1980), Franklin et al. (1988), Tsoutrelis et al. (1990), or Crosta (1995).

The major problem in automatic identification of discontinuities originates from changing rock mass conditions and the task to determine the geotechnically relevant (or significant) structures. Fully automatic approaches (Reid & Harrison 2000, Fasching 2000) do not deliver satisfactory results at present. Too much parameters in a chain of processing steps influence the final results and have to set individually. Current analysis tools are not robust to be adaptive to varying rock mass. Therefore an interactive analysis performed by an experienced geologist is proposed.

Using a software that allows the handling of the images, traces of discontinuities can be marked and are displayed as geometrical structures overlaid the original images. These structures are grouped to manage joint sets and stored in a hierarchical manner which simplifies the computation of statistical values (see also section 5).

An example is depicted in figure 3. It shows a rock wall from a quarry and the 2d structural map of the main joints grouped into three joint sets. It took an experienced geologist about 15 minutes to come to this result.

4.2 *Stereoscopic vision*

A major support for the interactive analysis is the

Figure 3: Image taken at a limestone quarry. The main geotechnical structures are annotated by an experienced geologist directly on the computer's screen. The resulting two-dimensional structural maps are displayed as graphical overlays and hierarchically managed.

use of stereoscopic vision that allows to inspect the images three-dimensionally on the computer. The two images of the rock mass exposure are simultaneously displayed and separated for each eye by means of graphic's hardware (e.g. synchronised shutter glasses) which enables three-dimensional perception (Foley et al. 1990). This allows a better assessment of ambiguous regions. In the working process the mode is switched between two-dimensional annotation and three-dimensional vision.

4.3 *Automatic surface reconstruction*

Surface reconstruction allows to recover the three-dimensional shape of the rock mass exposure. The principle is shown in figure 4. Going out from the stereoscopic image pair, three steps are performed:

1. *Matching*: This is the process of identifying corresponding points within the image pair. This task is an important basis for the quality of the reconstructed surface: the denser and more accurate the point correspondences are detected, the more reliable are measurements derived from the surface model.
2. *Three-dimensional point reconstruction* refers to the computation of the three-dimensional object co-ordinates of a surface point based on the corresponding image points and the orientation of the cameras. The results is an unorganised set of 3d points (point cloud)
3. *Mesh generation* ensures a connection between the single points of a point cloud. Often used are triangulated irregular networks (TIN) like the Delaunay Triangulation (Delaunay, 1934) which results in a surface description exclusively composed by triangles.

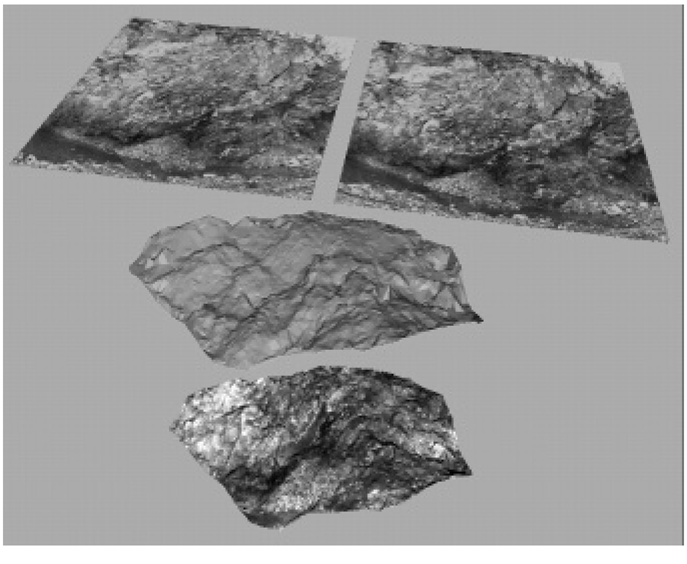


Figure 4: Surface reconstruction principle. A stereoscopic image pair (top) is used to compute a three-dimensional surface (middle). One image draped over the surface results in a textured surface reconstruction (bottom).

4.4 *Fusion of results*

The resulting structural maps from the interactive analysis (sec. 4.1) can be geometrically aligned with the automatically computed surface reconstructions (sec. 4.3) if both results base on the very same images. With that 2d structural maps become 3d existence and therefore enable the derivation of 3d magnitudes of the structures, like the true length of discontinuities or distances between them.

The resulting geotechnical surface models consists of 3d points, their connection among each other and the 3d structural data. The models are handled in a standard graphics file format called virtual reality modeling language (VRML) which is virtually supported by any internet browser. This allows easily to interchange such models using the world wide web.

4.5 *Discontinuity orientations*

The results so far enable 3d point measurements either in relation to the camera co-ordinate system or to an external object co-ordinate system. The measurement of spatial orientation information can be derived from single 3d point measurements: suppose a spatial triangle determined by three surface points. If the surface points are chosen to lie on a discontinuity then the normal vector to this surface triangle represents the orientation of this discontinuity. This principle was already used in geotechnical analyses based on conventional photographs (Linkwitz 1963, Rengers 1967).

Another way is to use the stereoscopic vision system mention in section 4.2. A virtual triangle can be navigated through three-dimensionally perceived rock mass by means of a 3d input device, like a space ball. This triangle is positioned until it matches the discontinuity and the (also displayed) normal vector represents the discontinuity orientation (Fig. 5).

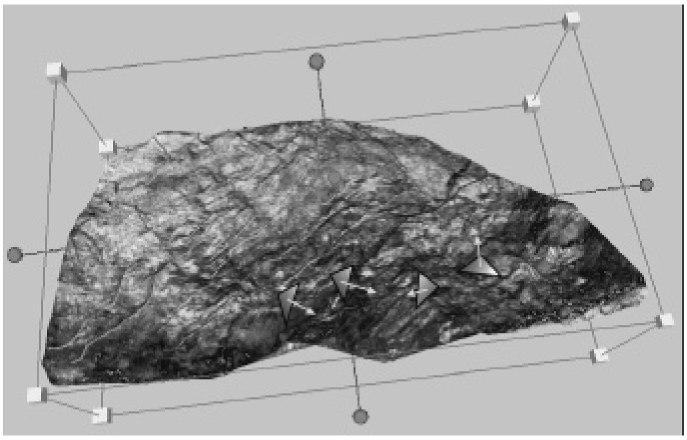


Figure 5: The reconstructed surface model is used to support the measurement of discontinuity orientation. Small triangular shapes are positioned in the virtual space until they fit the discontinuity.

5 DERIVED PARAMETERS

An evaluation of selected discontinuity parameter (trace length, normal spacing, relative orientation) has been performed with discontinuity traces (Fig. 6). The traces result from an interactive image mapping of a limestone cliff. The selected window has a size of about 17.5 m^2. Both evaluated discontinuity sets are oriented normal to the image plane.

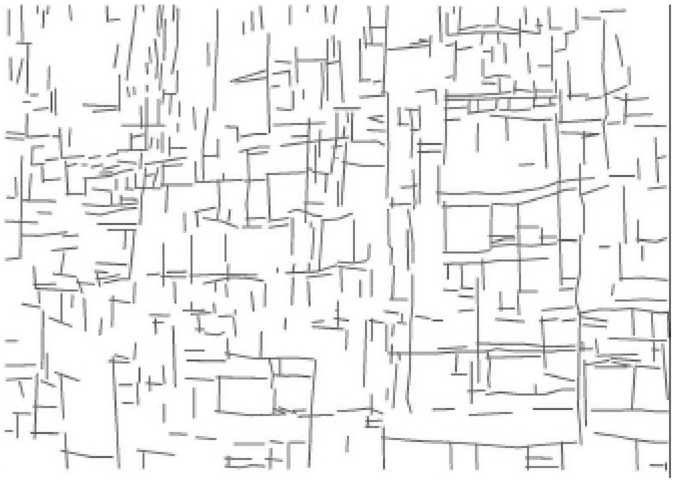


Figure 6: Discontinuity trace map. Horizontal discontinuity traces: bedding planes, 276 samples, vertical discontinuity traces: joint planes, 289 samples.

5.1 *Geotechnical parameters*

5.1.1 *Trace length*

The result of the detailed analysis of discontinuity trace length is displayed in Table 1. Structures with a length < 5 cm were included, but areas with extremely high jointing frequency were not evaluated in detail by the image mapping. The histogram (Fig. 7) demonstrates that discontinuities smaller than 0.1 m were not considered. When using a cut-off value of 0.1 m the histograms would show a negative exponential probability density distribution, typical for this type of geological data.

Table 1: Results of discontinuity trace length analysis.

Statistical parameter	*Horizontal set*	*Vertical set*
Mean value	0.21 m	0.23 m
Standard deviation	0.18 m	0.20 m
Minimum value	0.03 m	0.03 m
Maximum value	1.48 m	1.58 m
Number of samples	276	289

The analysis of discontinuity spacing X_n was performed for both discontinuity sets with a vertical distance of 0.2 m between the sampling lines. This distance was chosen as a consequence of the evaluation of discontinuity trace length. The results, as displayed in Table 2 show comparable characteristics for both discontinuity sets. The histograms (Fig. 8) show that intensely jointed areas with discontinuity spacing < 0.05 m were not considered.

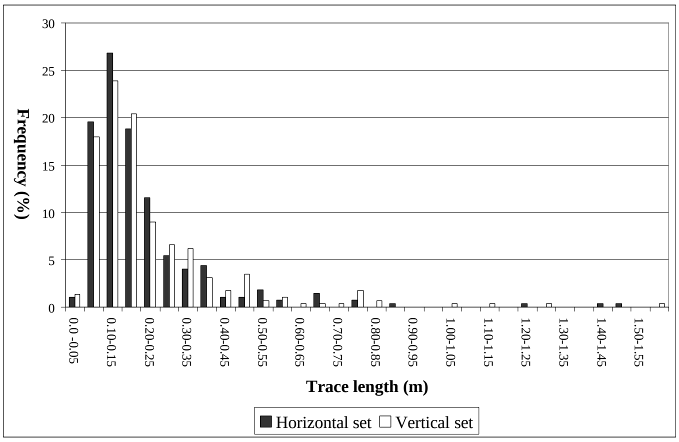


Figure 7: Discontinuity trace length histograms

Table 2: Results of discontinuity spacing analysis

Statistical parameter	*Horizontal set*	*Vertical set*
Mean value	0.25 m	0.26 m
Standard deviation	0.24 m	0.22 m
Minimum value	0.01 m	0.03 m
Maximum value	1.48 m	1.58 m
Number of samples	276	289
Number of sampling lines	50	35
Total length of sampling lines	134 m	157 m

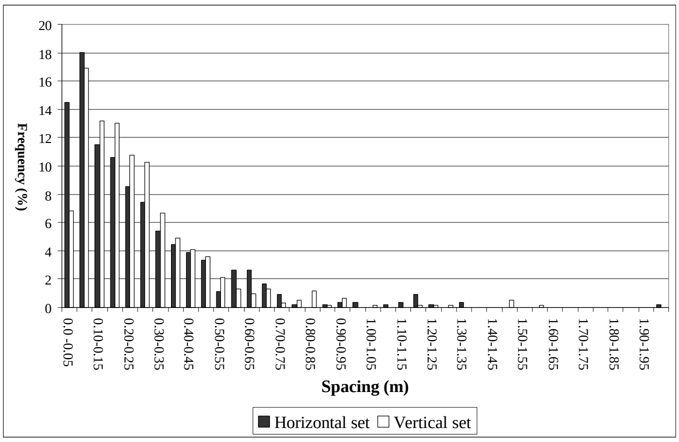
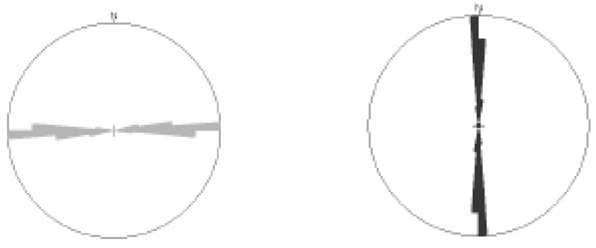


Figure 8: Discontinuity spacing histograms

5.1.2 *Orientations*

The evaluation of discontinuity orientations was performed relative to the image plane only, as no world co-ordinates were obtained during imaging. The rose diagrams, shown in Fig. 9, clearly reflect the encountered orthogonal discontinuity system of the limestone. The analysis result for the structural orientation data is displayed in Table 3.



(a) (b)

Figure 9: Rose diagram of relative discontinuity orientations, a) horizontal discontinuity set, b) vertical disconti-

Table 3: Results of statistical analysis of structural orientation data (Wallbrecher, 1986).

Statistical parameter	*Horizontal set*	*Vertical set*
Confidence limit	99 %	99 %
Amount of data	276	289
Cone of confidence	0,62°	0,49°
Spherical aperture	4,8°	3,9°
Center of gravity	180/03	89/88

6 BENEFITS / CONCLUSION

Geotechnical data acquisition supported by computer vision overcomes difficulties of current practice. The computer vision system consists of a proprietary high resolution stereoscopic imaging system and a combination of interactive and automatic image processing strategies in two and three dimensions.

The images itself represent a *comprehensive documentation* of the rock mass not available in present practice. The image processing on the computer and the three-dimensional vision on the computer enables *indirect observation* of the rock mass with *no access constraints* and allows the collection of geotechnical data *without pressure of time*.

Two-dimensional structural maps are generated by interactive annotation of significant discontinuities. This is supported by switching into a stereoscopic vision mode that allows a 3d inspection of the rock mass exposure which supports the geotechnical assessment at ambiguous regions. Another support is the possibility of changing the observation scale rapidly by zooming the image. This altogether makes the *geotechnical assessment easier*.

Photogrammetric principles allow to derive *metric measurements in 3d* from the images in relation to the surroundings. With it, *discontinuity orientations* can be derived and, as it is an indirect observation system, at an *arbitrary number* of measurements.

Summarising, the computer vision system is a supplement for the current field work of the geologist. It improves the present geotechnical data acquisition process completed by measurement and analysis possibilities not existing so far.

The results can be processed in order to serve as input for numerical simulations, for 3d visualisations of the rock mass and for documentation purposes. It allows the computation of additional magnitudes describing the rock mass, like discontinuity roughness or surface roughness parameters.

This results in geotechnical data of a new quality and should lead to a new standard for geotechnical data acquisition.

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