LASER SCANNING TECHNOLOGY FOR ROCK ENGINEERING APPLICATIONS

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Abstract: In situ rock structure characterization and displacement monitoring are two important operations in the stability assessment of excavations in rock. However, collecting structural data is a time-consuming exercise while the installation of rock support and production constraints usually leave very little time to undertake extensive structural mapping. In addition, displacement measurements in underground and open excavations are usually restricted to the monitoring of a limited number of points within the rock mass or on the excavation surface. The use of laser scanners enables one to cope with practical constraints encountered in rock engineering since it quickly provides a realistic and permanent representation of excavation surfaces regardless of the lighting conditions. Therefore, laser scanners have the potential to be employed on a regular basis as an efficient and unique tool to record input data required for various rock engineering analyses. The paper presents a case study where the Imager 5003 laser scanner of Zoller+Fröhlich has been employed to record the geometry of a tunnel during and after its excavation. The main objective of the work was to assess the potential of the technique in quantifying accurately geometrical characteristics of geological structures and in deriving time lapse surface displacement maps of rock outcrops with a high spatial resolution. The developed field methodology and preliminary results are presented in the paper.

1. Introduction

Engineering works in rocks induce disturbances from the original state of equilibrium in which rock masses are found. The response of a particular rock mass to these disturbances is greatly influenced by its internal structure resulting from the occurrence of geological discontinuities with different preferential orientations. This response usually involves rock mass deformations that can be observed by recording the displacements of points located within the rock or on excavation surfaces. In practice, the monitoring of such displacements is of great interest as it allows for the understanding of the mechanisms through which rock masses react to excavation-induced perturbations and for predicting potential stability problems that may occur in the future. As a consequence, in situ characterization of the rock
mass structure and displacement monitoring are two important operations which are routinely carried out during rock engineering projects.

Nevertheless, appropriate characterization of the rock mass structure is a time-consuming exercise as a sufficient number of features have to be sampled to achieve a reliable description of rock mass fracturing. Moreover, production constraints and installation of rock support systems such as steel meshes or concrete linings usually leave very little time to undertake an extensive survey of geological structures. On the other hand, discontinuity surveying requires safe access to rock surfaces that can only be guaranteed if adequate support is installed beforehand. Displacement monitoring is a common practice that is used to track the evolution of the rock mass behaviour. However, this operation is traditionally achieved by measuring the displacement of a limited number of points. Displacement monitoring of points located within the rock mass requires the drilling of boreholes and the installation of specific equipment. The measurement of surface displacements is therefore more frequently performed in practice. In this case, arrays of object points have to be installed firmly anchored within the first centimetres behind the rock surface at different locations along the surface. In both cases, it is necessary to monitor a sufficient number of points to achieve a reliable interpretation of the actual rock mass behaviour.

The use of 3D laser scanners allows for effective management of the practical constraints encountered in rock engineering since it provides quickly a realistic and permanent representation of excavation surfaces that requires the installation of a reduced number of physical targets used only for data referencing purposes. This is of great importance in the study of inaccessible and potentially unstable surfaces which are thus mapped at any time from a safe location regardless of the lighting conditions. Because of the high spatial resolution of the data, these tools can also be used for topographical surveys and the documentation of excavation surfaces, which are two additional procedures carried out routinely throughout construction work. Finally, the direct collection of digital data results in speeding up processing work through the use of modern computer resources. Therefore, this technology has the potential to be employed on a regular basis as it can be used as an efficient tool to record data required for various routine rock engineering applications and analyses.

Figure 1: Imager 5003 laser scanner of Zoller+Fröhlich and overview of the excavated tunnel
A major issue when dealing with underground excavations is the scanning field overview of the equipment which greatly affects the effectiveness of the laser scanner. Among the numerous available laser scanning systems, the 3D-laser scanner Imager 5003 of Zoller+Fröhlich (Figure 1) was found to be particularly well adapted to such conditions ([1], [2]). The paper presents a case study where the Imager 5003 has been used to measure the characteristics of geological structures as well as the surface displacements in an experimental tunnel in the Mont Terri Rock Laboratory, Switzerland. Several experiments are currently undertaken in this laboratory to understand the behaviour of a rock formation (the Opalinus clay) that has been identified as a potential host for a radioactive nuclear waste repository. The excavation is a 5 m long, 3.8 m diameter circular tunnel (Figure 1) that was extended in 7 steps with pauses for measurements and laser scanning. Figure 2 shows different views of the point cloud that resulted from the surveying of the tunnel at the end of its excavation. The main objective of the work was to assess the potential of the technique in quantifying accurately geometrical characteristics of geological structures and in deriving time lapse surface displacement maps of rock surfaces with a high spatial resolution. The developed field methodology and preliminary results are discussed in the paper.

![Figure 2: Point cloud representing the final geometry of the tunnel: outside view of the tunnel (left) and inside view of the tunnel (right)](image)

2. Laser Scanner “Imager 5003” of Zoller+Fröhlich

Several issues have to be considered when selecting the most appropriate laser scanner for a specific application. Important considerations include the required accuracy, the scene geometry, the range interval, the time available for scanning (i.e. scanning performance) and the minimum point density. In most cases, these requirements have to be placed in order by a project-specific hierarchy. The range interval is often the first criterion. Owing to the final dimensions of the excavation, the maximum range did not exceed more than 10 m during the construction of the experimental tunnel. Frequently, accuracy is the second criterion and the determination of this accuracy is dependent on the type of application. In this project, laser scanning was employed for several applications, which encompassed displacement monitoring and rock mass characterization. A higher degree of accuracy was required for the monitoring of displacements than for the characterization of the rock mass. However, the characterization of geological structures necessitates a point density that allows for the recognition of all salient features. Finally, the scanning performance is of great importance as the time available for in situ measurements is usually restricted. Throughout the field
investigations, the time allotted to laser scanning (including all necessary surveying work) was limited to two hours.

Given these requirements, the “Imager 5003” laser scanner of Zoller+Fröhlich was identified as particularly well adapted to applications in underground excavations as a full 360° view (i.e. vertical and horizontal) can be obtained in one scan. The scanner is based on a deflecting technique where the laser beam is deflected by a mirror which rotates around two axes (a horizontal axis and a vertical axis). For this reason, this laser scanner is called a panoramic scanner. The distance measurement system is based on the phase-shift principle which limits the maximum range to a distance of about 50 m. The combination of the high-speed rotations of the mirror and the fast detection of distances by using the phase-shift principle results in a high performance laser scanner with a scanning rate up to 625,000 points per second. Therefore, the minimum angle increment is 0.02°, which means a point spacing up to 3 mm in a distance of 10 m. The accuracy for single points and derived objects is less than 1 cm within the specified range of 10 m ([1], [3]). Further investigations and results regarding performance, accuracy and instrumental errors of the laser scanner “Imager 5003” can be found in [1] and [3].

3. Referencing

A major concern when measuring displacement data is the installation of an appropriate and stable reference system. This reference frame is defined by some reference points, which are fixed in regions that are not influenced by the excavation of the tunnel during the observation period. Based on previous displacement measurements (convergence measurements) made at the Mont Terri laboratory, the zones which are not influenced by the excavation of the tunnel were identified. Four control points (1, 2, 3, 4) defining a local reference frame were then installed in these regions. The left part of Figure 3 illustrates the location of the control points with respect to the location of the tunnel. Displacement monitoring was carried out using this local reference system. This procedure is necessary for calculating absolute displacements (see section 5) with a higher degree of accuracy. Furthermore, it facilitates the interpretation of the displacement data as it allows the alignment of one horizontal coordinate axis with the tunnel axis (axis Y, Figure 3).

Figure 3: Location of the experimental tunnel, the reference points and the arrays of object points (left), configuration of the object point arrays normal to the tunnel axis (right)
Five arrays (100, 200, 300, 400, 500) of object points were installed during and after the
tunnel excavation to assess the performance of displacement monitoring. The configuration of
the first four arrays normal to the tunnel axis is illustrated in the right part of Figure 3. Each
array has been oriented so that it is aligned with the assumed directions of the principal
stresses as it was expected that the largest displacements related to elastic response of the rock
mass to the excavation would be aligned with the direction of the major principal stress ($\sigma_1$).
Object points were installed every 45° to cover uniformly each investigated tunnel cross-
section. For practical reasons no object point was installed in the tunnel floor.

Bolts were utilized for both the reference points and the object points. These bolts were fixed
in concrete and rock using mechanical anchors. Finally, additional points (1000, 1001)
belonging to the surveying network of the Mont Terri laboratory were included to transform
the local coordinates into the reference frame of the laboratory (Swiss Projection System)
because the characterization of rock mass structure has to be performed with respect to a
north-orientated reference system.

4. Rock Mass Structure Characterization

Rock masses are traditionally considered as being constituted of intact rock intersected by
geological discontinuities forming the rock mass structure. As a consequence, understanding
the mechanical behaviour of rock masses requires an appropriate knowledge of the properties
of these discontinuities such as their orientation, size, aperture, surface conditions (roughness
and alteration) and frequency. The description of geological structures from rock exposures is
traditionally achieved using a compass, an inclinometer and a measuring tape. The data are
recorded on a notebook and the rock faces are then photographed with a camera for
documentation purposes. When a rigorous quantitative description of the rock mass structure
is needed, all relevant properties of the discontinuities intersecting a tape placed along the
rock surface are systematically measured. However, this method, known as the scanline
mapping method, has several drawbacks since it is time-consuming and cannot be applied to
physically inaccessible or unsafe areas and after installation of a lining support such as a
concrete liner. Furthermore, it only provides a linear sampling of a 3D domain resulting in
important biases in the collected datasets. Systematic mapping of the discontinuities
intersecting a rock surface area tends to reduce biases inherent in the sampling orientation,
while increasing significantly the amount of recorded discontinuities. This results in more
representative and accurate values of rock mass structure properties. Surface mapping
techniques based on 3D surface models constructed from pairs of digital photographs have
therefore been suggested to alleviate these practical difficulties (e.g. [4]). Nevertheless,
several constraints and difficulties are related to the use of photogrammetry since it is
necessary to ensure a good multi-view coverage of the excavation, to establish an appropriate
spatial distribution of ground control points, etc. Furthermore, the quality of the images is also
directly dependent on lighting conditions. Consequently, the laser scanning surveying method
seems to be a most powerful technology in the creation of 3D digital images of underground
rock surfaces since it quickly provides a great amount of 3D coordinates of points describing
the investigated surface in addition to reflectivity values to characterize these points.

Recent studies have focused on the measurement of the orientation and the roughness of
geological discontinuities from rock exposure surfaces as modelled from laser point clouds
(e.g. [2], [5]). It has been shown that good agreements between manual on-site measurements
and the results from modelled surfaces can be achieved provided that the density of the point
cloud is sufficiently high ([5]). It is however necessary to find an appropriate point density
value that will allow the recognition and the characterization of discontinuities while keeping the acquisition and processing time to a reasonable level. This value depends on the scale of the features to be recognized in the scene and on computational capabilities. It is therefore suggested to scan the rock surface several times at varying resolutions and distances before starting to systematically acquire and analyse laser scanning data.

Figure 2 shows the point cloud resulting from the scanning of the tunnel which is found to be intersected by several geological discontinuities. The left part of Figure 4 is a close-up of the point cloud illustrating one of these discontinuities in the upper part of the tunnel face. In this example, the average point spacing of the point cloud is about 5 mm. Comparing the image generated by the laser scanner with a digital image representing the same area (Figure 4, right), it can be seen that in this case the density of the point cloud is sufficient to produce a realistic rendering of the surface allowing the identification of geological features of interest.

Figure 4 also shows points that were selected to define and locate the discontinuity plane. The orientation of the discontinuity was then determined by calculating the orientation of the best-fit plane minimising the mean square distance to all selected points. Dip values of 50° and 46°, and dip direction values of 146° and 156° were obtained through the analysis of the point cloud and on-site manual measurement respectively. The measurements based on the laser point cloud are actually more representative of the overall orientation of the structure since manual measurements using a compass are directly influenced by local variations of the surface morphology. The geometry of these variations which correspond to the large-scale roughness of the discontinuity surface can be quantified easily using the distance between the best-fit plane and the selected points. Finally, the trace length (i.e. the length of the linear feature resulting from the intersection between the rock face and the discontinuity) is quantified by measuring the distance between two points selected on both extremities of the trace. By repeating this process with other discontinuities visible in the image it is possible to produce a database that can be further utilized to characterize and model the structure and the behaviour of the rock mass around the excavation. It is worth mentioning that this application does not require a high level of accuracy since the size of the features that require characterization is much larger than the mean distance between two neighbouring points in the point cloud.

5. Displacement Monitoring

5.1. Introduction

Displacement monitoring plays an important role in the identification of potential stability problems. In practice, displacements occurring at a particular location on the rock surface can result from the superposition of several processes such as elastic deformations and fracture generation due to the redistribution of the stresses around the excavation or movements along pre-existing discontinuities. Displacements can be measured either in a relative or in an
absolute way. Relative measurements are based on the distance between a pair of object points (e.g. convergence measurements). These measurements are relatively simple to carry out using extensometers providing an accuracy of less than 1 mm ([6]). Unfortunately, distance variations between points located in different areas around the excavation are difficult to interpret since it gives no information about the actual displacement orientation and magnitude of each point. As a consequence, the different mechanisms contributing locally to the displacement of the excavation surface cannot be identified. This type of investigation is however possible if the coordinates of object points are surveyed at different times with respect to a local or global reference system. An accuracy of less than 1 mm can also be achieved provided that an automated total station is utilized. Crucial issues associated with this monitoring method include the definition of a stable reference frame and the identification of appropriate reference points (see section 3). Besides the characterization of geological structures, laser scanning technology also has the potential to be used in the monitoring of excavation surface displacements. However, this innovative application of laser scanning calls for the development and the validation of methodologies for the acquisition, the processing and the analysis of data point clouds describing the same rock surface at different times.

Preliminary work aiming to investigate the applicability of the method in deriving absolute and relative displacements of the walls of the experimental tunnel during and after its construction is presented in this section. Total station surveying of a limited number of object points or targets installed on the tunnel surface was first carried out to assess the accuracy of utilizing the laser scanner as an alternative for the measurement of absolute displacements. The main focus during the excavation of the experimental tunnel was the identification of zones in the rock mass where the development of fractures sub-parallel to the surface is occurring. It is assumed that the propagation and the opening of such fractures produce local displacements of the surface towards the inside of the tunnel. The detection of these zones requires the construction of maps showing the distribution of the displacements along the rock surface. Such maps were derived from the comparison of different scans of the excavation taken at different stages of its construction. Subtracting different scans of the same surface is in reality a relative measurement of the displacements which allows for the identification and the quantification of local variations in the volume of the excavation.

5.2. Object Points

The object points of the arrays (Figure 3) were mounted with prisms and were surveyed after each excavation step using an automated total station (TCA 1100 of Leica Geosystems). The combination of this total station with the setup described in section 3 allowed achieving an accuracy of less than 1 mm. All prisms were surveyed in two faces and in several sets. The free station of the total station was defined by surveying all four reference points (Figure 3). The calculation of 3D coordinates of the object points was done in an adjustment. The achieved accuracy was less than 0.3 mm. The first measurement of the object points was used as an initial or reference measurement. Displacements that occurred between the initial and the i-th measurement session \((\Delta x_i, \Delta y_i, \Delta z_i)\) were calculated by subtracting the coordinates of session \(i\) \((x_i, y_i, z_i)\) from the initial coordinates of session 0 \((x_0, y_0, z_0)\). The resulting accuracy of the derived displacements of the object points in each coordinate direction \((\Delta x, \Delta y, \Delta z)\) was quantified as less than 0.5 mm. Therefore, the accuracy of 3D displacements for each point was calculated to less than 1 mm.
The object points can also be defined by spheres (instead of prisms) mounted on the bolts installed (Figure 1). Spheres are well adapted for laser scanning because of their attractive properties regarding visibility and deriving centre points. The diameter and the evenness of the surface of these spheres were calibrated previously. Each sphere was scanned and, based on the resulting point cloud, the coordinates of the centre point of the spheres were derived. These centre points were then estimated in an adjustment. This approach results in an accuracy of less than 3 mm ([3]). In addition, the centre points have to be referred back to the local reference frame. Nevertheless, it is not always possible in practice to scan both the reference points and the object points at the same time. Firstly, the distances from the laser scanner to the reference points are usually too long to achieve the required accuracy. Secondly, the reference points are not always visible from the position of the laser scanner. Looking at Figure 3, it can be seen that these two problems were encountered during the surveying work in the laboratory, which required positioning the laser scanner inside the experimental tunnel. To solve these problems, intermediate reference points were set up temporarily close to the laser scanner using tripods. These reference points were also surveyed with the total station and were included in the local reference frame. Then, the location of the laser scanner was determined by positioning the temporary reference points with respect to the permanent set of reference points (1, 2, 3 and 4, Figure 3). The accuracy of the position of the laser scanner lies within 3 mm. The resulting accuracy of the derived displacements in each coordinate direction ($\Delta x$, $\Delta y$, $\Delta z$) could be specified with less than 5 mm. Consequently, the accuracy of 3D displacements for each point was calculated to less than 9 mm.

The displacements of 28 object points were monitored during the excavation of the experimental tunnel. The displacements of object point 4 of the first object array (Figure 3) are used as an example in the discussion of the monitoring results (Table 1).

<table>
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<th>Laser Scanner (LS)</th>
<th>Difference (LS – TS)</th>
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<td>3D</td>
<td>dY dX dZ</td>
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</table>

Table 1: Displacements (in mm) of point 4 of the first object array provided by total station and laser scanner as well as differences between total station and laser scanner results.

The expected accuracy of displacement data has been discussed previously. Total station surveying was used to provide a high degree of accuracy of less than 1 mm for both coordinate differences and 3D point differences while the expected accuracy of the laser scanning was 5 mm for the coordinate differences and 9 mm for the 3D point differences. The results of total station surveying presented in the left part of Table 1 show that the displacements for that point are relatively small as they lie within +/- 3 mm. Looking at these results, one can also see that larger displacements of +/- 7mm were obtained with laser
scanning. Considering the displacements measured with the total station as nominal displacements, differences between laser scanning and total station can be calculated and appraised. The results are listed in the right part of the table. One can observe that most differences lie within the accuracy of laser scanning measurements.

5.3. Surface

Understanding the actual rock mass behaviour can be greatly improved if the distribution of the displacements along the excavation surface is investigated instead of considering the displacements of a few discrete points. For that purpose, point clouds representing surfaces scanned after different phases of the excavation can be used. Several software packages allow for the 3D comparisons of point clouds and surfaces. In this case study, the software Geomagic by Raindrop Geomagic Inc. was used. The procedure that was followed in the generation of time-lapse displacement maps is outlined below. Pre-processing of the point clouds consists of two operations. First, points representing blunders have to be detected and deleted automatically or manually. Then, the noise is reduced by means of a filtering process. This is an essential step as the noise due to the natural limits of scanning affects greatly the quality of the point cloud by making sharp edges dull and making smooth surfaces rough. The result is a more uniform arrangement of points. Subsequently, the processing entails the conversion of the initial or reference point cloud into a surface model that consists of small triangles (Triangular Irregular Network–TIN). This surface model represents the reference object that can be further processed if required (e.g. by deleting non-contiguous intersecting triangles, filling holes or surface smoothing). Finally, the residuals of a test object described by a point cloud or a TIN representing the same region at a different time can be computed by comparing it to the reference object. This operation is possible only if the test object has been transformed previously into the same reference system as the reference object.

The example in Figure 5 shows the displacement maps produced for the upper part of the final tunnel face. The displacements calculated were based on measurements carried out after the end of the excavation (11th March–session 0), two days later (13th March–session 1) and six days later (17th March–session 2). A TIN was created using the laser scanner data of session 0 and represents the reference object. The residuals of the point clouds for sessions 1 and 2 were then computed with respect to the reference object. Figure 5 shows that the displacements that occurred between sessions 0 and 2 did not exceed 1 cm. Therefore, they are of the same order of magnitude as the accuracy of the laser scanning for the determination of the object point displacements (section 5.2). However, changes in the concentration of

Figure 5: Surface displacements (in m) obtained by comparing the point clouds acquired during sessions 1 (left) and 2 (right) with the surface model corresponding to session 0
areas characterized by displacements greater than +/- 2 mm suggest that displacements increased with time and with distance from the centre of the tunnel face.

6. Conclusion

Laser scanning is considered a promising technique in the field of rock engineering since it has the potential to be used for the collection of data required for several routine tasks. However, it is essential to select the most appropriate laser scanner according to project-specific constraints such as range, excavation geometry, time available for scanning as well as point accuracy and point density. The latter two constraints depend on the objectives of the survey. The Imager 5003 of Zoller+Fröhlich was used in an experimental tunnel in the Mont Terri Rock Laboratory for characterization of geological discontinuities and displacement monitoring. This scanner was found to be particularly well suited for the rock mass characterization in underground excavations while yielding an accuracy of less than 1 cm in the determination of the displacement of object points. Nevertheless, preliminary results suggested that displacement maps with a higher degree of accuracy can be produced by taking advantage of the large quantity of spatial data provided by the laser scanner. The construction of accurate displacement maps would thereby greatly improve the understanding of the rock mass behaviour. Crucial issues identified for this application included referencing to a stable reference system, coordinate transformation, noise reduction and smoothing of point clouds.

Regarding rock mass characterization, efforts should be made to automate the recognition of discontinuities so that the time required for data analysis can be decreased significantly. Future work will focus on the development and comparison of processing algorithms in order to improve the accuracy of the displacement mapping. The resulting maps will be further compared to the results of other field investigation methods and to numerical models simulating the rock mass behaviour around the tunnel. The aim of this study will be to better assess the capability of laser scanning in monitoring geomechanical processes occurring in rocks.

References:


