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i²MON – Development of an integrated monitoring system for the detection of ground and surface displacements caused by coal mining

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Abstract

i²MON is an European Union Research Fund for Coal and Steel funded research project with a duration of four years, which started in July 2018 and will end in 2022. The project joins highly recognised research institutions and companies to develop an integrated monitoring service for the identification and assessment of ground and slope movements related to coal mining. The service comprises innovative monitoring tools including terrestrial laser and radar technology, space and airborne remote sensing, predictive modelling, and data management via a web-based monitoring platform with the aim to support the mining industry with a key evaluation and decision-making instrument. This paper details a specific sub-task of the project in order to extend existing point-related sensor information (e.g. low-cost GPS) with areal sensors with focus on long-range laser scanning. For this, the integration of the scanner data in a sensor network (data acquisition, data transfer) and appropriate data processing methods are analysed and implemented. This includes integration of 3D deformation analysis methods with proper georeferencing of the complete sensor network and sophisticated stochastic error modelling accounting relevant measurement influences and minimise false alarms. In addition to measuring key geometrical features by scanning, parameters for a suitable simulation of slope stability have to be derived. Thus, not only three-dimensional, but multidimensional information per observation point will be generated. For the potential users, this results in added value compared to normal monitoring of movements and offers an integrated tool for risk minimisation. Integrating appropriate monitoring into any design process allows for controlling all-important phenomena during the complete lifetime of the mine including the post-closure phase.

Keywords: *deformation analysis, online monitoring, laser scanning, geological mapping, slope stability, stability modelling*

1 Introduction

The definition of monitoring is widely used in literature and interpreted in different ways by different scientific disciplines. Monitoring is basically the detection of all types of systematic changes in the object under observation (Heunecke et al. 2013). In order to be able to detect geometric changes significantly, a monitoring program must be individually adapted to the object observed. Here it has to be considered that the object has to be spatially discretised according to the expected displacements. In addition to this restriction, temporal discretisation must also be taken into account. This means that no significant shifts may occur during a measurement epoch and that no movements may remain unobserved due to the interval between two measurements. Due to the increasing selection of sensors, these disadvantages can be reduced (Schröder 2018). According to Heunecke et al. (2013), the factors of spatial and temporal discretisation can be classified as integrity characteristics of qualitative monitoring (Figure 1). For proper monitoring, two further characteristics have to be added: one is the accuracy parameters, so that with the help of the sensors installed, corresponding displacements can be significantly detected; the second is the reliability parameters.

In detail, this means that the necessary information is available at a required point in time, thus enabling time-critical recommendations for immediate action.

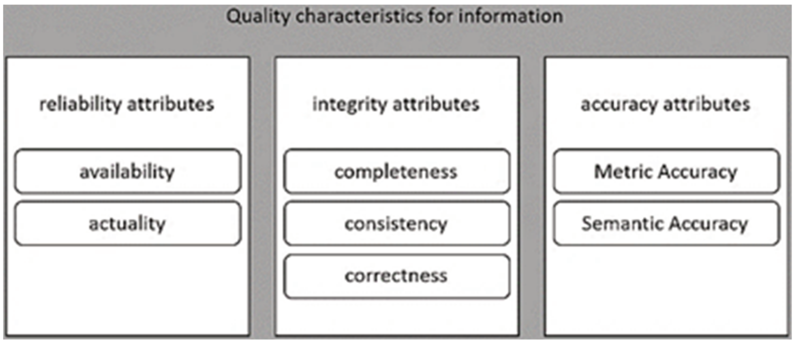

Figure 1 Quality characteristics for information (Heunecke et al. 2013)

With cost-effective sensor technology, more measuring points can be installed or the development of area-based measuring systems such as the laser scanner can capture an object in an extended grid, which fundamentally simplifies the question of the spatial discretisation of a measuring object. The modern development of communication devices and data management nowadays allow a high degree of automation, so that continuous measurements are possible, which is why a temporal discretisation also becomes uncritical. These developments lead to an optimisation regarding the compliance of all necessary criteria for information processing within a monitoring network.

2 Slope monitoring with laser scanners

2.1 General introduction

With terrestrial laser scanning, it is possible to scan an object without contact and with a high point density. The company RIEGL, from Austria, offers for the surveying in open cast mining areas the model VZ-2000i among others, which was especially designed for use at long distances and in mining (Figure 2). In comparison to competing products, this laser scanner offers hardware that is optimised in terms of accuracy, integrity and reliability, and is therefore excellently suited for use within a monitoring system.

Figure 2 RIEGL laser scanner for surveying an opencast mine (RIEGL 2019a)

The aim of the i2MON project is to detect displacements induced by mining activities underground and related to surface open pit operations. Different sensors are suitable for different environments. The laser scanner is to be used for applications where slopes and embankments can be observed above ground. Large-scale infrastructure installations, including embankments, have so far mainly been observed using tachymetry. For this purpose, an object is equipped with prisms and thus spatially discretised. This means that movements can only be derived from these individual points and that information is interpolated between these points. In order to be able to use the prisms effectively, existing knowledge about the possible displacements must be integrated into the conceptual design. For instance, using the example of a dam, 40 individual points are used for deformation analysis and are illustrated in Figure 3. This procedure can be applied analogously to the use of global navigation satellite system (GNSS) sensors.

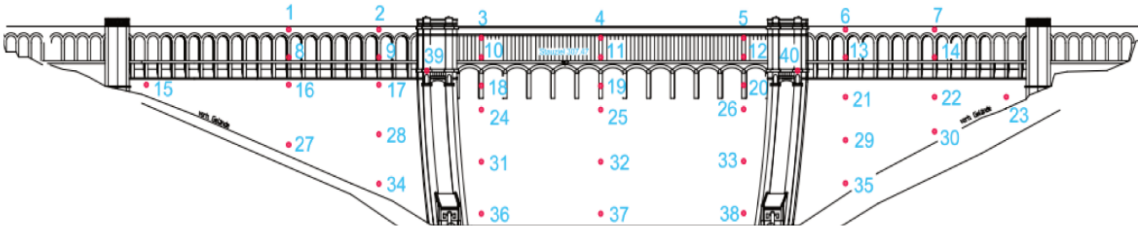

Figure 3 **Spatial discretisation of a dam using prisms for tachymetry (Müller et al. 2016)**

However, from a safety and logistical perspective, embankments are increasingly difficult to reach. Non-contact measurement technology has the advantage that the object to be observed does not have to be entered directly and no prisms or GNSS antenna have to be attached. The measurement technology of a laser scanner is particularly suitable here. In addition, an object is scanned area-wide by a laser scan and the question of spatial discretisation is of minor priority. In order to set up a monitoring system, no prior knowledge of the expected movement characteristics is required. In Figure 4, the survey of the dam can be seen with the help of a laser scanner and the area coverage with measured values is clearly visible. The colour of the image depends on the intensity values of the individual laser beams.

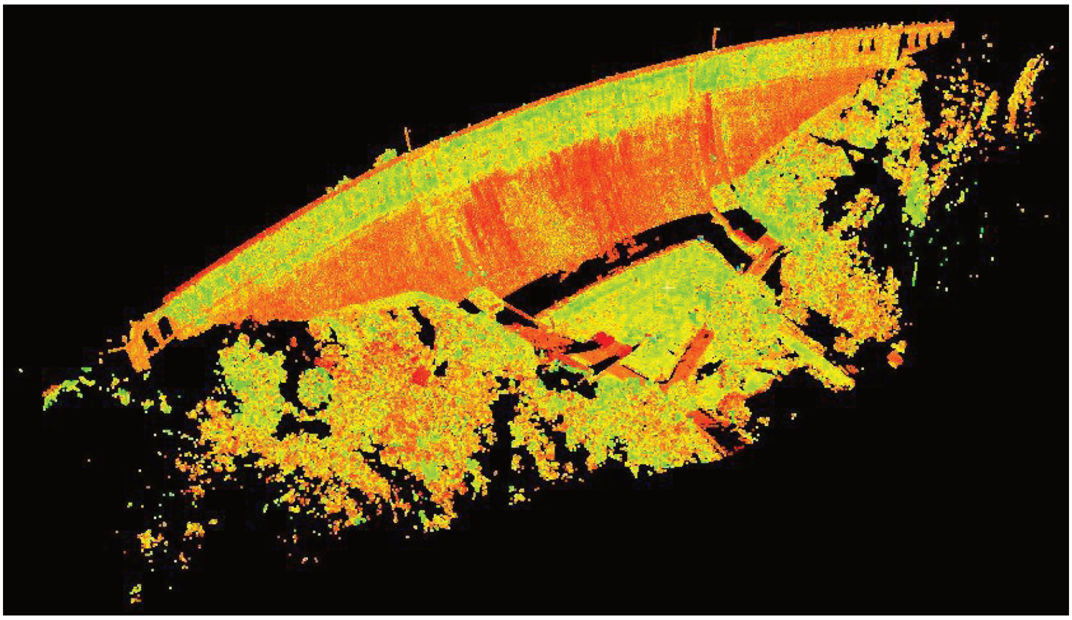

Figure 4 **Point cloud of a dam using the intensities of the reflected laser beams for colouring**

Most commercially available devices have a range that is within a few hundred metres, so that the scanner itself would have to be placed in the still endangered area. With the VZ-2000i, RIEGL offers a measuring device that has a range of up to 2,500 m. Thus, the scanner can be stably installed outside the sphere of influence. For this reason, this hardware is particularly suitable for use in an early warning system to prevent hazards caused by mining-induced landslides.

The RIEGL VZ-2000i used in the i2MON project stands for all terrestrial long-range laser scanners with similar technical equipment. We will classify those long-range laser scanners in the following subsections and thus demonstrate their suitability for this project.

2.2 System implementation

2.2.1 *Accuracy and integrity*

The VZ-2000i is able to measure objects with a very high accuracy (6 mm @ 100 m) up to a range of 2,500 m contactless by digitising the reflected echo signals and following waveform analysis. Tachymetry, as well as laser scanning and their statistical evaluation, differ fundamentally. In tachymetry, individual points are acquired and the accuracy of a single point measurement can be determined using the error propagation method. The 3D accuracy of a single point measurement can be derived from the values for the distance measurement accuracy (0.6 mm + 1 ppm) and the bearing (0.15 mgon). Furthermore, single points can be clearly identified and can be measured redundantly within a network measurement. This allows millimetre accuracy to be achieved for a single point over a distance of a few kilometres. Based on these values, measurement programs can be efficiently planned in advance. In the case of laser scanning, the extraction of accuracy metrics is more difficult. The manufacturer specifies an accuracy of 6 mm over a distance of 100 m. This specification refers to a RIEGL test distance and cannot be transferred linearly to higher distances. It is problematic that no single points are measured and that accuracy specifications can only be based on geometrically derivable reference numbers. No single points can be measured redundantly. Since laser scanning is a reflectorless measurement, the accuracy is additionally dependent on the angle of incidence and the surface condition. Experience shows that even in the range of 2,500 m, accuracies of a few centimetres can be achieved with the laser scanner. An extensive assessment is currently being carried out by the authors. It can be stated that the high accuracies of tachymetry and single point measurement cannot be achieved. However, a spatially high-resolution point grid is obtained, which provides additional information compared to the single point measurement and with reasonable accuracy.

The laser distance measurement is performed by high-precision pulse-time measurement. The evaluation with the help of waveform analysis is subject to patent protection by RIEGL and is therefore exclusively available on the market. Not a special feature of geodetic monitoring, but important for use in public spaces, is the fact that the laser is specified according to Class 1 and is therefore eye-safe. RIEGL also provides a special waveform data output. In addition to the measurement results from the online analysis of the waveforms, waveforms of the target echoes can also be digitally recorded and output. Especially for research projects, these digitally recorded data of complex multi-target situations provide an excellent basis for scientific analysis and derivation of additional attributes. Another feature supports reliability as well as accuracy and integrity. In order to be able to detect targets at long distances at high laser pulse rates up to 1,200 kHz and thus to adapt the temporal discretisation during the observation of an object in the best possible way to the behaviour of the object, the device uses the so-called multiple time around processing (MTA) technology known from radar technology. This enables precise and clear distance measurements to be made using pulse propagation time measurement, even if several emitted laser pulses with several reflected target echoes of the laser pulses are simultaneously in the air. With the help of special software developed for this purpose, RiMTA TLS (RIEGL 2019b), the specifically modulated laser pulses are automatically reassigned to the correct target echoes. This procedure is protected by the Austrian patent.

2.2.2 *Reliability*

In addition to the procedure described above for improving the temporal discretisation, the VZ-2000i also includes many other features that enhance reliability to a high degree. Regarding the integration within a monitoring system, interfaces are offered via RiVLIB (RIEGL 2019c), which makes it possible to control and integrate the scanner via external software, and via the Python programming language (Figure 5). The functionality of the scanner can thus be considerably extended. The scanner can be operated remotely via cloud connectivity and allows a data stream (Figure 6), so that the scanner can be operated and results can be presented via custom developed software (e.g. DMT SAFEGUARD). Reliability is also supported by the compact and robust design in a dustproof and splash-proof housing (IP64). All these features make the VZ-2000i a versatile measuring system that can be used to achieve the project goal.

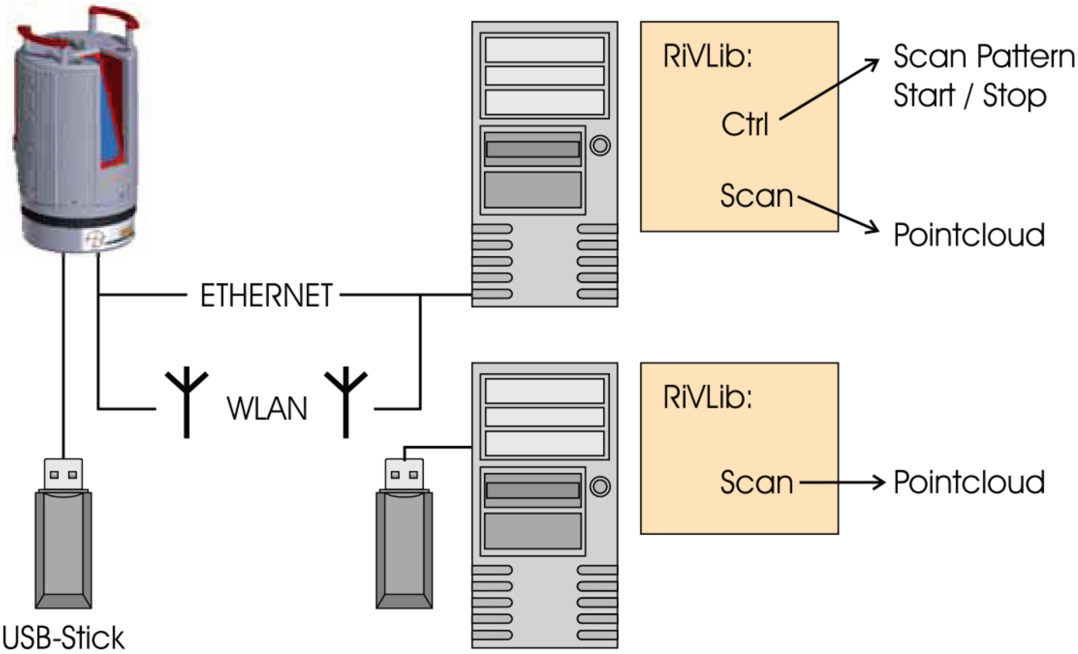

Figure 5 RIEGL VZ-2000i for surveying an opencast mine (RIEGL 2019e)

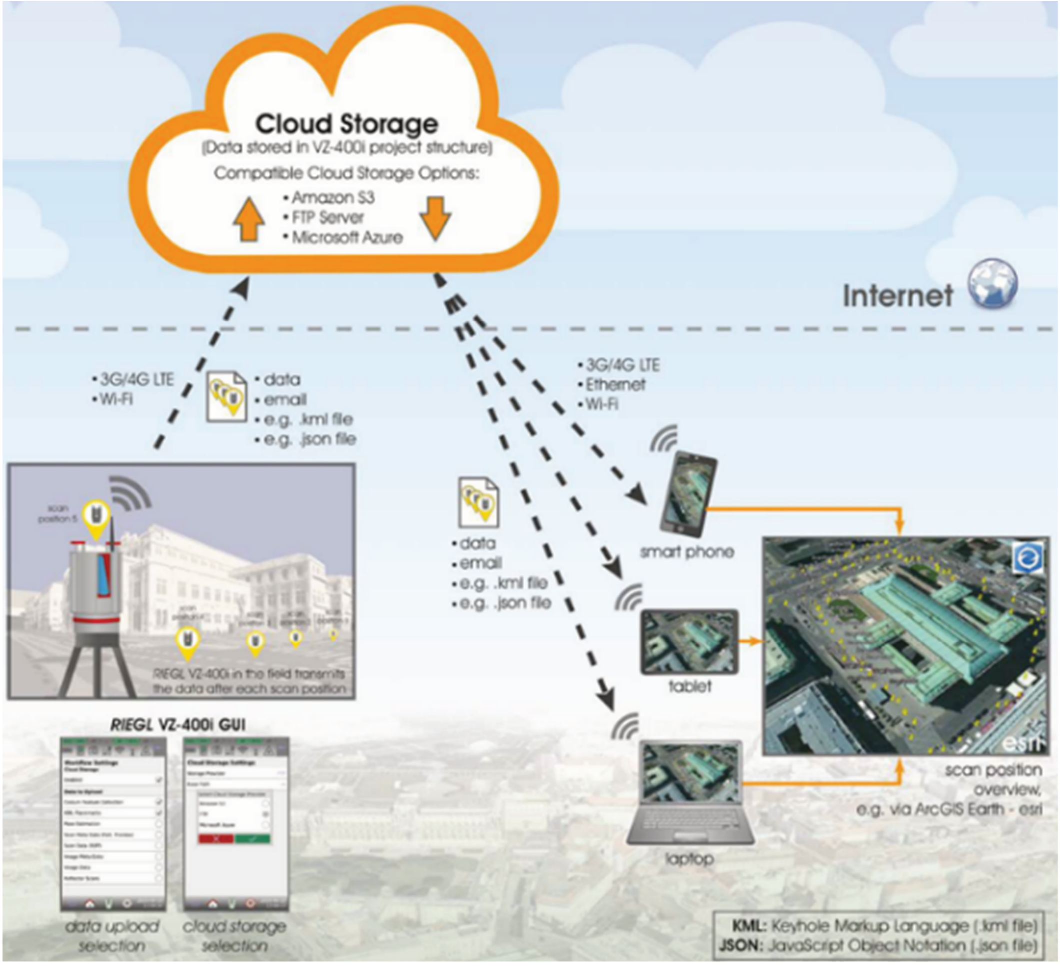

Figure 6 RIEGL VZ-2000i for surveying an opencast mine (RIEGL 2019d)

2.2.3 Data visualisation

In addition to the requirements for the sensor technology itself, the general conditions for data integration, data storage and, finally, visualisation must also be fulfilled. System and data integration is a main challenge of the digital age and specifically for what is called ‘Industry 4.0’—a collective term embracing a number of contemporary automation, automatic and intelligent data exchange and fully digitised manufacturing technologies (Zimmermann et al. 2019).

In the project, the web-based software product DMT SAFEGAURD (Figure 7), developed by DMT, will be used and further developed in a specific manner. DMT SAFEGUARD combines all the requirements for a monitoring system as explained in section 1. It offers the possibility of centrally storing a large amount of data and making it available to the user on a web-based system. Thus it is possible for every user to operate their project platform-independently from any workstation that has a connection to the internet. DMT SAFEGUARD is thus a modern, comprehensive database-driven software solution for monitoring tasks in geotechnics, geodesy, hydrogeology and geophysics.

DMT SAFEGUARD processes all types of sensor data in a single monitoring system, enabling the potential hazard area to be permanently monitored as part of professional risk management. An intelligent early warning, alarm and reporting system permits the most effective reactions, while long-term monitoring enables the early detection of potentially dangerous trends for targeted hazard prevention. The special feature of this solution lies in the manufacturer-independent hardware connection of ‘slow’ geotechnical measurement series to ‘fast’ acoustic and video measurement series.

Also integrated is a document management system and a journal to preserve evidence of all measures and incidents. Depending on the stage of expansion, all measurement data and documents are consistently processed on the basis of a database, freely configurable messages and internet-based access to the system as part of a GIS application.

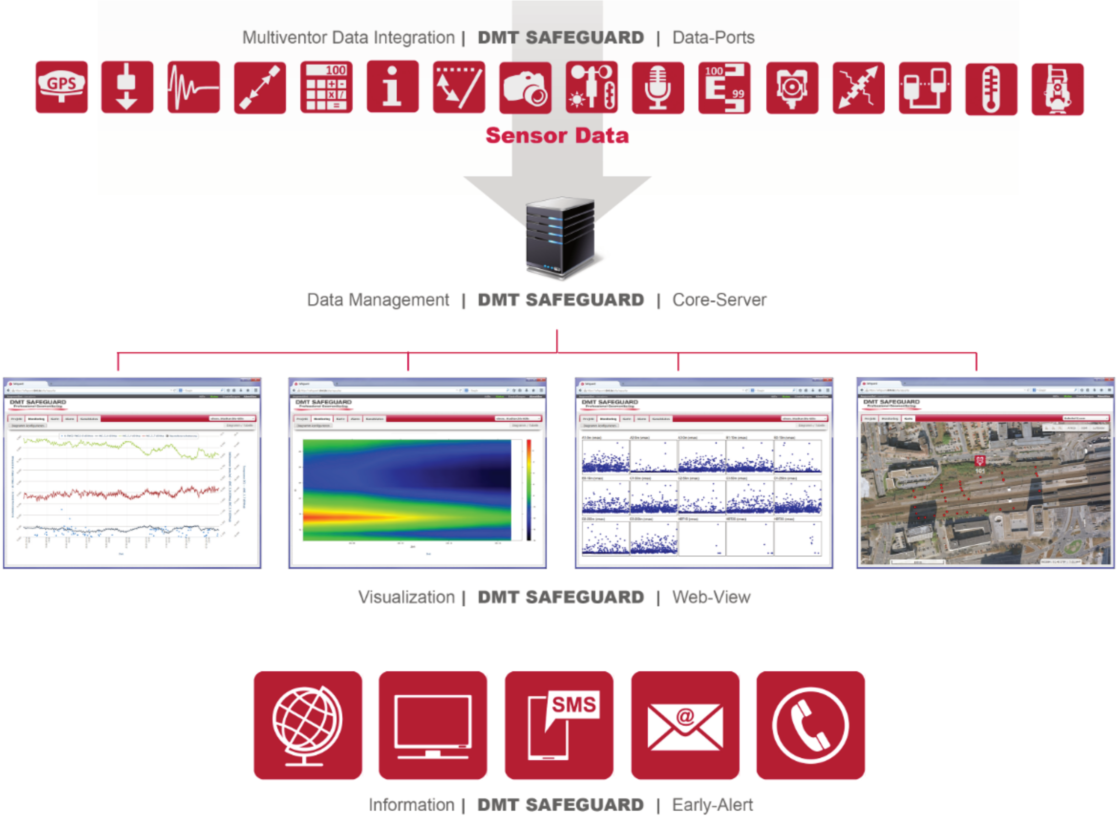

Figure 7 DMT SAFEGUARD service infrastructure

3 Derivation of geometric parameters

The problems and challenges by using 3D point clouds from terrestrial laser scanning (TLS) measurements for deformation analysis are well summarised in (Wunderlich et al. 2016). The following overview and methodologies for suitable deformation model for TLS observations stem from that article and have been further investigated at the University of Applied Sciences in Mainz.

In spite of increasing demand and application of TLS for areal deformation analysis in practice, the rigorous evaluation procedures are still under development and, in most cases, statistical tests of significance are missing. Thus, assessments often are based only on visual representations (e.g. heat maps) and straightforward comparison of deformations with stated thresholds. Moreover, a couple of strategies purely return one-dimensional deformations from the 3D point clouds of two epochs.

The main reason for the deficiencies comes from the fundamental problem of how to compare two point clouds. In contrast to the unambiguous investigation into the 3D coordinate change of a defined point between two epochs, for surfaces, various approaches with different prerequisites and algorithms are possible. Mukupa et al. (2016) and Mill (2016) distinguish three methods: point to point, point to surface and surface to surface. Ohlmann-Lauber & Schäfer (2011) suggested a differentiation into five categories.

3.1 Reducing systematical effects

Laser scanners, which operate in a measuring range from several hundred metres up to a few kilometres, are increasingly used for monitoring slopes. It is often assumed that the resulting point cloud from a scan project delivers an accuracy of a few millimetres. However, this works only when measurements are made under laboratory conditions and a single scan is viewed from a single scan position (Wujanz 2019). As soon as measurements are carried out in daily life (i.e. under the influence of wind, sun, humidity and temperature fluctuations) accuracy losses must be accepted. Influences on the time of flight of a laser beam can be modelled, but this can be done only at the position of the scanner itself or sometimes even at the object to be measured. Between both positions, assumptions must be made that deviate from reality and thus cause a deviation in the measurement result. When it comes to a multi-temporal comparison of different scans, georeferencing must also be taken into account. Georeferencing as well as atmospheric influences are time-dependent variables and are currently being discussed in science. In case of georeferencing, however, these problems are solved (Friedli et al. 2019).

For an automated monitoring system, these circumstances must be taken into account. The sensitivity and thus the significance level of a movement detection are influenced by both factors. In an experimental study by Friedli et al. (2019) it can be stated that the vertical refraction varies over the daily cycle and differences in the vertical angle of up to 10 mgon can occur (Figure 8). The maxima are reached at noon and minima at night.

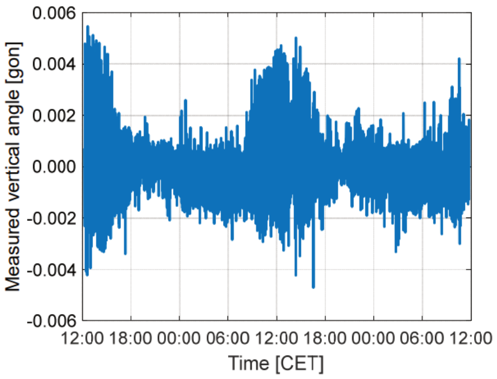

Figure 8 Variations of the measured vertical angle from TPS1 to T1 (Friedli et al. 2019)

According to Friedli et al. (2019), these inaccuracies due to environmental conditions lead to height changes of up to 30 cm at a distance of 2 km (Figure 9). Depending on the inclination of a slope, distance errors of up to 43 cm can be detected. Currently it is assumed that the vertical refraction has the most influence on the measurement results. A correction of the complete path of a laser beam by atmospheric data at the measuring position is currently not possible. Influences are not linear and cannot be generalised. Especially over long distances, water surfaces, vegetation or open rock can lead to a non-linear gradient. It is currently recommended to perform deformation measurements at periods of the day when the temperature gradient is low. This is mainly the case in the evening and night hours. According to the current state of science, however, this is an argument against a high temporal discretisation of a monitoring measurement series. In the future, ETH Zurich will follow a data-driven correction model that takes up the idea of local-scale parameters.

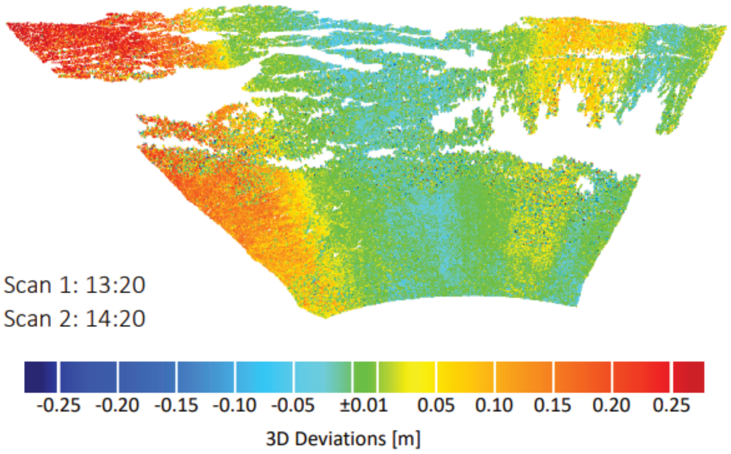

Figure 9 C2M comparison (see section 3.2.3) of two scan pairs acquired at noon (Friedli et al. 2019)

The project consortium within i²MON also works on this topic and current measurement series have already been made. The detailed evaluation of these data is still pending at the time of this paper's submission. Various test scenarios were developed and a series of measurements were carried out, for example across a river valley onto a rock face (Figure 10). The effects of atmospheric refraction are particularly noticeable here. In addition, three further test scenarios are currently being developed in which a reference geometry is measured with high precision and the effects are thus evaluated even better over a long series of measurements.

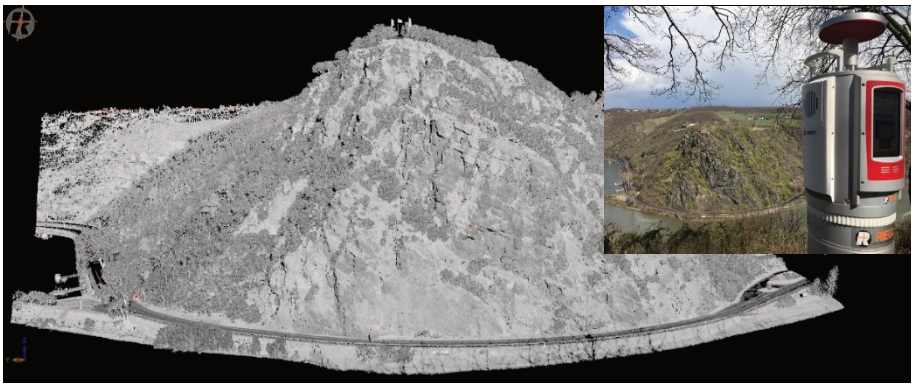

Figure 10 i²MON test scenario at river valley – point cloud and image of the setup

3.2 Data processing

3.2.1 Point based strategies

Very few point based strategies have won recognition of the scientific community. One of the few publications on the subject has been proposed by Little (2006) where coordinates respectively distances are compared to repeated observations. This approach is hence a vectorial comparison in relation to the scanner’s coordinate system. The reason why this strategy is not widespread can be justified by the fact that it is only applicable if the viewpoint of the scanner remains constant. If this prerequisite cannot be justified, the point sampling in object space notably differs, so that it is not possible to repeatedly observe discrete points which have been acquired in a previous epoch.

3.2.2 Point cloud based models

In point cloud based models, relationships between point clouds are established by using coordinate transformations. The most common algorithm of this kind of model is the Iterative Closest Point algorithm (ICP). Girardeau-Montaut et al. (2005) present three approaches for deformation monitoring. The key component of all methods is an octree structure (Samet 2006) where a point cloud is subdivided into several cubes of equal size. Operations are carried out within all cells which is very efficient in terms of computational demand. As a prerequisite, both point clouds must already be registered so that corresponding octree cells should contain data of the same area.

3.2.3 Surface based approaches

If the point clouds are modelled by building a surface consisting of point grids, the approach is surface based. Here, the corresponding points are either measured directly or they are interpolated. One of the first deformation models for point clouds was proposed in Cignoni et al. (1998). Their algorithm performs point to surface inspection, nowadays mostly referred to as cloud-to-mesh (C2M) or cloud-to-model if a comparison to a priori known shape is made. As a first step, a reference point cloud is triangulated while subsequent points are assigned to triangles based on which distances are computed. In a final step, points can be colourised based on their distance to the reference surface. This procedure is the most popular approach for generating colour-coded inspection maps and is hence implemented in nearly every commercially available point cloud processing software. A common method for deformation monitoring in earth sciences has been proposed in Lane et al. (2003). Therefore, two point clouds are converted into gridded digital elevation models (DEM) while a point-wise comparison is carried out. Schäfer et al. (2004) applied TLS on a hydropower station where a lock chamber has been surveyed at different water levels. Data has been acquired from one viewpoint in all epochs, while geometric changes have been derived as differences between interpolated grids based on the original point clouds. Hence, deformation can only be detected in one dimension, which was suitable for this case.

3.2.4 Geometry based methods

Geometry based methods are characterised by approximating analytical or free-form surfaces to the laser scans to reveal areal deformations. In many cases, these surfaces are built by geometric primitives based on planes or quadrics. Ioannidis et al. (2006) compared a point cloud of a cooling tower to an approximated hyperboloid of one sheet and to non-uniform rational B-spline (NURBS) model. Pesci et al. (2015) parameterise the four walls of a historical tower as planes and determine the vertical displacement of this tower by analysing the planes' inclinations. Although the investigations of Eling (2009) while monitoring a concrete dam have already been grouped as being point cloud based, they can also be considered as a geometry based method. Since the point cloud is reduced to reproducible points by a plane adjustment, analytical surfaces are used to increase the accuracy of the latter deformation analysis (Neuner et al. 2016). This example shows that the arrangement of the different deformation models listed in the beginning of the current section can be ambiguous in some cases.

3.2.5 Parameter based procedures

Parameter based procedures for deformation monitoring, as defined by Ohlmann-Lauber et al. (2016), are a special case of geometry based methods. Here, not the approximated analytical surface itself is of interest. Instead, the corresponding estimated parameters determine the deformation that is to be analysed. In some cases, these parameters' significance is tested similar to common point based deformation analyses (e.g. based on a total station). Holst (2015) mounted a TLS on a sub-reflector of a 100 m radio telescope in order to reveal gravity evoked variations of its focal length. The captured point clouds were then parameterised by a rotational paraboloid; the estimated focal length determines the areal deformation. Schneider (2006) applied a long-range laser scanner to monitor the bending line of a television tower. Therefore, the point cloud has been segmented by generating several slices of the conic tower. Each slice was approximated by a circle where the centre point was monitored over time.

4 Numerical modelling within the monitoring system

Today, ground control during mining works is usually assisted through numerical modelling. Prior to any mining works, the numerical model is based on available ground information and ideal ground conditions. At the beginning of any lining design, it is accepted that the information on ground conditions contains gaps. Furthermore, the simplification of some assumptions increases the uncertainty. A common approach to deal with potential risk is to perform a sensitivity analysis and risk assessment of selected parameters and, finally, to assume the most probable ground conditions, adjusted by various safety factors. Such an approach results, in most cases, in conservative lining design. However, two aspects usually remain insufficiently treated: the residual risk and the potential of design optimisation. Therefore, it is important to use tools for minimisation of the risk, and to include appropriate monitoring into any design process, allowing control of all-important phenomena not only during mining operations, but also during whole mine life.

As already described, within the integrative monitoring, not only the three-dimensional information of a slope movement shall be derived, but also conclusions about the cause as well as the future behaviour shall be made. In order to be able to make the right conclusions, it is essential to minimise artefacts through systematic error influences on laser scanning. For an initial feasibility study, we use the data from our test measurement across the river. In this case, we simulated a process chain in which a new tunnel was excavated under the measured rock.

If the onsite mapping gives reason for design model modification, the revised datasets for integration into numerical modelling are generated through a software routine. Moreover and after each survey cycle, the geometry of the model may be semi-automatically updated in order to analyse the impact of the in situ conditions on the lining stability and optimisation possibility. The current development is aimed on full automation of such updates as shown in Figure 11, where, for example, the changes in the assumed and existing location of the sandstone layer were introduced into the model.

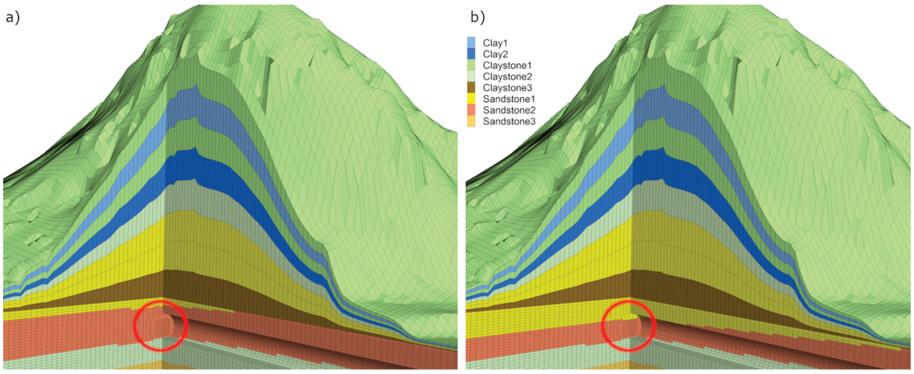

Figure 11 **Automation of the existing geological conditions for a tunnel excavated near the surface: (a) Initial idealised numerical model; (b) Updated numerical model based on the in situ measurements**

The continuous collection of new data makes it possible to extend an idealised numerical model with such important information as the existing overbreak and other as-built details (Figure 12). In that way, the reliability of the simulations increases and the impact of the mining operations may be better assessed. In that particular example, it was possible to identify risk areas on the surface, for which the monitoring measurements should be intensified for a specific excavation and lining scenario (Figure 13).

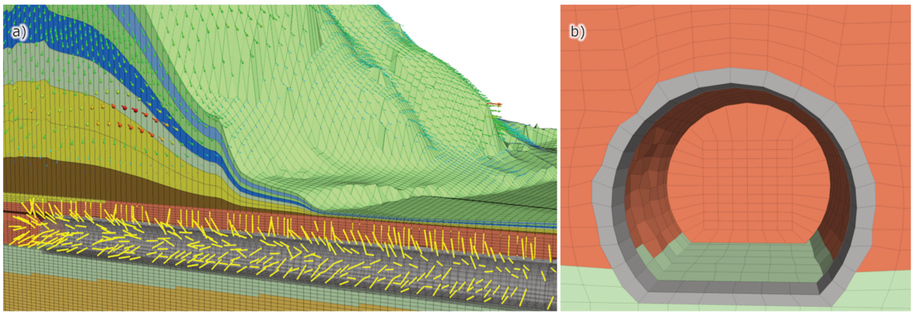

Figure 12 Example of automated correction of the model´s mesh during tunnel excavation: (a) Overview of the tunnel with position of installed mining bolts; (b) As-built liner after automated geometry correction based on wall measurements

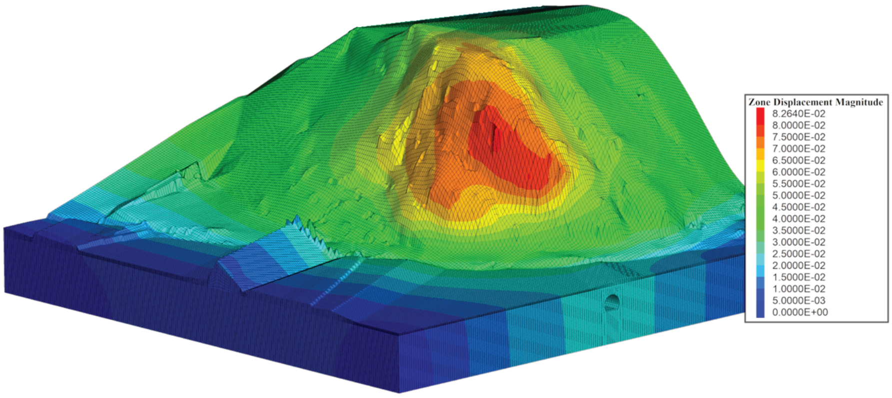

Figure 13 Identified risk areas on the surface based on the calculated ground movements for a specific excavation and lining scenario

5 Conclusion

The project started in 2018 and the first investigations, as well as tests, have shown a high potential for the use of a laser scanner within a spatial and time continuous monitoring system. The framework for the development of an integrated monitoring system is provided by the availability of hardware such as the RIEGL VZ-2000i or a software architecture within DMT SAFEGUARD.

The laser scanner will be integrated into an automated system so that research topics regarding the reliability, accuracy and integrity of 3D point clouds can be addressed. For this reason, in addition to the implementation of an integrated system, further basic research work has to be clarified within this project.

The current development is focussed on the implementation of the results from laser measurements into numerical models. Due to the large amount of data gained from surveys, it is necessary to automate the process of data integration. The current results show an improvement of the reliability of numerical models and provide a step forward in the automation of ground control. While the required components of logging and survey hardware, as well as the geomechanical modelling software, are readily available, the ground control software package shown is under development. The latter will also provide a full track on data collection and design history, and thus it will significantly increase project transparency.

The research work focusses on questions regarding the georeferencing, multi-temporal comparison of point clouds, and the update of numerical models, especially within open pit mines.

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