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Practical Aspects of Using Modern Laser Scanning Techniques for Measuring Mine Excavations

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Abstract: For more than a dozen or so years now, there has been growing interest in the use of modern laser scanning measurement methods in numerous mining operations engaged in underground excavation. However, the simple possession of a scanner does not guarantee satisfactory measurement results. This study sets out the results of scanning mine excavations in an active mine and describes the current guidelines on various aspects of the measurement process. These guidelines were developed on the basis of several hundred measurements carried out over the last dozen or so years.

This study also outlines the typical measurements errors observed over the course of many years. These errors, resulting partly from hardware limitations and partly from human error when planning or actually performing measurements, were an important factor behind the introduction of standards regulating underground measurements.

This study discusses in detail not only scanning that utilises traditional stationary laser scanners but also scanning based on mobile scanners. It also presents possible areas of future technological development in line with global trends.

Keywords: laser Scanning; excavation geometry; mine survey.

1 Introduction

The excavations covered by the research are located in an active rock salt mine located in LGOM in west-central Poland. At the beginning of the mine's operation, measurement techniques adapted to other types of excavations were used to create maps of the excavations. As work progressed, these methods were systematically modernised. In addition, the mine's analogue mining map was gradually converted into its digital equivalent. The transition to the digital version was fully completed in 2012. In 2015–2017, an attempt was made to create a comprehensive 3D geological model of the rock salt deposit. Additionally, a simplified three-dimensional model of the mine excavations was created.

Recent years have seen an increase in the use of laser measurement methods in mining (Chen et al., 2018) (Lipecki et al., 2015). This article looks at the various practical aspects of these methods in the mapping of mine excavations in a rock salt mine.

Properly performed laser scanning with appropriate georeferencing is the starting point for various analyses. Most often, these data are used to calculate the volume of excavations, the mass roughness or its discontinuities (Singh et al, 2023; Lai & Samson, 2016; Chena at al., 2018, Humair et al., 2015; Ge et al, 2018; Mah et al, 2013). These measurements are often carried out to check the design objectives of new structures or for research purposes (e.g. convergence) (Mukupa et al., 2017; Kukutsch et al, 2015). It is possible to perform inventory of the infrastructure or reverse engineering (Moon at al., 2019; Liu el al, 2024). In excavations serving ventilation functions, a quick analysis can be performed of the actual cross-sections of the excavation, which ensures greater accuracy and reliability of the air flow analysis (Janas & Krawczyk, 2021; Watson & Marshall, 2018). It often happens that the data obtained on one occasion are used many times for completely different purposes than those originally intended (Krawczyk, 2023).

2 Measurement conditions

One important factor affecting the measuring process is the occurrence of unfavourable atmospheric factors, such as air temperature. Many devices used for geodetic measurements have not been adapted to function in mining conditions, especially when temperatures exceed

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43°C (Technical specification sheet for Faro FOCUS S 350, 2024) (Technical specification sheet for LeicaFlexLine TS09plus Total Station, 2024) (Zeb Horizon - User manual, 2020). As a consequence, one common problem that occurs is the malfunctioning of measuring devices caused by their overheating.

Another factor hindering the measuring process is the presence of dust, which limits visibility to approximately 1 metre in the immediate vicinity of the operating mining machine or to several metres in the salt processing site (Figure 1). Visibility is only good in the ventilation shafts, where there is little mining machinery traffic. In dusty conditions, laser beams are unable to operate over long distances (Kajzar, Kukutsch & Heroldova, 2015). Moreover, the devices must meet high dustproof standards. Another major factor disturbing the measuring process is the presence of harmful gases such as hydrogen sulphide.

The unfavourable geometry of excavations stands as another major factor affecting laser measurements (Figures 7, 8, 10 and 11). The excavations are designed as long straight sections (up to 100 metres) ending with crosscuts several or several dozen metres in length. In relatively small sections, there may also be a significant difference in the height of the seam floor due to considerable folding of the salt layers (Piestrzyński, Banaszak & Zalewska-Kuczmierczyk, 2007).

It is important to note that if a mine excavation is located at a considerable depth, the clamping process is quite dynamic (Bieniasz et al. 2010). It should also be borne in mind that during the measuring process, many excavations fulfil important functions in the mine's operations: ventilation, transport, communication, functional (e.g. electrical switchboards) and safety (escape routes). As a consequence, mining services prioritise restoring these excavations at the expense of possible problems when carrying out geodetic measurements.



Figure 1: View of dust generated by a cutting machine during its operation.

3 Measuring tools

The primary instrument for measuring mine excavations in rock salt mines is the electronic mirrorless tachymeter. The range of such a device does not exceed 150 metres. For mine measurements, instruments with both medium (seven- and nine-second total station with a distance measurement accuracy of 2 mm + 2 ppm) and higher levels of precision (one-second tachymeters with a distance measurement accuracy of 1 mm + 1 ppm) are used (Technical specification sheet for LeicaFlexLine TS09plus Total Station, 2024) (Leica TS16 Total Station User manual, 2024).

In the salt mine in question, two types of scanners are used: stationary and mobile. The basic stationary scanner is the Faro Focus S 350. It has a range of up to 350 metres. According to the manufacturer, the device has a speed of up to 976,000 points per second. The measurement accuracy is 3.5 mm at 25 metres, and the field of view is 360°x300°. The laser used for measurements is not harmful to the eyes, and the device has an IP54 dust and waterproof rating. The scanner's operating temperature range is from +5°C to +40°C. The device can operate for up to 4 hours on a single battery (Technical specification sheet for Faro FOCUS S 350, 2024).

The second type of device used is a mobile scanner from the Zeb family. The model primarily designed for measurements in salt mines is the Zeb Horizon. It has a range of up to 40 metres. The speed of the device is 300,000 points per second. The measurement accuracy declared by the manufacturer ranges from 1 to 3 cm, and the field of view is 360°x270°. The device has the same waterproof and dustproof standard as that of the stationary scanner and is also not harmful to the eyes. The manufacturer did not provide the temperature range for the proper operation of this device. The maximum measurement time allows for up to 3.5 hours of continuous operation (Zeb Horizon - User manual, 2020).

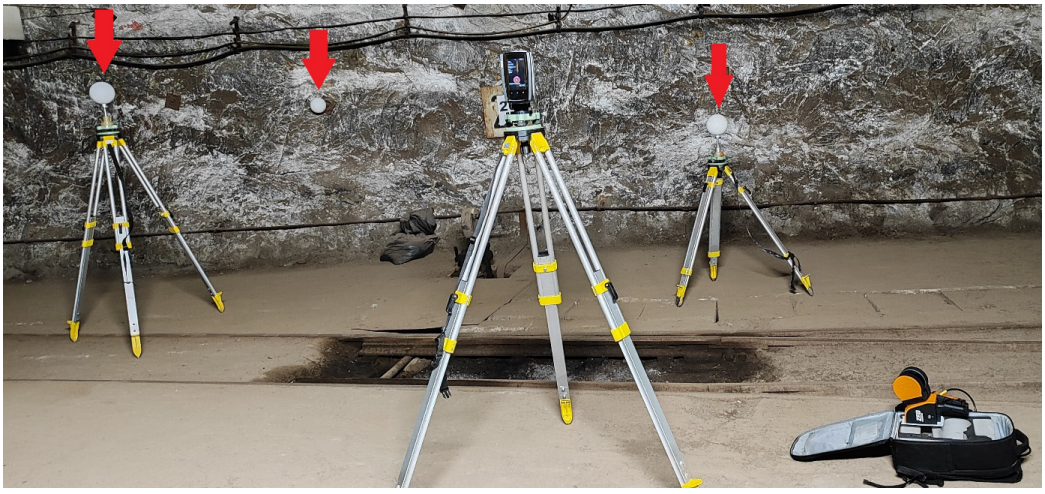

Figure 2: Measurement site with a laser scanner in a mining excavation. A stationary scanner is visible in the central part of the photo. In the lower right corner, there is a mobile scanner intended to perform the measurement. In the background, three measuring spheres are marked with red arrows – two spheres placed on tripods under the geodetic network points and one additional sphere attached to the side of the excavation.

4 Measurement technique

Laser measurements using stationary scanners require placing measuring spheres on geodetic points and performing appropriate scans (Figure 2). To ensure that measurements are carried out correctly, compliance is required with several guidelines, which are the result of experience gained over many years of working with such devices.

The measurement should be preceded by preparatory work, during which the location of individual measurement stations should be planned and the degree of overlap between adjacent scans should be considered. Experience shows that this overlap should be equal to approximately 30% of the common area of both scans. Information such as the location of electrical switchboards, the route of the conveyor belts, the movement of the machines, the location of the fans and ventilation dams should also be taken into account. Attention should also be paid to the location of any sources of strong electromagnetic radiation, which may cause the compasses built into the measuring devices to fail. The next part of the preparatory work consists in analysing the possible use of individual points in the geodetic control network.

After the planning stage, the measurement team carries out the measurement itself. Each geodetic point is marked by a tripod setup together with a measuring sphere attached directly under this point (Figure 2). It is assumed that the XY coordinates of the centre of the sphere are the same as the coordinates of the point where it was placed, and the height coordinate will be calculated as the difference in the height measured between the highest point of the sphere and the geodetic point (Figures 3 and 4). If there are not enough points to ensure georeferencing or their arrangement is unfavourable, additional control points should be established. The spatial coordinates are most often determined by means of tachymeters, which measure classic polygon lines. Each time the station with a scanner attached is set up, the visibility of all the positioned spheres is assessed (Figures 2 and 3). Empirical testing has shown that the distance of the scanner from the farthest sphere used should not be more than 40 metres, and the recommended maximum distance is 30 metres (Nghia, Long, Cuc & Bui, 2019). For a single measurement, at least 4 spheres with known coordinates must be visible from the measuring station (Lipecki & Jaśkowski, 2009). If a larger number of scans are performed, to ensure the optimal arrangement of the spheres, they must be spaced as far apart as possible (Figure 5). If a geodetic point can be scanned in a crosscut up to the measured points, such a geometrical improvement should be used at the expense of performing redundant scans (Figure 6). Scanner-based measurements should, if possible, be made in the absence of machine traffic and with minimal pedestrian traffic.

When taking measurements using mobile scanners, the measurement team arranges the spheres in a similar pattern to stationary scanning. However, a mobile scanner operates in a completely different way from stationary scanners. In the initial phase, the scanner should be placed on a stable, flat surface (Figure 2), which must be marked appropriately so that the scanner can be put back in the same place (accurate to within a few centimetres).

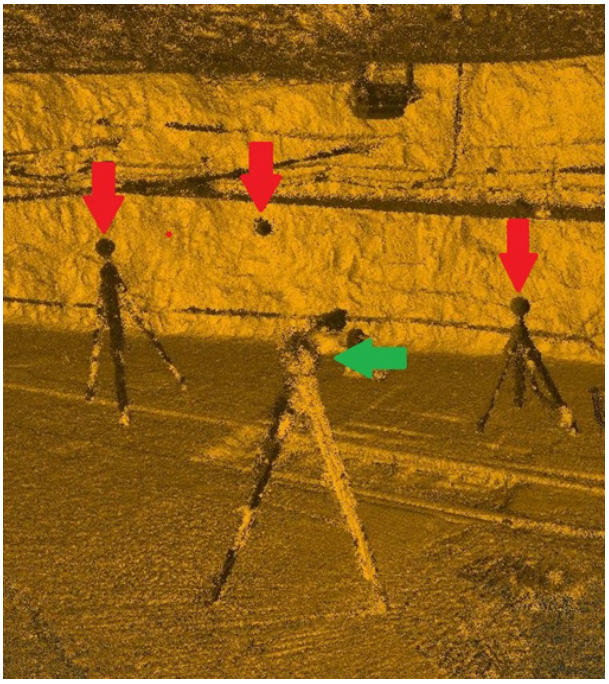

Figure 3: Example of spheres placed on tripods in a mining excavation. Red arrows mark the scanned spheres, and the green arrow indicates the location of the stationary scanner.

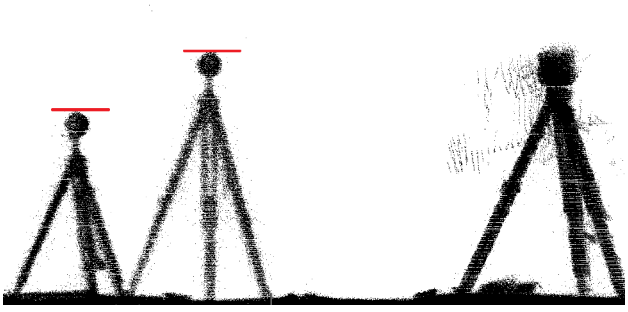

Figure 4: View of filtered point cloud with visible measuring spheres (on the left) and a stationary scanner (on the right). The red lines mark the place where the height of a given sphere is measured.

This point should be at least one metre away from any elements in the excavation. The movements of the scanner head should be smooth and take place on every plane. Passage through narrow sections should proceed at a slow pace. Passage through doors and dams should proceed with an appropriate pause in the measurement so that the scanner can simultaneously record the space in front of and behind the obstacle. The pause itself should last for several seconds. Avoid sudden head movements as this may result in incorrect data processing (Figure 10) (Jones, 2020). After the measurement has been made correctly, place the scanner back at the starting point and wait several dozen seconds for the measurement starting point to be re-scanned.

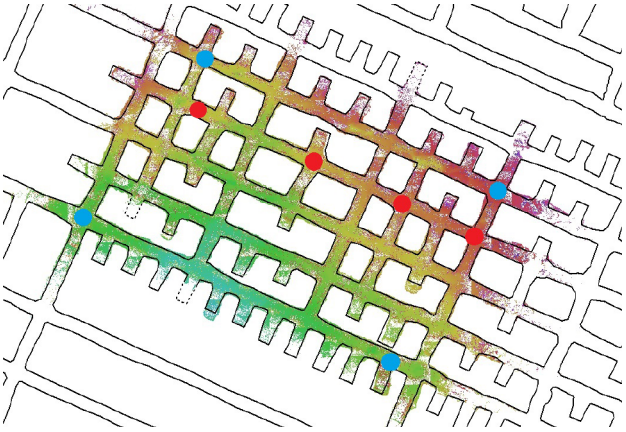

Figure 5: Diagram showing the distribution of points used for georeferencing purposes. Points with an unfavourable distribution are marked in red. Correctly distributed points are marked in blue for further use in calculations.

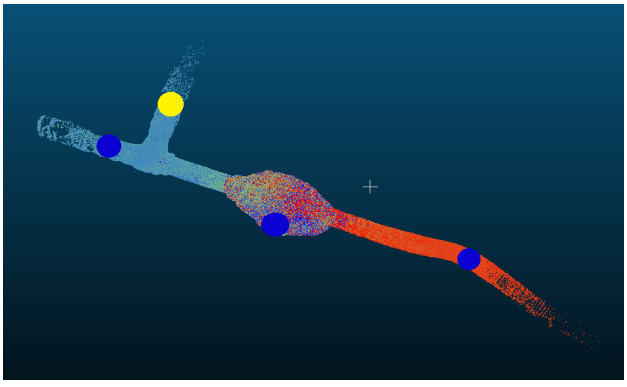

Figure 6: Sample scan showing undesirable arrangement of measurement points (blue circles). The yellow circle marks an additional point on the crosscuts, which have also been measured to correct the unfavourable geometry of the reference points.

Preparing a measurement using mobile scanners mainly involves analysing possible obstacles encountered along the route. Similar to stationary scanners, the feasibility of utilising all points within the geodetic control network is assessed. Additionally, the geometry of excavations is analysed to maximise the frequency of revisiting previously measured locations (Figures 7 and 8). The final stage in the planning process involves estimating the time needed to cover individual distances during the measurement.

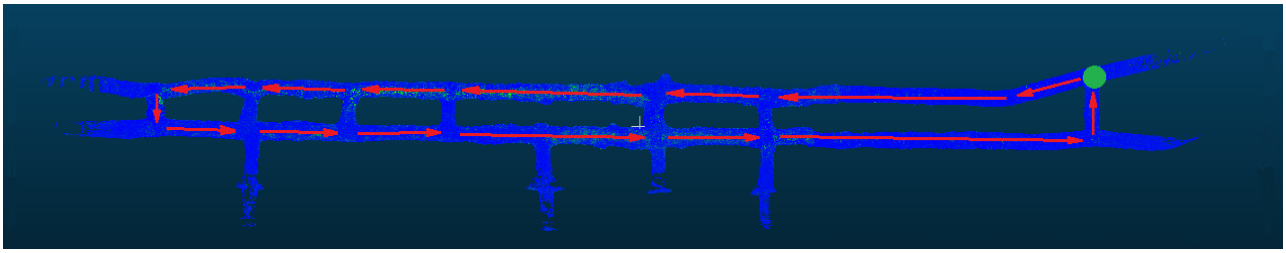

Figure 7: Preparatory mine excavation with an unfavourable geometry. Both the starting and finishing points of the scan (green circle) and the incorrectly planned scanning route (red arrows) are marked.

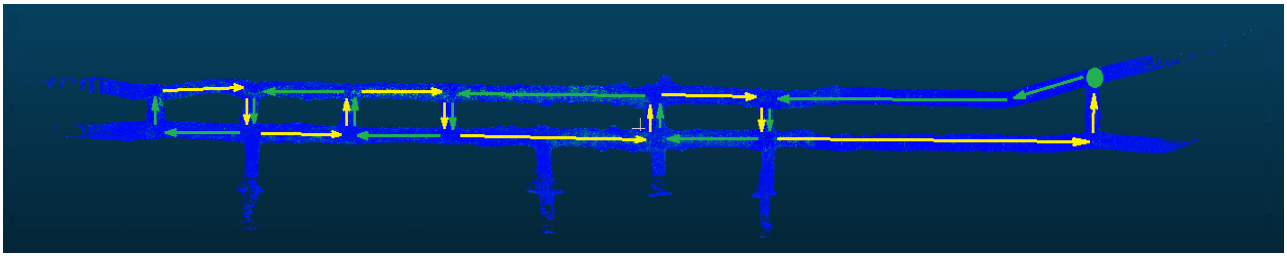

Figure 8: Preparatory mine excavation with unfavourable geometry but measured correctly. The starting and finishing points of the scan are marked (green circle). The forward measurement route is marked with green arrows and the return route with yellow arrows.

5 Measurement results

Applicable law currently stipulates that every measurement made of a mine excavation should be linked to the state geodetic coordinate system. Georeferencing software requires the presence of additional elements in the excavation (spheres, targeting shields) with known spatial coordinates (Fan, Smethurst, Atkinson & Powrie, 2015). By indicating a specific point on a given element, it is possible to manually or semi-automatically set parameters for the transition of a particular scan to the appropriate coordinate system. This approach gives rise to a few complications. The first problem is how to provide enough geodetic control network points – at least 3 points with known XYZ coordinates are required. At least 1 additional point is also needed to verify whether the transition has been carried out correctly. These points should not be located on one plane (for example, on the axis of the excavation) (Figure 5 and 6). Ensuring enough control points for several measurements is a very difficult. Consequently, ad hoc methods are often employed to mark additional points on the side walls solely for the needs of a given scanner measurement (the central sphere attached to the side wall is shown in Figure 2).

Another drawback is the appearance of duplicate planes from two adjacent scans (Figure 9). Most often, these occur at a considerable distance from the geometric centre of the scan. There are several reasons for this phenomenon. The first is the fact that points located in salt excavations undergo a process of convergence, which occurs at different rates in various areas of the mine. Using points with coordinates determined at different times also leads to the emergence of the mentioned errors. The inaccuracies during pointing out points with known coordinates on the scan in the software (Figure 4) contribute to the errors as well. The accuracy of correctly indicating points used for transformation depends on the experience of the operator.

A major improvement in georeferencing accuracy was achieved by introducing the option of combining point clouds by means of the cloud-to-cloud method (Diaz et al., 2024). The use of this technique significantly reduced plane duplication. It also meant less work was required to correctly combine individual data. If a measurement is taken correctly, the average margin of error when it comes to fitting adjacent clouds to each other can be up to 1 cm. The use of this method also changes the way in which the points used for the transformation are arranged. The distribution of the points is based on their spatial location in relation to all the scans (Figure 5).

The results of measurements using a mobile scanner depend largely on the accuracy of the measurement itself. Employees with extensive experience perform measurements with much greater precision than less experienced operators. The key to the measurement process is how the scanner head is moved. If these

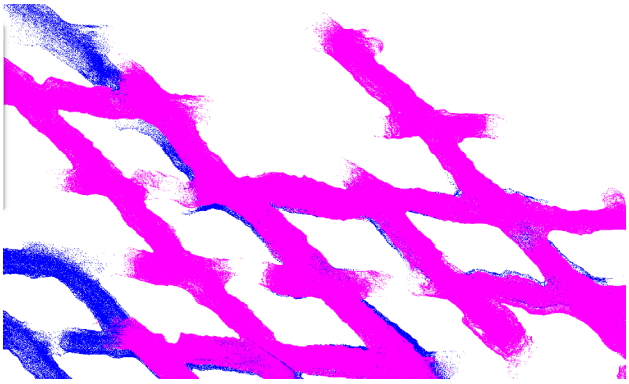

Figure 9: Overlay of two scans with each scan independently georeferenced. Places where there is a perfect fit for the scan are visible (blue scan is not visible) as are those places where the surfaces of the side walls are duplicated (blue scan points visible).

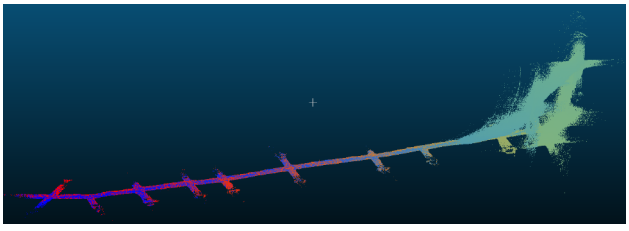

Figure 10: Example of a measurement performed by an inexperienced operator. As a result of the operator tripping, the scanner head moved too rapidly, which completely deformed the scan visible in the right part of the drawing.

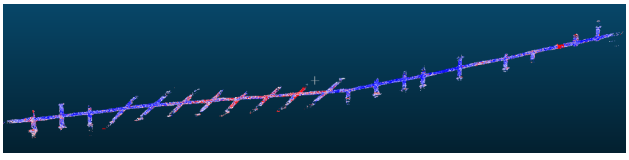

Figure 11: An example of the phenomenon of inertial system drift. The course of the scanned excavation is straight (this was confirmed by an independent measuring method), and the visible curvatures of the course of the excavation are due to the improper movement of the scanner head by the operator.

movements are made too quickly or suddenly, they will have a negative effect on the accuracy of any reading of accelerations by the built-in inertial system. It often happens that if an employee makes a simple trip or slip when taking a measurement, the results can no longer be processed with the manufacturer's software (Figure 10). In turn, if movement of the scanner in one plane is too monotonous, the inertial system will drift, and the longitudinal shape of the excavation will be measured in the form of an unnatural arc (Figure 11). For these reasons, all attempts to mount the scanner on machines moving along the mine did not produce satisfactory results. The next factor is the speed of movement in the working. If the movement is too fast, the scan cannot be processed in the manufacturer's software. In turn, too slow a walking pace results in the formation of a point cloud that is too dense, which makes subsequent processing too time consuming. Experience indicates that the optimal distance travelled by the scanner operator should be approximately 300–400 metres back and forth or approximately 600 metres when performing a loop scan. An experienced operator can plan a single measurement route in such a way as to return to those places they have already scanned as often as possible (Figure 8). The more previously scanned places there are on the measurement route, the better the results of the excavations modelling will be. A major obstacle to the measurement process occurs when the space directly behind them changes dramatically. Any passages that limit the view (closed doors, rubber barriers in passages) result in a deterioration in the scan quality. Experience shows that removing or reducing an obstacle quickly enough (opening a door or removing a rubber barrier) can significantly minimise potential problems. Consequently, it is recommended that each measurement be performed in teams of two. Very narrow spaces pose a similar problem for the algorithm processing the measurement data. By default, the scanner software filters and excludes from processing all points located within 50 cm of the head. The place and method of initialisation and final initialisation of the scanner affect the accuracy of the measurement to a slightly lesser extent.

6 Conclusions and recommendations

As further advances are made in the technology available in scanning devices, so too will the methods of carrying out measurements and processing subsequent data evolve. A dozen or so years ago, the measurement range, accuracy, and operating time of devices were greatly limited. Only stationary devices were available on the market, using targeting marks for orientation in space and subsequent georeferencing. However, progress in scanning accuracy and laser speed as well as the more simplified operation of such devices has made the use of laser scanning measurements in underground mines a reality and has established a new level of quality when it comes to gathering geometry data. The very act of obtaining sufficiently accurate and reliable data is still largely dependent on the experience of the team

performing the measurement. On one hand, the operation of measuring devices is now simpler, while on the other, employees performing laser scanning procedures have, based on their own experience, developed methods and guidelines ensuring proper increasingly accurate measurements. A major step forward came with the development of mobile scanners. They changed the way in which measurements and subsequent data processing are performed. The scanning process itself now makes it possible to measure excavations several times greater in length than was previously possible. Of course, it should be noted that such scanning reduced the accuracy of point determination. The algorithms controlling the processing of raw measurement data are still a trade secret of device manufacturers, thanks to which the measurement process can only be optimised by means of subsequent trial and error. It should, however, be pointed out that manufacturers provide general instructions on the measurement process and update the algorithm itself, which allows the user to recalculate archived data and possibly correct the results later.

The conclusions presented in this article are the result of many years of efforts to adapt terrestrial laser scanning to the conditions and specificity of an active underground rock salt mine. Many of the measurements carried out were unsuccessful. However, each failed measurement brought an added value as they were converted into knowledge regarding the causes of failure during the different stages of planning, execution and data processing.

Looking into the future, we should strive for an increasingly better, faster and less time-consuming method of georeferencing (Singh et al., 2021). It can be assumed that the methods used to combine scans can be greatly improved. The recommended coverage of adjacent scans is given with a little extra to spare, which results in significant data redundancy. Data signalling methods may also undergo dramatic change soon. The practice of setting up and measuring four spheres placed on geodetic tripods is far from ideal. Nonetheless, it remains the most established and reliable method for marking points within a mine excavation at present.

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