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Application of terrestrial laser scanning in documenting an underground coal mine pumping station

Uporaba terestričnega laserskega skeniranja za dokumentiranje črpališča podzemnega premogovnika

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Abstract

Recently, a new underground pumping station was constructed 41.5 m below sea level and equipped, which has now become the main underground pumping station of the Velenje Coal Mine (VCM). In this study, use of terrestrial laser scanning (TLS) to acquire the 3D data of the engine room of the underground pumping station is presented. TLS is an advanced technique in spatial information data acquisition, which allows the equipment in the underground pumping station to be digitally captured with unprecedented resolution and accuracy. Integration with metric imagery allows 3D photorealistic models to be created for interpretation and visualisation. The final result shows the actual 3D image of the object recorded with a relative accuracy of a few millimetres. TLS is ideal for capturing the original state before construction commences and the final state after its completion, as well as for both observation of surface changes and detection of deformations. When we have an accurate 3D model of each component in the engine room of the underground pumping station, any maintenance, future upgrades, or modifications can be made with reference to the original state.

Key words: terrestrial laser scanning, 3D model, underground pumping station, coal mine

Izvleček

V zadnjih letih je potekala izgradnja in opremljanje novega podzemnega črpališče na koti -41,5 metrov, ki je postalo glavno podzemno črpališče Premogovnika Velenje. V članku je predstavljena uporaba terestričnega laserskega skeniranja (TLS) za zajem 3D podatkov strojnice podzemnega črpališča. TLS je napredna tehnika zajema prostorskih podatkov, s katero smo z izjemno resolucijo in natančnostjo posneli vgrajeno tehnološko opremo v strojnico podzemnega črpališča. Integracija z 2D posnetki omogoča izdelavo 3D foto-realističnih modelov, ki omogočajo natančno interpretacijo in vizualizacijo. Končni rezultat prikazuje dejanski 3D model posnetega objekta z relativno natančnostjo nekaj milimetrov. Uporaba TLS je idealna za zajem in izdelavo dokumentacije prvotnega stanja pred začeto gradnjo in končnega stanja po zaključeni gradnji, nadalje za opazovanje površinskih sprememb in odkrivanje deformacij. Ko razpolagamo z natančnim 3D modelom vseh posameznih komponent strojnice jamskega črpališča, lahko z ozirom na prvotno stanje brez težav planiramo nadgradnje in modifikacije ter zagotavljamo nemoteno izvajanje vzdrževalnih del.

Ključne besede: terestrično lasersko skeniranje, 3D model, podzemno črpališče, premogovnik

Introduction

The Velenje Coal Mine (VCM), with an annual underground coal production of >3 million tonnes in 2016, operates on the largest Slovenian coal deposit and on one of the thickest known coal layers in the world. The underground coal extraction is carried out using the Velenje Mining Method (VMM) [1] and the mining process is exposed to various hazards, including water-related problems. In existing underground mines, ground water control methods consist of limiting the water inflow into the mine area and pumping out of water from the mine. Due to the expected impacts of coal mining excavation on the old main pumping station's engine room, in 2013, a new one, 41.5 m below sea level at a location where future impacts and deformations are not expected, was constructed, which has now become the main underground pumping station of VCM. The new pumping station is composed of two ~40 m long mine roadways, which are connected to each other by a 20 m long passage (Figure 1). One mine roadway and a part of the passage are used as a storage tank for mine water of approximate capacity of 200 m^3, while the pumping station engine room and the electricity room are located in the second mine roadway [2]. The engine room is equipped with three pumps of capacity 2.5 m^3/min, which continuously pump mining water to the surface. By installing the BAT electro-mechanical equipment, the pumps can be operated without the presence of workers in the pumping station. Because >2.5 m^3 of water has to be pumped per minute from ~400 m below the ground surface, a reliable operation of the water drainage of the VCM pits is crucial. For this reason, knowing the original state of the engine room after completion of construction is necessary. Through collaboration of the VCM mine surveying team and C&G Company, terrestrial laser scanning (TLS) of the engine room of the new main underground pumping station was performed with a phase scanner Z+F Imager 5006i of Zoller & Fröhlich GmbH.

Materials and methods

The TLS system used

The TLS technology was used for surveying the main underground pumping station of VCM ~400 m below the surface. Field measurements were carried out with the Z+F Imager 5006i phase-based scanner, suitable due to its accuracy, resolution, and data capture rate of >500,000 points/second. The scanner uses laser light at near-infrared wavelengths and its motorised head permits data to be acquired with 360° (horizontal) × 310° (vertical) coverage. The shortest distance of detection is 0.4 m. Therefore, it is ideal for scanning underground spaces with complex equipment installed. The technical specifications of the Z+F Imager 5006i scanning system are listed in Table 1 [3].

The instrument accuracy is usually lower in practical applications due to unfavourable conditions, especially in the underground environment. The underground coal mine environment is very demanding for TLS projects because of darkness, dust, high humidity, and high temperature, especially because of the potentially increased concentrations and explosions of coal gases. As the Z+F Imager 5006i scanner is not an explosive protected instrument and therefore not intended for use in areas with potentially explosive atmospheres such as underground coal mines, the TLS measurements were performed under strict safety regulations and continuous onsite gas measurements, according to Slovenian Mining Law and subsidiary legislations [4]. Although explosion-proof laser scanners are available on the market, e.g., the Z+F Imager 5006EX – a joint venture product of Z+F GmbH and DMT GmbH [5], unfortunately, we did not have such an instrument available.

Measurement principles of the TLS technology

Currently, TLS is useful as an advanced and cost-effective technology for the fast, accurate, and reliable acquisition of millions of 3D points in highly demanding engineering environments. A terrestrial laser scanner consists of a transmitter and a receiver of the laser light, a scanning device, and a timing device. To obtain object point distances, TLS uses either the time-of-flight measurement method or phase-

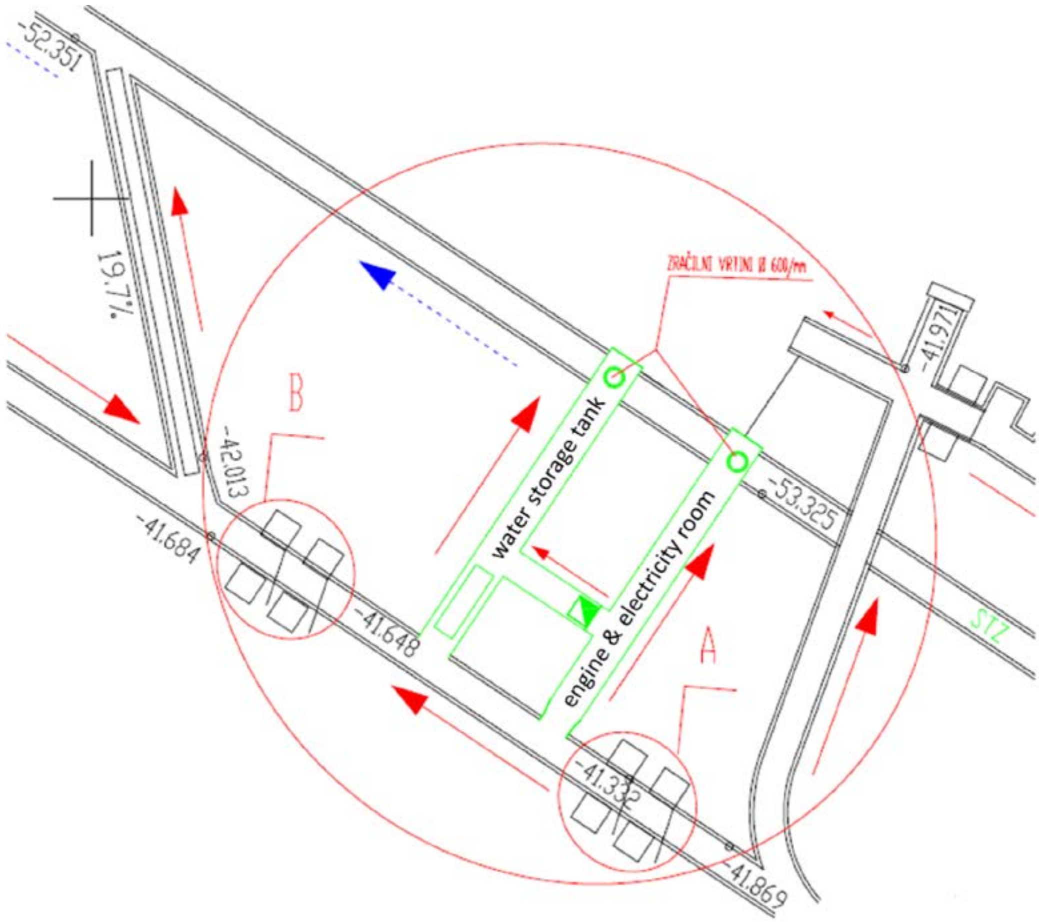

Figure 1: *Location of underground pumping station (in green).*

Table 1: *Technical specifications according to manufacturer*

Z+F Imager 5006i		
Scanning method		Phase difference
Scanning speed (points/s)		≤508,000
Precision	Position	10 mm/50 m
	Distance	6 mm/50 m
Spot size at 10 m		3.2 mm
Scan distance		0.4–79.0 m
Angular resolution	Hz	0.0018°
	V	0.0018°
Laser wavelength		658 nm
Laser class		3R
Field of view		360° x 310°
Working temperature		–10°C to 45°C
Weight		14 kg

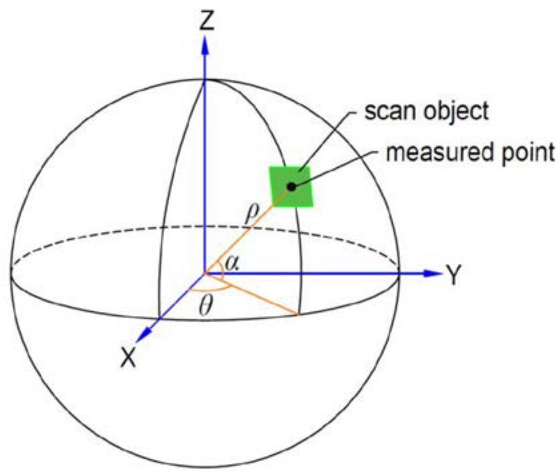

Figure 2: *Spherical measuring system with a terrestrial laser scanner system.*

based measurement method. In the case of phase-based TLS, the time of flight of the laser light from the sensor to the object and back results directly in a phase difference between the transmitted and the received laser light [6]. Thus, the distance ρ is calculated as follows:

(1)

where c is the speed of light, $\Delta\phi$ is the measured phase shift between the emitted and received laser light, f is the frequency of the emitted light, and n is the integer number of full wavelengths. The TLS instrument operates in a spherical coordinate system in which the TLS instrument is in the centre of the coordinate system; for each point, we obtain the distance ρ and two orthogonal angles θ (horizontal angle) and α (vertical angle), together with the additionally registered intensity of the returning signal (Figure 2). The Cartesian coordinates of the point cloud are computed from the measured spherical coordinates as shown in Equation 2.

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix}_{i=1\ldots n} = \rho_i \begin{bmatrix} \cos\theta_i \cos\alpha_i \\ \sin\theta_i \cos\alpha_i \\ \sin\alpha_i \end{bmatrix}_{i=1\ldots n} \quad (2)$$

While measuring an object with complex geometry, multiple TLS scans are required to generate an appropriate 3D model. Therefore, transformation from multiple adjacent point clouds into a uniform Cartesian reference coordinate system is needed. The relationship between two overlapping TLS point clouds is defined as a 3D similarity transformation. As the scale parameter is one, six parameters are estimated, which are needed for transformation of overlapping point clouds (Equation 3).

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \lambda \boldsymbol{R} \begin{bmatrix} X_2 - X^c \\ Y_2 - Y^c \\ Z_2 - Z^c \end{bmatrix} \quad (3)$$

where (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) correspond to point cloud coordinates of Scan 1 and Scan 2, R is a rotation matrix formed from three axial rotation angles, and (X^c, Y^c, Z^c) corresponds to the translation components between Scan 1 and Scan 2. Once the six transformation parameters (scale is assumed fixed) are computed between the point clouds, the *XYZ* coordinates of all scan points can be transformed into a reference coordinate system [7].

Data acquisition and processing

While the purpose of TLS in VCM was to acquire geometric data on the original state of the engine room of the pumping station in the same vertical and horizontal coordinate system as is determined for mining surface and underground structures, i.e., VCM's reference Cartesian coordinate system, great attention was given to defining the VCM's reference coordinates points as starting points for the needs of TLS. VCM's underground reference coordinates points are the results of periodic measurements and calculations of transferring the coordinate system from the surface into the underground mine, as described by Koželj et al. [8]. The scanning started outside the pumping station, and it was necessary to capture VCM's reference points to be further used in the registration and geo-referencing procedures. The coordinates of the reference starting points in front of the

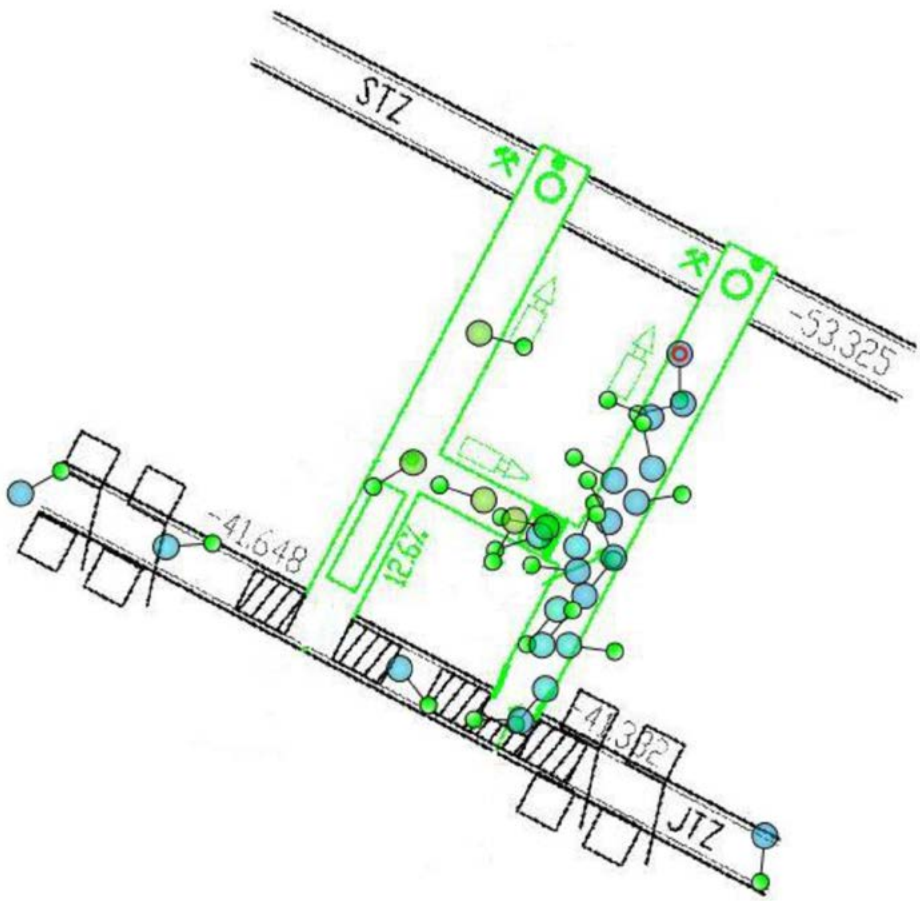

Figure 3: *Location of the 26 scans in pumping station area.*

pumping station were determined by traverse survey and direct levelling methods. For registration purpose, 43 plastic and paper spherical targets, i.e., control points, all over the pumping station engine room were distributed such that they lay within the overlapping area of adjacent scans and could be identified. Due to the complexity of the engine room components that had to be scanned, 26 scans were necessary to document the entire area of ~700 m^2 (Figure 3). From each scanning position, a 360° point cloud, of ~40 million spatial points and with its own local coordinate system, was generated (Figure 3). Each scanning procedure took <10 minutes and, altogether, including moving of the instrument to all scan positions, ~6 hours.

Basic processing of the obtained data was accomplished using the Z+F Laser Control software. Laser Control software allows, in addition to easy control of the 3D laser scanner via a laptop, review of scans, visualisation of point clouds, extensive measurement facilities in both the 2D and 3D views, and registration via marked points (targets). Because of the high density of the measured points, point clouds resemble high-resolution photography, as shown in Figure 4(a). For comprehensible presentation, an orthogonal view of the scan values, also called the bubble view, is used (Figure 4(b)). In Figure 4, control points in the form of targets on tripod and paper targets on objects are nicely visible. The original 2D view always looks distorted, which is not the case in the bubble view [9]. Figure 4(c) shows the corresponding point cloud in the form of *XYZ* coordinates, where the TLS instrument is in the centre of the local coordinate system and is shown in blue colour.

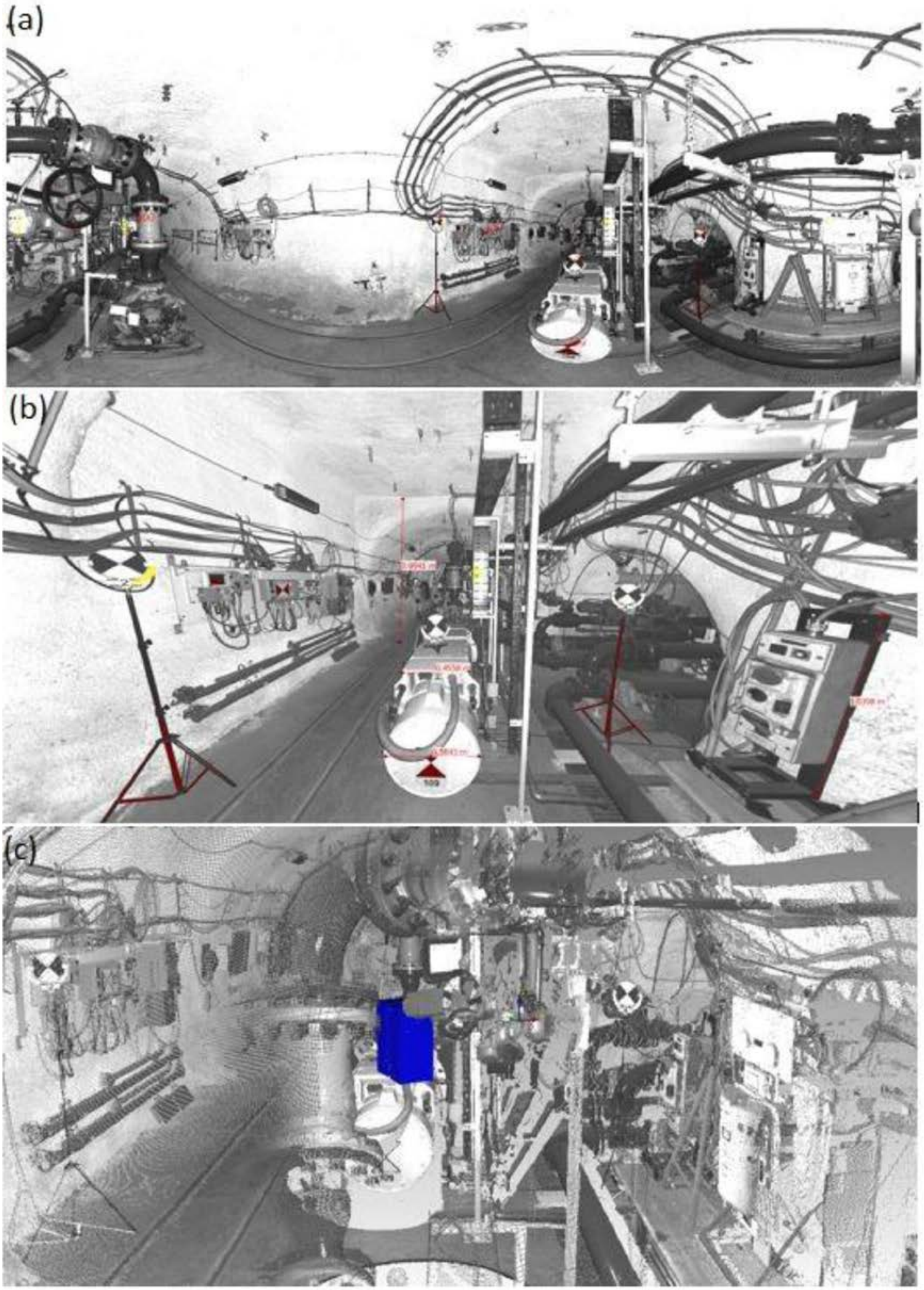

Figure 4: *(a) Terrestrial laser scan (point cloud) in the engine room, (b) part of corresponding bubble view, and (c) corresponding scan in the form of XYZ coordinates.*

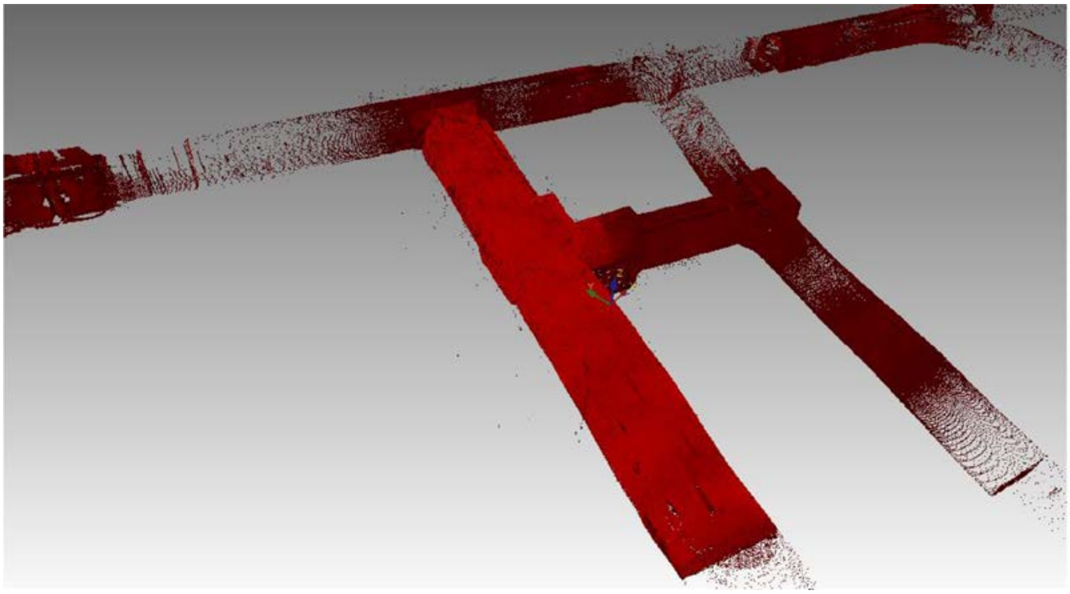

Figure 5: *Resulting point cloud of 26 adjacent scans in the pumping station area.*

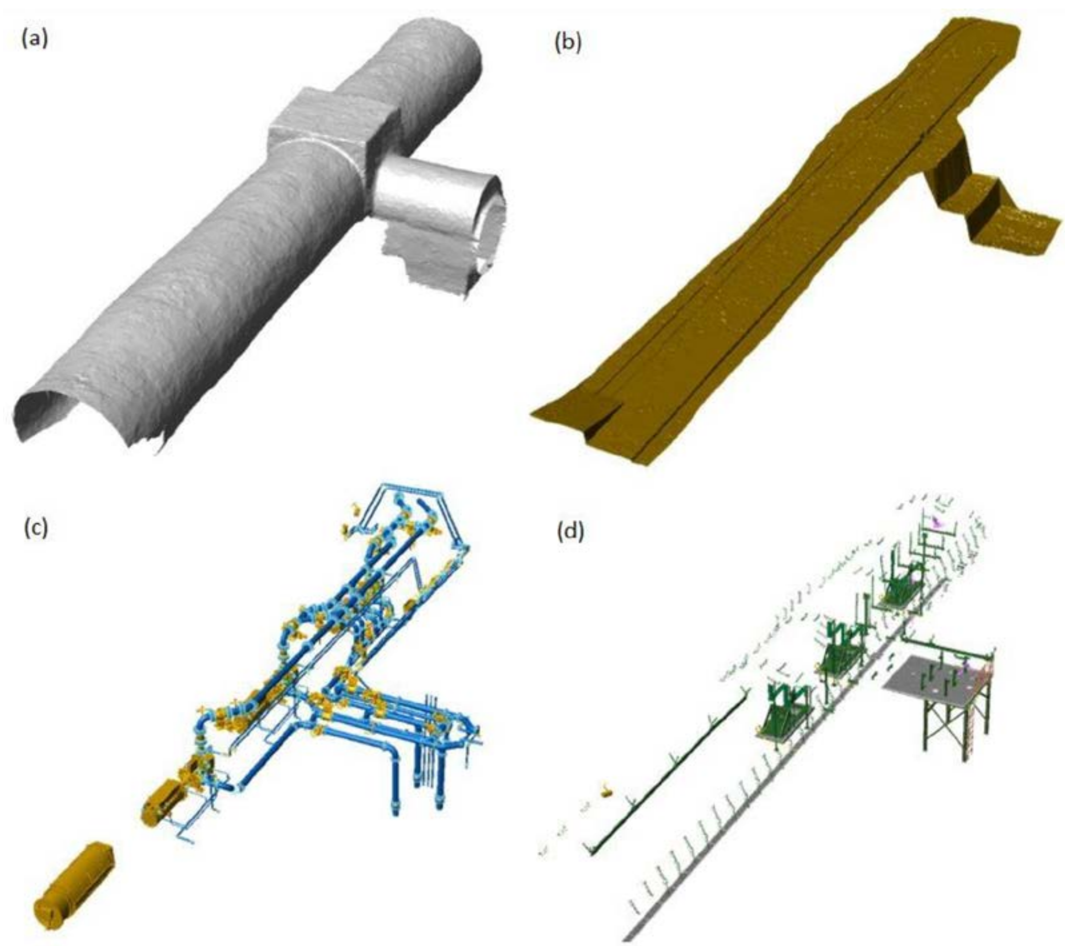

Figure 6: *Classification or object recognition from the point cloud in 3D modelling process: (a) mine roadway walls, (b) ground surface, (c) pumps and pipelines, and (d) other features.*

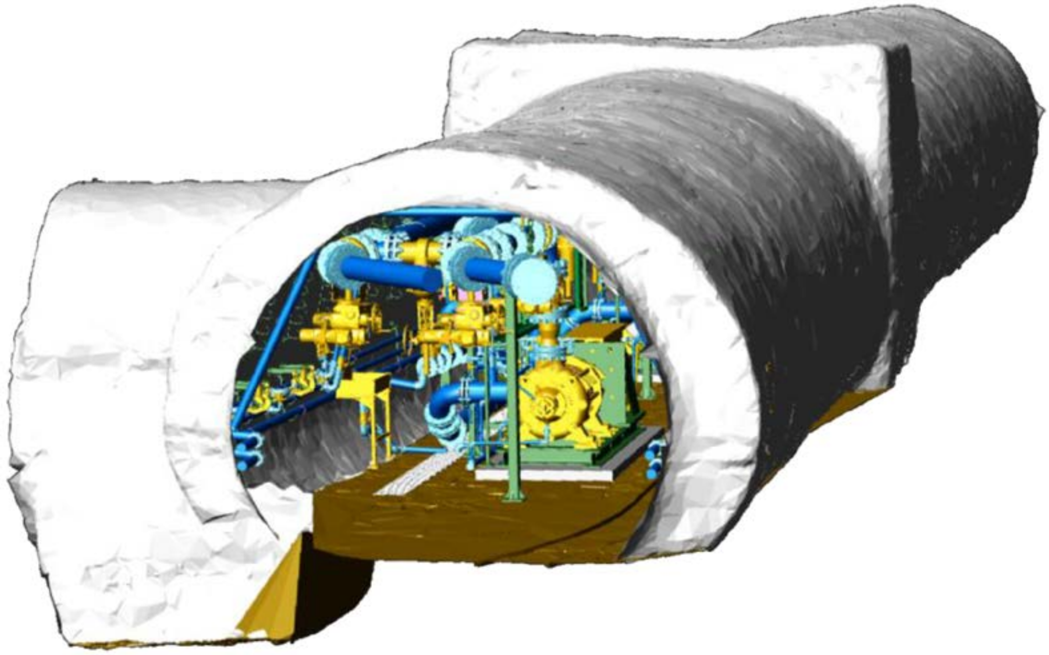

Figure 7: *Complete 3D model of pumping station engine room.*

Further processing comprises the processes of registration, geo-referencing, filtering, classification, and 3D modelling. With software Laser Control, registration of targets within the overlapping region of adjacent scans can be done automatically. The basic requirement for automatic registration of two overlapping scans is that there should be at least four targets for each scan, and the transformation parameters can then be determined. Finally, the multiple point clouds are merged into a combined point cloud file with >1 billion points (Figure 5). The redder the area, the greater is the number of points that were generated during TLS. While the objective of the project was to collect data of the pumping station's engine room, many more measurements were carried out in this area. As all scans must be oriented to an existing VCM's coordinate system, a supplementary activity called geo-referencing was performed, using known points measured and marked independently with classical geodetic methods prior to the TLS execution.

During filtering, erroneous and unwanted data is removed from the point cloud, such as overlapping points, outliers, and obstructions. Since point cloud accuracy decreases with distance from the scanner location, elimination of distant points is required to ensure that the most accurate points for each scan location are used. The TLS deliverable is the point cloud that presents the XYZ location of each point, along with the intensity for each point. Thus, identification and classification of the different features in the point cloud, such as ground surface, mine roadway walls, pumps, pipelines, and other important features, are required. With additional processing, the data were translated into 3D AutoCAD model. Finally, surface meshes and 3D solids were created from the point cloud data (Figure 6).

Results and discussion

The raw result of TLS is the point cloud in which many metrical tasks, i.e., height and width measurements, as well as area and volume calculations, can be processed. In Figure 4(b), a few height and width measurements can be seen. Significant value can be obtained by converting the point cloud data into a more usable coloured 3D model. Additionally, all equipment is separated onto the corresponding CAD layers. In Figure 7, the final 3D model of the pumping station's engine room with a relative accuracy

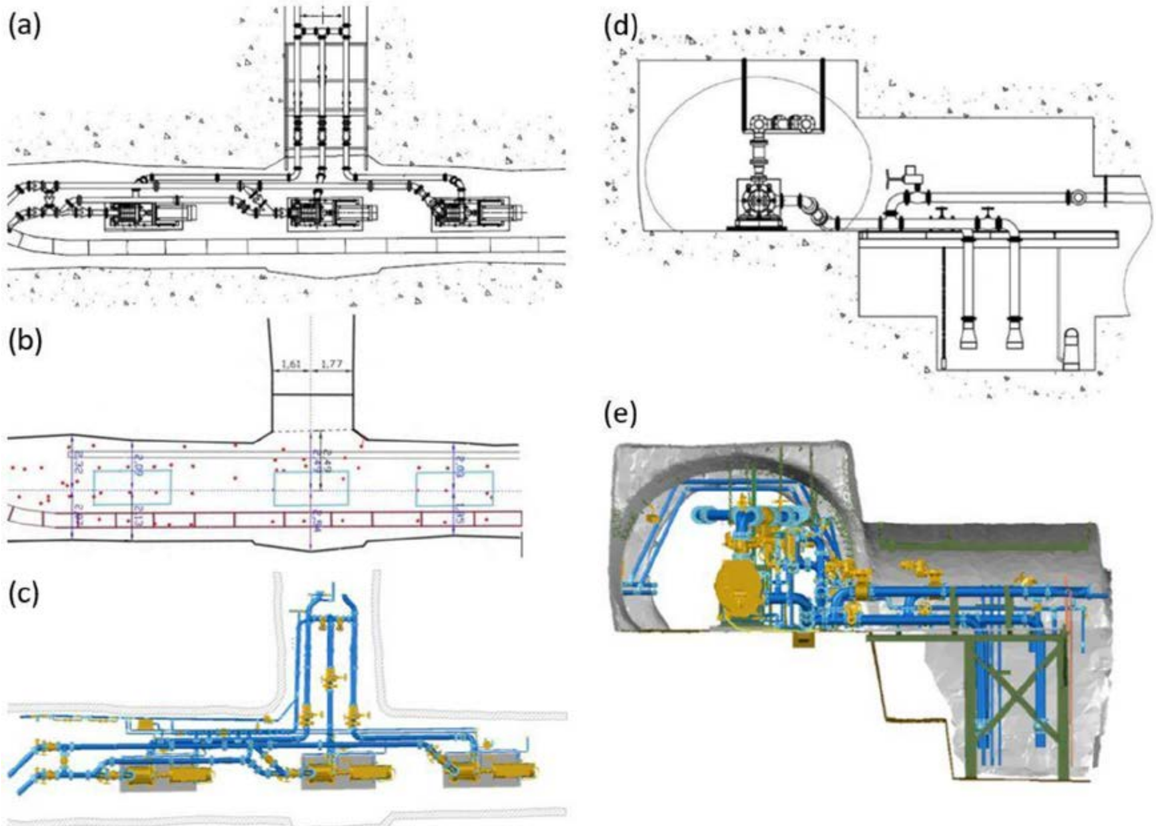

Figure 8: *Comparison of engine room ground plan and cross section of design model and actual state after completion: (a) and (d) AutoCAD design model; (b) theodolite measurement result; and (c) and (e) TLS modelling.*

of a few millimetres is shown. With repetitive and comparative measurements, a precise definition of accuracy would be possible. Nevertheless, the relative accuracy of 1–2 cm is more than adequate for the engineering purposes encompassing designing, maintaining, or installing additional equipment.

From a comparison between the AutoCAD design model of the machinery and pipelines installed in the engine room and the result of TLS, deviations can be identified (Figure 8). When comparing the results between mechanical theodolite and tape measurements (when certain safety precautions are taken, surveying with a total station is also possible) and TLS, there are some essential differences. The most relevant difference is of course the number of measured points – a few dozen points against tens of millions of points. Consequently, it is unthinkable to measure and draw in 3D all components of the engine room using mechanical theodolite or even a total station. In Figure 8, a comparison of the engine room ground plan and the cross section of the AutoCAD design model [2], the ground plan based on measurements with theodolite and measurement tape [10,11], and the ground plan and cross section derived from TLS measurements is shown. It is normal that during installation of complex mechanical and electrical equipment, minor changes are made due to unforeseen complications and time constraints. In this manner, TLS provides the actual state after completion.

Mechanical theodolite is an instrument that can be used in coal mines with potential methane hazard on daily basis without special permissions, as per Slovenian Mining Law and subsidiary legislations. Thus, it is indispensable and vitally important for mine surveying. We cannot compare the efficiency levels between theodolite and TLS measurements, as a TLS instrument captures >500,000 points/second, whereas theodolite captures 500 points in 4 hours [12]. Furthermore, surveying with a theodolite or total station is only feasible when the object can be modelled by a limited number of characteristic points [13]. However, in special cases [14], among which certainly falls the capturing of complex installations of an engine room, TLS has much to offer. The ability to examine accurate detailed data in 3D has a number of benefits, such as those shown by Greaves and Hohner [15]:

- Reducing time onsite for inspection;
- Point clouds and 3D models allow walk-through views;
- 2D plans and cross sections, as well as 3D views, can be made at any point within the model;
- Providing advanced interference and clash detection for new installations without the need for return on site;
- Executing construction activities with fewer mismatches and design errors.

Acquiring data using TLS does not require a lot of work and, thus, less time is necessary directly on the area of interest. While scanning measurements take only a few minutes for a single scan location, in a few hours, very complex objects can be captured. Consequently, the most time-consuming step is the handling and spacing of the instrument and to determine and set the target at the desired locations. Apart from these benefits, there are also some disadvantages when using TLS in an underground coal mine. Certainly, some of the disadvantages are a complex and time-consuming data processing step, creation of 3D models, and solid body modelling. Two of the most limiting environmental factors are dustiness and darkness [16]. Low visibility in a dusty environment affects the speed of scanning. Further, conditions of reduced light in the darkness and dustiness cause poor targeting; the latter in turn influences the accuracy. Additionally, point cloud and 3D model data can reach sizes of hundreds of gigabytes and hence, special attention must be paid to computer software and hardware.

As the presented 3D model gives only the physical properties of all the components installed in the engine room, future work involves forming a building information model (BIM). A BIM has the capability to supplement physical properties with additional attributes – metadata, which in our case could include at least time of installation, as well as equipment and manufacturer data, e.g., equipment model number, specifications, and maintenance schedules. However, forming a BIM application calls for joint multidisciplinary and multiprofessional collaboration.

Conclusions

TLS is a high-speed, non-contact 3D measurement technology for generating as-built documentation. The purpose of 3D TLS in the VCM was to capture the original state after construction and equipment installation of the pumping station's engine room. A point cloud, which is geo-referenced, was the output of the scans. Further, 3D AutoCAD models were prepared. By having an accurate 3D model of all components installed inside the engine room, any maintenance, future upgrades, or modifications can be made with reference to the original state rather than the AutoCAD design model. There are also many other possible applications of TLS in VCM, including capturing the physical properties of large mining equipment (hydraulic support systems at longwall faces, conveyors), monitoring the geometry of mine roadways during excavation, shaft alignment, making deformation measurements, and detecting geological features as shown in previous studies [12,17,18]. Nevertheless, we must be aware that the use of TLS in coal mines is limited due to the safety regulations related to potential risk of explosions of methane gas and coal dust.

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References

[1] Medved, M., Golob, L., Kotnik, A. (2009): Velenje Coal Mine (VCM) mining method and modern mechanized faces. In: Proceedings of the 3rd Balkan Mining Congress—Balkanmine, Izmir, Turkey, 1–3 October 2009; pp. 109-117.

[2] Špegel, B. et al. (2009): RP-360/2009BŠ, Izdelava jamskih objektov za glavno jamsko črpališče na k.-41.5, Premogovnik Velenje, 2009.

[3] Zoller+Fröhlich GmbH [online]. Z+F IMAGER® 5006i [cited 12/6/2016]. Available on: <http://www.zf-laser.com>.

[4] Slovenian Mining Act [online]. Zakon o rudarstvu ZRud-1, 2010 [cited 1/5/2017]. Available on: <http://www.energetika-portal.si/predpisi/rudarstvo/slovenija/krovni-zakon-zrud/>.

[5] Zoller+Fröhlich GmbH [online]. Z+F IMAGER® 5006EX [cited 12/6/2016]. Available on: <http://www.zf-laser.com>.

[6] Ergün, B. (2011): Terrestrial Laser Scanning Data, Integration in Surveying Engineering. In: Laser Scanning, Theory and Applications, Wang, C.C. (ed.). InTech, pp. 473-494.

[7] Al-Manasir, K., Fraser, C.S. (2006): Registration of terrestrial laser scanner data using imagery. In: Proceedings of the ASPRS 2006 Annual Conference, Reno, Nevada, 1–5 May 2006; 9 p.

[8] Koželj, M., Slatinšek, J., Ambrožič, T. (2015): Mine surveillance measurements during the building of NOP II shaft. *Geodetski vestnik*, 59, pp. 13-27.

[9] Zoller+Fröhlich GmbH (2013): Z+F LaserControl Manual ver. 8.4.

[10] Špegel, B. et al. (2011): RP-360/2009BŠ – PID, Izdelava jamskih objektov za glavno jamsko črpališče na k.-41.5, Premogovnik Velenje, 2011.

[11] Špegel, B. et al. (2011): RP-376/2011BŠ, Elektrostrojna oprema za glavno jamsko črpališče na k.-41.5, Premogovnik Velenje, 2011.

[12] Van der Merwe, J.W., Anderson, D.C. (2012): Applications and benefits of 3D laser scanning for the mining industry. The Southern African Institute of Mining and Metallurgy, Platinum 2012, pp. 501-517.

[13] Lemmens, M. (2011): Geotechnologies and the Environment, vol. 5; Geo-information, Technologies, Applications and the Environment. Series Editors: Gatrell, J.D. & Jensen, R.R. Springer, 2011, 349 p.

[14] 3DriskMapping (2008): Theory and practice on Terrestrial Laser Scanning; Training material based on practical applications, 2008 [cited 02/20/2017]. Available on: <https://lirias.kuleuven.be/bitstream/123456789/201130/2/Leonardo_Tutorial_Final_vers5_ENGLISH.pdf>.

[15] Spar Point Research [online]. Greaves, T. and Hohner, L.N.: 3D Laser Scanning: Benefits and Paybacks for Industrial Plant Design, Construction and Operation [cited 01/24/2017]. Available on: <http://www.aec.faro.com>.

[16] Kukutsch, R., Kajzar, V., Konicek, P., Waclawik, P., Ptacek, J. (2015): Possibility of convergence measurement of gates in coal mining using terrestrial 3D laser scanner. *Journal of sustainable mining*, 14, pp. 30-37.

[17] Wang, W., Zhao, W., Huang, L., Vimarlud, V., Wang, Z. (2014): Applications of terrestrial laser scanning for tunnels: a review. *Journal of Traffic and Transportation Engineering* (English Edition), 1(5), pp. 325-337.

[18] Kos, A., Novaković, G., Uršič, L., Vulić, M. (2013): New methods for modern technology for the evaluation of spatial parameters of underground structures. *RMZ – Materials and geoenvironment*, 60, pp. 121-129.