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Potential of Using Terrestrial Laser Scanning in Mining Industry

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In recent years, the use of terrestrial laser scanning (TLS) technology in the mining industry has grown in popularity because of its many benefits, including non-contact measurement, high precision, rapid data acquisition, and large-scale coverage. This study provides a thorough overview of the application of the TLS method in underground, open-pit, and closed mines, using data from 56 publications over the past fourteen years, from 2010 to May 2024. The reviewed literature shows that the TLS approach can be applied in five main operations in mining areas, particularly for monitoring deformation, displacement, subsidence, and landslides, as well as generating maps, 3D models, and point clouds. The findings reveal that TLS is an excellent technology for multitasking in any type of mine. In addition, future development trends for the mining industry based on the integration of TLS with machine learning and AI technologies are also discussed in this study. The results of this study may suggest directions for creating the specifications required for TLS deployment on mine sites.

Keywords: *terrestrial laser scanning, spatial information data, underground mine, open-pit mine, closed mine.*

Introduction

An advancement in the collection of spatial information data is the terrestrial laser scanner (TLS), which enables data capture with previously unprecedented precision and accuracy ***[1]***. Compared with traditional measurement methods, TLS technology allows for much faster acquisition of three-dimensional (3D) point information. According to ***[2]***, 3D data can be obtained quickly, effectively, precisely, and with great detail using TLS. Point clouds is the term used to describe the acquired set of data points ***[3]***. Due to its precision, dependability, and efficiency, TLS technology has become a useful tool for a wide range of applications, such as evaluating different tunnel characteristics ***[4]***, mapping building surfaces ***[5]***, civil engineering ***[6]***, 3D surveying ***[7]***, the architecture, engineering, and construction industry ***[8]***, geology ***[9]***, monitoring deformation ***[10]***, engineering geodesy ***[11]***, etc. Moreover, high precision, fast speed, and proximity to the prototype are the key features of 3D laser scanning technology, which is extensively utilized in a variety of mapping and other sectors. It provides a comprehensive and highly accurate reconstruction scan that can be accessed physically and quickly ***[12]***. In addition, TLS is an outstanding technology that can be applied not only in many other fields but also in the mining sector. This approach has been used in many publications for mining management ***[13]*** and can perform operations in underground ***[1]***, open-pit ***[2]***, and closed mines ***[14]***.

To provide an overview of the application of this technology in various fields, several reviews have been conducted. ***[15]*** summarized studies and uses of TLS for monitoring ground and building deformation. In the architecture, engineering, and construction industry, ***[8]*** introduced TLS and described its prospective advantages for this sector. According to ***[4]***, although TLS techniques are

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not yet frequently used in tunnel studies, there is still great potential to explore. Thus, they offered a review focusing on how different tunnel characteristics can be measured using TLS approaches. In addition, ***[16]*** presented the application of TLS technology in modeling, monitoring, and mapping geohazards in British geological surveys. Moreover, recent developments in TLS instrument design were reviewed in ***[17]***, along with their possible effects on TLS applications in the Earth sciences in the future.

Alongside assessments of TLS applications in different fields, many scientists have also published reviews of its use in the mining industry. While ***[3]*** conducted a thorough investigation of TLS technology, including its principles of operation, measurement, 3D TLS software, and benefits, ***[18]*** presented applications of 3D TLS in the mining industry, and ***[19]*** provided an overview of laser scanning uses in underground mining for geological and geotechnical purposes. The current state and future trends of 3D laser scanning technology in the mining industry were discussed in ***[12]***. In another study, this approach was used for geological and geotechnical applications in underground mining ***[19]***. Furthermore, some advantages and applications of TLS in the mining industry were presented in ***[20]***, and improvements in underground mine surveys based on SLAM-enabled handheld laser scanners were analyzed in ***[21]***.

From the analysis of the above reviews, it can be seen that most authors did not review all publications related to the topic of this article. In addition, most reviews did not systematically analyze the applications of TLS in mining and did not mention its use in closed mines. Typically, ***[19]*** only evaluated the TLS method for geological and geotechnical applications in underground mines. In ***[12]***, the authors discussed five applications of TLS but did not address its use in estimating volume or monitoring tram tracks in a mine. Moreover, these applications were presented too briefly, and the authors did not cover all studies related to them. However, this study did present some trends of this technology in the near future. In addition, ***[18]*** described some uses of TLS but only relatively briefly and did not provide the advantages and disadvantages of the method. Similarly, ***[3]*** evaluated TLS applications and highlighted its advantages in mining but omitted any discussion of its drawbacks.

In summary, from the existing studies evaluating TLS technology in the mining sector, it is evident that no systematic assessment has been conducted on its application in mines by classifying the mining process into three types: underground, open-pit, and closed mines. Furthermore, no study has analyzed in depth the applications of TLS in the mining industry, evaluated their advantages and disadvantages, and proposed future trends. Therefore, this study was conducted to meet the above objectives.

Methodology

Performing a thorough study, categorizing, and summarizing the concepts, ideas, and innovations proposed by different authors and international research teams in the application of TLS technology in the mining sector is the first primary objective of this review. The second objective is to classify applications based on keywords. The keywords used in the study include "Terrestrial Laser Scanning" OR "TLS" AND "underground mine," "open-pit/surface mine," "closed/abandoned mine," OR "mining industry," OR "mine sector," OR "mine areas/sites." Data from major sources published between 2010 and May 2024, such as Google Scholar, Web of Science, IEEE, and ScienceDirect, were used in this study. Based on the titles, abstracts, and full texts of the publications, 56 papers were collected for review.

Application of Terrestrial Laser Scanning Technology in Mining

1. Underground Mines

The superficial layer of the rock mass changes irregularly in both vertical and horizontal directions as a result of underground mining activity. Thus, in order to ensure the safety of mining sites, it is crucial to identify surface geometry changes in construction objects situated within underground mining exploitation regions. ***[22]*** used multi-temporal TLS point clouds to construct a semi-automated approach for determining the displacement field in areas affected by underground mining. The parameters of the proposed approach and the registration algorithm settings were optimized to meet the research goal. The method enables substantially higher precision of displacement vectors compared with those obtained in previously published studies, as both internal and external accuracy analyses demonstrate.

Also related to identifying displacement, ***[1]*** described a transportable terrestrial laser scanning system and method, which have been used to measure the geometric deformation of vertical shaft parts at several vertical shafts in Polish mines. The results show that high precision of 1–3 mm is provided by this method for each horizontal cross-section. Processing time is very fast and requires only a few personnel to operate all systems. In another study, ***[23]*** discussed the potential applications of TLS technology for the surveillance of engineering objects. This technology enables comprehensive spatial documentation of an object affected by active mining operations. Point clouds taken during two measurement periods were compared to identify changes in the geometry of the structure. The findings revealed changes in the trestle bridge's direction toward the mined coal wall, together with object deformation.

According to ***[24]***, TLS technology is helpful in characterizing rock masses. Therefore, they used laser scanning in an underground limestone mine to characterize the rock bulk and create a discrete fracture network. From there, procedures employed in an underground limestone mine to characterize discontinuities using laser scanning were introduced. In addition, the topographical roughness of rock surfaces is an important consideration for evaluating the effectiveness of extractive processes in mining and tunneling applications, including blasting backbreak, haulage surface condition, and excavation geometry. Thus, ***[25]*** offered a scale-dependent technique that uses 3D point clouds of rock surfaces gathered from terrestrial laser scanner (LiDAR) surveys to characterize overall rock surface roughness. To assess various aspects of extraction operations, the technique was thoroughly explained and implemented in different operational settings at two underground mines.

Moreover, monitoring operations are regularly conducted in underground coal mines to assess the stability of tramway tracks. The purpose of this activity is to provide precise information about the current condition of the rail system, as well as early detection of displacement and deformation. Thus, ***[26]*** presented the results of using TLS technology to monitor tram tracks in underground coal mines. In another paper, for the purpose of determining cross-penetrating length and volumes, ***[27]*** used TLS technology to provide findings of a highly precise control survey conducted during the Oyu Tolgoi project's underground mining. The aim of the measurements was to verify that excavation and penetration works' heading, total length, and volume were carried out in compliance with the intended and designed dimensions.

Furthermore, generating 3D models in mining areas based on TLS technology is also discussed in some studies. In Vietnam's underground mines, the development of a procedure for processing ground laser scanning data to create 3D models for checking the status of deep vertical wells has not been widely mentioned. To confirm the effectiveness of TLS in surveying the current status of vertical wells, ***[28]*** presented a process combining scanning stations and TLS data processing using specialized software Magnet Collage from Topcon to generate a 3D model of vertical wells at the Nui Beo coal mine with a depth of 400 m. Also related to generating 3D models in underground mines, ***[29]*** presented a method to create a 3D model using TLS at the Da Dang hydroelectric tunnel area (Lam Dong) with a quick measurement and processing time of 18 hours. This enabled determination of the collapsed tunnel location and spatial conditions at the incident site to support rescue work.

In addition to using TLS to generate 3D models, point cloud data can also be created by combining TLS with Unmanned Aerial Vehicles (UAV). Using integrated UAV and TLS point clouds, ***[30]*** created 3D CityGML models of mining industrial structures in the Nui Beo underground coal mine, Quang Ninh province, Vietnam. In this study, they built 3D CityGML models of buildings and mining industrial facilities in the surface plant area of an underground coal mine by gathering data across this area. Figure 1 shows the TLS point cloud displayed in SCENE software with over 32 million points. The study concluded that in mining industrial domains, both UAV and TLS technologies demonstrate strong potential for data collection for 3D model construction, particularly when used together.

To create an intelligent mine database for managing production in underground coal mines, ***[31]*** described how a 3D point cloud created by TLS and UAV photographs was integrated to generate a comprehensive 3D model of the ground plant of the Nui Beo underground coal mine at a depth of +35 m. The findings show that UAV and TLS supplement missing parts of point cloud data from each approach, and their combination allows the establishment of a complete 3D point cloud. Similarly, ***[32]*** introduced a solution to integrate point cloud data generated by UAV and TLS measurement technology performed at the open-pit mine industrial yard near a vertical well. TLS technology can effectively collect 3D point cloud data inside the well tower of the mine, while UAV imaging can generate point clouds of the outside part of the well tower, especially across the industrial yard. With the same conclusion, ***[33]*** confirmed that this method is ideal for modeling excavation surfaces and producing dense 3D point clouds, which can quickly yield precise and comprehensive geometric information in underground mines. Based on this study, it is feasible to survey and evaluate morphological changes in subterranean marble quarries using TLS and UAV approaches.

Besides generating 3D models, integration of UAV and TLS can also be applied to determine displacement in mining areas. According to ***[34]***, it is possible to precisely and rapidly monitor local rock mass movements at millions of locations using photogrammetry and laser scanning. Thus, they used this remote sensing technology to monitor rock mass motions and supporting systems in underground mine sites. On the other hand, literature shows that 3D models and other map products can typically be created using TLS alone or in combination with UAV. However, in a recent study, ***[35]*** integrated TLS, GNSS (Global Navigation Satellite System), and TS (Total Station) to generate these products. To create a 3D model of the examined pillars, the DEM and orthophoto of the quarry, as well as profiles of Brillouin frequency shift, strain, and temperature variation, TLS surveys were carried out with the assistance of GNSS and TS measurements.

2. Open-pit Mines

Applications of TLS in open-pit mines have become popular ***[36]***. According to ***[2]***, the emergence of modern technologies such as 3D laser scanning creates new opportunities, particularly for expansive and challenging locations like open-pit mines. To guarantee safe and continuous mining operations, systematic slope stability monitoring is required. The use of 3D terrestrial laser scanning to track landslides and slope displacements in open-pit mines has been addressed in ***[2]***.

To overcome the limitations of traditional methods, ***[37]*** proposed a TLS-based subsidence monitoring approach without targets in mining regions. With this approach, the primary task is transferred to the internal industry, labor intensity is reduced, and the field measuring process is simplified. It is suitable for monitoring surface subsidence in environments with complex topography and severe external conditions. Similarly, ***[38]*** described a method for monitoring subsidence in mining areas using TLS without targets. Compared with traditional techniques, this method transfers the primary

Fig. 1. TLS point cloud displayed in SCENE software ***[30]***

work to the internal industry, reduces labor intensity, and optimizes the field measuring process. It is appropriate for monitoring surface sinking in environments with challenging topography and harsh external conditions.

In addition, ***[39]*** presented the use of optical transducers, 3D laser scanners, and digital image processing methods to physically describe strata movements relevant to mining. They offered physical modeling of mining-induced subsidence using a variety of data processing techniques and several new optical and laser-based monitoring instruments. In ***[40]***, TLS was applied as the data acquisition tool to predict subsidence and horizontal displacement at Gubei Coal Mine in Huainan, China. Based on a small observation area, the analysis results revealed that the mining subsidence monitoring approach described in this study is capable of obtaining surface deformation across a large mining-impacted area. Furthermore, based on TLS point clouds, ***[40]*** proposed an automated technique for extracting building deformation in mining locations. The absolute error between the deformation values obtained by this method and the manual method was less than 8 mm, and the results were nearly identical. The suggested approach demonstrated greater stability compared with manual extraction.

In another study, this technique was used in situ to validate spatial variations (movements and deformations) of mining operations at a selected mining location in the Czech portion of the Upper Silesian Coal Basin. At Lazy Mine, the primary goal of 3D laser scanning was to track roadway deformation prior to approaching the longwall face on the chosen tailgate ***[41]***. Regarding displacement determination, ***[20]*** assessed the effectiveness of a stop-and-go laser scanning technique in the mine shaft to pinpoint the precise location, angle, and deviation of bunton plates at Thembelani Mine. The findings revealed that the real advantages of laser scanning are evident when continuous data analysis is required. Extensive laser scan datasets are available for off-site review and ongoing work by multiple departments and teams for a wide range of applications, including planning, design, engineering, safety, geology, and rock engineering.

In addition to using TLS technology to evaluate deformation during mining, this method is also applied to survey topography and produce maps. ***[42]*** discussed the features of TLS technology as well as its benefits for mapping and surveying in mining areas. Experiments indicate that the proposed approach can enhance the effectiveness of mapping and surveying in mining areas, and the resulting 3D model can be used to track extraction. According to ***[43]***, traditional surveys such as total stations are typically used to create maps of open-cast and underground mines; however, low point density often leads to low-precision maps. Thus, they used TLS to create high-definition maps and evaluated the possibility of using GeoMax Zoom 300 equipment to generate high-quality maps in specific coal mines in Vietnam where unfavorable conditions could affect measurement outcomes. The results show that this method meets all requirements for 3D mine mapping. TLS also provides important information that can aid in producing precise spatial findings.

Another application of TLS in open-pit mines is volume estimation. TLS has proven to be an effective tool for mining companies to monitor and survey their mines, boosting productivity and competitiveness in the market. This was demonstrated in ***[44]*** by comparing field test results using two different TLS instrument types for various mining applications, including volume estimation. The experiment showed that volume could be computed significantly more precisely with TLS than with a traditional total station. It is clear that TLS is a highly useful tool in the mining sector. Furthermore, the measurement of exploitative volumes in open-pit mines has already been proven feasible with TLS techniques in ***[36]***. This study proposed a coarse-to-fine method using terrain-invariant zones to register temporal TLS surveys. The suggested registration method outperformed state-of-the-art techniques and achieved strong results in terms of convergence rate and registration accuracy, according to experimental tests conducted in an open-pit mine in China.

According to ***[45]***, rapidly determining the amount of raw material collected from a surface quarry is a common issue in mineral resource extraction, particularly for heterogeneous resources. To determine the bulk density of raw material under in situ conditions, they conducted a study comparing laboratory and non-contact surveying methodologies in the field, where confirming the bulk density of extracted heterogeneous raw material is critical. Moreover, a crucial component of real-time mining management is the geometric characterization of bucketwheel excavators acquired by 3D laser scanning. Therefore, they used this tool to establish mathematical models of machine movement dynamics in three dimensions and to ascertain essential geometric properties of the devices ***[13]***.

Another application, not widely mentioned in studies but considered promising, is determining the discontinuous characteristics of limestone mines. ***[46]*** evaluated the possibility of employing laser scanning technology to characterize geometric discontinuities and determine the optimal scan configuration in terms of cost-benefit, balancing field time with positional quality of results.

Besides being used in isolation, this equipment can be integrated with other technologies to manage mining more efficiently and safely in open-pit mines, such as UAV, GNSS, and remote sensing. ***[47]*** combined TLS with UAV-based photogrammetry for three-dimensional mapping and monitoring of surface mine regions. The results also indicate that point clouds obtained by TLS can be used as ground control points in situations where conducting a GPS survey is challenging, such as in hilly or high-risk locations. Similarly, in ***[48]***, TLS 3D point clouds were merged with RGB images and digital photogrammetry from UAVs to map the open-pit mine located in Botticino. In addition to establishing a map, this technology can be utilized to interpolate 3D models of pit walls. ***[49]*** conducted experiments at the Coc Sau open-pit mine in Quang Ninh province, Vietnam, and at the experimental mine of Akademia Górniczo-Hutnicza University of Science and Technology in Cracow, Poland, to investigate mesh methods for interpolating 3D pit wall models. Using the same technology, ***[50]*** analyzed point clouds obtained with SfM photogrammetry and TLS in the Dreveník quarry, Slovak Republic. The findings indicated that both approaches are suitable as a foundation for systematic quarry monitoring.

In addition to UAVs, TLS also combines with ground-based synthetic aperture radar in mining activities. According to ***[51]***, slope stability monitoring has significantly improved in recent years thanks to the introduction of TLS, which allows three-dimensional assessment of slope motions. The implementation of TLS systems was previously restricted to short-range circumstances due to the instruments' useful range being constrained by the balance between laser power and eye safety. However, thanks to new developments and the application of infrared wavelengths, these restrictions have been overcome, and monitoring applications beyond 2,000 meters can now be carried out at high measurement rates without the safety risks associated with standard class 3R long-range laser scanners.

In addition to combining photogrammetry data, TLS can integrate with GNSS technology to monitor activities in surface mines. ***[52]*** used GPS and TLS combined monitoring technology to establish a ground surface digital elevation model of the mining area for subsidence monitoring. This method integrated the advantages of both GPS and TLS. TLS provides access to subsidence basin data in the mining area, compensating for GPS's point-based observational shortcomings and offering supplementary benefits. Figure 2 shows the dynamic subsidence basin between two scanning periods (January 31, 2008–February 13, 2008). Besides combining with GPS, this technology has also been integrated with ground-based synthetic aperture radar in slope stability research. Furthermore, by combining UAV point clouds and TLS data with GNSS positioning, geospatial experts can now generate 3D virtual surfaces thanks to large-scale, accurate, and time-efficient data collection made possible by terrestrial laser scanning and UAV photogrammetry. To create 3D surface models from independent spatial data collection technologies including UAV, TLS, and GNSS, ***[53]*** analyzed the consequences of integrating data sets and evaluated their accuracy for volume calculations in mining operations.

3. Closed Mines

In areas where mines have closed, topographic monitoring using laser scanning is helpful in identifying and preventing issues that could have a detrimental impact on the environment and the population. Using a network supported by GNSS technology, terrestrial laser scanning was carried out on the surface of the Victoria mine at the Slănic Prahova salt deposit, Prahova County, with a 3D laser scanner. The findings show that the use of laser scanning reduces the time required to perform measurements, which aids in accurate target interpretation ***[14]***. Figure 3 shows deformations occurring between the reference surface and that obtained from 3D scanning.

Results and Discussions

The study analyzed 39 research publications covering all aspects of TLS applications in the mining industry. Table 1 shows the distribution of TLS applications in mining and the corresponding references ***(Table 1)***.

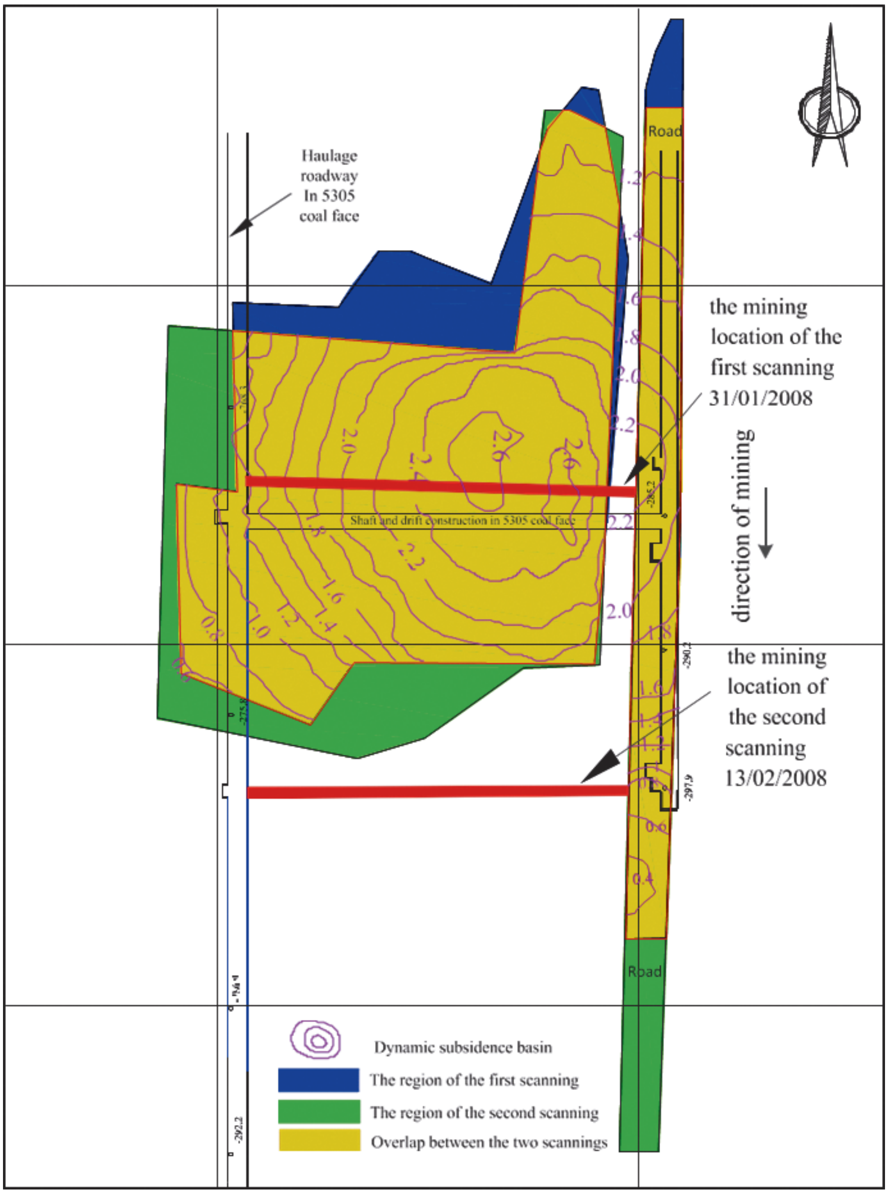

Fig. 2. Dynamic subsidence basin in Yanzhou coal mining area between two scanning periods *[52]*

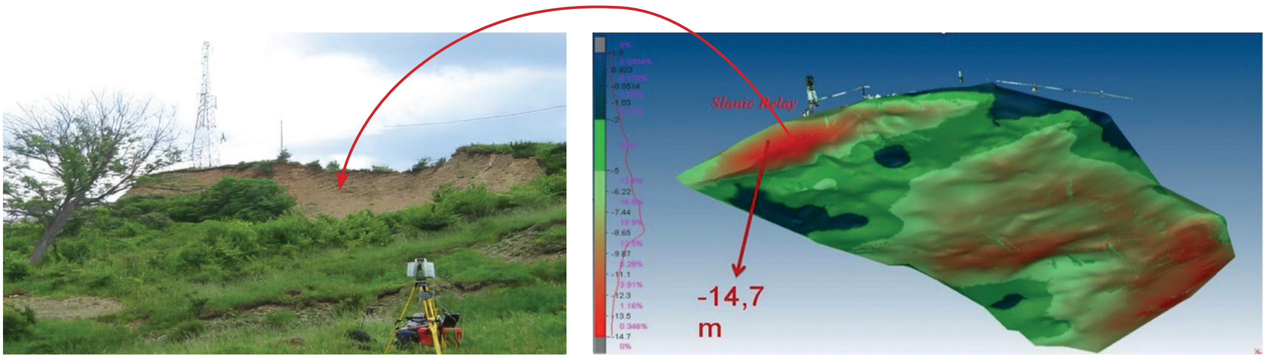

Fig. 3. Deformations occurring between the reference surface and that from 3D scanning *[14]*

Distribution of TSL application in mining and corresponding references

Kind of mine	Applications	Technology	References
Underground mines	Determine displacement	TLS	***[22]***
	Measure the geometric deformation		***[1]***
	Monitor deformation		***[23]***
	Characterize the rock bulk and create a discrete fracture network		***[24]***
	characterize the overall roughness of a rock's surface		***[25]***
	monitor tram tracks		***[26]***
	determining cross penetrating length and volumes		***[27]***
	Create 3D model		***[28]***, ***[29]***
	Create 3D model	TSL and UAV	***[30]***, ***[31]***, ***[34]***
	Generate point cloud data		***[32]***
	3D point clouds		***[33]***
	Determine the motions of rock masses		***[34]***
	Create 3D model	TSL, GSNN, and TS	***[35]***
Open-pit mine	Track landslides and slope displacements	TLS	***[2]***
	Monitor subsidence		***[37]***, ***[38]***, ***[39] [40]***
	Identify deformation		***[40]***
	Determine movements and deformations		***[41]***
	Assess mine shaft		***[20]***
	Mapping and surveying		***[42]***
	Create maps		***[43]***
	Estimate volume		***[44]***
	Measure exploitative volumes		***[36]***
	Determine geometric parameters of bucket-wheel excavators		***[13]***
	Determine the amount of raw material collected from a surface quarry		***[45]***
	Characterize discontinuities in a limestone quarry		***[46]***
	Mapping and monitoring of surface mine regions	UAV and TLS	***[47]***
	Map the open-pit mine		***[48]***
	Interpolate 3D models		***[49]***
	Analysis of point clouds		***[50]***
	Monitor slope stability	TLS and ground-based synthetic aperture radar	***[51]***
	Monitor subsidence	GPS and TLS	***[52]***
	Generate 3D virtual surfaces	UAV, TLS, and GNSS	***[53]***
Closed mine	Monitor deformation	TLS, and GNSS	***[14]***

Table 2. **The number of studies in each application in three types of mines**

Application	Underground mine	Open-pit mine	Closed mine	Total
Monitoring deformation/ displacement/ subsidence/ landslides	4	9	1	14
Generate a map/ 3D model/ point clouds	8	7		15
Estimate volume/ exploitative volumes/ raw material	1	3		4
Monitor slope stability/ topography	2	3		5
Monitor tram tracks	1			1
Total	16	22	1	

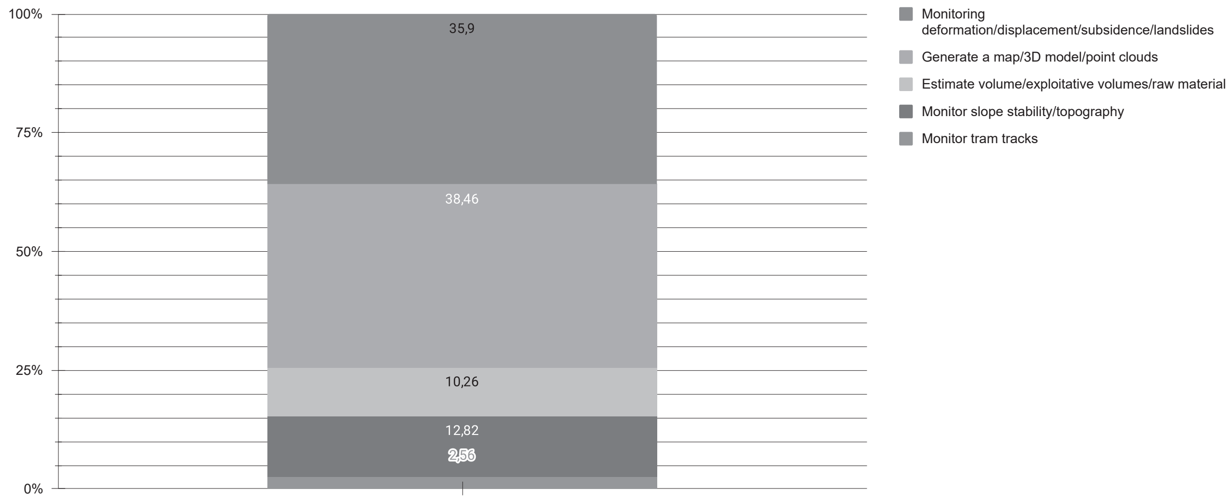

Fig. 4. Percentage distribution and number of studies that used TSL technology in mining

Based on the review, the following trends were identified as leading to the classification of existing TLS uses in mining ***(Table 2)***:

(1) Monitoring deformation, displacement, subsidence, and landslides (14)
(2) Generating maps, 3D models, and point clouds (14)
(3) Estimating volume and exploitative volumes (3)
(4) Monitoring slope stability and topography (4)
(5) Monitoring tram tracks (1)

The percentage distribution of each TLS application in mining, along with the number of studies under each category, is displayed in Figure 4. The results show that generating maps/3D models and monitoring deformation/displacement/subsidence were the most prevalent applications, accounting for around 40% of the reviewed studies. However, the number of studies applying the TLS method to these two applications in underground mines is lower than in open-pit mines. Applications of TLS in monitoring topography and estimating volume accounted for 12.82% and 10.26%, respectively. The least used application is monitoring tram tracks, with 2.56%. Notably, abandoned mines receive less attention than the other two types of mines, with only one study using this technology for such sites. Open-pit mines account for the largest share, with 22 publications across all applications.

Advantages, Challenges, and Future Trends

The findings show that TLS allows for quick and easy updates to plans and sections, making it the most suitable option for maintaining survey tempo in mining operations ***[18]***. This method outperforms geodetic and photogrammetric methods in terms of precision, speed, and effectiveness when performing the necessary computations throughout the measurement process. Compared with traditional techniques, this approach optimizes field measurement procedures, reduces labor intensity, and assigns the majority of tasks to the internal industry ***[38]***.

In addition, TLS technology provides objective, more accurate, and precise data on discontinuity orientations at a lower cost than previous approaches. Terrestrial laser scanning can be completed within minutes and offers a thorough investigation of rock surfaces. This system creates a controlled safety zone between 4 and 800 meters from the study field, reducing the risk of accidents ***[3]***. Furthermore, due to its wide range, it can reach places that are difficult to access. At the same time, it is suitable for monitoring surface deformation in challenging topographic settings and hostile external environments. TLS can also be integrated with GNSS systems to georeference points in the cloud ***[54]***. Moreover, using a laser is not harmful to human health, particularly to the skin or eyes. These advantages help explain why this technology is becoming increasingly common.

Despite these advantages, applying TLS technology in mining also has some limitations. Firstly, the point cloud generated, due to the large amount of information it contains, demands high computational and graphical processing capacity, requiring powerful processors and video cards ***[54]***. This makes the cost of purchasing hardware and software still relatively high. In addition, although manual target setup for point cloud registration provides high precision, it presents significant risks to personnel and instruments, and therefore its use is restricted. Consequently, reducing operational burden through 3D point cloud registration without targets is necessary for practical application and represents a step toward future development.

Furthermore, the findings indicate that most TLS advancements over the last fourteen years have focused on boosting measurement speed, enhancing reliability and precision, and improving the usability and functionality of instruments. Even though incremental progress is still being made in all three of these areas, the use of TLS in the mining industry is unlikely to undergo a breakthrough transformation. In the near future, research that combines TLS scanners with passive spectrum measurements (such as hyperspectral photography), as well as extended-range autonomous monitoring and scanning, will likely lead to revolutionary developments in the use of TLS. Additionally, scanners capable of providing information about material types and object characteristics by using multiple laser wavelengths should be studied and applied in different types of terrain ***[17]***.

Moreover, when discussing the future of TLS, it is important to consider several technological advancements that go beyond terrestrial laser scanning, as they can serve as both supportive and competitive instruments. First, there are recent advancements in generating 3D models from unstructured photo collections (generally referred to as Structure from Motion). According to ***[55]***, Structure from Motion (SfM) can produce 3D models equivalent to LiDAR in terms of accuracy and resolution, but generally at lower cost and with simpler use. Even though SfM has certain drawbacks, particularly its inability to penetrate vegetation, combining laser scanning and SfM for high-resolution modeling to maximize the advantages of both techniques is likely to become the preferred method for Earth scientists.

The second technological advancement is high-accuracy scanning implemented by UAV (ULS). To date, this technique has not been widely used in the mining industry, probably because investment in such systems is expensive. In fact, ULS may be a better data collection method in densely vegetated areas than ground-based technology ***[17]***. A complete point cloud for an entire object can be obtained by combining surveys from TLS and ULS. Gaps in point clouds that arise from TLS or ULS individual measurements can be eliminated through integrated approaches.

In addition, applying machine learning technology to TLS data should also be included in future research trends. This combination has already been applied in fields such as determining displacement of cultural heritage structures ***[56]***, differentiating wood and leaf points ***[57]***, semantic segmentation ***[58]***, and extracting building component data ***[59]***. However, this method has not yet been applied in the mining industry. A potential and essential prerequisite for boosting mining productivity and ensuring environmental protection is the application of machine learning technology in the mining sector ***[60]***. With reduced costs, increased efficiency and productivity, continuous production, enhanced safety, and less worker exposure to hazardous conditions, artificial intelligence, machine learning, and autonomous technologies offer the mining industry numerous financial advantages ***[61]***. Therefore, with these advantages, TLS technology should be integrated with machine learning and AI to increase the efficiency and safety of mining development and mineral exploration.

Conclusion

In this review, scholarly research on the use of TLS technology in mining over the last ten years was analyzed. A collection of 56 studies on the use of TLS was identified, published in academic journals as well as MSc and PhD theses. Their detailed contents were examined for systematic review. The findings indicate that the proposed method can be applied in many operations in the mining industry, such as monitoring deformation, displacement, subsidence, and landslides; generating maps, 3D models, and point clouds; estimating volume; monitoring topography; and tracking tram tracks. These applications are used mainly in open-pit mines, then in underground mines, and only rarely in closed mines. The applications of this technique are expanding, as it has been shown to be more beneficial than conventional methods in terms of operability, reliability, and cost- and time-efficiency. Furthermore, the results reveal that the TLS method is most widely used in monitoring displacement and creating maps/3D models. In the future, this approach should be integrated with AI and machine learning technologies to provide numerous financial advantages to the mining sector.

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Потенціал використання наземного лазерного сканування в гірничодобувній промисловості

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Останнім часом використання технології наземного лазерного сканування в гірничодобувній промисловості набуло популярності завдяки її численним перевагам, включаючи безконтактність, високу точність, швидкість і значний масштаб. Це дослідження має на меті дати ґрунтовний огляд застосування методу наземного лазерного сканування у підземних, відкритих та закритих шахтах, використовуючи дані з 56 публікацій за останні чотирнадцять років (2010–2024 рр.). Розглянуто масив спеціальної літератури, що показує, що підхід наземного лазерного сканування може бути застосований у п'яти основних операціях в гірничодобувних районах, а саме: для моніторингу деформацій, зміщень, просідання, зсувів, а також 3D-моделюванні. Результати дослідження показали, що наземне лазерне сканування є чудовою технологією для багатозадачності в будь-якому типі шахт. Крім того, у цьому дослідженні також окреслено майбутні тенденції розвитку гірничодобувної промисловості, засновані на інтеграції технологій наземного лазерного сканування, машинного навчання і штучного інтелекту. Результати цього дослідження можуть бути використані для створення специфікацій, необхідних для розгортання наземного лазерного сканування в різних типах шахт.

Ключові слова: *наземне лазерне сканування, просторові інформаційні дані, підземна шахта, відкрита шахта, закрита шахта.*

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