Application of Terrestrial Laser Scanning and Global Navigation Satellite System in the Mining Area

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Abstract

Terrestrial Laser Scanning and Global Navigation Satellite System technologies are increasingly prevalent in geodetic mapping work, playing a significant role in mine surveying tasks such as drawing maps for volume calculation, monitoring displacement, and deformation of mine surfaces and structures above mine tunnels. Currently, there are many studies on the application of these technologies in various aspects of mine surveying work. This paper will synthesize these studies to evaluate the effectiveness of applying GNSS and TLS technologies in mining surveying. The authors has reviewed 44 papers/projects in recent years and found that these technologies are developing rapidly, with the accuracy of coordinate and altitude measurement increasingly improving to approximately millimeters in both horizontal and vertical directions.

Keywords: *Terrestrial Laser Scanning, Global Navigation Satellite System, mine mapping, displacement, deformation, subsidence, open-pit mine, mining*

1. Introduction

Surveying to establish maps, update terrain, and serve blasting in open-pit mines is a daily task. In addition, surface deformation monitoring due to mining impacts is also carried out on a monthly, quarterly, or annual cycle. Currently, terrain surveying work serving the above purposes mainly uses TLS and GNSS equipment, the advantages of these technologies are high accuracy up to millimeters, reducing fieldwork time compared to measurement with electronic total stations. Currently, there are many advanced GNSS and TLS devices capable of measuring coordinates and elevation with high accuracy, such as Trimble R8 GNSS/RTK dual frequency.

GNSS stands as one of the most sophisticated technological instruments in today's world. The advent of contemporary satellite positioning systems has led to the widespread application of GNSS technologies such as COMPASS, GPS, GLONASS, and GALLIEO in fields like spatial information science, military operations, transportation, and resource exploration [1]. Several reviews have been conducted to date on the topic of surface deformation determination due to mining. In the research [2], authors offers a comparative analysis of diverse methodologies employed to assess subsidence related to mining. The results obtained indicate that over the past two decades, the primary techniques for detecting and measuring land subsidence incidents have included GIS and remote sensing, Light Detection and Ranging (LiDAR), and Differential Interferometric Synthetic Aperture Radar (DiNSAR). In a similar vein, authors discuss surface displacement measurement techniques used at underground mining sites, drawing on a comprehensive review of a substantial body of scientific literature and relating these to geodetic and remote sensing approaches [3]. [4] undertakes an analysis of a considerable number of research publications on the mapping and assessment of mining-induced subsidence using geographic information systems, while [5] provides an overview of techniques for monitoring, calculating, and simulating ground subsidence caused by coal mining. Also contributing to the review of displacement determination methods, [6] endorses the perspective that InSAR is an effective and sufficiently precise method for tracking ground displacements triggered by mining-induced earthquakes. Furthermore, from a subsidence management viewpoint, [7] proposes recommendations and methodologies to enhance the existing mine stability evaluation methodologies.

An innovative advancement in the collection of spatial information data is the terrestrial laser scanner (TLS). This cutting-edge technology enables the capture of data with a level of precision and accuracy that was previously unimaginable [8].. When compared to traditional measurement methods, TLS technology offers a significantly faster means of acquiring three-dimensional (3D) point information. According to [9], 3D data can be gathered rapidly, efficiently, with high precision, and in great detail using TLS. The term "point clouds" is used to describe the sets of data points that are acquired through this process [10]. Owing to its precision, reliability, and efficiency, TLS technology has become an invaluable tool for a diverse range of applications. These include evaluating various tunnel characteristics [11], mapping building surfaces [12], civil engineering projects [13], 3D surveying tasks [14], and activities within the architecture, engineering, and con-

Fig. 1. Modern GNSS and TLS equipments. Source: (left) https://ts-geosystems.com/product/trimble-r8-rtk-gps/ and (right) https://ajhsurveyors.com/wp-content/uploads/2020/11/2-3.jpg

Rys. 1. Nowoczesne urządzenia GNSS (lewa) and TLS (prawa)

struction industries [15]. Additionally, it is applied in fields such as geology [16], engineering geodesy [17] and deformation and displacement monitoring [18]. Furthermore, the key features of 3D laser scanning technology — its high precision, rapid speed, and close proximity to the prototype — make it extensively used across various mapping and other sectors. This technology provides a comprehensive and highly accurate reconstruction scan that can be accessed physically and quickly [19]. Beyond these applications, TLS is recognized as an exceptional technology with potential uses in numerous other fields, including the mining sector. Within this domain, it can be applied in many publications for mining management [20] and is capable of performing various operations in both underground [8] and open-pit mining environments [9].

It can be observed that studies on the application of GNSS and TLS in open-pit mining have been relatively extensive, covering a diverse range of topics. These studies encompass the use of these technologies in mapping, supporting drilling and blasting operations, monitoring surface displacement and deformation, and environmental fluctuation surveillance. This research aims to catalog the projects that have been implemented to date and, based on this review, propose new research directions for the future.

2. Material and methodology

The process of conducting a systematic review involves identifying relevant works and concepts, transforming these into search terms and syntax, conducting a systematic search across various databases, and collecting a comprehensive collection of relevant literature. The review begins with the identification of key works and specific concepts that are relevant to the topic at hand. These identified works and concepts are then transformed into search terms and syntax that can be used to retrieve related studies. In the context of this particular research, the search terms and syntax have been established as follows: (1) The search syntax includes terms such as "Global Navigation Satellite System" or "GNSS"; "Terrestrial Laser Scanning" or "TLS"; "Mine surveying"; "Mapping"; "Subsidence" or "Displacement"; and "Mine", "Mining", or "Open-pit mine". These terms are carefully chosen to ensure that the search results are as relevant as possible to the research topic; (2) This search syntax is then used to conduct a systematic search across various databases. The databases that are searched include Google Scholar, Scopus, Web of Science, and ScienceDirect. These databases are chosen for their extensive collection of academic and scientific literature; (3) The primary language used for conducting these searches is English. This is because English is the most commonly used language in scientific literature, and using English as the primary search language ensures that the search results are as comprehensive as possible; (4) The result of this systematic search is a comprehensive collection of scientific literature that covers many aspects of mapping and subsidence investigation by GNSS and TLS techniques. This collection of literature provides a wealth of information and insights into the topic at hand; (5) The types of literature that are collected include book chapters, conference proceedings, and original papers that have been published by international journals following a rigorous peer review process. These types of literature are chosen for their academic rigor and their relevance to the research topic.

3. Application of GNSS technology in mining area

The RTK method has become extensively utilized for monitoring deformation in mining sites. The application of the GNSS method in subsidence monitoring dates back to the early years of the last decade. To meet the precise requirements of surface deformation monitoring. In [21], authors proposed an innovative GPS RTK surveying technique that incorporates rod measurement. This technique mitigates the influence of multipath error in the U direction, effectively prevents the impacts of vertical deviation and shaking error of the surveying g rod, and further enhances positioning precision. Similarly, in the study [22], the GPS RTK approach has been adopted to improve the accuracy and reliability of mine surface subsidence monitoring. An in-depth analysis of the mechanism responsible for the primary systematic errors was conducted, drawing on several theories and techniques. This method can significantly increase the accuracy of estimations by completely eliminating inevitable shaking errors, vertical deflection, and to some extent, reducing the multipath effect. In this research [23], based on GNSS technology, findings from two years of ground deformation monitoring in coal mining regions in Upper Silesia, Poland, are presented. Real-time (RT) and near real-time (NRT) GNSS techniques were employed to verify long-term subsidence events, and these were cross-referenced with daily postprocessing solutions. Additionally, [24] provided the processing procedure and findings from their analysis of earth surface displacement data observations during coal mining at the Kostenko mine of the Coal Department of ArcelorMittal Temirtau JSC in the Karaganda Coal Basin using GNSS methods. The obtained results indicate that the proposed method of observing the displacement of the earth's surface is more economically ad-

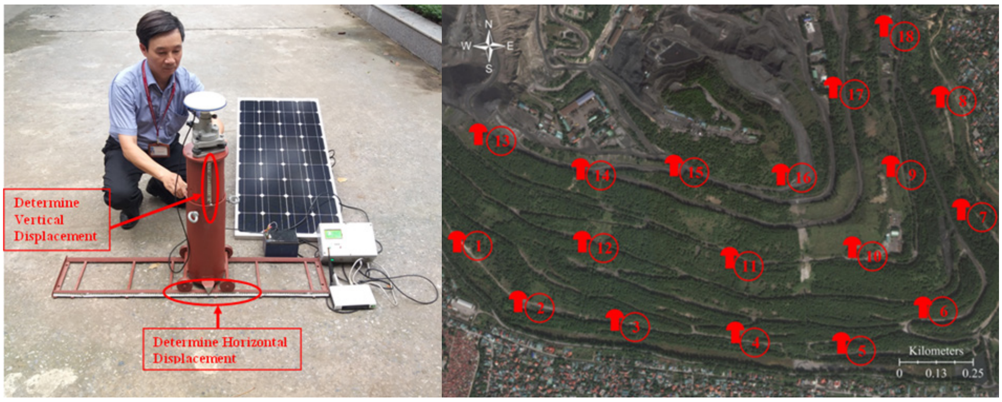

Fig. 2. GNSS/CORS-Based Technology for Real-Time Monitoring of Landslides on Waste Dump [27]
Rys. 2. Technologia oparta na GNSS/CORS do monitorowania w czasie rzeczywistym osuwisk na zwałowisku [27]

vantageous and requires significantly less time compared to traditional, expensive geodetic methods. According to [1], to establish real-time and quasi-real-time deformation monitoring methods, the GNSS Continuously Operating Reference Station (CORS) offers services for navigation based on pseudo range measurements and provides carrier phase information. Therefore, in light of mining technology for CORS, they suggested a large-area 3D deformation monitoring system for mining areas. The results showed that the proposed GNSS-RTK can improve both the temporal and spatial resolution of mine deformation monitoring. In another study, it has been demonstrated that it is possible to evaluate displacements both vertically and horizontally with great precision using geodetic networks. These networks consist of inclinometers and GPS networks to facilitate the detection of horizontal motions, while high-precision leveling systems are capable of estimating subsidence values. This study presented the results and observations on the use of a GPS geodetic network for continuous surface deformation monitoring in waste dumps of the Bages region of Catalonia (Spain) [24]. Furthermore, the utilization of GNSS satellite receivers and robotic total stations to monitor open pit mines is presented in [25]. This study demonstrated the combination of robotic total station equipment and GNSS receivers to provide a completely automated, accurate, efficient, and economical survey monitoring system for large open pit mines. The study [26] was shown that large-scale mobility in the mining area can be detected using continuous-time or GNSS location time series with high sample rates. Consequently, they presented a GPS method for monitoring seismic events and surface displacement that occurs during mining-induced tremors.

In the study GNSS/CORS-Based Technology for Real-Time Monitoring of Landslides on Waste Dump – A Case Study at the Deo Nai South Dump, Vietnam, the authors have self-produced a monitoring system using GNSS technology and tested it at the Deo Nai mine (Vietnam). The results demonstrated that this system operates well, with measurement accuracy comparable to major brands' monitoring equipment such as Leica and Topcon.

Moreover, the accuracy of the GNSS method is emphasized in various studies. For instance, [28] examined the duration necessary for GPS sessions in ground deformation measurements within mining areas. The findings revealed that a GPS session should last a minimum of twelve hours to achieve sub-centimeter precision in height coordinates at a 95% confidence level in a single observation session. Additionally, [29] conducted a study on monitoring local deformation using GNSS in an open-pit mine, addressing the challenge of achieving millimeter-level accuracy in displacement measurements with GPS. According to [29, high-accuracy geodetic surveys are essential for determining deformation indices in areas impacted by open-pit mining, facilitating the identification of potential hazards. Consequently, they discussed the fundamentals of precisely determining three-dimensional displacements using GPS technology. The results demonstrated that the 3-D coordinates of the observed points could be accurately determined to within mm accuracy.

In addition to determining deformation caused by mining, GNSS methods are extensively utilized for monitoring ground subsidence in mining areas. According to [30], the amplitude of ground subsidence in coal-mining regions can reach up to 10 cm per day, occurring continuously. This highlights the necessity for timely and accurate monitoring to ensure the safety of coal-mining areas. The study presents a real-time ground subsidence monitoring system that continuously operates on the Global Navigation Satellite System. Unlike traditional leveling surveying approaches, this method meets the precision requirements for ground subsidence monitoring and provides continuous subsidence information in real-time. Moreover, the application of GNSS methods extends beyond routine deformation monitoring to encompass large-scale subsidence observations. A high-precision GNSS monitoring system was constructed to precisely observe extensive mining subsidence areas. This system utilizes neighboring International GNSS Service (IGS) stations as reference points to enhance accuracy [31]. The proposed theory was successfully implemented to monitor mining subsidence in China's northern Anhui coal mine, demonstrating the system's efficacy in providing precise and reliable data. The significance of these advancements lies in their ability to provide real-time, continuous monitoring of ground subsidence, which is crucial for maintaining the integrity and safety of mining regions. Traditional leveling methods, while accurate, are often labor-intensive and time-consuming, limiting their effectiveness in providing immediate data necessary for proactive safety measures. In contrast, the GNSS-based systems leverage real-time data transmission, allowing for immediate analysis and response to subsidence events. This capability is particularly important

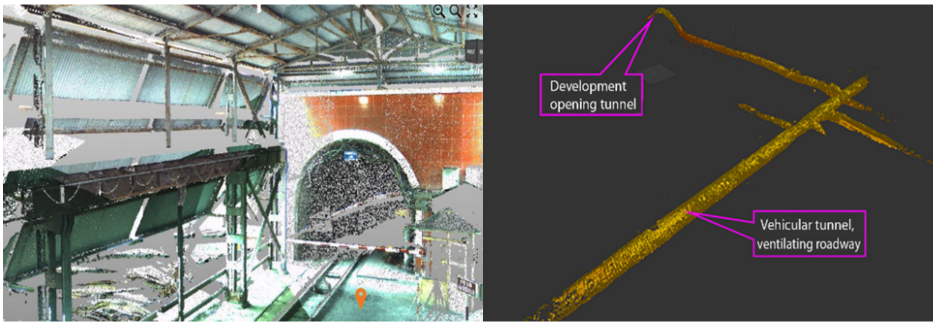

Fig. 3. Application of TLS in Khe Cham underground mine, (a) High definition mapping of inclined drift entrance; (b) Point cloud data of Khe Cham underground mine at the level of -170 m [40]

Ryc. 3. Zastosowanie TLS w podziemnej kopalni Khe Cham, (a) Mapowanie w wysokiej rozdzielczości pochyłego wejścia do sztolni; (b) Dane chmury punktów podziemnej kopalni Khe Cham na poziomie -170 m [40]

in coal-mining regions where subsidence can rapidly progress, posing risks to infrastructure and human safety. Furthermore, the integration of neighboring IGS stations as reference points, as detailed in [31],, enhances the precision of the GNSS monitoring system. These stations provide a stable and reliable framework for reference, enabling the system to detect even minute changes in ground levels with high accuracy. This approach not only improves the overall reliability of subsidence monitoring but also expands the system's applicability to larger geographic areas, thereby offering comprehensive surveillance over extensive mining regions. The study conducted in northern Anhui, China, exemplifies the practical application of this advanced monitoring technology. By implementing a high-precision GNSS system, researchers were able to obtain detailed subsidence data, which is critical for developing effective mitigation strategies and ensuring the long-term safety of the mining operations. The successful application of this technology in such a significant coal-mining area underscores its potential for widespread adoption in other regions facing similar subsidence challenges. The use of GNSS methods for monitoring ground subsidence in mining areas represents a significant leap forward in terms of precision, real-time data availability, and overall efficiency. These systems not only provide critical safety data but also facilitate a more proactive approach to managing the inherent risks associated with mining activities. By continuously monitoring subsidence and utilizing advanced reference frameworks, GNSS-based methods offer a robust solution for safeguarding mining regions and mitigating the impacts of ground deformation.

4. Application of TLS in mining site

The advent of modern technologies such as 3D laser scanning has opened new possibilities, especially for expansive and challenging environments like open pit mines [9], Systematic slope stability monitoring is essential to ensure safe and continuous mining operations. The application of 3D terrestrial laser scanning for tracking landslides and slope displacements in open pit mines has been extensively discussed in [9]. To overcome the limitations of traditional methods, , [32] proposes a TLS-based subsidence monitoring approach that operates without targets in mining regions. This method shifts the primary workload to the internal industry, reduces labor intensity, and simplifies the field measurement process. It is particularly suitable for monitoring surface subsidence in areas with difficult topography and harsh external conditions. Similarly, [33] describes a method for monitoring subsidence in mining areas using TLS without the need for targets. Compared to traditional techniques, this method transfers the main tasks to the internal industry, reduces labor demands, and optimizes the field measurement process. It is well-suited for environments with challenging topography and severe external conditions. Additionally, [34] discusses the use of optical transducers, 3D laser scanners, and digital image processing methods to physically describe the movement of strata related to mining. They presented physical modeling of mining-induced subsidence using various data processing techniques and innovative optical and laser-based monitoring instruments. In the study by [35], TLS was employed as the data acquisition tool to predict subsidence and horizontal displacement at Gubei Coal Mine in Huainan, China. The analysis results from a small observation area demonstrated that the mining subsidence monitoring approach described in this study could effectively capture surface deformation in a large mining-impacted area. Moreover, [36] developed an automated technique based on TLS point cloud data for extracting building deformation in mining locations. The absolute error between deformation values obtained by this method and those obtained manually was less than 8 mm, indicating a high degree of accuracy. This approach showed greater stability compared to manual extraction methods. Another study aimed to validate spatial variations (movements and deformations) in mining operations by applying this technique in situ at a chosen mining site in the Czech part of the Upper Silesian Coal Basin. At Lazy Mine, the primary goal of 3D laser scanning was to monitor the deformation of roadways as they approached the longwall face on the selected tailgate [37].

Additionally, [38] assessed the effectiveness of a stop-and-go laser scanning technique in a mine shaft to accurately determine the position, angle, and deviation of the bunton plates at Thembelani Mine. The findings revealed the significant advantages of laser scanning, particularly when continuous data analysis is required. Extensive laser scan datasets are available for off-site review and ongoing work by multiple departments and teams, supporting a wide range of applications including planning, design, engineering, safety, geology, and rock engineering. These advancements underscore the transformative impact of 3D laser scanning technology in mining operations. The ability to conduct high-precision monitoring of slopes, subsidence, and structural deformations in real-time enhances safety and operational efficiency. By leveraging TLS, mining companies can reduce labor intensity, streamline field operations, and obtain highly accurate data critical for various applications. This technology is particularly beneficial in environments with complex topographies and harsh conditions where traditional methods fall short. The integration of 3D laser scanning with other modern monitoring tools and data processing techniques further expands its utility, enabling comprehensive and precise modeling of mining-induced ground movements. Overall, the adoption of these advanced monitoring approaches represents a significant step forward in ensuring the stability and safety of mining operations. Many projects use TLS for mines and tunnels, shaft, etc., which helps in detailed 3D simulation of these mines and displacement determination [8, 39]. In Vietnam, this technology has been tested at the Khe Cham coal mine [40]. In addition, TLS has also been tested in 3D modeling measurements at the Coc Sau coal mine. This shows that this technology is gradually being put into practical use in Vietnam [41].

According to [42], quickly determining the amount of raw material extracted from a surface quarry is a common challenge in the extraction of mineral resources, especially heterogeneous ones. To address this, a study was conducted comparing and evaluating laboratory and non-contact surveying methodologies to determine the bulk density of raw material under in situ conditions. Confirming the bulk density of extracted heterogeneous raw material is critical, and the study highlighted the effectiveness of TLS in achieving this. Additionally, the geometric characteristics of bucket-wheel excavators, essential for real-time mining management, can be accurately acquired using 3D laser scanning. This technology was used to establish mathematical models of the movement dynamics of these machines in three dimensions and determine their essential geometric properties [20]. Another significant application of terrestrial laser scanning (TLS) in open pit mines is volume estimation. This method is proving to be an invaluable tool for mining companies, enabling them to monitor and survey their operations more effectively, which in turn can enhance productivity and competitiveness in the market. This was demonstrated in [43], where field tests using two different types of TLS instruments for various mining applications, including volume estimations, were compared. The experiment revealed that volume could be calculated with significantly greater precision using TLS compared to traditional total stations. The results clearly indicate that TLS is a highly useful tool in the mining sector. Furthermore, the capability of TLS techniques to measure exploitative volumes in open-pit mines has been established in study [44].. This research proposed a coarse-to-fine method utilizing terrain-invariant zones to register temporal TLS surveys. According to experimental tests conducted in an open-pit mine in China, the proposed registration method outperformed state-of-the-art techniques, achieving superior performance in terms of convergence rate and registration accuracy.

The application of TLS for volume estimation in open pit mines allows for more accurate and efficient monitoring of extracted materials. The precision of TLS surpasses that of traditional methods, enabling mining companies to better manage resources and optimize their operations. This technology not only improves the accuracy of volume measurements but also facilitates the continuous monitoring of mining activities, providing real-time data that can be used for immediate decision-making. Moreover, the ability to measure bulk density of raw materials using non-contact surveying methods such as TLS offers significant advantages in terms of speed and safety. By avoiding the need for direct contact with the material, these methods reduce the risk of accidents and allow for quicker data collection. This is particularly important in the context of heterogeneous mineral resources, where the variability in material properties can make traditional sampling methods less reliable. The use of 3D laser scanning to capture the geometric properties of mining machinery further underscores the versatility and utility of TLS in the mining sector. By creating detailed models of equipment like bucket-wheel excavators, mining companies can better understand the dynamics of their machinery and optimize their use. This can lead to improvements in efficiency and reductions in maintenance costs, as well as enhanced safety for workers. The application of TLS in open pit mining for volume estimation, bulk density measurement, and equipment modeling represents a significant advancement in mining technology. The precision, efficiency, and safety benefits of TLS make it an indispensable tool for modern mining operations, enabling companies to remain competitive in a challenging market.

5. Conclusion

This in-depth study explores the application of TLS and GNSS techniques in mining areas, drawing from a wide range of publications that have emerged in recent years. The review embarked on a thorough analysis of 44 papers, all of which are related to mapping and displacement monitoring in mining areas using the TLS and GNSS methods. These papers, published in reputable scientific journals, provide a rich source of information on the subject. The results obtained from this comprehensive review demonstrate that both TLS and GNSS technologies can be effectively utilized to determine surface deformation in various mining environments, including underground mines, shafts, open-pit mines, and waste dumps. This capability to accurately measure and monitor displacement is crucial in maintaining the safety and efficiency of mining operations. As evidenced in this paper, the monitoring results achieved through these technologies are remarkably precise, with accuracy reaching the millimeter level. This high level of accuracy ensures the effective use of these technologies in the future, indicating that they can provide many long-term beneficial applications in mapping and monitoring movements in mining areas. This study, therefore, not only discusses the utilization of these techniques but also highlights their potential in transforming the way displacement is monitored in mining areas, thereby contributing to safer and more efficient mining operations areas.

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Zastosowanie naziemnego skaningu laserowego i globalnego systemu nawigacji satelitarnej na obszarze górniczym

Technologie naziemnego skanowania laserowego (TLS) i globalnego systemu nawigacji satelitarnej (GNSS) są coraz bardziej powszechne w pracach związanych z kartowaniem geodezyjnym, odgrywając znaczącą rolę w zadaniach geodezyjnych w kopalniach, takich jak tworzenie map do obliczania objętości, monitorowanie przemieszczeń i deformacji powierzchni i konstrukcji nad wyrobiskami górniczymi. Obecnie prowadzonych jest wiele badań nad zastosowaniem tych technologii w różnych aspektach prac geodezyjnych w kopalniach. W artykule dokonana została synteza tych badań w celu oceny efektywności zastosowania technologii GNSS i TLS w górnictwie. Autorzy dokonali przeglądu 44 artykułów/projektów z ostatnich lat i stwierdzają, że technologie te bardzo szybko się rozwijają, a dokładność pomiaru współrzędnych i wysokości wzrasta do poziomu pojedynczych milimetrów zarówno w kierunku poziomym, jak i pionowym.

Słowa kluczowe: *Terrestrial Laser Scanning, Global Navigation Satellite System, mapowanie kopalń, przemieszczenie, deformacja, osiadanie, kopalnia odkrywkowa, górnictwo*