



A Review of the Application of Terrestrial Laser Scanning in Challenging Environments

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Abstract

Terrestrial Laser Scanning (TLS) technology has become a highly effective tool for capturing detailed and precise 3D data across various fields, especially for challenging environments such as complex terrain. Its key features, including high precision and rapid data acquisition, make it extensively used in mapping, geology, construction, and mining areas. TLS is particularly beneficial in the mining sector, aiding in detailed mapping, monitoring slope stability, and volume estimation. The technology's ability to quickly capture millions of data points enhances efficiency and reduces costs compared to traditional surveying methods. Additionally, TLS is adaptable to various environments, from urban settings to rugged terrains, making it valuable for environmental monitoring and research. Reviews have highlighted its effectiveness in monitoring ground deformations, enhancing accuracy in construction projects, and improving safety and efficiency in challenging environments. The integration of TLS with other technologies, such as UAV photogrammetry and GNSS, further enhances its capabilities, providing comprehensive data for various applications. This study aims to provide a thorough overview of the application of TLS in complex terrains, using data from publications over recent years. The reviewed literature demonstrates that TLS can be effectively applied in challenging environments.

Keywords: Terrestrial Laser Scanning, TLS, Complex terrain, Mountain area, Open-pit mine, Landslide.

1. Introduction

According to [1], TLS can quickly, effectively, and precisely capture 3D data with great detail. According to [2], key features of Terrestrial scanning technology are high precision, rapid speed, making it extensively used in various mapping and other sectors. TLS provides a comprehensive and highly accurate reconstruction scan that can be accessed physically and quickly. Additionally, TLS is an exceptional technology that can be applied in many fields. This approach is frequently utilized in publications for the management of mining [3]. Furthermore, TLS technology's ability to capture detailed and precise 3D data makes it invaluable for various industries. For instance, in civil engineering, it aids in the accurate mapping of structures and terrain, ensuring that projects are built to exact specifications [4]. In geology, TLS helps in the detailed study of rock formations and fault lines, providing critical data for understanding geological processes [5]. Additionally, TLS is used in monitoring deformation, where it tracks changes in structures or landscapes over time, providing essential data for maintenance and safety assessments [6]. In the mining sector, TLS technology is particularly beneficial. It allows for the detailed mapping of mine interiors, which is crucial for planning and safety [3]. This versatility and precision make TLS an indispensable tool across various fields, enhancing the accuracy and efficiency of numerous applications. Moreover, the speed at which TLS can collect data is a significant

advantage over traditional methods. Traditional surveying techniques can be time-consuming and labor-intensive, often requiring multiple visits to a site to gather all necessary data. In contrast, TLS can capture millions of data points in a matter of minutes, providing a complete and detailed 3D representation of the surveyed area [1]. This efficiency not only saves time but also reduces costs associated with data collection. The precision of TLS is another critical factor that sets it apart from other measurement methods. The technology can detect minute details and variations in the surface being scanned, which is essential for applications that require high accuracy. For example, in the field of architecture, precise measurements are crucial for the restoration of historical buildings, where even the smallest error can lead to significant issues [7]. Similarly, in civil engineering, accurate data is necessary for the design and construction of infrastructure projects, ensuring that they meet safety and regulatory standards [4]. Additionally, TLS technology is highly adaptable and can be used in various environments, from urban settings to remote and rugged terrains. This adaptability makes it a valuable tool for environmental monitoring and research. For instance, in geology, TLS can be used to monitor changes in landscapes over time, such as erosion or landslides, providing valuable data for predicting and mitigating natural disasters [5]. In forestry, TLS can help in the assessment of forest

structure and biomass, contributing to better forest management and conservation efforts.

To gain a comprehensive understanding of the application of TLS technology across various fields, several reviews have been conducted. For instance, [8] provided an extensive summary of studies and applications of TLS for monitoring ground and building deformations. This review highlighted the effectiveness of TLS in capturing precise deformation data, which is crucial for structural health monitoring and geotechnical assessments. In the architecture, engineering, and construction (AEC) industry, [7] introduced TLS and elaborated on its potential benefits for this sector. The review emphasized how TLS can enhance accuracy in construction projects, streamline workflows, and improve project outcomes by providing detailed 3D models of construction sites. This technology is particularly advantageous for complex projects where precision and detail are paramount. According to [9], while TLS techniques are not yet widely adopted in tunnel studies, there is significant untapped potential. The review explored how TLS could be utilized to measure various tunnel characteristics, such as cross-sectional profiles, surface deformations, and structural integrity. By leveraging TLS, engineers can obtain high-resolution data that can improve the safety and efficiency of tunnel construction and maintenance. Additionally, [10] discussed the application of TLS technology in the context of British geological surveys, focusing on its role in modeling, monitoring, and mapping geohazards. This review showcased how TLS can be used to assess landslides, rockfalls, and other geological hazards, providing

valuable data for risk assessment and mitigation strategies. Moreover, recent advancements in TLS instruments were reviewed by [11], who examined their potential impact on future applications in Earth sciences. This review highlighted innovations such as increased scanning range, improved accuracy, and enhanced data processing capabilities. These developments are expected to expand the use of TLS in various Earth science applications, including environmental monitoring, natural disaster assessment, and climate change studies. In summary, these reviews collectively illustrate the diverse applications and significant benefits of TLS technology across multiple fields. From monitoring structural deformations and enhancing construction accuracy to assessing geological hazards and exploring tunnel characteristics, TLS continues to prove its value as a versatile and powerful tool. As advancements in TLS technology continue, its adoption and impact are likely to grow, offering even more opportunities for innovation and improvement in various scientific and industrial domains. In addition to evaluating TLS applications in various fields, numerous scientists have also explored its use in the mining industry. For instance, [12] conducted a comprehensive investigation into TLS technology, covering its operational principles, measurement techniques, 3D TLS software, and benefits. Meanwhile, [13] focused on the applications of 3D TLS within the mining sector, and [14] provided an overview of laser scanning's uses in underground mining for geological and geotechnical purposes. Additionally, [2] discussed the current state and future trends of 3D laser scanning technology in mining.



Figure 1. Some notable TLS devices from leading manufacturers [15]
Rys 1. Niektóre znane urządzenia TLS od wiodących producentów [15]

2. Methodology

The primary objective of this review is to conduct a comprehensive study that categorizes and summarizes the concepts, ideas, and innovations proposed by various authors and research teams worldwide regarding the application of TLS

technology in the mining sector. This involves a meticulous examination of the literature to identify and classify the different ways TLS has been utilized in mining operations. To achieve this, the study employs a systematic approach to gather and analyze relevant publications. The first step involves identifying and selecting appropriate keywords that encapsulate the

scope of the research. The keywords used in this study include "Terrestrial Laser Scanning", "TLS", "open-pit mine", "surface mine", "mining industry", "mountain area", and "landslide". These keywords are crucial for ensuring that the search captures a wide range of studies related to the application of TLS in mining. The data for this review were sourced from several significant academic databases and repositories, including Google Scholar, Web of Science, IEEE Xplore, and ScienceDirect. These platforms were chosen due to their extensive collections of peer-reviewed articles, conference papers, and other scholarly publications. The search process involved using the selected keywords to find relevant studies published in these databases. Once the initial search was completed, the next step was to screen the results to ensure relevance and quality. This involved reviewing the titles, abstracts, and full texts of the publications to determine their suitability for inclusion in the review. Studies that directly addressed the application of TLS in mining were selected, while those that did not meet this criterion were excluded. This rigorous screening process ensured that only the most relevant and high-quality studies were included in the final review. In total, 43 documents including papers and information on website were collected for this review. These papers were then analyzed to extract key information about the application of TLS technology in the mining sector. The analysis focused on identifying the specific uses of TLS, the benefits and challenges associated with its implementation, and the innovations and advancements that have been made in this field. The collected data were then categorized based on the identified applications of TLS in mining. This categorization helped to organize the information in a coherent manner, making it easier to identify patterns and trends in the use of TLS technology. The categories included applications such as slope stability monitoring, volume estimation, mapping and surveying, and integration with other technologies. By systematically categorizing and summarizing the concepts, ideas, and innovations from the selected

studies, this review provides a comprehensive overview of the current state of TLS technology in the mining sector. It highlights the significant advancements that have been made, the challenges that remain, and the potential future directions for research and development in this field. This methodology ensures that the review is thorough, well-organized, and provides valuable insights into the application of TLS technology in mining.

3. Application of TLS for challenging environments

The use of TLS for various tasks, such as monitor landslides in mountain areas and riverbanks, help for understanding and management of natural hazards, open-pit mining works, has become increasingly popular, with notable research projects. Landslides pose significant threats to human life and development. Monitoring and early warning are crucial but challenging in mountainous areas due to difficult terrain and data issues. A method combining TLS and UAV photogrammetry to monitor landslides in complex terrains was introduced. TLS enhances ground control points (GCPs) for UAVs, and assumed control points (ACPs) help calculate landslide displacement in blind areas. Applied to a real case, this method successfully monitored landslides despite access limitations, enabling high-precision measurements for emergency and long-term risk evaluation [16]. For over a decade, digital elevation models (DEM) from LIDAR technology have advanced geomorphologic and landslide studies. Terrestrial laser scanning (TLS) offers versatile applications, useful for both monitoring and emergency hazard assessments. This abstract highlights three case studies demonstrating TLS's effectiveness in landslide volume quantification, profile creation, and time series analysis. The examples include landslides in sensitive clays in eastern Canada and small rotational slides in river banks in Switzerland [17].

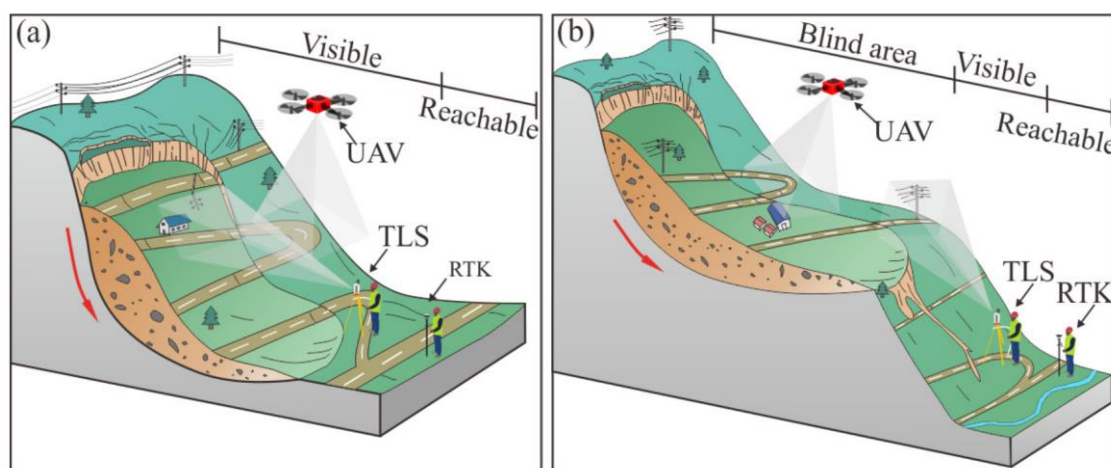


Figure 2. Landslide monitoring in complex terrain conditions [16]
Rys 2. Monitorowanie osuwisk w warunkach skomplikowanego terenu [16]

Monitoring permafrost in Alpine environments is crucial due to its sensitivity to climate change and slope destabilization. Rock walls react quickly to climate changes, posing hazards. Using terrestrial laser scanning help for understanding and management of natural hazards. It analyzes two scan systems for monitoring a deglaciated permafrost rock wall at Gemsstock, Swiss Alps, optimizing referencing methods and accuracy. Over four years, mass movements of about 1800 m³ and mean erosion rates of 6.5 mm/year were detected. Volumetric changes from rock falls and melting ice were measured with 4%-10% accuracy [18]. For better risk management, detailed measurements of channel and stream-bed structures are essential. The study examines how TLS acquisition protocols affect data accuracy in mountain channels. It tested the impact of scanner height and incident angle on point density and accuracy, and the effect of minimum point spacing on the Digital Terrain Model (DTM). Combining multiple TLS data from different directions improved accuracy, while denser point clouds did not. TLS data for a cascade unit showed lower accuracy, requiring special consideration [19]. Sediment yield is crucial for river basin management due to its environmental impact. The link between weather, river flow, and bank erosion is not well understood. This study used high-resolution 3D models from multi-temporal terrestrial laser scanning to monitor four riverbanks in Val Tartano, Northern Italy, over a year. The research aimed to understand how, when, and how much erosion occurs. The method effectively measured both eroded and deposited volumes, providing insights into erosion processes and their triggers. An attempt to extrapolate these findings to a basin scale was also made [20]. This study presents a novel approach combining TLS and UAV-based close-range photogrammetry to map complex alpine

terrain. Applied in the Tatry Mountains, Slovakia, the method addresses challenges like data shadows in rugged, deglaciated areas. TLS provides accurate point clouds, supplemented by UAV data where TLS coverage is insufficient. The iterative closest point adjustment between UAV and TLS data achieved centimeter-level accuracy, with millimeter-level standard deviation in TLS scans. The resulting high-resolution DEM was validated against SRTM, TanDEM-X, and national DMR3 DEMs, proving effective for various geomorphologic applications [21]. The study evaluates high-resolution photogrammetric DEMs and orthomosaics from 2020 aerial images over Hornsund, Svalbard, and compares them with 2021 DEMs. Both datasets were georeferenced using reliable ground control points but had gaps due to image overlaps and TLS range limits. By integrating both techniques, a continuous, gapless DEM was created, revealing geomorphological changes over a year, such as ice core melting, shoreline changes, and snow thickness variations. This approach enhances understanding of Arctic processes [22]. The study focused on evaluating and assessing the accuracy of a method for quantifying extreme events. Tie-point based registration was insufficient, requiring Multi Station Adjustment to reduce height errors to less than 10%, comparable to ALS campaigns. Complex terrain and dense shrub vegetation posed challenges, necessitating a specialized filter algorithm. ALS data overestimated ground heights by an average of 70 cm. Despite these issues, the method was effective for extreme event quantification. Debris flow volumes of 5000 to 12,000 m³ were assessed, with better accuracy for erosional features. The magnitude of flows was influenced by catchment size, topography, and historical deforestation [23].

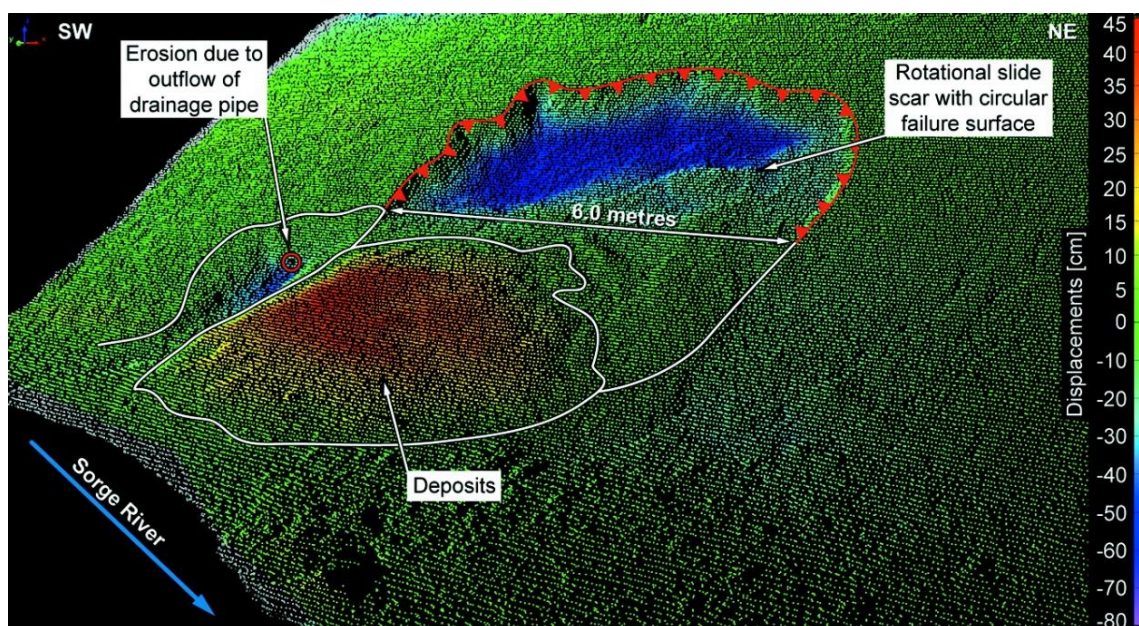


Figure 3. Use of terrestrial laser scanning for the characterization of retrogressive landslides [17]
Rys 3. Wykorzystanie skanowania laserowego do charakteryzacji osuwisk regresywnych [17]

Multi-temporal airborne laser scanning (ALS) surveys are crucial for detecting landslide movements and assessing risks in mountainous areas. The National Center for Airborne Laser Mapping (NCALM) conducted three ALS surveys at the Slumgullion landslide site in Colorado in July 2015. These surveys showed that ALS can detect minimum elevation changes of 5 cm in flatter areas and 10 cm in rugged terrains. However, caution is needed for highly rugged areas. The accuracy of ALS varies from 10 cm to 30 cm, depending on terrain roughness and vegetation. These findings help estimate ALS performance in similar regions [24].

The application of TLS technology in open-pit mines has gained significant popularity due to its numerous advantages and capabilities [25]. This technology has revolutionized various aspects of mining operations, from monitoring slope stability to volume estimation and mapping. Modern technologies like 3D laser scanning have opened new opportunities for expansive and challenging locations such as open-pit mines [1]. Systematic slope stability monitoring is essential to ensure safe and continuous mining operations. The use of 3D terrestrial laser scanning to track landslides and slope displacements in open-pit mines has been extensively discussed [1]. To address the limitations of traditional methods, a TLS-based subsidence monitoring approach without a target has been proposed [26]. This method simplifies the field measuring process, reduces labor intensity, and is suitable for environments with challenging topography and severe external conditions. Similarly, another study

described a TLS-based method for monitoring subsidence in mining areas, highlighting its efficiency compared to traditional techniques [27]. In addition to slope stability, TLS technology has been utilized to physically describe the movement of strata relevant to mining using optical transducers, 3D laser scanners, and digital image processing methods [28]. For instance, TLS was applied to predict subsidence and horizontal displacement in the Gubei Coal Mine in Huainan, China, demonstrating its capability to obtain surface deformation in large mining-impacted areas [29]. An automated technique for extracting building deformation in mining locations based on TLS point clouds has also been developed, showing greater stability compared to manual methods [29]. Furthermore, TLS technology has been used to validate spatial variations in mining operations, such as tracking roadway deformation at Lazy Mine in the Czech Republic [30]. The effectiveness of a stop-and-go laser scanning technique in pinpointing the precise location, angle, and deviation of bunton plates in mine shafts has also been assessed [31]. The extensive datasets generated by laser scanning are valuable for off-site revision and ongoing work by various departments, including planning, design, engineering, safety, geology, and rock engineering. TLS technology is also applied to survey topography and establish maps in mining areas. Experiments have shown that TLS can enhance the effectiveness of mapping and surveying, with 3D models being used to track the extraction of mining areas [32].



Figure 4. Application of TLS in open-pit mines [33]
Rys 4. Zastosowanie TLS w kopalniach odkrywkowych [33]

Another significant application of TLS in open-pit mines is volume estimation (Figure 5). Field tests comparing different TLS instruments have demonstrated that volume can be computed more precisely with TLS than with traditional total stations [34]. This technology has proven to be a valuable tool in the mining sector, capable of measuring exploitative volumes in open-pit mines with high accuracy [25].

Rapidly determining the amount of raw material collected from surface quarries is a common issue in mineral resource extraction. Studies have compared laboratory and non-contact surveying methodologies to confirm the bulk density of extracted heterogeneous raw material [35]. Additionally, 3D laser scanning has been used to establish mathematical models of the movement dynamics of bucketwheel excavators,

providing essential geometric properties for real-time mining management [3]. The potential of laser scanning technology to characterize the geometric characteristics of discontinuities in limestone mines has also been evaluated, balancing cost-benefit considerations [36]. TLS technology can be integrated with other technologies to enhance mining operations. For example, combining TLS with UAV-based photogrammetry allows for three-dimensional mapping and monitoring of surface mine regions [37]. This integration is particularly useful in challenging locations where conducting a GPS survey is difficult. TLS data can also be merged with RGB images and

digital photogrammetry from UAVs to map open-pit mines and interpolate 3D models of pit walls [38] [39]. Furthermore, combining TLS with ground-based synthetic aperture radar has improved slope stability monitoring, allowing for high measurement rates over long distances without safety risks [40]. In addition to photogrammetry, TLS can integrate with GNSS technology to monitor surface mines. This combination compensates for the limitations of GPS and provides comprehensive subsidence basin data [41]. By merging UAV point clouds, TLS data, and GNSS positioning, geospatial experts can generate accurate 3D virtual surfaces for various mining applications [42].

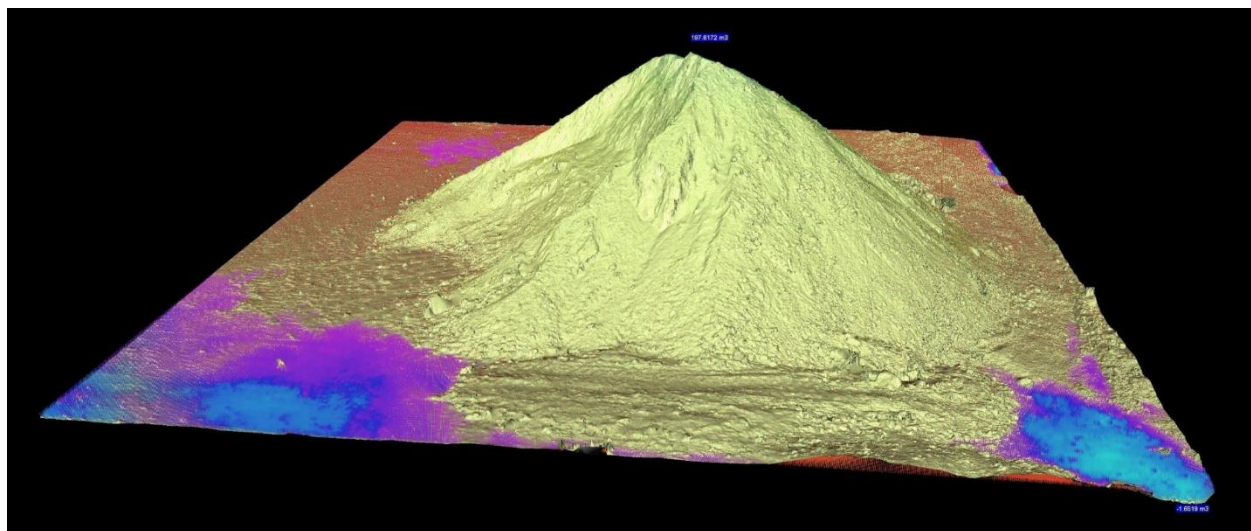


Figure 5. Using Laser Scanning for Volume Calculations [43]
Rys 5. Wykorzystanie skanowania laserowego do obliczeń objętości [43]

4. Conclusion

Terrestrial Laser Scanning technology has significantly transformed data acquisition and analysis across various industries by providing unmatched precision and efficiency. Its diverse applications in mining, civil engineering, geology, and construction highlight its versatility and essential role in these fields. The integration of TLS with other advanced technologies further enhances its capabilities, making it an indispensable tool for modern engineering and environmental monitoring. As TLS technology continues to advance, its impact on improving accuracy, safety, and efficiency in multiple sectors is expected to increase.

This ongoing evolution will solidify TLS's position as a fundamental component of contemporary data acquisition and analysis methodologies, driving innovation and excellence in numerous applications. The continuous development and refinement of TLS technology promise to expand its utility, ensuring it remains at the forefront of technological advancements in data collection and analysis. Consequently, TLS is poised to play a crucial role in addressing the complex challenges of modern engineering and environmental management, reinforcing its status as a cornerstone of precision measurement and analysis.

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TYTUŁ: Przegląd zastosowania skanowania laserowego w trudnych środowiskach

Technologia skanowania laserowego (TLS) stała się wysoce skutecznym narzędziem do rejestrowania szczegółowych i precyzyjnych danych 3D w różnych dziedzinach, zwłaszcza w trudnych środowiskach, takich jak skomplikowane tereny. Jej kluczowe cechy, w tym wysoka precyzja i szybkie pozyskiwanie danych, sprawiają, że jest szeroko stosowana w mapowaniu, geologii, budownictwie i górnictwie. TLS jest szczególnie korzystna w sektorze górnictwym, wspomagając szczegółowe mapowanie, monitorowanie stabilności zboczy i szacowanie objętości. Zdolność technologii do szybkiego rejestrowania milionów punktów danych zwiększa efektywność i obniża koszty w porównaniu z tradycyjnymi metodami pomiarowymi. Ponadto TLS jest dostosowana do różnych środowisk, od miejskich po trudne tereny, co czyni ją cenną dla monitorowania środowiska i badań. Recenzje podkreśliły jej skuteczność w monitorowaniu deformacji gruntu i budynków, zwiększaniu dokładności w projektach budowlanych oraz poprawie bezpieczeństwa i efektywności w badaniach tuneli. Integracja TLS z innymi technologiami, takimi jak fotogrametria UAV i GNSS, dodatkowo zwiększa jej możliwości, dostarczając kompleksowych danych do różnych zastosowań. Niniejsze badanie ma na celu dostarczenie szczegółowego przeglądu zastosowania TLS w skomplikowanych terenach, wykorzystując dane z publikacji z ostatnich lat. Przeglądana literatura pokazuje, że TLS może być skutecznie stosowana w trudnych środowiskach.

Słowa kluczowe: Skanowanie laserowe, TLS, Skomplikowany teren, Obszar górski, Kopalnia odkrywkowa, Osuwisko.