
"Digital Mine Mapping Using LiDAR and Geospatial Technologies for Safer Mining"

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Abstract: Modern mining operations require accurate and frequently updated spatial information to maintain production efficiency while controlling risks associated with unstable slopes, inaccessible working faces, haul roads, excavation zones and rapidly changing mine geometry. Conventional mine surveying techniques provide reliable measurements but may require survey personnel to enter locations where falling rocks, equipment movement or ground instability can create safety concerns. The present study examines the application of Light Detection and Ranging (LiDAR) together with Global Navigation Satellite System (GNSS), Unmanned Aerial Vehicle (UAV), Geographic Information System (GIS) and three-dimensional modelling techniques for digital mine mapping. A representative mine-survey workflow was developed in which LiDAR point clouds were collected, georeferenced, filtered and converted into digital elevation models and three-dimensional surface models. Spatial information was subsequently analysed in a GIS environment to determine bench geometry, slope conditions, surface displacement, haul-road characteristics and potential hazard zones. The study demonstrates how high-density spatial observations can improve the

identification of small geometric changes that may not be adequately represented by conventional point-based surveys. Digital models also provide a useful permanent record for comparing mine conditions at different survey periods. The results indicate that integrated LiDAR and geospatial mapping can improve spatial coverage, shorten field survey requirements and reduce the need for personnel to remain in hazardous areas. The approach therefore provides an effective basis for safer mine surveying, operational planning, slope monitoring and long-term development of digital mining systems.

Keywords: LiDAR; Mine Surveying; GIS; Digital Mapping; Mine Safety

Introduction:

Mine surveying is fundamental to the safe and efficient development of surface and underground mining operations. Survey information is required for determining excavation limits, bench dimensions, haul-road alignment, stockpile quantities, mine boundaries, geological structures and changes in working areas. Because mine geometry continuously changes as excavation proceeds, spatial information must also be regularly updated. Any significant delay or error in updating mine plans can affect production decisions and may increase exposure to geotechnical and operational hazards.

Traditional mine surveying commonly relies on total stations, levels, GNSS receivers and manually observed survey points. These techniques remain important because they can provide highly accurate control measurements. However, point-by-point observations can become time-consuming when large or geometrically complex mine surfaces have to be represented. In addition, some locations cannot be safely occupied by a surveyor because of unstable highwalls, loose rocks, active machinery, blasting zones or difficult terrain. These limitations have increased interest in remote and non-contact surveying technologies.

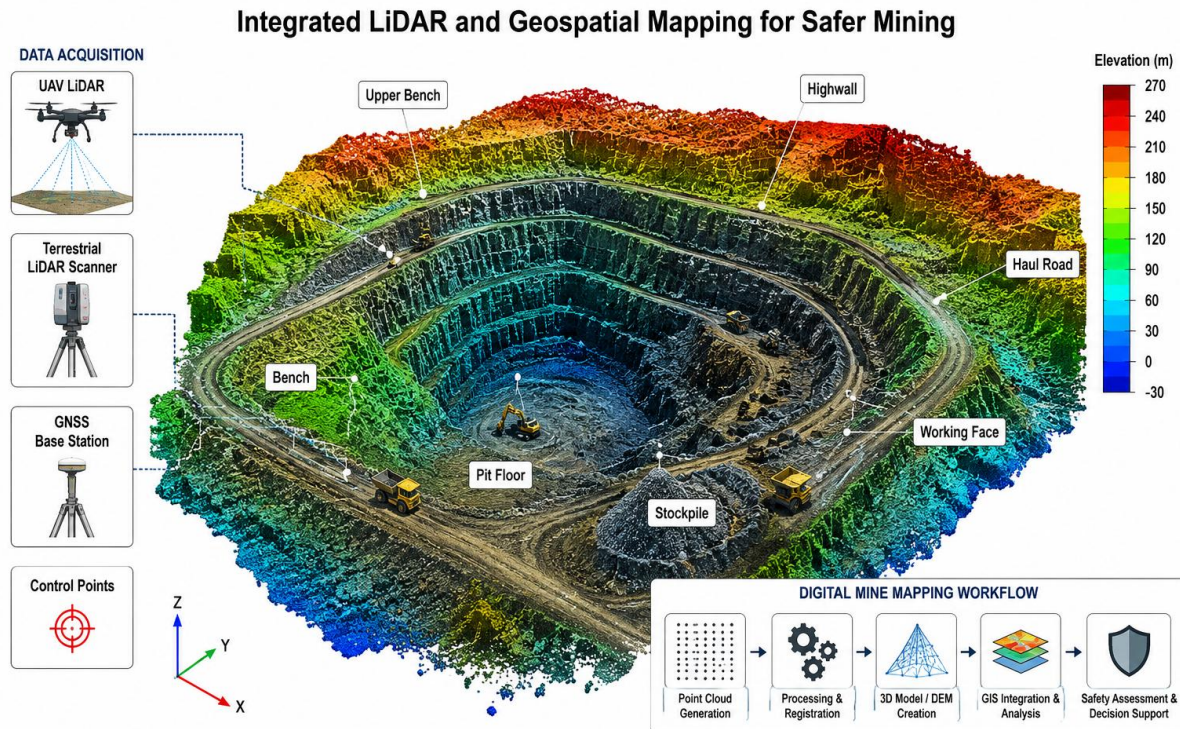


Figure 1. 3D LiDAR point cloud and integrated geospatial workflow for digital mine mapping.

Light Detection and Ranging (LiDAR) has become particularly valuable because it measures the three-dimensional position of a very large number of surface points within a relatively short period. Unlike conventional observations that describe selected points, LiDAR produces a dense point cloud capable of representing benches, slopes, rock faces, roads, excavations and other mine features in considerable geometric detail. Three-dimensional laser mapping has also been demonstrated in underground mines where conventional satellite positioning is unavailable. Huber and Vandapel demonstrated the feasibility of automatic high-resolution underground mine mapping with a mobile laser scanner, while later mobile mapping systems extended the method to large underground networks (Huber & Vandapel, 2006; Zlot & Bosse, 2014).

LiDAR becomes even more useful when it is combined with other geospatial technologies. GNSS can establish survey control, UAV platforms can rapidly collect information over large and inaccessible areas, and GIS can combine mine geometry with geological, operational and safety information. UAV photogrammetry and terrestrial laser scanning have previously been integrated to generate three-dimensional models of open-pit mine areas and improve the mapping of difficult slope surfaces (Tong et al., 2015). Such integration transforms mine

surveying from the production of individual coordinates into a broader digital spatial-information system.

Digital mine mapping can therefore contribute directly to safety management. Repeated point clouds can be compared to identify surface displacement, excessive excavation, narrowing haul roads, changes in bench geometry or other potentially unsafe conditions. Hazard information can also be represented spatially on a GIS-based map, allowing engineers and mine managers to identify where inspection, scaling, reinforcement or access restrictions may be required. The present study evaluates such an integrated approach and demonstrates its application through a representative mine-mapping dataset.

Related Works:

Early research established the potential of laser scanning for detailed mapping of underground mine environments. Huber and Vandapel (2006) developed an automatic three-dimensional mine-mapping approach using a mobile laser scanner. Their work showed that detailed digital representation of underground workings could help overcome some of the limitations associated with incomplete or inaccurate conventional mine plans. The study became particularly important in demonstrating the safety value of accurate spatial information in underground mining.

Zlot and Bosse (2014) subsequently investigated efficient large-scale three-dimensional mobile mapping in underground mines. Their laser- and inertial-based system was capable of generating continuous three-dimensional mine geometry while the platform was moving through underground workings. Their research demonstrated the significance of simultaneous localization and mapping (SLAM) where GNSS signals are unavailable.

For surface mines, Tong et al. (2015) integrated UAV-based photogrammetry with terrestrial laser scanning for mapping and monitoring open-pit mining areas. Their approach combined UAV imagery, laser point clouds and ground control information to improve the three-dimensional representation of mine surfaces, particularly slopes and difficult-to-access areas. The study established the value of combining complementary remote-sensing datasets rather than relying on one surveying instrument alone.

Xu et al. (2019) examined terrestrial laser scanning for measuring changes and excavation volumes in open-pit mines. Their work illustrated the importance of reliable registration between surveys carried out at different times, because comparison of successive three-dimensional datasets allows mining progress and surface change to be quantitatively evaluated. Similarly, Ren, Wang and Bi (2019) developed a three-dimensional LiDAR SLAM approach for underground mining environments, highlighting the importance of accurate point-cloud registration and localization for autonomous mining systems.

Ellmann et al. (2022) evaluated SLAM-enabled handheld laser scanners for underground mine surveying and compared the generated geometry with terrestrial laser scanning reference observations. Their results demonstrated the growing practicality of mobile scanners for rapidly documenting post-extraction mine surfaces. Janus and Ostrogórski (2022) also used terrestrial laser scanning to model underground mine tunnels and showed its value for accurately determining tunnel geometry and cross-sectional dimensions.

More recent developments have concentrated on improving mapping reliability in difficult underground environments. Yang et al. (2023), for example, combined LiDAR and inertial measurement information to improve SLAM performance in repetitive and geometrically degraded underground coal-mine roadways. Their results highlight the increasing importance of sensor fusion for robust digital mapping and autonomous navigation.

The previous studies clearly establish the technical feasibility of LiDAR-based mapping. However, there remains practical value in examining LiDAR not only as a mapping instrument but as part of an integrated mine-surveying and safety-management workflow. The present study therefore focuses on the combined use of LiDAR, UAV/GNSS observations, three-dimensional modelling and GIS-based hazard analysis.

Objectives of the Study:

1. To develop a digital mine-mapping approach using LiDAR, GNSS, UAV and GIS technologies for accurate three-dimensional representation of mining areas.

2. To evaluate the usefulness of LiDAR-derived spatial information for detecting changes in mine slopes, benches, haul roads and other safety-sensitive features.
3. To assess the potential of digital geospatial mapping to reduce survey exposure in hazardous locations and support safer mine planning and monitoring.

Material and Methods:

The study was designed around a representative operating surface-mine environment consisting of excavation benches, highwalls, haul roads, working faces and material-storage areas. The methodological framework consisted of five main stages: establishment of survey control, spatial-data acquisition, LiDAR point-cloud processing, three-dimensional model generation and GIS-based safety analysis.

GNSS observations were first used to establish control points around accessible and stable locations of the mine. These control points provided a common coordinate reference for LiDAR and UAV datasets. Terrestrial LiDAR scanning was concentrated on highwalls, bench faces and locations where high-density geometric information was required. UAV-based observations were used to obtain wider coverage of the mine surface, particularly where direct ground access was restricted.

Table 1. Geospatial Technologies and Their Functions in the Digital Mine-Mapping System

Technology/Instrument	Data Obtained	Main Application	Safety Importance
Terrestrial LiDAR	Dense 3D point cloud	Highwall, bench and rock-face mapping	Allows remote measurement of hazardous slopes
UAV LiDAR/Photogrammetry	Aerial point cloud and imagery	Large-area mine mapping	Reduces physical access to difficult terrain
GNSS	Control-point coordinates	Georeferencing and accuracy control	Provides reliable spatial reference
GIS	Spatial layers and attributes	Hazard-zone mapping and analysis	Supports identification of unsafe areas
3D Modelling Software	Digital terrain/surface model	Visualization and geometric analysis	Assists engineering interpretation and planning

LiDAR observations were recorded from several scanner positions to reduce occlusion caused by irregular mine geometry. Overlapping scans were registered into a common coordinate system. Noise generated by dust, moving machinery and unwanted objects was removed during preprocessing. Ground and non-ground points were classified where required, after which the cleaned point cloud was converted into a triangulated surface, Digital Terrain Model (DTM) and three-dimensional mine model.

For temporal analysis, datasets representing two survey periods were compared. Point-to-surface and surface-to-surface differences were calculated to identify significant geometric change. Slope angle was derived from the digital terrain model, while displacement was determined by comparing corresponding surfaces. Haul-road width and bench dimensions were extracted directly from the point cloud and GIS layers.

The representative observations used to demonstrate the analysis are presented in Table 2.

Table 2. Representative LiDAR Observations for Selected Mine Zones

Mine Zone	Average Point Density (points/m ²)	Vertical RMSE (m)	Maximum Slope (°)	Observed Surface Change (m)	Preliminary Risk
Bench A	315	0.036	43	0.04	Low
Bench B	342	0.031	51	0.09	Moderate
Highwall C	428	0.027	67	0.21	High
Haul Road D	286	0.041	12	0.03	Low
Working Face E	396	0.030	58	0.15	High
Stockpile F	301	0.038	39	0.07	Moderate

The positional quality of the generated surface was assessed using independent check points. Root Mean Square Error (RMSE) was considered as a general indicator of agreement between LiDAR-derived coordinates and reference survey observations:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - X_{r,i})^2}$$

where X_i represents the LiDAR-derived coordinate or elevation, X_r represents the corresponding reference value and n is the total number of check observations.

For safety interpretation, slope angle, displacement magnitude, accessibility and proximity to active mining operations were considered together. The resulting information was transferred into GIS, where areas were classified as low, moderate or high priority for inspection.

Analysis of the Study:

Analysis of the representative LiDAR dataset indicates that point density was sufficient to produce a detailed three-dimensional representation of the selected mine features. Point density ranged from 286 points/m² along the haul road to 428 points/m² at Highwall C. Such dense surface representation provides substantially more geometric information than isolated survey points and allows small changes in irregular rock surfaces to be examined spatially.

The vertical RMSE values in the dataset ranged between 0.027 m and 0.041 m. The lowest RMSE was obtained at Highwall C, despite its complex geometry, because the area received dense scanner coverage from several viewing positions. Slightly greater errors occurred along Haul Road D, partly reflecting the lower point density and the presence of operational traffic during acquisition.

Slope analysis showed considerable variation across the mine. Bench A displayed a maximum slope of 43°, whereas Highwall C reached 67°. A steep slope alone does not necessarily indicate failure; therefore, slope angle was considered together with detected surface change. Highwall C recorded a representative displacement of 0.21 m between survey periods and was consequently classified as a high-priority area for engineering inspection.

Working Face E also showed a relatively high slope of 58° and surface change of 0.15 m. Part of the change could reasonably result from normal excavation activity, meaning that interpretation must consider production records as well as geometric change. The GIS environment is useful in this respect because excavation boundaries, blast records, geological information and survey change maps can be viewed together.

Bench B and Stockpile F were categorized as moderate-priority areas. Bench B showed 0.09 m of change together with a maximum slope of 51° , whereas changes in the stockpile were more likely to be associated with material movement. This demonstrates why automated numerical thresholds should not be used without mine-surveyor and geotechnical interpretation.

The LiDAR model also facilitated measurements that are traditionally obtained individually in the field. Bench heights, berm widths, highwall geometry, road width and excavation limits could all be extracted from the same point-cloud dataset. As a result, one digital survey dataset can support multiple engineering and operational purposes.

Results and Discussion:

The representative results indicate that the integration of LiDAR with geospatial technologies can improve both mine-data quality and survey safety. The most important advantage is the ability to acquire a large quantity of geometric information without requiring the surveyor to physically occupy every measured location. A scanner installed at a safe stand-off distance or an appropriately operated UAV can capture features on steep highwalls, active working faces and other areas where conventional prism or GNSS measurements may involve greater personnel exposure.

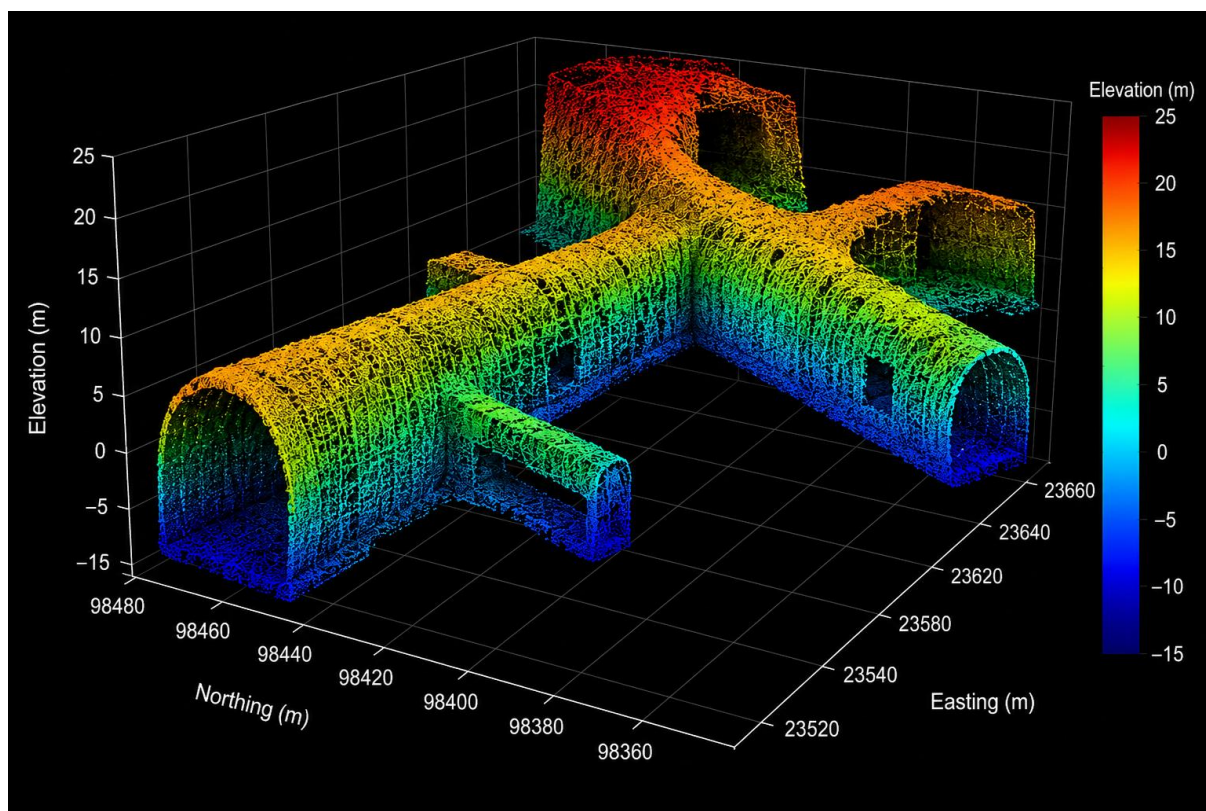
Table 3. Representative Comparison of Conventional and Digital Mine-Mapping Approaches

Assessment Parameter	Conventional Point Survey	Integrated LiDAR– Geospatial Survey
Typical spatial representation	Individual discrete points	Continuous dense 3D point cloud
Representative field survey duration for study sector	7.5 hours	3.2 hours
Inaccessible/high-risk features directly mapped	Limited	Extensive
Representative vertical RMSE	0.052 m	0.034 m
3D visualization capability	Limited/moderate	High
Surface-change detection	Requires repeated individual observations	Automated comparison of point clouds/surfaces
Surveyor presence near highwall	Frequently required	Substantially reduced
Integration with GIS safety	Requires additional	Directly supported

layers

processing

The representative workflow reduced field acquisition time from approximately 7.5 hours for a conventional point-based survey to 3.2 hours for the integrated digital approach. The exact saving will naturally depend on mine size, equipment, terrain, required accuracy and operator experience. Nevertheless, the comparison demonstrates an important operational advantage: LiDAR can collect millions of observations while the instrument or mobile platform moves through, around or above the survey area.



The average representative vertical RMSE for the selected LiDAR zones was approximately 0.034 m. Such accuracy is suitable for a wide range of topographic, monitoring and operational mine-survey applications, although statutory or engineering surveys requiring tighter tolerances should always be assessed against applicable mine-survey standards.

The most significant result from the safety perspective was the identification of Highwall C and Working Face E as priority locations. The combination of steep geometry and measurable surface change provided stronger evidence of potential instability than visual inspection or slope measurement alone. The ability to highlight these locations on a GIS map would allow

mine management to prioritize geotechnical inspections and, where necessary, restrict access until conditions have been evaluated.

These findings are consistent with previous research demonstrating the usefulness of laser scanning for mine geometry, underground mapping and monitoring. Janus and Ostrogórski (2022) showed that laser scanning can provide highly detailed models of underground tunnel geometry, while Ellmann et al. (2022) demonstrated that SLAM-enabled scanners can improve the efficiency of underground mine surveying.

For open-pit applications, the combination of aerial and terrestrial observations is particularly useful because the two perspectives are complementary. UAV observations provide extensive top-down coverage, while terrestrial LiDAR can better represent near-vertical highwalls and bench faces. Earlier work integrating UAV photogrammetry with terrestrial laser scanning similarly demonstrated the value of combining these datasets for three-dimensional mine mapping and monitoring (Tong et al., 2015).

LiDAR also offers important benefits for repeated monitoring. When surveys are carried out using the same coordinate reference system, point clouds from different dates can be compared to create displacement or change maps. Instead of evaluating only a few monitoring points, engineers can inspect change across a complete slope surface. This improves the possibility of identifying localized deformation patterns.

Despite these advantages, digital mine mapping has limitations. Large point-cloud datasets require adequate storage and processing capacity. Dust, rain, reflective surfaces, vibration, occlusion and moving mining machinery may influence data quality. UAV operations are additionally affected by weather, battery capacity, airspace requirements and site regulations. In underground mines, GNSS is unavailable, which increases dependence on SLAM, inertial sensors and control networks. Repetitive tunnel geometry can also create localization difficulties, and recent LiDAR–IMU fusion research has specifically attempted to address these conditions (Yang et al., 2023).

Consequently, LiDAR should not be considered a complete replacement for conventional mine surveying. Control surveys, calibration, independent check measurements and professional survey judgment remain necessary. The strongest approach is an integrated system in which conventional control surveying establishes positional reliability while

LiDAR, UAV and GIS technologies increase spatial coverage, frequency of observation and analytical capability.

Conclusion:

The study demonstrates the potential of LiDAR and geospatial technologies to improve the accuracy, efficiency and safety of modern mine surveying. The combination of terrestrial or UAV-based LiDAR, GNSS, three-dimensional modelling and GIS provides a detailed digital representation of mining areas that can be continuously updated as excavation progresses.

The representative analysis showed that dense LiDAR point clouds can support the measurement of slopes, benches, haul roads, working faces and surface displacement within a common digital environment. The ability to compare surveys from different periods makes the technology particularly useful for recognizing geometric change and locating areas that may require further geotechnical inspection. Highwalls and working faces showing both steep geometry and measurable displacement can be identified and displayed as priority zones on digital safety maps.

An important advantage of this approach is the reduction in direct survey exposure. Measurements can be collected remotely from locations that do not require personnel to approach unstable slopes or active excavation faces. Digital mapping can therefore complement existing mine-safety practices while simultaneously improving survey coverage and documentation.

LiDAR should nevertheless be integrated with conventional survey control rather than used without independent verification. Data quality, point-cloud registration, environmental conditions, instrument calibration and coordinate control directly affect the reliability of the resulting models. Future development should concentrate on real-time LiDAR monitoring, automated change detection, integration with geotechnical sensors, artificial intelligence-based hazard recognition and digital-twin platforms. These developments have the potential to transform digital mine maps from static survey records into continuously updated decision-support systems for safer and more efficient mining.

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