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IN GEOLOGICAL AND GEOTECHNICAL PROCESSES IN THE MINE USE OF TECHNOLOGICAL SCANNING EQUIPMENT IN THE UNDERGROUND MINING METHOD

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Abstract

Laser scanning and 3D point cloud data is used extensively in open pit and underground mining operations. Point cloud data generated with laser scanners has improved survey, conformance, and geotechnical process efficiency and has become a key data component for planning, operations and decision-making. The advent of new software tools designed specifically to manage real-time 3D scan data has also improved the accuracy, quality and usability of underground scan data, revolutionising workflows through the industry. In this paper, several case studies will demonstrate the versatility and value of laser scanning in the context of underground operations demonstrating the use of laser scanning and derived point cloud data to improve efficiency, reduce costs and increase the safety of staff and assets across the operation. Laser scanning technology has advanced significantly in terms of mobility and mapping, but there are constraints in coherent and consistent data collection at certain mines due to feature deficiency, dynamics, and environmental influences such as dust and water. Studies suggest that laser scanning has matured over the years for change detection, clearance measurements and structure mapping applications. However, there is scope for improvements in lithology identification, surface parameter measurements, logistic tracking and autonomous navigation. Laser scanning has the potential to provide real-time solutions but the lack of infrastructure in underground mines for data transfer, geodetic networking and processing capacity remain limiting factors. Nevertheless, laser scanners are becoming an integral part of mine automation thanks to their affordability, accuracy and mobility, which should support their widespread usage in years to come.

Keywords: Laser scanning, filtering, modelling, productivity**,** mine automation, point cloud, rock mass characterization, change detection,data registration, georeferencing.

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Introduction

Laser scanning began as a simple tool for capturing topography. Today, laser scans are used by geologists, mining engineers, and geotechnical engineers. Some applications include design compliance, geological mapping, monitoring, geotechnical analysis and volumetric control. New underground scanning hardware improves the field scan workflow and data processing in the software. This paper presents several underground applications of laser scanning technology. Technical aspects about the workflow to capture data, recording options, filtering and data modelling are explained. The paper also correlates laser output to value for mining companies. However, the applicability of multi-sensor technologies in underground mines has been limited due to (1) a lack of availability of a spatial reference framework, (2) intrinsic-safety related hazards for certain mines (particularly coal mines) and (3) uneven terrain and dusty conditions. Laser sensors are becoming increasingly affordable due to the recent boost in autonomous and driverless vehicles that require 3D spatial information to successfully operate. These sensors provide rich geometric information through rapid scanning, in the form of a 3D point cloud, which can be used to digitally reconstruct the environment. The current means of producing point clouds in underground mines mainly involve terrestrial laser scanning (TLS) and mobile laser scanning (MLS). In the former, the environment is scanned from a fixed point, while in the latter, mobility is achieved using simultaneous localisation and mapping (SLAM) algorithms for scanning. MLS offers several benefits over TLS in terms of simplicity, scale and avoiding blind spots during data capture. Researchers are continually trying to improve the mapping and localisation of MLS; still, the accuracy remains mostly in centimetres. Currently far superior, TLS can provide up to millimetre-level accuracy. Nevertheless, the sensor mobility of MLS is an important aspect in terms of efficiency that affords it a range of applications that had previously been challenging in mining when using stationary sensing. Accuracy requirements dictate the decision made when selecting a laser scanner in underground mines for a particular application. To monitor a small area with high accuracy, such as for convergence measurement, TLS is suitable. Meanwhile, applications favour MLS when they require rapid and routine monitoring of a large area, such as for change detection, deformation monitoring, object detection or localisation, for which the permissible error may only be a few centimetres. In terms of operational value, mine operators increasingly request MLS solutions as they are easy to operate, quickly scan large areas and facilitate wider applications and scanning options (e.g. human backpack, vehicle- and drone-mounted). This research review aimed to identify the challenges with acquiring accurate point clouds in underground mines and review the suitability of point clouds, obtained either via TLS, MLS or structure from motion (SfM), for relevant geological and geotechnical mining applications. The rest of the paper is arranged into six Sections,outlines the method we followed to filter relevant studies and sets out the statistical meta-analysis of published research. reviews the factors associated with mapping and mobilities in underground mines to identify challenges and future areas of potential,investigates how we can collect coherent and spatially referenced multi-temporal 3D point cloud data in an environment lacking a global navigation satellite system (GNSS) signal,provides a critical review of all the major geological and geotechnical applications for laser scanning in underground mines. This section also reviews the processing

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algorithms for selected applications and provides insights into the scope for future improvements, explores relevant potential applications for laser scanning technology where a current issue may be addressed and also proposes future research directions. Finally, concluding remarks are presented. The reviewed applications were selected based on their relevance to mining in regards to construction, planning, safety/hazard management and temporal monitoring. The underground environment we analysed concerns GNSS-denied caves, tunnels and underground mines.

Mapping the 3D representation of sensor properties

ase-differences between the emitted and reflected rays are measured to determine the distances between the sensor and target objects. Together with extrinsic parameters of sensors, such as position and orientation, measured ranges can be converted into a 3D point cloud, which represents the digitally scanned environment. The accuracy of the generated map and measured coordinates depends on factors such as the specifications of the LiDAR sensor and surface properties of the scanned environment. Sensor characteristics: Prominent sensor-related factors leading to mapping errors include sensor beam divergence, inertial measurement unit (IMU) bias (for MLS) and improper intrinsic and extrinsic calibration of sensors (Pic 1. 3a). Sensor beam divergence refers to the gradual increase in the footprint of a laser pulse with distance due to the solid conal angle projected by a laser beam (Pic.1 a1). As a consequence of beam divergence, distant measurements tend to increasingly be affected by error due to a large uncertainty region in measuring a single point. To limit the error from beam divergence, a threshold cut-off distance is set, the maximum measurable range, beyond which readings are ignored. Where that range is set depends on the intensity of laser pulses, operational wavelength and signal attenuation over time. Before using laser scanning for any application in an underground mine, characteristics of the scanner must be evaluated such as its range precision, beam divergence and minimum mappable unit (resolution/discernability) through suitable benchmarking tests for efficient mapping. Such tests help to investigate the quality of data produced by the scanner and provide insights into the processing required to remove errors or inaccuracies from point clouds. Beyond this, in mobile mapping, a primary source of error—besides odometry measurement errors caused by cycle slips—comes from inertial sensors, such as IMUs. Inertial sensors inherently accumulate drift over time, leading to a substantial difference in the measured and actual locations of sensors during mapping (Pic.1a2). When a noisy output signal from an IMU is integrated, for instance integrating angular rate signals to determine angles, the integration drifts over time due to noise. The drift is referred to as a random walk as the integration seems to take random steps from one sample to the next. Angle random walk and velocity random walk are two main types of random walks in inertial sensors which apply to gyroscope and accelerometer measurements, respectively. Orthogonality errors that consist of cross-axis sensitivity and misalignment, are also often encountered which impacts IMU measurement capabilities. Sensors mounted to an IMU need to be perfectly orthogonal. The cross-axis sensitivity error originates when a particular sensor axis responds to an input that is orthogonal to the sensing direction. Similarly, misalignment errors appear when the internal sensing axes do not align with the marked axes on the IMU case. In such

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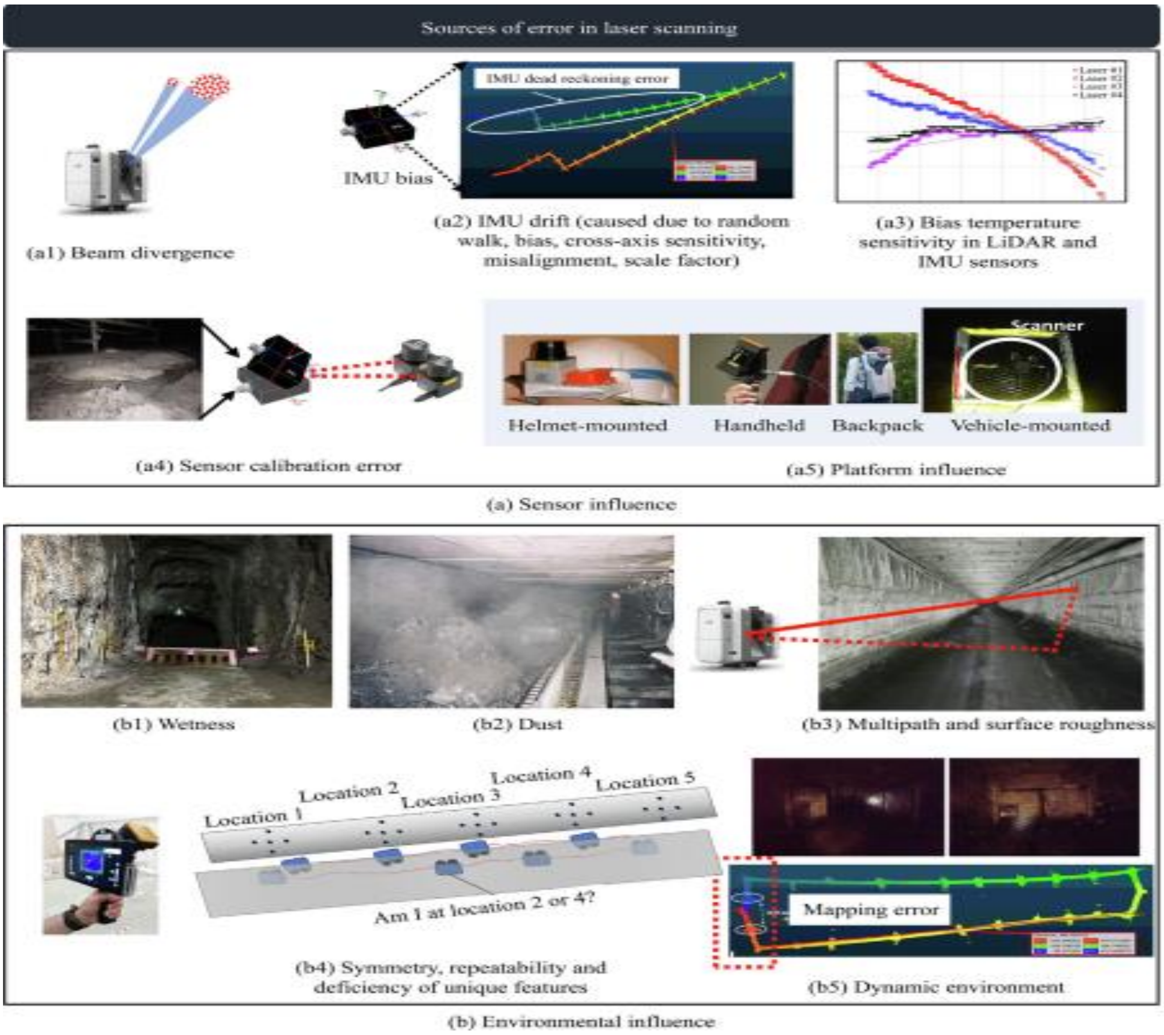
cases, extensive equipment calibration between the sensors such as LiDAR or camera with IMU is required to overcome factory-calibrated misalignment errors. Other sources of error in laser sensors and IMU include bias temperature sensitivity, scale factor and random error. The bias is a constant offset of the output value from the input value. When a sensor is started up, there is an initial bias present that may fluctuate based on thermal, mechanical and electrical variations. Also, the bias drifts over time during operation at a constant temperature. Since the sensor operates in a range of temperatures, the biases may respond differently to each temperature that must be calibrated Pic. 1a3). The scale factor is a ratio of output to the input over the measurement range. It varies with time and should be calibrated accurately before using the sensor. Random errors exist inherently in the system and affect the precision of the measurements in LiDAR and IMU. Improper intrinsic and extrinsic calibration of IMU and LiDAR sensors is also a major factor that results in distorted 3D maps.



Picture 1. Major sources of mapping errors through laser scanning in underground mining environments. Beam divergence, IMU error, sensor bias , calibration error and platform influence are primary sensor related sources of error. Whereas lighting condition, water, dust, multipath , surface roughness, and structural complexity are environment related sources of error.

Level of stability in underground mines

The software allows for import of point data without coordinates, which are registered against existing scans which contain coordinates. When registering free scans, information about scanner location is required. The end user calls on field experience to recognise the level of overlapping needed to align the new and existing scans. The free scan registration process allows for a short time in the field. One 360° scan can be performed in about three minutes, which is convenient for quick scans after scaling a round. The quick turnaround time for the scan limits disruption to the mining cycle. The end user can manually move scans to approximate the alignment of a free scan to an existing scan that includes coordinates. With one click, automatic initial registration automatically aligns a free scan to an existing scan which includes coordinate data. Global registration accurately aligns a free scan against a reference scan which contains coordinates. Global registration works best when point sets contain common features and strategic overlaps.

Practices in underground mines

MLS systems are considered relatively new to the mining sector, but their impact on how we can collect useful information for critical mining applications is already being seen. The prominent offthe-shelf MLS systems currently in use are shown in Pic. 2. A large-scale presentation and comparison of multi-sensor versus single-sensor SLAM for mapping were offered by Jacobson et al. Two underground hard rock mines in Australia, Queensland (12.3 km mapping length) and New South Wales (32.3 km), were mapped using laser-only, camera-only and laser+camera+odometer+IMU sensors. A sensor positioning error of 0.68 m was observed for fused sensors in the Queensland mine dataset, which was comparatively lower than for the laser-only (0.94 m) and camera-only (4.49 m) SLAM. Similarly, for the New South Wales dataset, errors of 122.4, 1.38 and 1.32 m were observed for the laser-only, camera-only and fused sensors, respectively, with superior results exhibited by fused sensors. A laser-only solution is not sufficient for accurate mapping in underground mines; fusion with other sensors is necessary for a more robust solution. A comparative evaluation of TLS, MLS and SfM for mapping voids in underground mines and tunnels was presented by. The test area consisted of an unstructured (feature-deficient and with unknown geometry) corridor, structured corridor and unstructured intersection.

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Name	System name	Base scanner	Data rate (pts/s)	Range (m)
	CSIRO ExScan 3D	Hokuyo UTM-30LX	43000	30
	GeoSLAM Zeb-Revo	Hokuyo UTM-30LX	43000	30
	GeoSLAM Zeb-Horizon	Velodyne Puck VLP-16	300000	100
	Emesent Hovermap	Velodyne Puck VLP-16	300000	100
	Leica Pegasus	Leica laser scanner	600000	200
	Gexcel Heron	Velodyne Puck VLP-16	300000	100

Pic.2. Off-the-shelf mobile laser scanning (MLS) systems available for mapping underground mines.

Most mine sites either use the MLS system in handheld mode or mount it on a scanning vehicle. The use of a fully autonomous mapping system is still rare in underground mines. Few studies have conducted experiments with a fully autonomous aerial system for mapping, localisation, exploration or search and rescue, demonstrated the use of an autonomous MLS system in an underground tunnel for localization and 3D mapping through inter-scan feature matching. The experiment was performed over a small scale (25 m), and a root mean square error of 0.05 m2 was achieved when the mapped tunnel section was compared to a manual survey. Meanwhile, when MLS was used in a dusty underground environment, substantial errors appeared in localisation and mapping for large scenarios. As discussed above, developing an accurate 3D map over a large scale in an underground mine remains challenging due to factors such as (1) accumulated inertial sensor bias causing dead reckoning error, (2) false loop-closure detection due to a featureless or highly symmetric/repeatable environment, (3) a dynamic environment, (4) feature deficiency caused by a low scan rate of the equipment and/or (5) loss of data due to a sensor fault or low-resolution data due to a high travelling speed. Consequently, though the development of a robust solution that is intrinsically safe and applicable to all kinds of mine sites (metal and coal) is highly desirable, no such feat has yet been achieved. A key issue to consider is that the walls and roof of underground mines are usually covered with shotcrete, thereby reducing the number of distinct features on the surface, meaning SLAM algorithms frequently encounter false loop-closures.

Conclusions

As it has been presented, laser-derived point cloud data is a powerful tool for a variety of underground applications. The possibility of collecting and processing data in short periods of time can reduce considerably the gap between the field and the office, improving quantity and quality of data. The examples outlined in this paper show the value of speed, accuracy and safety. Cost reduction can be obtained by controlling key factors such as overdig and underdig applications (haulage cost optimisation), drillhole deviation control, and faster adjustment time of the driller (reducing driller downtime per round and accelerating the drill and blast process). Alimak raise application has shown a different approach to collect highly detailed information from inaccessible areas in a safe manner. The examples also demonstrate how visualisation in a 3D environment helps facilitate understanding and communicates the outputs in an easy way to the stakeholders in the mine. The acquisition of 3D information is a starting point for digital databases, which are part of a process of continuous improvement. The present examples have shown some key elements for engineers and geologists to improve the decision-making process and optimise operational assets. However, by optimising processing algorithms and implementing GPU for some of the workflow, it is increasingly becoming possible to process data on-site if a quick analysis of the site is required. Currently, in some cases, particularly in coal mines, the applicability may be restricted by intrinsic safety constraints and fire-related hazards. Developments in safety and fire-proof enclosures aim to tackle such issues, but are yet to be tested in sensitive underground mines for their accuracy and robustness in data collection. At the same time, smartphone-based low-power LiDAR is gaining popularity, and it will be interesting to compare its performance with conventional TLS and MLS systems in the years to come. The findings from this review suggest there is scope to improve processing algorithms to increase their efficiency and accuracy for already well-researched areas such as change detection and rock mass characterisation.

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