IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

Comparison of TLS and SLAM technologies for 3D reconstruction of objects with different geometries

To cite this article: Aleksandra Szrek *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1295** 012012

IOP Conf. Series: Earth and Environmental Science 1295 (2024) 012012 doi:10.1088/1755-1315/1295/1/012012

Comparison of TLS and SLAM technologies for 3D reconstruction of objects with different geometries

Aleksandra Szrek[1], **Kinga Romańczukiewicz**[1], **Paulina Kujawa**[1], **Paweł Trybała**[1,2]

[1] Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, Na Grobli 15, 50-421 Wroclaw

[2] 3D Optical Metrology unit, Fondazione Bruno Kessler, via Sommarive 18, 38121 Trento

E-mail: aleksandra.szrek@pwr.edu.pl

Abstract. Technological advances have made the 3D mapping process easily available and simpler. However, there are still aspects that need to be improved and enhanced. The efficient acquisition of 3D data and reconstruction of objects with high accuracy continues to be a challenge for the scientific community. One of the most frequently used 3D mapping methods is Terrestrial Laser Scanning (TLS), which allows the collection of high-resolution and precise data. Another method gaining popularity among researchers and professionals is mobile scanning technology, which enables real-time data capture. Its mobility and speed make it an effective alternative to traditional scanning technologies. This article compares two mapping technologies: SLAM (Simultaneous Localization and Mapping) and TLS taking into account the technical aspects of the instruments, processing methods, time and cost, and concluding with an assessment of the final accuracy. The geometry of several selected objects was analyzed. The resulting root mean square error (RMSE) for the compared distances on the two point clouds was 5 cm, which proves that the SLAM technology can be successfully applied for scenarios requiring centimeter-level accuracy.

1. Introduction

Laser scanning is used to accurately and quickly capture information about the shape, size, and geometry of various objects. Light Detection And Ranging (LiDAR) technology is based on repeatedly emitting light impulses and measuring the return time of the beam [1]. The reflection intensity of the laser beam is often recorded along with the spatial coordinates, providing additional information about the reflection properties of the scanned objects or surfaces. There are various types of laser scanners differing in scan parameters such as maximum measuring range, accuracy, precision, laser wavelength, field of view, scan rate, and point density, as well as in hardware specifications - physical dimensions, weight, portability, possible integration of external devices or systems [2]. The choice of both scanner and scanning method mainly depends on the intended application, accuracy, scale, type, and localization of measured objects but also on available equipment, budget, and time needed for measurement. Laser scanning can be applied in various fields, such as geodesy, civil engineering, urban planning, architecture, or mining. 3D data can be used, e.g., for monitoring the geometry of engineering structures or infrastructure [3, 4, 5], surface roughness assessment [6], 3D city modeling [7], BIM [8], architectural conservation [9]. In the mining sector LiDAR technology is often used to map underground tunnels and evaluate their geometry [10, 11], utilize 3D models of tunnels to analyze airflow [12] or to monitor the condition of mining infrastructure [13].

A commonly used method in the industry is Terrestrial Laser Scanning (TLS), which is an advanced surveying technology that uses laser beams to precisely measure distances and capture detailed three-dimensional information about objects and terrain. It uses an active LiDAR sensor that, rotating at a high frequency, accurately determines the distance to objects at which the laser pulse is directed. TLS scanners are usually placed directly on the ground or mounted on ground platforms such as tripods, often equipped with additional components such as cameras or Global Navigation Satellite System (GNSS) receivers [14]. Another often used method is Mobile Laser Scanning (MLS) where the LiDAR sensor is handheld or mounted onboard a moving platform (a car, a boat, or a robot) [15]. In the case of flying platforms, it is called Aerial (or Airborne) Laser Scanning (ALS) [16].

The mobile mapping systems, operating outdoors, often uses global positioning. The most commonly used positioning systems are GNSS, aided with Inertial Measurement Units (IMU) and odometers. The location information can also be correlated with LiDAR data to enhance the accuracy and georeference collected data. Positioning is especially needed when employing robotic devices [17]. Utilizing robots is particularly useful when measurements are taken in hazardous environments such as underground mines [18, 19] or on disaster sites [20, 21]. The use of an autonomous robot even more significantly reduces the risk of danger by not requiring the physical presence of a robot operator. In order for a robot to operate autonomously, it is necessary for it to be aware of its surrounding.

Simultaneous Localization and Mapping (SLAM) is a technique in which a mobile device maps the environment and estimates its position in it by processing data collected by sensors [22]. LiDAR is one of the most often used sensors for SLAM. As it scans, the point cloud is created and by extracting features the mapping is carried out. At the same time, the SLAM algorithm determines the robot's position based on the created point cloud map and other positioning data. As the robot moves, new point representations of the environment are recorded and data association is performed. The algorithm then optimizes the resulting map and the robot's position. The highest gain of the optimization process happens when the robot completes a loop and revisits a previously mapped location. This allows the map and the robot position to be adjusted and causes the reduction of the alignment errors [23]. LiDAR-based SLAM not only enables the robot to autonomously conduct a requested type of operation, but also a coherent 3D point cloud of the measured environment can be obtained, thus effectively performing a surveying job.

The aim of this study is to compare TLS and SLAM technologies for metric 3D reconstruction purposes. Selected outdoor objects with different geometries were measured using terrestrial laser scanner RIEGL VZ-400i and mobile laser scanner Livox Avia. The comparison includes the specification of scanners, accuracy, and the level of detail of the scanned objects, as well as the characteristics of the measurement itself including labor- and time-consuming aspects.

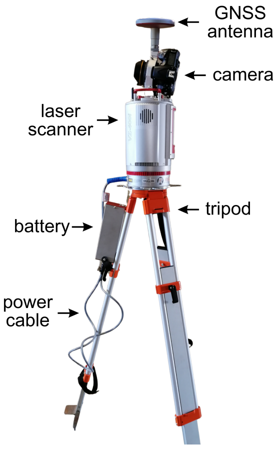
2. Methodology

To compare TLS and SLAM technologies, measurement was performed on external objects located near each other. The selected objects are the upper part of the building facade, pillars, a street lamp, and a tree. Objects differ in geometry, size, and level of detail. Measurement was conducted by using Riegl VZ-400i (for TLS) and Livox Avia (for SLAM). The scanners' specifications are shown in Table 1 and their photos are shown in Figure 1.

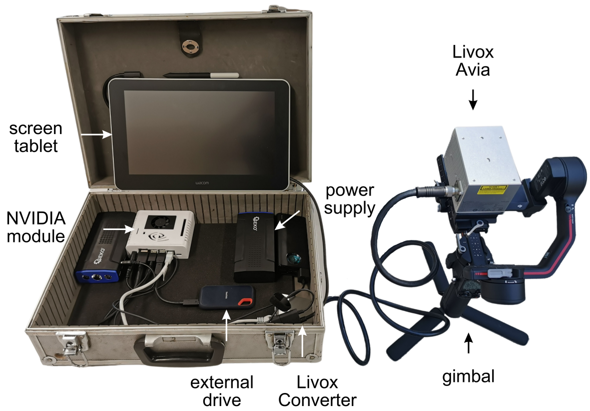
IOP Conf. Series: Earth and Environmental Science 1295 (2024) 012012 doi:10.1088/1755-1315/1295/1/012012

Table 1: Technical specification of the used laser scanners

Scanning technology	**TLS [24]**	**SLAM [25]**
Laser scanner	RIEGL VZ-400i	Livox Avia
Laser wavelength	1 550 nm	905 nm
Max. detection range	120-800 m	190-450 m
Range precision	0.3 cm @ 100 m	2.0 cm @ 100 m
Scanning pattern	Line	Line / Circular
Scanning mode	Repetitive	Repetitive / Non-repetitive
Field of view (horizontal x vertical)	360° x 100°	70.4° x 4.5° / 70.4° x 77.2°
Point rate	500 000 points/s (1200 kHz)	240 000 points/s (up to 3 returns)
GPS receiver	Integrated, with antenna	-
Weight (without equipment)	9.6 kg	0.5 kg



(a)



(b)

Figure 1: Laser scanners with equipment: (**a**) RIEGL VZ-400i and (**b**) Livox Avia.

The measurement using TLS technology with a Riegl VZ-400i pulse scanner was performed without additional equipment such as a camera or GNSS receiver. To ensure appropriate coverage of the study area with all objects of interest, 7 scanner stations were planned at a distance of about 10-15 m. The positions of the instrument stations were planned to obtain a large overlap of areas scanned from adjacent stations. The following scanning parameters were used for the measurement: laser pulse repetition rate of 1 200 kHz, scanning resolution of 0.05°, scanning time at the bench of 30 s, and point cloud resolution of 44 mm (distance between points) at a distance of 50 m. TLS data processing was carried out in RISCAN PRO software (version 2.9). In the first stage, the processing involved filtering individual scans using the parameters of reflectance, amplitude, and deviation. In addition, points with two or more targets were removed, keeping only the first return signal. These two steps removed noise and outlier points. The scans were then automatically registered based on voxels extraction and fitting, and the alignment was performed using the Multi Station Adjustment (MSA) method. The error (standard deviation) obtained from the registration was 2 mm.

For SLAM processing, the data was acquired using a Livox Avia LiDAR connected to an NVIDIA Jetson Xavier module running Ubuntu and Robot Operating System (ROS). It enabled the SLAM algorithm to be run and processed using Fast LiDAR Odometry and Mapping (FAST LIO SLAM) algorithms to create a 3D point cloud of the measured area. Livox is a compact and lightweight mobile scanner with a built-in IMU Module, a wide field-of-view (FOV), high precision, and a long detection distance (up to 450 m). The Livox scanner was placed on the gimbal to ensure its smooth motion. The rest of the equipment was carried in a briefcase for easy and comfortable movement during scanning. A walk-through route was planned to ensure the visibility of all objects of interest and to perform a loop closure. The FAST-LIO-SLAM algorithm, which is a robust LiDAR-inertial SLAM framework, was used to process the data. It combines LiDAR point data with IMU data allowing navigation in motion. This algorithm was found to be computationally efficient and able to reach high mapping accuracy. Raw point data is acquired and accumulated creating a map of the surrounding environment. Odometry is estimated by comparing features of the current position with the previous one, and correspondence between positions is established. The pose is optimized and points are registered and merged to the map [26]. The resulting product of the SLAM technique is one, unified 3D point cloud representing the entire environment measured by the scanner. The postprocessing was carried out in the open-sourced software CloudCompare, it mainly involved cleaning the scan, removing moving objects, and filtering with an intensity parameter. The final point cloud was then segmented so that each object was separated for analysis.

For the two point clouds obtained from TLS and SLAM technologies, the objects extracted were the building facade, a lamp, pillars, and a tree for further comparative analysis.

3. Results and discussion

TLS and SLAM technologies were compared, taking into account the quality and accuracy of the scanned objects, as well as the characteristics of taking measurements and processing the data. Table 2 summarizes the research observations.

The accuracy of TLS is higher, but with the SLAM technique, the measurement was carried out much faster and with less effort. Because of the weight of the Riegl VZ-400i scanner and the necessity to move it, taking a TLS measurement is more difficult and requires more physical labor. With SLAM, data was acquired four times faster than in TLS. However, the short measurement time and mobile scanner parameters are associated with a lower density of the obtained point cloud. Livox Avia acquires almost two times fewer points per second than Riegl VZ-400i.

Processing data from both technologies requires pre-cleaning to remove noise and moving objects (people or vehicles). For the filtering of the noise, TLS has more capabilities and options due to the larger number of laser pulse parameters determined for each measured point. Livox LiDAR registers only one parameter: intensity. However, in SLAM technology, there are algorithms enabling automatic removal of dynamic objects from the point cloud (for example, [27]), while there are none for TLS due to its stationary scanning nature. Scan registration and alignment are necessary steps for point cloud processing with TLS, making this technology more time-consuming. In comparison, SLAM technology can already provide a coherent point cloud after finishing the survey.

Figure 2 and Figure 3 present dimensioned point cloud visualizations of the selected objects. The point clouds have been artificially colorized for clarity. The level of details of scanned objects acquired from TLS is visibly higher compared to scans of objects from SLAM. The facade scan acquired by SLAM technology has an uneven density of points, dense coverage is only visible in one corner of the object, and window edges are not as sharp. Tree reconstruction is incomplete, as points were not registered at the top and on both sides of the tree. Lamp shape lines shown in Section A-A' and the information plate placed on the lamp are not clearly distinguishable.

Table 2: Comparison of TLS and SLAM methods

Scanning technology	**TLS**	**SLAM**
Accuracy of a single point	5 mm	2 cm
Density	approx. 11 000 points/m^2	approx. 1 000 points/m^2
Level of detail	Visible facade and window details, lamp edges, whole tree shape with visible details	No details visible, sharp walls edges, indistinct lamp edges, tree shape without part on the top, and distinctive details such as leaves
Measurement time (excluding preparation time)	7 stations - approx. 20 minutes	100 m - approx. 5 minutes
Labor input in measurement	Scan station planning to ensure coverage, manually moving and positioning of the scanner at 7 stations	Equipment preparation, route planning, sensor holding, and approx. 100 m walk (possible use of a robot)
Post-processing time	approx. 1 hour	approx. 15 minutes
Labor input in post-processing	Manual cleaning and filtering of individual scans, automatic registration and alignment, extraction of the objects of interest	Algorithm parameter adjustment and automatic merging of scans, filtration of noise, extraction of the objects of interest
Price of the sensor with equipment	approx. $120 000	approx. $2 000

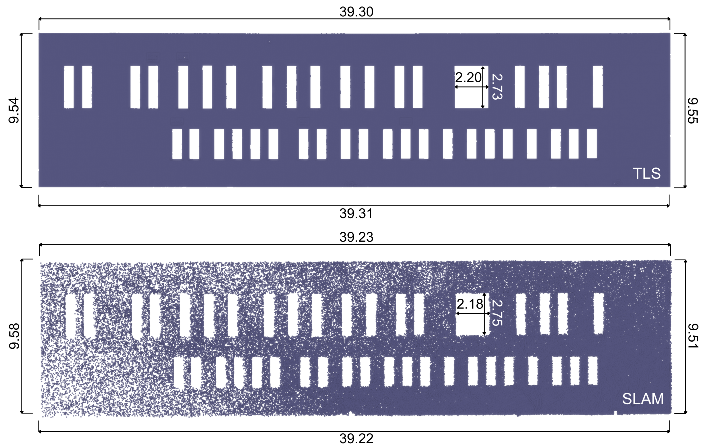


Figure 2: Dimensioned facades (in meters) on the point cloud obtained from TLS and SLAM technologies

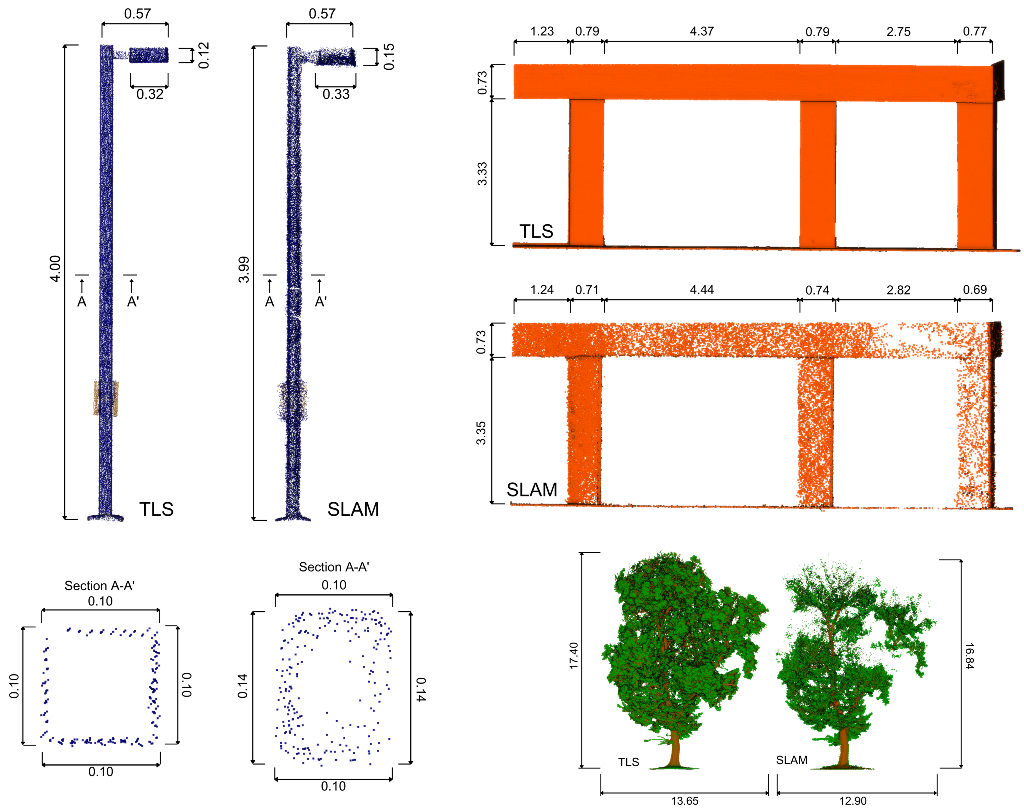


Figure 3: Dimensioned objects (in meters) on the point cloud obtained from TLS and SLAM technologies

To assess the accuracy of SLAM technology, the dimensions of the scanned object were compared with those of TLS scans. The largest differences of about 7 - 9 cm are noticeable in the measurement of the length of the facade and pillars. For the lamp, these differences are no greater than 4 cm. Large discrepancies occur for the length and height of the tree, but the linear measurements are not very accurate due to the complicated geometry and the point clouds are too incomplete to be able to include these values in the comparison.

Taking into account all the obtained differences in length values (Table 3), Root Mean Square Error (RMSE) was calculated according to the formula [28]:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} e_i^2} \tag{1}$$

where:
e_i—values of observations,
n—number of samples.

The calculated RMSE error is 5 cm.

IOP Conf. Series: Earth and Environmental Science 1295 (2024) 012012 doi:10.1088/1755-1315/1295/1/012012

Table 3: Measured lengths and differences (in meters) between point clouds from TLS and SLAM methods

	TLS	SLAM	Difference		TLS	SLAM	Difference
Lamp	4.00	3.99	0.01	**Pilars**	4.37	4.44	-0.07
	0.57	0.57	0.00		3.33	3.35	-0.02
	0.32	0.33	-0.01		2.75	2.82	-0.07
	0.12	0.15	-0.03		1.23	1.24	-0.01
	0.10	0.14	-0.04		0.79	0.71	0.08
	0.10	0.14	-0.04		0.79	0.74	0.05
	0.10	0.10	0.00		0.77	0.69	0.08
	0.10	0.10	0.00		0.73	0.73	0.00

	TLS	SLAM	Difference
Facade	39.30	39.23	0.07
	39.31	39.22	0.09
	9.54	9.58	-0.04
	9.55	9.51	0.04

4. Conclusions

This study compares TLS and SLAM technologies in the 3D reconstruction of objects with various geometries. Technical specifications of chosen scanners, cost and time of measurement conduction, processing methods, and accuracy are considered. Building facade, pillars, lamp, and tree were scanned with Livox Avia (SLAM) and Riegl VZ-400i (TLS).

Each of the technologies discussed has its advantages and limitations. Measurements using SLAM technology enable time-efficient data collection with limited manual labor. With TLS, point clouds are more difficult to acquire. The scanner with all the components is heavier and more expensive, and the obtained data requires proper processing. However, point clouds from TLS technology have higher density and better resolution.

It is worth highlighting that the choice of the appropriate method for 3D reconstruction depends on the measurement object, the available instruments, and the required accuracy wanted to obtain. The comparison of measured distances between corresponding elements in the two point clouds revealed an RMSE error of 5 cm. SLAM technology can be successfully used to model objects requiring centimeter-level accuracy. Considering also the measurement time, this technology is highly recommended for long-range coverage measurements, particularly when the main aim is to quickly obtain accurate geometric data for objects such as underground excavations, urban landscapes, and forested areas. TLS however, is more suitable for object reconstruction where high accuracy is important, for purposes such as digital documentation of historic buildings, architectural inventories, industrial facilities, and infrastructure.

Funding

This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation. This work is supported by EIT RawMaterials GmbH under Framework Partnership Agreement No. 21119 (V0T3D: Ventilation Optimizing Technology based on 3D-scanning). The project is co-financed by the Polish Ministry of Education and Science within the framework of the program titled International Co-financed Projects.

References

[1] M. Lemmens. Terrestrial laser scanning. In *Geo-information*, pages 101–121. Springer Netherlands, 2011.

[2] I. Puente, H. González-Jorge, P. Arias, and J. Armesto. Land-based mobile laser scanning systems: a review. *International archives of the photogrammetry, remote sensing and spatial information sciences*, 38(5/W12), 2011.

[3] Z. Muszyński and P. Kujawa. Some Remarks on Registration Techniques of Point Clouds Obtained from Terrestrial Laser Scanning. *IOP Conference Series: Earth and Environmental Science*, 906(1):012078, November 2021.

[4] A. Capra, E. Bertacchini, C. Castagnetti, R. Rivola, and M. Dubbini. Recent approaches in geodesy and geomatics for structures monitoring. *Rendiconti Lincei*, 26(S1):53–61, May 2015.

[5] W. Wang, W. Zhao, L. Huang, V. Vimarlund, and Z. Wang. Applications of terrestrial laser scanning for tunnels: a review. *Journal of Traffic and Transportation Engineering (English Edition)*, 1(5):325–337, October 2014.

[6] M. Wyjadłowski, Z. Muszyński, and P. Kujawa. Application of Laser Scanning to Assess the Roughness of the Diaphragm Wall for the Estimation of Earth Pressure. *Sensors*, 21(21):7275, November 2021.

[7] Y. Wang, Q. Chen, Q. Zhu, L. Liu, C. Li, and D. Zheng. A Survey of Mobile Laser Scanning Applications and Key Techniques over Urban Areas. *Remote Sensing*, 11(13):1540, June 2019.

[8] R. Rashdi, J. Martínez-Sánchez, P. Arias, and Z. Qiu. Scanning Technologies to Building Information Modelling: A Review. *Infrastructures*, 7(4), 2022.

[9] D. M. Barber, R. W. A. Dallas, and J. P. Mills. Laser Scanning for Architectural Conservation. *Journal of Architectural Conservation*, 12(1):35–52, January 2006.

[10] P. Trybała, D. Kasza, J. Wajs, and F. Remondino. Comparison of low-cost handheld lidar-based SLAM systems for mapping underground tunnels. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-1/W1-2023:517–524, 2023.

[11] Adam Wróblewski, Jacek Wodecki, Paweł Trybała, and Radosław Zimroz. A method for large underground structures geometry evaluation based on multivariate parameterization and multidimensional analysis of point cloud data. *Energies*, 15(17):6302, August 2022.

[12] A. Wróblewski, P.Trybała, A. Banasiewicz, M. Zawiślak, N. Walerysiak, and J. Wodecki. Possibilities of 3D laser scanning data utilization for numerical analysis of airflow in mining excavations. *IOP Conference Series: Earth and Environmental Science*, 1189(1):012009, May 2023.

[13] P. Trybała, J. Blachowski, R. Błażej, and R. Zimroz. Damage Detection Based on 3D Point Cloud Data Processing from Laser Scanning of Conveyor Belt Surface. *Remote Sensing*, 13(1):55, December 2020.

[14] J. Telling, A. Lyda, P. Hartzell, and C. Glennie. Review of earth science research using terrestrial laser scanning. *Earth-Science Reviews*, 169:35–68, 2017.

[15] P. Trybała, J. Szrek, B. Dębogórski, B. Ziętek, J. Blachowski, J. Wodecki, and R. Zimroz. Analysis of lidar actuator system influence on the quality of dense 3d point cloud obtained with slam. *Sensors*, 23(2), 2023.

[16] F. Pirotti, A. Guarnieri, and A. Vettore. State of the Art of Ground and Aerial Laser Scanning Technologies for High-Resolution Topography of the Earth Surface. *European Journal of Remote Sensing*, 46(1):66–78, January 2013.

[17] A. Adán, B. Quintana, and S. Prieto. Autonomous Mobile Scanning Systems for the Digitization of Buildings: A Review. *Remote Sensing*, 11(3):306, February 2019.

[18] P. Trybała. LiDAR-based Simultaneous Localization and Mapping in an underground mine in Złoty Stok, Poland. *IOP Conference Series: Earth and Environmental Science*, 942(1):012035, November 2021.

[19] J. Szrek, R. Zimroz, J. Wodecki, A. Michalak, M. Góralczyk, and M. Worsa-Kozak. Application of the Infrared Thermography and Unmanned Ground Vehicle for Rescue Action Support in Underground Mine—The AMICOS Project. *Remote Sensing*, 13(1):69, December 2020.

[20] P. Kim, J. Park, Y. K. Cho, and J. Kang. UAV-assisted autonomous mobile robot navigation for as-is 3D data collection and registration in cluttered environments. *Automation in Construction*, 106:102918, October 2019.

[21] P. Fritsche, B. Zeise, P. Hemme, and B. Wagner. Fusion of radar, LiDAR and thermal information for hazard detection in low visibility environments. In *2017 IEEE International Symposium on Safety, Security and Rescue Robotics (SSRR)*, pages 96–101, 2017.

[22] T. J. Chong, X.J. Tang, C.H. Leng, M. Yogeswaran, O.E. Ng, and Y.Z. Chong. Sensor Technologies and Simultaneous Localization and Mapping (SLAM). *Procedia Computer Science*, 76:174–179, 2015.

[23] B. Alsadik and S. Karam. The simultaneous localization and mapping (SLAM)-An overview. *Surv. Geospat. Eng. J*, 2:34–45, 2021.

[24] RIEGL VZ-400i datasheet. Brochure, 2021.

[25] Livox Avia Quick Start Guide. Brochure, 2021.

[26] W. Xu and F. Zhang. PFAST-LIO: A Fast, Robust LiDAR-inertial Odometry Package by Tightly-Coupled

Iterated Kalman Filter, 2021.

[27] G. Kim and A. Kim. Remove, then revert: Static point cloud map construction using multiresolution range images. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 10758–10765, 2020.

[28] T. Chai and R. R. Draxler. Root mean square error (RMSE) or mean absolute error (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscientific Model Development*, 7(3):1247–1250, 2014.