Automated As-built 3D Reconstruction Using Quadruped Robot and 3D LiDAR Sensor

Vincent J.L. Gan[1,2], Difeng Hu[1], Ruoming Zhai[1,3], Yushuo Wang[1]

[1] Department of the Built Environment, National University of Singapore, Singapore
[2] Centre of 5G Digital Building Technology, National University of Singapore, Singapore
[3] School of Geodesy and Geomatics, Wuhan University, China
vincent.gan@nus.edu.sg (correspondence), e0788081@u.nus.edu,
ruomingzhai@whu.edu.cn, wangyushuo@u.nus.edu

Abstract –

Advancements in automated 3D scene reconstruction are crucial for accurately documenting and sharing knowledge about the current state of the building and infrastructure facilities. Traditional methods of 3D reconstruction involve laser scanning to capture the building's as-built conditions, which is often a tedious and time-consuming process. This study introduces an automated as-built 3D reconstruction method, with the aid of quadruped robot and 3D LiDAR sensor. The core of this approach is the integration of LiDAR Simultaneous Localisation and Mapping (SLAM) algorithm with robotic control, aiming to achieve detailed 3D/2D mapping and complete point cloud data acquisition. A practical field experiment was conducted to test this approach in reconstructing the building interiors. The results demonstrate the effectiveness of this novel 3D scanning method in achieving high completeness and density in point cloud data.

Keywords –

Quadruped Robot; LiDAR; 3D Reconstruction; Mobile 3D Scanning; Dense Measurement

1 Introduction

Condition monitoring, inspection and quality assessment of architecture, engineering, and construction (AEC) projects requires accurate data with respect to the as-built conditions. This process requires laser scanning to automatically capture 3D as-built point cloud data, followed by manual processing of the captured point clouds to create 3D scene, which is laborious, time-consuming, and error-prone. While automatic 3D BIM reconstruction is an emerging vision, the development still faces exceptional difficulties. Several studies [1-5] attempted to use Light Detection And Ranging (LiDAR) integrated with quadruped robots or unmanned ground vehicles for 3D scene reconstruction of the built environment.

UGVs, equipped with LiDAR, were able to devise a route, navigate towards specific targets, and gather point cloud data from the built environment. Unmanned Aerial Vehicles (UAVs) were tasked with the efficient collection of radiation data by surveying outdoor areas, a method proving more efficient than that of Unmanned Ground Vehicles (UGVs). In a notable development, Kandath et al. [6] introduced a UAV-UGV collaborative system designed to enhance UGV navigation within indoor settings through UAV-provided obstacle location data. Similarly, Peterson et al. [7] crafted a multi-robot system integrating a UGV with a multirotor drone, aimed at improving exploration and navigation efficiencies in outdoor environments. Kim et al. [8] furthered this innovation by creating a UAV-aided automated framework for task execution within cluttered spaces, deploying UAVs initially to generate a 3D terrain map that includes obstacle details through the processing of photographic imagery, thereby optimising ground robot navigation paths.

Despite its success in outdoor point cloud acquisition, LiDAR-equipped mobile laser scanning faces significant challenges in indoor environments due to GPS limitations, restricting its application in these settings. To overcome this, researchers are exploring the use of Simultaneous Localisation and Mapping (SLAM) algorithms as an alternative to global navigation for indoor 3D reconstruction [9, 10]. SLAM functions by determining the scanner's location within an environment while concurrently mapping the 3D scene using LiDAR sensors. This approach is advantageous as it does not rely on GPS signals, allowing the scanning system to be robot-mounted for real-time tracking and 3D scene creation of interior spaces. Specifically, incorporating a robotic dog into this system could significantly enhance indoor navigation capabilities, thanks to its advanced maneuverability and stability in varied terrains. This integration promises to refine scan planning algorithms substantially, leading to the generation of higher quality point cloud data. However, current research in this domain is still evolving and has yet to achieve optimal scanning quality [11]. Existing robot-assisted LiDAR sensing method can hardly capture the completed dense 3D measurement of the building's as-built conditions because the SLAM algorithms have yet fully incorporated the scanning requirement for dense measurement. Integration of the point cloud data quality and completeness over 3D scanning into robot navigation and control for optimising the scanning process is a central task.

This study introduces a new automated as-built 3D reconstruction method, with the aid of quadruped robot and 3D LiDAR sensor to obtain completed and accurate scanned data in regard to the as-built conditions. This requires the use of autonomous robot navigation, localisation, and mapping algorithms in a GPS-denied environment while LiDAR sensor captures dense 3D measurement of buildings. The application provides potential added values to automated smart city reconstruction, constant monitoring, surveillance of built environment, and smart facilities maintenance management.

In line with academia's research agenda, this study aims to develop a new 3D BIM reconstruction approach for automatic point cloud data acquisition. This contributes to the creation of new knowledge, method, and algorithm in the field of automated 3D scanning and as-built BIM reconstruction. The conventional approach separates the 3D scanning and mapping. The study introduces a quadruped robot-assisted automatic scanning and mapping approach utilising SLAM to capture updated as-built information. This research enriches our understanding by integrating robot navigation and optimal pathfinding with SLAM algorithms, enabling comprehensive 3D measurements of as-built conditions.

2 Methodology

As discussed previously, integration of the robotic navigation with LiDAR SLAM is needed to reconstruct the completed and accurate point clouds with respect to the as-built conditions. The requirement for LiDAR scanning to capture the as-built conditions is integrated with robot navigation. The proposed new method controls robot navigation by taking account of 3D scanning, which is different from previous studies.

In this study, a quadruped robot, enhanced with the high-resolution Ouster OS1 LiDAR sensor, is developed for detailed 3D data capture in complex settings. This research proposes two 3D scanning approaches: the first integrates 3D reconstruction with 2D mapping using only the 3D LiDAR sensor, while the second employs an additional 2D LiDAR sensor for navigation, decoupling 3D reconstruction from 2D mapping. Then, an experiment is undertaken in NUS campus to compare and validate the proposed quadruped robot-based LiDAR scanning as a viable approach. Detailed methodology is presented in the following sections.

2.1 Quadruped robot-based LiDAR scanning

Figure 1 presents the configuration of the quadruped robot equipped in this study, which is augmented with the Ouster OS1 LiDAR sensor. Each of the robot's legs is powered by three high torque density electric motors—referred to as the knee motor, thigh motor, and hip motor—which govern the movement of the corresponding joints. This control system allows the quadruped robot to perform a variety of maneuvers such as walking, leaping, and executing pitch, roll, and yaw actions to facilitate 3D scanning in confined and cluttered environments such as indoor. The Ouster OS1 LiDAR sensor is a state-of-the-art device designed for high-resolution 3D data acquisition, providing unparalleled precision and range for various applications. The LiDAR sensor is able to capture detailed spatial information, making it an ideal component for integrating with robotic systems in complex environments.

Figure 1. Quadruped robot equipped with 3D LiDAR sensor for automated 3D scanning

In this study, two 3D scanning solutions are proposed. The first solution couple 3D reconstruction and 2D mapping (for robot navigation) together using solely the 3D LiDAR sensor. Alternatively, the second solution decouples the 3D reconstruction from the 2D mapping by employing an additional 2D LiDAR sensor dedicated exclusively to robot navigation. The objective of contrasting these two solutions is to pinpoint any hardware or software challenges that may arise during the scanning process. Detailed methods are discussed in the followings.

2.1.1 Coupled 3D Reconstruction and 2D Mapping

Figure 2 depicts the coupled 3D reconstruction and 2D mapping for data acquisition and navigation. In this dual-processing technique, a 3D LiDAR scanner collects point cloud data to create a detailed three-dimensional reconstruction of the environment. Concurrently, this 3D point cloud data is processed and translated into a two-dimensional map. This 2D map, while less detailed in terms of vertical information, is crucial for navigation purposes as it provides a simplified and accessible overview of the environment, highlighting pathways and obstacles relevant for guiding quadruped robot.

The key advantage of this coupled method is that it allows for simultaneous localisation and mapping in both three and two dimensions. The 3D reconstruction offers a high-fidelity representation of the environment, which is essential for tasks that require depth information. Meanwhile, the 2D map facilitates efficient path planning and real-time navigation, providing a clear layout of the environment that can be easily interpreted by robotic navigation algorithms.

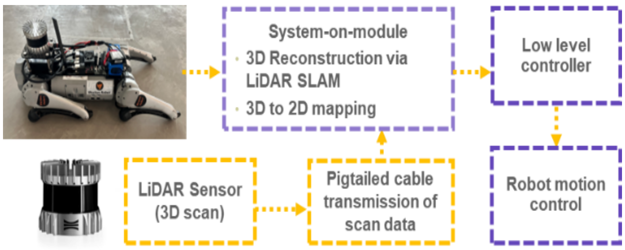

Figure 2. Proposed solution based on coupled 3D reconstruction and 2D mapping

2.1.2 Decoupled 3D Reconstruction and 2D Mapping

Figure 3 displays decoupled 3D reconstruction and 2D mapping where the generation of a three-dimensional model and the facilitation of navigation are separated. Here, a 3D LiDAR sensor gathers point cloud data to construct a three-dimensional representation of the environment. In parallel, a separate 2D LiDAR sensor (e.g., RPLIDAR) operates independently, scanning the environment at a single elevation to collect planar point cloud data. This data is then processed through mapping algorithms to create a two-dimensional map. Unlike the complex 3D model, the 2D map offers a streamlined, birds-eye view of the terrain, instrumental for navigation purposes. The map simplifies the environment to its basic contours and obstacles, providing the necessary information for pathfinding and movement within a space.

This decoupled approach ensures that the 3D reconstruction can be rich in detail and structure without being encumbered by the requirements of real-time navigation. Meanwhile, the dedicated 2D mapping allows for quick and responsive navigation solutions, optimized for real-time operational needs. Together, they form a dual system that caters to the high-resolution modelling and efficient navigational demands of the quadruped robot.

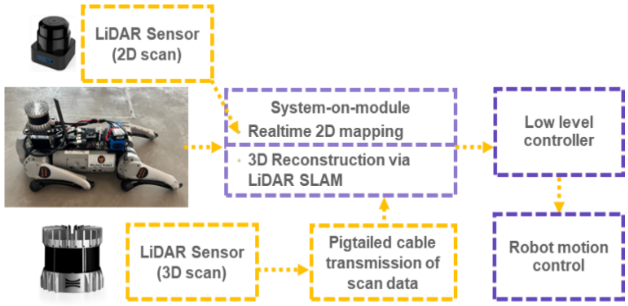

Figure 3. Proposed solution based on decoupled 3D reconstruction and 2D mapping

2.2 3D Reconstruction Using LiDAR SLAM

In this study, LiDAR SLAM is leveraged to reconstruct the point clouds for representing the as-built conditions. Specifically, Lidarslam_ros2 [12] is used to reconstruct the 3D scene of point clouds. It features offline reconstruction that allows for processing all current and past observation data to estimate LiDAR sensor poses and the map, which is advantageous to online reconstruction that relies on current data.

The present study uses Lidarslam_ros2 because comprehensive data analysis is required to produce a precise 3D model. By considering the full spectrum of LiDAR data, the algorithm allows for a more thorough and potentially more accurate pose estimation of the LiDAR sensor at different points in time, leading to a refined and cohesive map. This is particularly beneficial in environments where the LiDAR sensor might experience occasional obstructions or in scenarios where every detail is critical for the creation of an accurate 3D representation. It follows a general LiDAR slam to reconstruct the 3D scene:

- 3D LiDAR sensor collects 3D point clouds of the environment (initial scan).

- Odometry (abbreviated as odom) information is calculated to estimate change in position over time. It is used to estimate the 3D LiDAR sensor or quadruped robot position relative to the starting location.
- When travelling to the next positions, new 3D point clouds are collected and matched with previously collected data using the odometry information to form partially the 3D scene.
- Error accumulates when mapping the point clouds. Thus, when the sensor revisits a previously mapped area, loop closure is detected to optimise the 3D scene.

2.3 2D Mapping for Robot Navigation

2D mapping aims to localise the robot's positions and guide its movement. In this study, the movement of the quadruped robot is controlled remotely through either by entering specific coordinates or by interactively selecting the destination on a 2D map, which then prompts the robot to move accordingly.

Since two contrastive solutions are proposed in this study, the source of information for 2D mapping might vary. For **coupled 3D reconstruction and 2D mapping**, the scan data from the 3D LiDAR sensor are converted to 2D for the first instance, and then analysed with the odometry obtained from the quadruped robot to generate the 2D map. This is because Lidarslam_ros2 in this study is an offline 3D reconstruction algorithm, which couldn't produce the odometry in real-time to support the 2D mapping.

For **decoupled 3D reconstruction and 2D mapping**, a 2D LiDAR sensor (e.g., RPLIDAR) is used to localise the robot's positions and guide its movement. It follows the same regime as 3D reconstruction, which first generates point clouds for one scan, and then automatically registers point clouds from subsequent scans in the shared global frame of coordinates by estimating the scanner's real-time position and orientation. Figure 4 shows the transformation of the information from 2D LiDAR sensor into the 2D map. Typically, rplidar_node is meant to interface with the RPLIDAR sensor and provide scan data. However, it doesn't inherently provide odometry data, as odometry usually comes from motion sensors, encoders, or other motion-related sources in robots. That said, the RPLIDAR sensor derive "pseudo" odometry from the 2D scan data. This is usually achieved through scan matching techniques that estimate the robot's motion by aligning consecutive LIDAR scans. In this study, a ROS package called GMapping is used to undertake the 2D mapping, which then guides the quadruped robot in real-time navigation in the built environment.

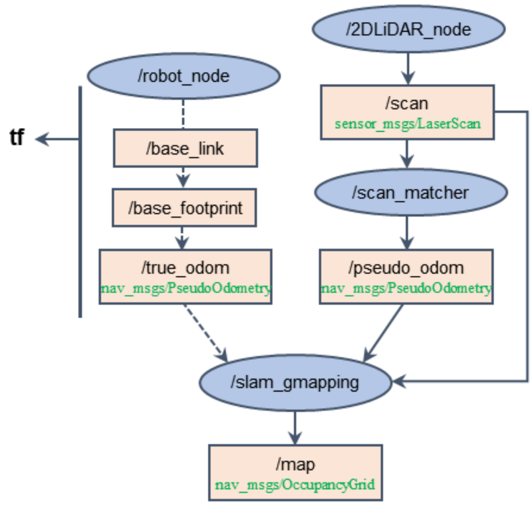

Figure 4. tf tree for 2D mapping

2.4 Field Testing

The Quadruped robot-based LiDAR scanning in this study is validated through field tests conducted on the National University of Singapore (NUS) campus, particularly focusing on the scanning of one educational building. For these tests, a 3D LiDAR sensor is installed and configured on the robot, which then navigate autonomously and perform 3D measurements of the built environment (see Figure 5). This setup aims to rigorously assess the robot's capabilities and its effectiveness in capturing detailed spatial data.

Figure 5. 3D view of the experimental site

Following the completion of the experiments, the gathered point clouds undergo a thorough evaluation, focusing on two key parameters: the density of the point clouds and their completeness. The success of these tests demonstrates the potential of this approach in providing accurate as-built 3D measurements of the built environment, using robotics and LiDAR sensor.

3 Results and Discussion

3.1 Scanned 3D Scenes

Figure 6 shows the 2D map and the quadruped robot movement trajectory. As mentioned, the movement of the quadruped robot is controlled remotely through entering specific coordinates or by interactively selecting the destination on a 2D map, which then prompts the robot to move. The experimental site is the corridor outside a series of research offices and laboratories. Once inputting the destination, the quadruped robot moves along the corridor while scanning the built environment. Figure 7 depicts the point clouds in the reconstructed 3D scene offline using Lidarslam_ros2. The results demonstrate that mobile 3D scanning with the quadruped robot and 3D LiDAR sensor yields decent point cloud quality that surpasses that of previous studies, notably without any point cloud mismatching.

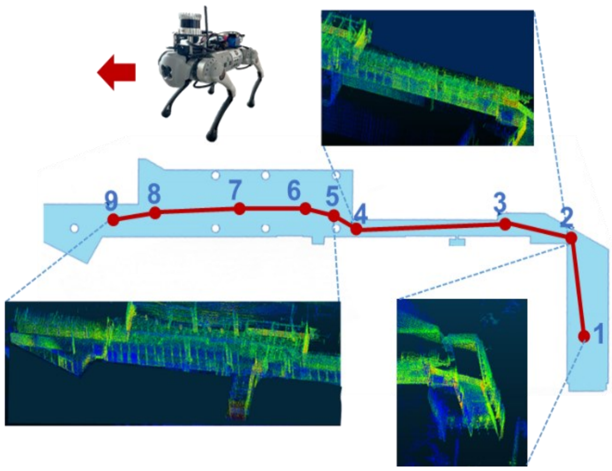

Figure 6. 2D map and the quadruped robot movement trajectory

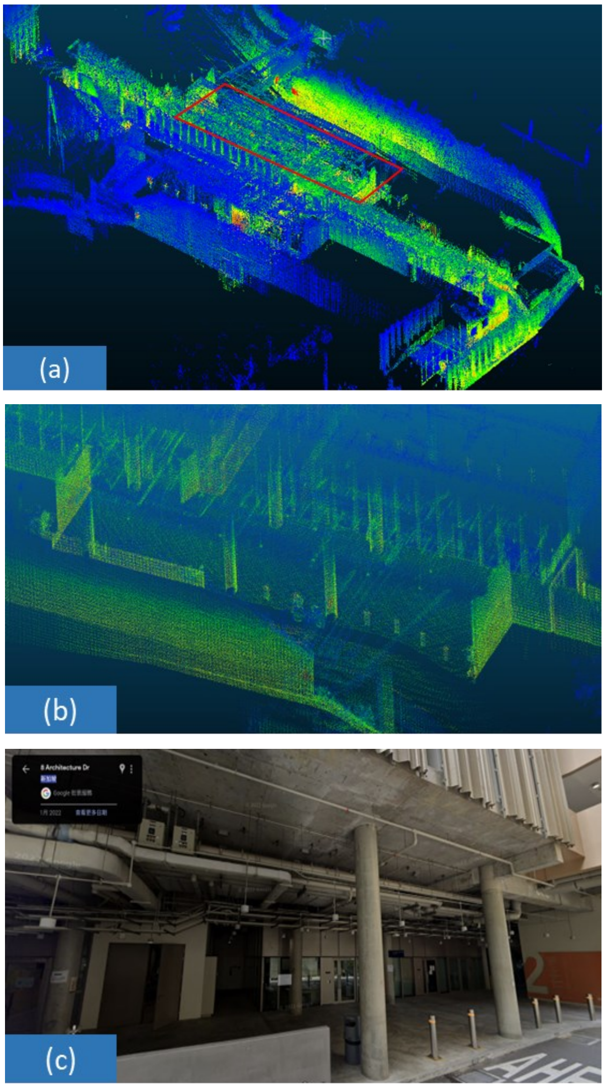

Figure 7. (a) Reconstructed 3D scene offline using Lidarslam_ros2; (b) As-built conditions of the building components; (c) Overview of the 3D scene

3.2 Comparison of Coupled and Decoupled 3D Reconstruction & Navigation

While promising results are obtained using quadruped robot and 3D LiDAR sensor. The system is not without issues. For example, integrating 3D scan to 2D mapping has encountered problems because the objective of 3D scan, which emphasises accuracy, is far different from 2D mapping, which focuses on real time processing and perception. The issue arises in terms of hardware and software perspectives.

When using a wireless connection between the 3D LiDAR sensor (through an additional NX Xavier) and the robot's system-on-module, data transfer is restricted due to wireless bandwidth limitations. The NX Xavier might also face constraints in caching the scanned data due to its limited computational capacity.

Transitioning to a direct cable connection for scan data to the robot's system module improves data transmission. Yet, challenges arise when converting 3D scan data to 2D and performing real-time mapping. The resultant 2D map lacks proper organisation due to insufficient odometry details from the 3D LiDAR, making it unsuitable for navigation. This is because the LiDAR SLAM algorithm in this study is offline 3D reconstruction, and the "pseudo" odometry information is calculated after scanning is completed which cannot be used for the real-time 2D mapping. Consequently, odometry data from an alternative source, such as the quadruped robot, is utilised for creating the 2D map as shown in Figure 8. However, this approach may compromise the map's quality due to potential discrepancies in data integration. A preferable solution is to use separate 3D and 2D LiDAR sensors for independent 3D reconstruction and 2D mapping.

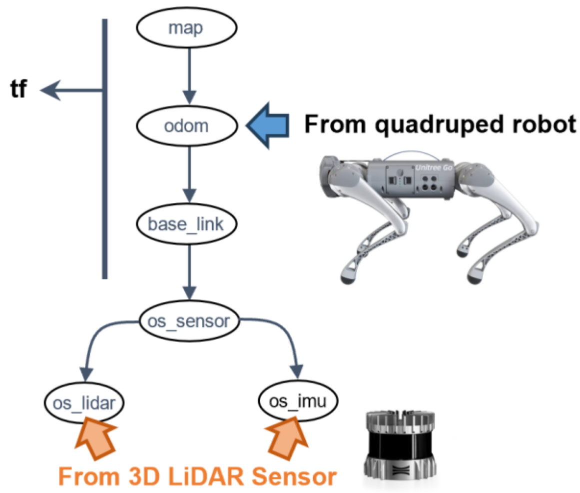

Figure 8. Use of quadruped robot odometry with 3D LiDAR information for 2D mapping

4 Conclusion

This research presents a novel automated as-built 3D reconstruction technique utilising a quadruped robot and a 3D LiDAR sensor. At the forefront of this method is the integration of the SLAM algorithm with enhanced robot motion control for automatic 3D scanning, which facilitate the generation of as-built point cloud data for buildings or infrastructure facilities. This synergy aims to facilitate comprehensive 3D mapping and ensure the thorough collection of point cloud data. A field experiment focusing on the reconstruction of building interiors was conducted. The outcomes of this experiment highlight the mobile scanning method's capability in delivering point cloud data with remarkable completeness and density, showcasing its potential in advanced 3D reconstruction applications.

However, this study has certain limitations, which the research team will further address in future studies. Firstly, the optimal scan positions and robot control strategy need meticulously crafted to optimise the point clouds for both density and completeness. A holistic scan planning optimisation approach, with the consideration of different sensor perception (such as 3D LiDAR sensor, terrestrial laser scanner), will be needed to model the scanning operation and optimise the scan positions. Additionally, the quadruped robot's low-angle viewpoint affects the accurate mapping of features on vertical surfaces and elevated horizontal areas, including MEP utilities and ceiling. The ambient lighting and the limitations in detecting transparent materials such as glass are essential for thorough mapping. The deployment and testing of 3D LiDAR sensors are crucial to verify the proposed scanning method as a robust approach for point cloud data acquisition. This process necessitates a quantitative evaluation, specifically aimed at gauging the completeness and density of the scanned point clouds against benchmarks set by advanced terrestrial laser scans. This evaluation process will focus on assessing the completeness and density of the scanned point clouds. A key method in this evaluation will be the orthographic projection of the point clouds, derived from building elements in 3D space, onto a plane. The projected data will then be converted into a regular grid. This grid-based representation will align with the predetermined minimum requirements for point cloud density in this study, allowing for a more structured and measurable analysis.

The present study evaluates Lidarslam_ros2, an offline reconstruction algorithm. Recognising the challenge associated with real-time point cloud processing, this research aims to advance towards potential solutions including online 3D scene reconstruction algorithms and/or ensuring robust bandwidth of connections to facilitate uninterrupted data transmission to a remote server for point cloud processing. Addressing these technical considerations is essential, as it enables future iterations of this research. The outcome of the present study will contribute to the automation and precision of point cloud data acquisition in the built environment. This advancement will enable us to extend our research into the realms of scan-to-BIM and as-built BIM generation.

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References

[1] El-Halawany, S.I. and Lichti, D.D., "Detecting road poles from mobile terrestrial laser scanning data." GIScience & Remote Sensing, 2013. 50(6): p. 704-722.

[2] Yen, K.S., Lasky, T.A., and Ravani, B., "Cost-benefit analysis of mobile terrestrial laser scanning applications for highway infrastructure." Journal of Infrastructure Systems, 2014. 20(4): p. 04014022.

[3] Gené-Mola, J., et al., "Fruit detection in an apple orchard using a mobile terrestrial laser scanner." Biosystems Engineering, 2019. 187: p. 171-184.

[4] Rosell-Polo, J.R., et al., "Kinect v2 sensor-based mobile terrestrial laser scanner for agricultural outdoor applications." IEEE/ASME Transactions on Mechatronics, 2017. 22(6): p. 2420-2427.

[5] Hu, D., Gan, V.J.L., and Yin, C., "Robot-assisted mobile scanning for automated 3D reconstruction and point cloud semantic segmentation of building interiors." Automation in Construction, 2023. 152: p. 104949.

[6] Kandath, H., Bera, T., Bardhan, R., and Sundaram, S., "Autonomous navigation and sensorless obstacle avoidance for UGV with environment information from UAV." In 2018 Second IEEE International Conference on Robotic Computing (IRC), 2018. IEEE.

[7] Peterson, J., et al., "Online aerial terrain mapping for ground robot navigation." Sensors, 2018. 18(2): p. 630.

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

[9] Chong, Z.J., et al., "Synthetic 2D LIDAR for precise vehicle localization in 3D urban environment." In IEEE International Conference on Robotics and Automation, 2013, IEEE: Karlsruhe, Germany. p. 1554–1559.

[10] Hu, D., Gan, V.J., Wang, T., and Ma, L., "Multi-agent robotic system (MARS) for UAV-UGV path planning and automatic sensory data collection in cluttered environments." Building and Environment, 2022. 221: p. 109349.

[11] Aryan, A., Bosché, F., and Tang, P., "Planning for terrestrial laser scanning in construction: A review." Automation in Construction, 2021. 125: p. 103551.

[12] Sasaki, R., "lidarslam_ros2." Available at https://github.com/rsasaki0109/lidarslam_ros2, 2022.