# ROBOTIC SYSTEMS FOR AUTONOMOUS DATA ACQUISITION IN CONSTRUCTION: A CASE STUDY

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## Abstract

Traditional data acquisition methods in construction often struggle with accuracy, efficiency, and adaptability, especially in dynamic jobsite conditions. These shortcomings can lead to elevated error rates, schedule overruns, and increased resource consumption. To address these issues, this paper presents the development of an autonomous robotic system that synergizes Simultaneous Localization and Mapping (SLAM), autonomous exploration, and robust data handling algorithms for enhanced reality capture and reduced human involvement. Building upon state-of-the-art SLAM solutions, our approach leverages LiDAR-based 3D mapping to enable real-time environment reconstruction, while an autonomous exploration algorithm guides the robot through unknown areas. A semi-autonomous robotic platform was deployed and tested in an active construction environment. By integrating a relational database framework and low-latency communication protocols, the platform efficiently handles large volumes of sensor data, facilitating both immediate oversight and post-processing analysis. Preliminary results indicate that the system adapts effectively to shifting on-site conditions, providing comprehensive and timely data that enhances project management and decision-making processes. This research highlights the value of autonomous robotic solutions as a cornerstone of the emerging Construction 4.0 paradigm, offering a roadmap for more sustainable, efficient, and data-driven operations.

**Keywords:** autonomous robots, construction 4.0, data management, reality capture, SLAM

**Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2025.**

## 1. Introduction

In the rapidly evolving construction technology landscape, the integration of artificial intelligence (AI) and robotics represents a significant advancement with the potential to dramatically enhance efficiency, accuracy, and sustainability. Historically, the construction industry has been characterized by its labour-intensive processes and slow adoption of technological innovations, presenting a prime opportunity for transformative change. This change, often referred to as Construction 4.0, aims to tackle prevalent issues such as project delays, cost overruns, and safety hazards through automation and digitalization.

By developing and deploying autonomous robots for reality capture tasks in construction sites, the project seeks to reduce human error, improve data collection processes, increase the frequency at which data is captured, and optimize project management through dynamic, AI-driven decision-making tools that take into consideration all the collected data. This approach not only promises to elevate the precision and reliability of construction operations but also to significantly reduce the environmental impact associated with traditional construction practices.

This paper outlines the development process of our robotic system, tasked with autonomous data acquisition in construction sites. Through a state-of-the-art literature review, existing methodologies have been studied in order to identify essential characteristics of robotic platforms for effective operation in construction sites. Next, the methodology section showcases the current data collection process of

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the robot, with details regarding the robotic platform, autonomous navigation methods, data collection and data handling. Additionally, the proposed robotic system has been tested in an active construction site, which is described in the case study section. The current drawbacks of the proposed system have also been outlined in the discussion and limitations section, describing components of the autonomous workflow that will need to be improved in future work.

## 2. Previous work

### 2.1. Autonomous navigation

Recent advancements in autonomous robotics have significantly improved the efficiency and accuracy of construction processes. Autonomous robots are now capable of navigating complex construction environments, avoiding obstacles, and performing data collection with minimal human intervention. Yuwei Cheng et al. [1] introduced the USV Inland Multi-Sensor Dataset, gathered using a semi-autonomous inflatable boat with multiple sensors to tackle challenges like fog and dynamic waters, improving navigation systems for inland waterways. Another significant contribution is by Fraj Hariz et al. [2], who proposed a method integrating SLAM and ROS for large-scale 3D point cloud mapping in GNSS-challenged areas, enhancing mapping accuracy by combining LiDAR, IMU, and GPS in real time. Chong Xu [3] advanced UAV-based forest mapping using LiDAR, GNSS, and IMU sensors, employing SLAM techniques such as FASTLIO-SC and LIOSAM to produce precise 3D maps for wildfire risk assessment. Han Wang et al. [4]  proposed Intensity-SLAM, integrating intensity data from LiDAR to improve mapping accuracy via robust feature detection and pose optimization, addressing geometric-only SLAM limitations in complex environments. Haala et al. [5] analyzed the StreetMapper mobile laser scanning system, demonstrating its capability to rapidly collect dense 3D point clouds in urban settings with high accuracy.

SLAM algorithms are essential for simultaneously mapping environments and determining a robot's pose. While visual SLAM produces high-quality maps, it is less reliable under poor illumination, which is common in construction sites. Our research indicates that LiDAR-based 3D SLAM methods are more effective, as 2D SLAM struggles with height variations (e.g., stairs) [6].

LeGO-LOAM [7], optimized for low-power ground robots, includes loop-closure detection to enhance mapping reliability. FAST-LIO2 [8], although more computationally efficient, lacks loop-closure capabilities, while LIO-SAM [9] employs a robust factor graph, incorporating IMU data, loop closure, and optional GPS inputs, making it well-suited for dynamic construction environments.

In addition to reconstructing the 3D environment through SLAM methodologies, the robot needs to be able to move autonomously through a given environment. Exploration algorithms are used to determine which direction the robot should autonomously move toward to complete exploration most efficiently. The most popular exploration algorithms are frontier-based exploration strategies that enable the robot to explore a generic 2D environment by defining frontiers between regions of known and unknown space [6]. Additionally, some techniques utilize a cost/gain function with adjustable parameters that allow the algorithm to be adapted to different applications. Some of these methods are discussed below.

Lu et al. [10] presented the Optimal Frontier Selection algorithm, a 3D exploration method that utilizes frontier exploration through an Octomap with a cost-gain function. Similarly, Autonomous Exploration Planner (AEP) [11] employs a potential information gain function driven by separate local and global planners. Frontier-based exploration is used as the global planner, while Receding Horizon Next-Best-View Planning (RH-NBVP) is employed at the local scale. The AEP uses a Rapidly exploring Random Tree (RRT) to determine the most efficient pose with low run time. Also making use of the RRT, the Dual-Stage Viewpoint Planner (DSVP) [12] uses a two-stage approach to enhance performance in highly convoluted environments. Lastly, Graph-based Path Planning (GBP) [13] makes use of rapidly-exploring random graph search (RRG) and Dijkstra's algorithm to determine the robot's exploration goal; GBP then triggers the global planner to determine whether it is feasible to reach the desired pose, considering the robot's battery level.

## 2.2. Data handling

Efficient data management is essential for the success of construction projects, as it facilitates accurate tracking and effective oversight. Martínez-Rojas et al. [14] illustrate how integrating Information and Communication Technologies (ICT) transforms construction project management by improving data handling, cost control, and risk management. Their work highlights ICT's potential to streamline decision-making and enhance overall project efficiency, proving it to be an invaluable tool in modern construction management.

Building on these advancements, El-Omari et al. [15] developed an innovative tracking and control system that automates data collection on-site, utilizing barcoding, RFID, LiDAR, and digital imaging. The data gathered is organized in a central database, enabling more accurate reporting and timely project management decisions. This automated system addresses the growing need for precise and accessible data throughout project timelines. Similarly, Ward et al. [16] explored wireless data collection through the IEEE 802.11b protocol, enabling real-time access to information on construction sites. This system not only improves data flow across sites but also helps reduce costs and improve contract performance by facilitating timely access to project data.

In addition, Chassiakos et al. [17] created a web-based construction management system using relational databases to handle project data efficiently. This system enhances the reliability and speed of information exchange, supporting streamlined communication among project teams and reducing delays and misunderstandings during project execution. Together, these technologies underscore how essential efficient data handling is for seamless project progress tracking and management.

As data volume and complexity increase on modern construction sites, robust SQL databases have become indispensable, especially in robotic data management. Unlike NoSQL, SQL databases offer structured models and robust interfaces that support complex queries and transactions essential for the reliability and accuracy needed in construction. A recent example involves an intelligent platform for engineering construction that leverages SQL Server to manage backend data, demonstrating SQL's capability to handle construction project demands through secure and structured data management [18].

## 3. Methodology

This section outlines the data collection methodology, emphasizing the shift from traditional manual techniques to an autonomous approach that leverages robotic systems and LiDAR technology. Historically, construction site data collection required substantial human labor and time, with multiple points of manual intervention. By incorporating advanced robotics and a commonly used robot software framework (e.g., Robot Operating System, ROS), the proposed approach significantly reduces human involvement while boosting efficiency. The BPMN flowchart in **Hiba! A hivatkozási forrás nem található.**Figure 1 illustrates the key steps of this autonomous data collection process.

A mobile robotic platform with a modular architecture would be ideal for the integration of the required sensors, including a high-precision 3D LiDAR scanner. For more information about the development of such a platform, readers may refer to [19]. Moreover, compatibility with ROS ensures efficient communication between onboard sensors and autonomous control systems, thereby optimizing data acquisition and navigation processes.
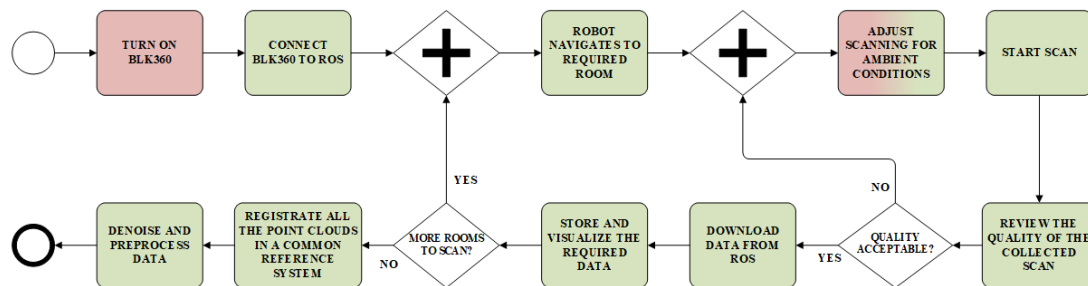


Figure 1. BPMN flowchart of the data collection process. The red background represents a manual process. The green background represents an automated process. A gradient between red and green represents a semi-autonomous process.

Once the mobile robot reaches a designated location on the construction site, the onboard 3D LiDAR scanner autonomously captures data for applications such as progress monitoring and quality control. The scan parameters are dynamically adjusted in response to environmental factors or user-defined settings. The captured point cloud data is then processed, registered within a shared reference frame, and subjected to a quality review. If the data meets predefined standards, the process concludes; otherwise, additional scans are performed autonomously.

This autonomous data collection paradigm markedly improves operational efficiency, enhances accuracy, and minimizes human error. By employing Simultaneous Localization and Mapping (SLAM), the platform accurately maps the environment while autonomous exploration algorithms guide its movement across the site. A robust infrastructure for data transmission, storage, and management preserves data integrity and ensures accessibility for subsequent analysis.

*3.1. Autonomous navigation*

The robotic system integrates simultaneous localization and mapping (SLAM) and autonomous navigation to enable data acquisition in construction environments. SLAM is responsible for constructing a map of the surroundings while localizing the robot within it. To achieve this, the system combines lidar-inertial odometry (LIO) for motion estimation with a mapping framework that maintains a consistent global representation of the environment. While LIO provides high-frequency motion updates by fusing lidar and inertial measurements, the SLAM backend ensures map optimization through loop closure and global consistency.

For lidar-inertial odometry, we implemented LIO-SAM, which utilizes factor graph optimization to fuse lidar and IMU data while incorporating loop closure to minimize drift over extended operations. Preliminary simulation experiments were conducted to compare different methods, providing insights into their performance in construction-like environments and allowing us to identify the most suitable approach before real-world deployment. This method was selected due to its ability to provide robust localization in environments where external positioning systems are unavailable. The SLAM component then processes this data to generate a globally consistent map, ensuring accurate spatial representation of the construction site. Thanks to the loop closure, dynamic objects do not persist in the map, since they're removed during the scan-matching updates.

For autonomous navigation, the system initially used graph-based path planning (GBP), which employs a rapidly-exploring random graph (RRG) structure combined with Dijkstra's algorithm to optimize the selection of waypoints. GBP was chosen due to its ability to balance efficient exploration with adaptive path selection.

However, due to its computational overhead, an alternative frontier-based exploration algorithm, Explore-Lite, was ultimately selected. This method enables the robot to explore systematically by identifying and navigating toward the boundaries between mapped and unmapped regions. Additionally, the algorithm allows for operator intervention when necessary, ensuring adaptability to changing site conditions.

*3.2. Data collection*

The selection of the most suitable LiDAR system for our autonomous data collection was done considering various criteria ensuring all the requirements for effective integration with the robotic platform were considered.

To identify the optimal LiDAR system, we compared several models: the FARO S150, Trimble X12, Matterport Pro3, and Leica BLK360 G1, as can be seen in Table 1. The comparison was based on key factors such as design and portability, performance specifications, environmental adaptability, connectivity and control, ease of use, and integration with the most used software platforms.

*Table 1. Comparison details between different LiDAR systems.*

|  | Leica BLK360 | FARO S150 | Trimble X12 | Matterport Pro3 |
|---|---|---|---|---|
| Weight | 1 kg | 4.2 kg | 6.7 - 7.7 kg | 2.2 kg |
| Battery Life | > 40 setups | 4.5 hours | 5 hours | >220 scans continuously |
| Speed | Up to 360,000 pts/sec | 976,000 pts/sec | Up to 2.187 million pts/sec | 100,000 points per second |
| Precision | 4mm @ 10m | ±1mm | ≤ 1 mm + 10 ppm/m | ±20 mm @ 10 m |
| Range | 0.6 - 60 m | 0.6 - 150 m | 0.3 - 365 m | Up to 100 m |
| FoV | 360° × 300° | 360° × 300° | 360° × 320° | 360° × 295° |
| Data Types | 3D point clouds, thermal data, RGB data | 3D point clouds, RGB data | 3D point clouds, RGB data | 3D point clouds, RGB data |

While the compared laser scanners have their own strengths and capabilities, the Leica BLK 360 emerges as a compelling choice for autonomous data collection and navigation in construction environments. Its lightweight and compact design, combined with its ease of use and remote operation capabilities, make it well-suited for integration into autonomous robotic platforms. The BLK 360's comprehensive data collection, including 3D point clouds, spherical imaging, and thermography, can provide valuable insights into the construction site, addressing a wide range of needs. Additionally, its environmental adaptability and software integration capabilities further enhance its suitability for construction applications. The BLK 360's balanced performance specifications, while not the highest among the compared scanners are sufficient for the data collection requirement in construction projects.

### 3.3. Data handling

The data management strategy for this study centers on structured storage and easy retrieval, both vital for handling the substantial sensor data generated by the robotic platform in construction site environments. We implemented a relational database that organizes each ROS topic into separate tables for each sensor, streamlining data retrieval and facilitating consistent data handling. This structured setup, combined with robust indexing and querying, enhances performance, data integration, and reliability, which are critical for deploying advanced robotics solutions.

To gather this data, the platform relies on sensors that provide continuous streams of environmental and operational data. To balance real-time requirements with the need for comprehensive data analysis, we adopted a hybrid collection approach. This involves both local storage on the robot via ROSbag files and live telemetry for immediate data transmission. This method allows us to monitor the robot's real-time performance while ensuring that detailed data is available for post-mission analysis, supporting both instant decision-making and comprehensive review if any issues arise.

Efficient data transmission is essential, particularly for real-time applications where both speed and reliability are crucial. We utilized WebSockets with rosbridge, which allows low-latency communication over a single TCP connection. This setup proved ideal for high-bandwidth data transmission, enabling robust, real-time monitoring and facilitating bidirectional communication for sensory and kinematic data.

For data visualization, effective tools are necessary to allow operators to monitor real-time data and robot status remotely. Solutions such as Foxglove provide flexible options for tracking data without requiring direct access to the robot's network. These visualization methods enhance flexibility and enable continuous monitoring, which is particularly useful on dynamic construction sites.

This integration of structured data management, hybrid collection methods, low-latency transmission, and remote visualization forms a comprehensive approach to real-time monitoring and post-operation analysis, as depicted in Figure 2**Hiba! A hivatkozási forrás nem található.**.
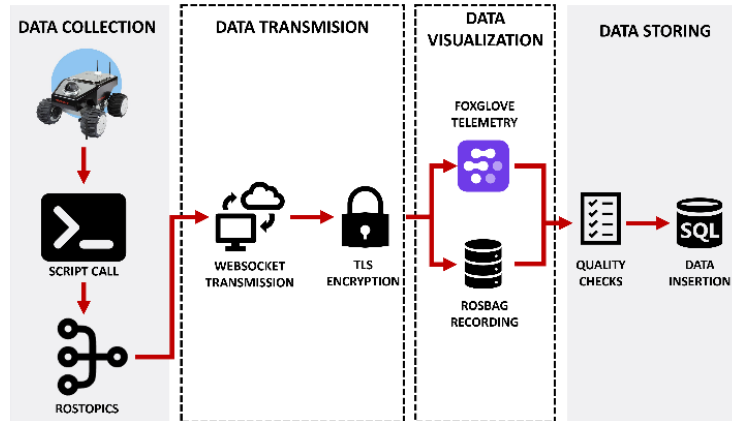
*Figure 2. Data handling process, starting with the collection and ending with the storing.*

These elements ensure that our system provides reliable, accessible insights into the operational demands of construction sites.

## 4. Case study

### 4.1. Overview of the robotic platform

The robotic system used for this study is based on the SUMMIT-XL mobile platform (Figure 3**Hiba! A hivatkozási forrás nem található.**), chosen for its adaptability to dynamic and complex environments. The platform features a four-wheel holonomic drive system, enabling precise manoeuvrability in both indoor and outdoor settings. Its modular architecture allows for the seamless integration of multiple sensors and computational units required for autonomous operation.
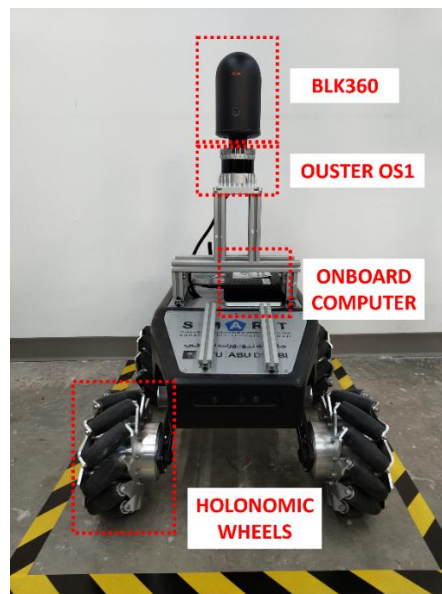


*Figure 3. Overview of the modified SUMMIT-XL platform and its main components.*

For navigation and mapping, the platform is equipped with the Ouster OS1 LiDAR, which provides real-time 3D SLAM capabilities. This sensor generates dense point clouds with up to 120m in range, with an FOV of 45°×360°, facilitating accurate localization and obstacle detection in challenging environments. Additionally, the Leica BLK360 scanner is integrated for high-resolution data acquisition, with up to 60m in range and an accuracy of 4mm@10m, enabling detailed 3D reconstructions at predefined waypoints. The platform is equipped with an Intel NUC12 as an onboard computer, with an i9-12900 processor and 64GB of RAM.

The platform is controlled via a ROS-based architecture, ensuring efficient communication between sensors, the onboard computer, and the exploration and SLAM algorithms. This modular system architecture enhances the platform's flexibility, enabling its application in diverse construction scenarios.

*4.2. Overview of the construction site*

The experiments were conducted in a construction site spanning approximately 500 m², characterized by its dynamic and complex layout. The site included narrow corridors, evolving structural layouts, and various static and moving obstacles such as temporary barriers and scattered construction materials. These features provided a realistic testbed for evaluating the robotic system's navigation, mapping, and data acquisition capabilities.

The construction site's dynamic nature posed challenges for real-time mapping and obstacle avoidance, making it an ideal environment to test the Ouster OS1's SLAM capabilities and the Leica BLK360's precision scanning.

*4.3. Results obtained*

To effectively demonstrate the capabilities of the developed robotic system, we designed three experiments, each addressing specific objectives within the context of autonomous navigation, data collection, and mapping on a construction site. The purpose of these experiments was to progressively evaluate the system's functionalities under varying levels of autonomy and complexity.

The relationship and objectives of the experiments are summarized in Table 2 below. Each experiment builds on the insights gained from the previous one, offering a holistic evaluation of the system's performance.

*Table 2. Summary of the performed experiments.*

| Experiment | Objective | Key features |
|---|---|---|
| 1. Teleoperated SLAM | Establish a baseline 3D map for comparison | Manual control, 3D point cloud generation, Ouster OS1 |
| 2. Autonomous exploration | Evaluate autonomous navigation and 3D SLAM, as well as the creation of 2D obstacle map | Fully autonomous exploration, combined 3D/2D mapping, Ouster OS1 |
| 3. Waypoint-based scanning | Assess precision and high-resolution scanning at predefined locations | Waypoint execution, high-resolution 3D scanning, BLK360 |

*4.3.1. Experiment 1: Teleoperated 3D SLAM*
In the first experiment, the SUMMIT-XL was teleoperated to navigate through the construction site while performing 3D SLAM using the Ouster OS1. This teleoperated run served as a baseline for comparison in subsequent experiments.

During this run, the robot was manually guided through various sections of the site, generating a comprehensive 3D point cloud of the environment. This baseline map was later used to evaluate the performance of the autonomous runs in terms of map completeness and accuracy.

*4.3.2. Experiment 2: Autonomous exploration with 3D SLAM and 2D mapping*
The second experiment involved fully autonomous exploration, where the robot was tasked with navigating the construction site on its own, using the explore-lite algorithm for autonomous exploration and the LIO-SAM algorithm for 3D SLAM. In this run, the robot was not given any pre-defined waypoints; instead, it autonomously explored the environment, generating both a 3D point cloud and a 2D map of the site.

The robot successfully covered all critical areas, capturing a detailed 3D map of the site (Figure 4 a**Hiba! A hivatkozási forrás nem található.**) comparable to the teleoperated baseline (Experiment 1). Additionally, the robot produced a 2D map (Figure 4 b**Hiba! A hivatkozási forrás nem található.**), w hich provided a top-down view of the environment, showing key features like walls and obstacles. Since the navigation system operates in a 2D plane, a 2D map is required for path planning and waypoint generation in the next Experiment.
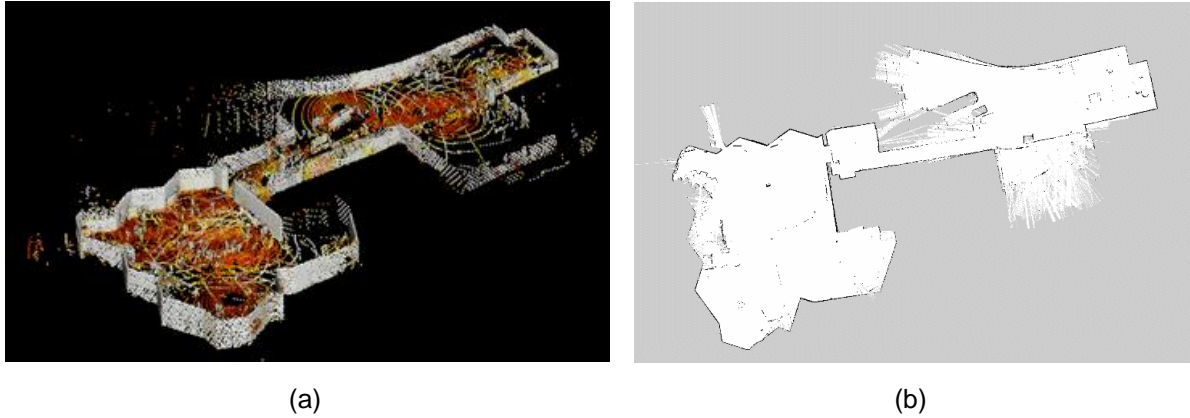
*Figure 4. (a) Point cloud collected with the SLAM algorithm and the Ouster OS1. Ceiling has been removed for visualization purposes. (b) Generated 2D map during the exploration process.*

### 4.3.3. Experiment 3: Predefined waypoints with BLK360 scanning

In the third experiment, a set of waypoints was predefined on the 2D map generated in the previous experiment. The goal was for the robot to autonomously navigate to these waypoints, stop, and perform high-resolution scans using the BLK360 scanner. The waypoints were strategically manually placed at areas of interest within the site, including narrow corridors and key structural features.

At each waypoint, the BLK360 scanner was autonomously activated, capturing high-resolution 3D scans of the surrounding environment (Figure 5**Hiba! A hivatkozási forrás nem található.**). The robot successfully stopped at all waypoints and performed the scans without intervention, demonstrating the effectiveness of integrating SLAM-based navigation with precision scanning tasks.
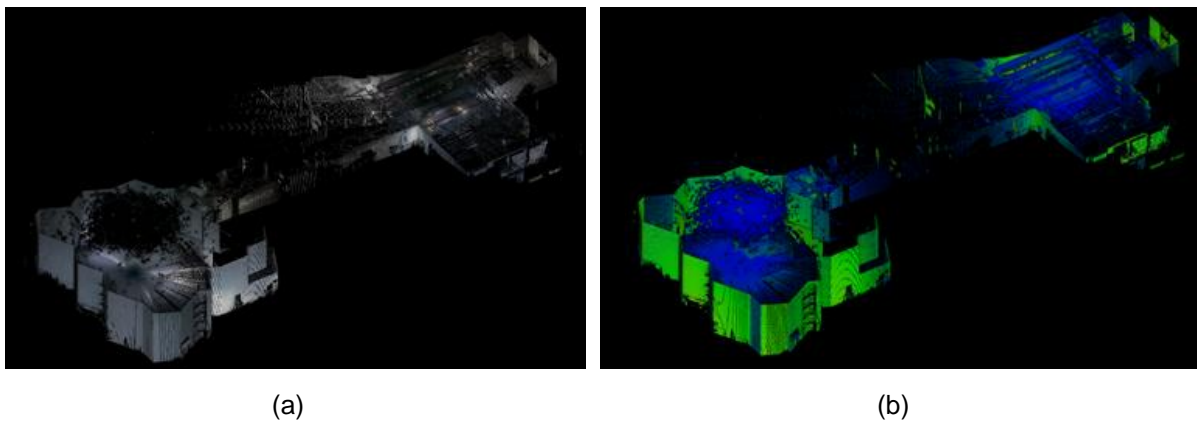


*Figure 5. Point cloud collected with the BLK360 scanner showing (a) RGB color information and (b) reflectance information.*

## 5. Challenges and limitations

Throughout the project, we encountered several challenges during navigation and data collection that necessitated additional testing and modifications. Implementing navigation algorithms on our hardware required multiple adjustments, particularly with the GBP exploration algorithm, which was originally designed for static environments like tunnels. On dynamic construction sites, moving obstacles caused cluttered maps, reducing the robot's efficiency. Properly tuning map generation parameters was critical: over-tuning created excessive clearance, while under-tuning introduced clutter that hindered real-time exploration.

Another key issue involved defining the robot's safety bounds. Although a larger safety buffer minimized collision risks, it limited manoeuvrability in narrow corridors, requiring iterative adjustments to balance safety and flexibility. Furthermore, while our 3D exploration algorithm performed well in controlled lab conditions, it failed on-site due to hardware and communication issues within the ROS network. Given

time constraints, we reverted to a 2D exploration algorithm on-site but retained 3D SLAM for generating detailed point clouds, providing valuable spatial data despite reduced exploration capabilities.

Data collection presented unique challenges, particularly due to the limitations of the Leica-provided API and scarce online resources. Initial connectivity issues between the BLK360 sensor and the robot's computer were resolved through upgrades. We also overcame obstacles in point cloud colorization by switching from HDR to LDR panoramic imaging. Data downloading issues, which previously led to incomplete downloads, were resolved by establishing a logical acquisition sequence.

On the data handling side, network latency issues between the ROS master and the robot initially hindered real-time operations. Enhancing the network infrastructure and optimizing WebSocket configurations reduced lag, which improved the fidelity of real-time visualizations. Compatibility issues between ROS Noetic and an outdated version of Ubuntu also caused crashes, particularly during high data throughput. Transitioning to the correct Ubuntu version and stabilizing ROSbag recordings through shell script-based execution eliminated these interruptions and ensured continuous data collection.

While these challenges created setbacks, they also provided valuable insights, enabling us to enhance the system's robustness and the quality of collected data.

## 6. Conclusions and future work

This research set out to address key limitations in construction data acquisition by developing an autonomous robotic system that combines SLAM and advanced data handling. We successfully validated the system through real-world testing, achieving reliable navigation and precise data collection in a dynamic construction site environment. The outcomes demonstrate that our robotic platform adapts well to on-site challenges, highlighting the potential for reducing human intervention and enhancing data reliability in construction management. This project serves as a foundational step, illustrating the viability and benefits of autonomous systems in the field.

The automation of data collection plays a key role in improving precision, reliability, and sustainability in construction operations. By removing human inconsistencies, the system ensures consistent and comprehensive data acquisition, reducing the risk of missing critical site details. This increased precision enables better decision-making and early detection of potential issues, which in turn helps mitigate delays, cost overruns, and material waste. Additionally, the availability of frequent and accurate site data allows for more efficient resource allocation and process optimization, contributing to a reduction in environmental impact over time. While this study focuses on the implementation and validation of the robotic system, its long-term benefits lie in its ability to support smarter, data-driven construction practices.

To further enhance the system, future work will focus on addressing the limitations identified, particularly in navigation flexibility, by implementing a 3D exploration algorithm and real-time data handling. Improvements will target more robust algorithms to better handle moving obstacles, as well as optimize data transmission processes to reduce latency and increase real-time capabilities. Additionally, expanding sensor compatibility and refining autonomous exploration algorithms will improve adaptability to even more complex environments, strengthening the system's utility in diverse construction scenarios.

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