Autonomous Data Acquisition of Ground Penetrating Radar (GPR) Using LiDAR-based Mobile Robot

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Abstract – In this paper, we propose a ground mobile robot that can perform both surface mapping and subsurface mapping using a three-dimensional LiDAR Simultaneous Localization and Mapping System (3D LiDAR SLAM system) and a ground penetrating radar (GPR). The robot consists of a mobile platform equipped with a 3D LiDAR sensor and a GPR antenna mounted on a fixed chassis. The robot can autonomously navigate the environment and collect data from both the surface and the subsurface. The surface mapping is done by using the 3D LiDAR sensor of ±3 cm range accuracy to observe the point cloud of the terrain, which is then processed to generate the 3D surface map. The subsurface mapping is done by using the GPR antenna to emit electromagnetic pulses into the soil and receive their reflections, which are then processed to generate a 3D subsurface map. Then, we can fuse the surface and subsurface maps to obtain a comprehensive representation of the terrain. We demonstrate the performance of our robot in real-world scenarios, such as bridges. We show that our robot can achieve high accuracy and efficiency in surface mapping tasks and GPR data acquisition.

Keywords –

Autonomous mobile robots; GPR; Surface mapping; LiDAR SLAM; subsurface mapping; 3D LiDAR

1 Introduction

Surface mapping and subsurface mapping are essential tasks for various applications, such as geology, engineering, archaeology, and environmental monitoring[1]. However, conventional surface and subsurface mapping (Hybrid Mapping) methods are often limited by their accuracy, efficiency, and accessibility. For example, surface mapping using aerial or satellite imagery may not capture the fine details of the terrain, while subsurface mapping using ground penetrating radar (GPR) may require the corresponding surface mapping to access the required subsurface features accordingly. Therefore, there is a need for a novel method that can build hybrid mapping using a single mobile robot[2].

This paper presents a ground-mobile robot that can perform hybrid mapping using a three-dimensional LiDAR Simultanoues Localization and Mapping System (3D LiDAR SLAM system) and a GPR. The robot consists of a mobile platform equipped with a 3D LiDAR sensor, a camera, and a GPR antenna, which are mounted on a wheeled chassis. The robot can autonomously navigate the environment and collect data from both the surface and the subsurface. Surface mapping is done using the 3D LiDAR sensor to capture the point cloud of the terrain, which is then processed to generate a 2D orthophoto. The subsurface mapping is done by using the GPR antenna to emit electromagnetic pulses into the soil and receive their reflections, which are then processed to generate a 3D subsurface map. The robot can also fuse the hybrid maps to obtain a comprehensive representation of the terrain.

We demonstrate the performance of our robot in a real-world bridge scenario. We show that our robot can achieve high accuracy and efficiency in both surface and subsurface mapping tasks. We also discuss the advantages and limitations of our method compared to existing methods. Our paper contributes to the advancement of mobile robotics research by providing a novel solution for combining surface mapping and subsurface mapping using two complementary sensors.

This paper is organized as follows: the related works are introduced in section 2; section 3 explains the problem statement, the proposed robot design, the processing framework, and the experimental setup; section 4 presents the results; and finally, the conclusions are drawn in section 5.

2 Literature Review

Ground penetrating radar (GPR) is a geophysical technique that can produce high-resolution subsurface images by measuring the backscattered electromagnetic waves from the objects in the ground. GPR has been widely used for various applications in civil engineering, such as detecting buried utilities, mapping soil layers, monitoring geothermal resources, and exploring archaeological sites. However, conventional GPR methods require manual data acquisition and processing, which are time-consuming, labour-intensive, and prone to human errors. Therefore, there is a need to develop automated and intelligent systems that can perform GPR data collection and analysis in real-time and provide accurate and reliable results[3].

One of the promising solutions for this challenge is using autonomous mobile robots (AMRs) equipped with GPR sensors. AMRs can operate autonomously or remotely in complex and hazardous environments, such as minefields, disaster zones, or inaccessible areas. To enhance their capabilities, AMRs can also carry additional sensors or devices, such as cameras and LiDARs. By integrating GPR with other sensors or devices, AMRs can perform multi-sensor data fusion and analysis to obtain more information about the subsurface features and objects.

This paper will introduce recent works[4-14] in GPR robots, demonstrating their potential and challenges in different domains. In [4], a novel robotic inspection system was proposed to combine impact-echo (IE) and ground penetrating radar (GPR) sensors to detect and map subsurface defects in concrete structures. The system leverages vision-based positioning and pose information to guide the robot to the target area and integrates learning-based and classical methods to process the IE data and reconstruct the underground objects. The system also uses GPR data processing techniques to create a 3D map of the subsurface features for better visualization. In addition, their work demonstrated the effectiveness and efficiency of the system through field testing on concrete slabs, showing that visual inspection alone can reveal shallow defects that are otherwise invisible.

Another recent work [5] was the proposed robotic system that automatically collects and analyses ground penetrating radar (GPR) data to detect and visualize underground utilities for construction surveys. The system consists of a mobile robot equipped with a GPR sensor, a localization module, and a data processing module. The localization module uses a visual-inertial odometry (VIO) algorithm to estimate the robot's pose and trajectory. The data processing module uses a convolutional neural network (CNN) to segment the GPR images and identify the underground objects. The system also employs a graph-based method to reconstruct the 3D shape and position of the underground utilities from the segmented GPR images. The authors evaluate their system on both synthetic and real-world GPR data and demonstrate its advantages over existing methods in terms of accuracy, robustness, and usability.

In [8, 10], The main contribution of these two studies is to propose and demonstrate novel robotic systems that use non-destructive evaluation (NDE) methods, such as ground penetrating radar (GPR) and acoustic emission (AE), to inspect and evaluate the condition of bridge decks. [8] presents an autonomous robotic system that employs GPR, electrical resistivity (ER), and a camera for data collection. The system is capable of performing real-time, cost-effective bridge deck inspection and is comprised of a mechanical robot design, machine learning, and pattern recognition methods for automated steel rebar picking to provide real-time condition maps of the corrosive deck environments.

The second study [10] proposes a novel algorithm for automated rebar detection and analysis using GPR data. The algorithm integrates machine learning classification using image-based gradient features and robust curve fitting of the rebar hyperbolic signature. The approach avoids edge detection, thresholding, and template matching that require manual tuning and are known to perform poorly in the presence of noise and outliers. The detected hyperbolic signatures of rebars within the bridge deck are used to generate deterioration maps of the bridge deck. Both studies show that their robotic systems can achieve high accuracy, efficiency, and reliability in bridge deck inspection using NDE methods.

3 Problem statement and experiment

The problem this study addresses is the lack of efficient and reliable methods for combining surface and subsurface mapping (Hybrid Mapping) in complex and dynamic environments. Surface mapping is essential for understanding the topography, morphology, and features of the terrain, while subsurface mapping is essential for detecting anomalies, hazards, and resources in the soil. However, hybrid mapping methods are often limited by factors such as high cost, low accuracy, slow speed, and human intervention.

To overcome these limitations, this study proposes using an autonomous mobile robot mounted by ground penetrating radar (GPR) to perform hybrid mapping. GPR is a non-invasive technique that can penetrate various types of soil and rock layers and generate high-resolution images of the subsurface structure. The robot can also be used to map the surface features using a camera or a LiDAR sensor attached to it. By combining GPR with other sensors, such as LiDAR (light detection and ranging), this study aims to achieve high-precision and high-efficiency hybrid mapping in challenging terrains.

The main challenges that this study faces are:

- Designing a robot that can drag the GPR antenna along predefined paths without damaging it or losing signal quality.
- Designing a LiDAR SLAM (simultaneous localization and mapping) system that can accurately locate and map the robot in three-dimensional space while avoiding obstacles and maintaining stability.
- Merging the surface and subsurface maps generated by GPR and LiDAR into a unified 3D model that can be used for further analysis or visualization.

The significance of this study lies in its potential applications for various fields such as health monitoring of structures, mining, construction, agriculture, defense, environmental monitoring, disaster management, archaeology, geology, hydrology, etc. Using an autonomous mobile robot mounted by GPR to perform hybrid mapping simultaneously; this study can provide valuable information that can enhance decision-making processes, improve operational efficiency, reduce risks, optimize resources utilization, etc.

3.1 Robot Design

The design of a ground-mobile robot for hybrid mapping is presented in this paper. As shown in Figure 1, the robot consists of a chassis, four wheels, a 3D LiDAR sensor (LSLiDAR C32), which can provide up to 150 m range with ±3cm range accuracy and 31° vertical field of view, and a GPR antenna (GSSI 1600 MHz) which provide a depth range of 50 cm. The 3D LiDAR sensor provides high-resolution point cloud data of the surrounding environment, while the GPR antenna enables the detection and localization of buried features. The robot is powered by two batteries that can last for 4 to 6 hours, depending on the workload. The robot is equipped with a LiDAR SLAM system that processes the point clouds from the LiDAR sensor to model the surrounding surface environment. The robot can be controlled remotely or autonomously using wireless communication protocols. The robot's performance is evaluated on a real outdoor site.

The main challenge of designing such a robot is to balance the trade-off between accuracy, speed, reliability, and energy consumption. To achieve high accuracy, the robot needs to have a robust and efficient algorithm for point cloud registration and modeling. To achieve high speed, the robot needs to have a fast and lightweight hardware platform that can handle large-scale data processing. To achieve high reliability, the robot needs to have a robust and adaptive navigation system that can cope with dynamic and uncertain environments.

The proposed solution addresses these challenges by using state-of-the-art robotics techniques. The robotics system uses LeGO-LOAM [15], a 3D-LiDAR SLAM system for surface mapping and robot localization. In addition to the A* path planner [16] as a global path planner and time-elastic-bands (teb)-local planner [17-19] for local path planning and obstacle avoidance.

The proposed solution has several advantages over existing methods for surface mapping using mobile robots. First, it can cover large areas with high resolution in real-time. Second, it can accurately detect buried features and utilities using GPR signals that penetrate different soil layers depending on their electrical conductivity.

In conclusion, this paper presents an innovative design of a ground mobile robot that a 3D LiDAR sensor and GPR antenna for hybrid mapping applications can be mounted and work for at least four hours.

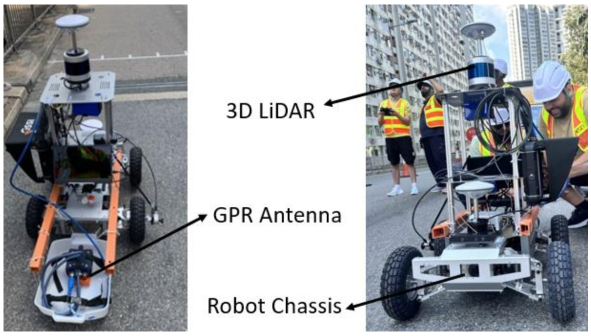

Figure 1. The main components of the robot are the chassis, 3D-LiDAR sensor, and GPR antenna.

The robot's battery system consists of four batteries: two batteries are for the robot and the other two are for the 3D-LiDAR sensor. The robot uses one battery at a time, while the other serves as a backup in case of power failure. Similarly, the 3D-LiDAR sensor switches between two batteries to ensure continuous operation. The battery system is designed to provide sufficient power for the robot and the sensor to perform at least 4 hours of continuous working.

3.2 Processing Framework

The process diagram in Figure 2 illustrates the steps involved in mapping the surface and subsurface of an environment using a robot equipped with a 3D-LiDAR sensor, a ground-penetrating radar (GPR), and a distance measurement indicator (DMI). The first step is data acquisition, where the robot collects 3D-LiDAR and GPR data along with DMI data that indicates the distance travelled by the robot. The second step is data processing, where the 3D-LiDAR data is used to perform simultaneous localization and mapping (SLAM) to estimate the robot's pose and generate a point cloud representation of the surface. The GPR data is interpreted to produce a subsurface map that shows the location and depth of buried objects.

The DMI data is used to align the GPR data with the robot's trajectory. The third step is processing output, where the point cloud is converted into a surface map showing the surface's shape and texture. The robot's trajectory is also displayed on the surface map. The subsurface map is overlaid on the surface map using the DMI data as a reference. The final step is integration, where the surface and subsurface maps are combined to provide a comprehensive view of the environment.

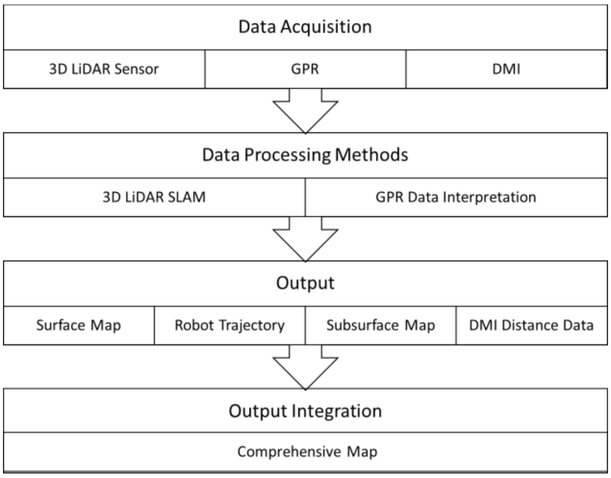

Figure 2. Process diagram of The GPR robot.

3.3 Experiment

The case study was conducted on a round 80-meter section of a bridge in Hong Kong, as shown in Figure 3, that was suspected of severe corrosion damage on its steel bars. The bridge was selected based on its age, traffic volume, environmental conditions, and structural design. The bridge was closed for inspection and preparation before the start of the case study. The GPR robot was deployed on both sides of the bridge at different locations to collect data from different depths and directions. The data were then transmitted back to a central server, where they were processed and analyzed.

Figure 3. Case study: corrosion inspection of a bridge in Hong Kong.

4 Results

The surface results of the GPR robot using the LiDAR SLAM method are presented in this section. The surface results show that the GPR robot successfully mapped the bridge deck features. The 3D point cloud of the bridge, as shown in Figures 4 to 6, was created using the point cloud data obtained from the 3D LiDAR sensor mounted on the GPR robot. The point cloud data were processed using the LiDAR SLAM method, which is a technique that simultaneously localizes the robot and maps the environment using the LiDAR measurements. The LiDAR SLAM method consists of three main steps: scan matching, loop closure detection, and pose graph optimization. Scan matching is the process of aligning consecutive scans to estimate the relative motion of the robot. Loop closure detection is the process of identifying previously visited places and correcting the accumulated drift. Pose graph optimization is the process of refining the robot poses and the map by minimizing the error between the measurements and the estimated state. The sharpness of the final point cloud of the bridge is shown in Figure 7.

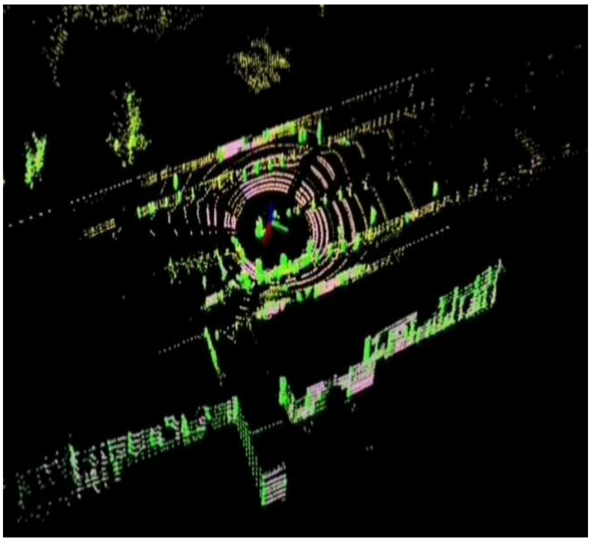

Figure 4. The start of the bridge mapping using the LiDAR SLAM system.

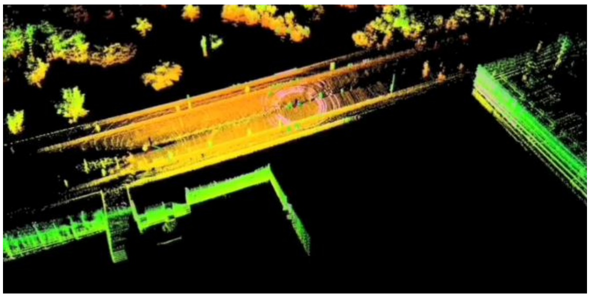

Figure 5. The middle of the bridge mapping using the LiDAR SLAM system

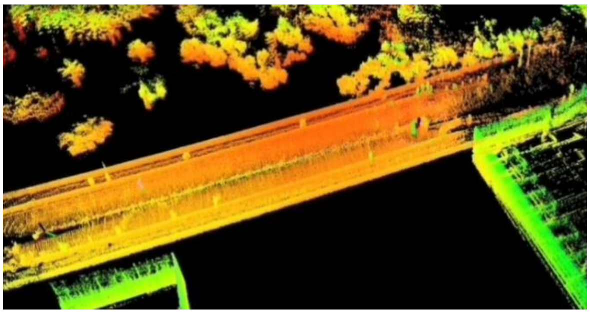

Figure 6. The end of the bridge mapping using the LiDAR SLAM system

One of the advantages of the proposed system is that it can fuse the GPR data with the 3D point cloud to create a comprehensive map of the indoor environment. The collected GPR data can be merged with the final 3D point cloud using the robot trajectory, as shown in Figure 7, and the distance measured indicator (DMI) data, which is connected to the GPR antenna to trigger the GPR data acquisition according to the distance. The DMI data provides the precise location of each GPR scan along the robot path, which can be aligned with the corresponding 3D point cloud frame. The merged GPR and 3D point cloud data can provide rich information about indoor and outdoor environments' surface and subsurface features, such as pipes, wires, and defects.

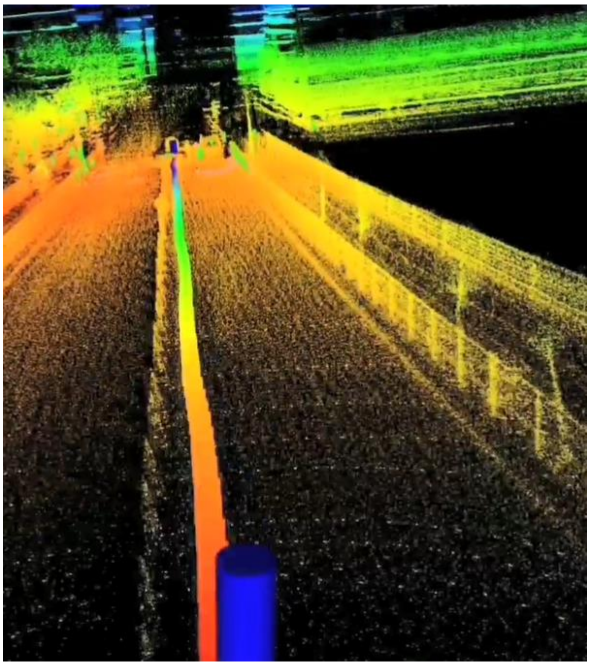

Figure 7. Zooming view of the bridge mapping using the LiDAR SLAM system.

5 Conclusion

In this paper, we presented a novel approach for surface mapping using an autonomous mobile robot equipped with a ground penetrating radar (GPR) antenna. The objective of our study was to evaluate the feasibility and performance of this method for detecting buried utilities and creating a 3D subsurface map. We designed and built a GPR system that can be mounted on a specially designed trailer that can be towed by the robot. We applied our method to an experimental site with an 80-meter-long bridge section, where we collected data using GPR and a 3D LiDAR sensor. Our method also demonstrated its potential for long-term mapping in outdoor and indoor environments where GPS signals are unavailable or unreliable. Our work opens up new possibilities for using GPR as a tool for robot navigation applications in various domains such as mining, construction, archaeology, and environmental monitoring limited by the environment accessibility to enable the ground wheeled robot for navigation.

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