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Enhanced Indoor Inspection of Nuclear Facilities through Non-Rigid Airship-Based SLAM System

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ABSTRACT

This paper presents a novel approach for indoor inspection of nuclear sites using a non-rigid airship (NRA) equipped with the RPLIDAR S1, BerryIMU v4 and Raspberry Pi for simultaneous localization and mapping (SLAM). The proposed system addresses the limitations of multi-rotor UAVs, including the particulate aerosols caused by downdraft, limited flight time and radiation affecting onboard electronics.

The NRA's utilization of helium gas enables extended weeks of stationary flight due to buoyancy, surpassing the flight time constraints of multi-rotor UAVs. Furthermore, the simpler onboard electronics of the NRA are less susceptible to radiation, eliminating the need for complex shielding. Additionally, the gentle upward draft created by the NRA reduces disturbance to the environment, minimizing aerosolization compared to the downdraft generated by multi-rotor UAVs.

The proposed system incorporates the RPLIDAR S1 2D laser scanner and BerryIMU v4 for localization and mapping. To obtain distance data from the third dimension, a mirror is attached to the side of the RPLIDAR at a 45-degree angle, transforming the 2D lidar into a 2.5D lidar. This modification enables the RPLIDAR to capture both vertical and horizontal information. The Raspberry Pi serves as an onboard computer, running ROS nodes for the RPLIDAR, and transmitting data to a laptop for further processing. This multi-sensor integration meets the limited payload requirement of the NRA (~200g for a 2m long, 1.5m^3 NRA), ensuring efficient operation within the system's constraints.

The proposed approach offers a safer and more efficient method of inspecting nuclear sites indoors while minimizing risks to personnel and equipment. By employing the NRA for indoor inspections, significant cost and complexity reductions can be achieved while enhancing the accuracy and comprehensiveness of data collection.

Keywords: Non-rigid airship, SLAM, Indoor inspection, Nuclear sites, UAV limitations, RPLIDAR S1, BerryIMU v4.

1 INTRODUCTION

The inspection of nuclear sites is crucial for ensuring the safety and security of both the environment and the people working in and around these facilities. Nuclear sites contain radioactive materials that can pose significant risks if not properly managed. Regular inspections help to identify potential hazards, assess the effectiveness of safety measures, and ensure compliance with regulations [1][2][3]. As of July 2023, the global inventory includes 436 operable nuclear power reactors, with an additional 59 reactors under construction and 111 planned, while 321 more reactors are proposed [4]. These statistics underscore the profound importance of robust inspection procedures to avert potentially catastrophic nuclear accidents. Traditionally, inspections have been carried out by human inspectors. However, this approach can be time-consuming, costly, and potentially dangerous for the inspectors. Due to radiation exposure limits (100mSv for radiation workers averaged over 5 years), the conventional approach of employing human inspectors faces formidable challenges [5]. In recent years, there has been a growing interest in using robotics to assist with inspections. Unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) are two types of robots that have shown promise in this area [6].

UAVs, also known as drones, can be used to quickly survey large areas from the air. They can be equipped with cameras and other sensors to gather data on the condition of structures and equipment. UAVs can also be used to monitor radiation levels and detect leaks or other hazards [7][8]. UGVs, on the other hand, can navigate on the ground and perform more detailed inspections. They can be equipped with manipulators to interact with their environment, for example by taking samples or performing repairs. The use of UAVs and UGVs in nuclear environments has several advantages over traditional inspection methods. These robots can access areas that may be difficult or dangerous for humans to reach. They can also work continuously without the need for breaks, increasing efficiency and reducing costs. Furthermore, they can gather data more quickly and accurately than human inspectors [9][10]. For example, the Nuclear Decommissioning Authority (NDA) in the UK has conducted a project to catalogue all previous instances of the use of UAVs across the NDA group to assist with decommissioning and related activities [11]. In another example, a vision-based UAV-UGV collaboration method was proposed for autonomous construction site monitoring [12]. Additionally, UAV swarms have been proposed for early warning of Chemical, Biological, Radiological and Nuclear (CBRN) threats [13].

The integration of robotic systems into the nuclear industry has witnessed remarkable progress, reshaping various dimensions of nuclear operations and safety protocols. Robotics has emerged as a cornerstone technology, facilitating critical tasks encompassing inspection, maintenance, decommissioning, and hazardous material handling while concurrently mitigating the risks associated with radiation exposure for human operatives. Notably, in the realm of nuclear site inspection, robotic entities are harnessed to navigate intricate and confined spaces, penetrate high-radiation zones, and execute comprehensive visual assessments [14]. Evidencing this paradigm shift are instances such as the aftermath of the Fukushima Daiichi nuclear disaster in 2011, wherein ground-based robots were deployed for radiation mapping, debris clearance, and containment vessel exploration. This amalgamation of robotic technologies engenders heightened operational efficacy, concurrently tempering the vulnerabilities intrinsic to human intervention and furnishing a realm of enhanced safety and precision. By embodying robotics as a cornerstone, the nuclear industry steadfastly evolves, propelling the quest for augmented accuracy, dependability, and operational security across a diverse spectrum of applications.

2 OVERVIEW OF UAV SLAM TECHNIQUES

Simultaneous Localization and Mapping (SLAM) is a fundamental technique block in the indoor-navigation system for most autonomous vehicles and robots. SLAM aims at building a global consistent map of the environment while simultaneously determining the position and orientation of the robot in this map [15]. Significant advances have been made in visual SLAM techniques in the past several years. However, due to the fragile performance in tracking feature points in environments that lack texture, e.g., a warehouse with blank white walls, visual SLAM can hardly provide a reliable localization [16]. Compared with visual SLAM, LiDAR SLAM can often provide more robust localization in indoor environments by using 3D spatial information directly captured by LiDAR point clouds. Thus, LiDAR SLAM techniques are often employed in industrial applications such as automated guided vehicles (AGVs).

In the past decades, a number of LiDAR SLAM methods have been proposed. However, the strength and weakness points of various LiDAR SLAMs are not clear, which may perplex the researchers and engineers. In an article published in IEEE Transactions on Intelligent Transportation Systems, analysis and comparisons are made on different LiDAR SLAM-based indoor navigation methods, and extensive experiments are conducted to evaluate their performances in real environments. The comparative analysis and results can help researchers in academia and industry in constructing a suitable LiDAR SLAM system for indoor navigation for their own usage scenarios [16].

Although Light Detection and Ranging (LiDAR) based Simultaneous Localization and Mapping (SLAM) has been widely used for ground robot's autonomous localization, there is difficulty in localizing an unmanned aerial vehicle (UAV) due to variation in altitude and motion dynamics. Especially, the positioning error will increase speedily when UAV flies in the environment with sparse features. In a paper presented at the 2018 15th International Bhurban Conference on Applied Sciences and Technology (IBCAST), a Micro Electro Mechanical Systems Inertial Measurement Unit (MEMS-IMU) aided SLAM method in sparse indoor environments with few features is proposed, namely LiDAR/MEMS-IMU tightly integrated positioning method. The introduction of MEMS-IMU as the state prediction in the SLAM, feature searching range can be reduced and the positioning accuracy is improved drastically through this algorithm. The experiments conducted showed that the proposed LiDAR/MEMS-IMU tightly integrated positioning algorithm had 10 times better positioning accuracy comparing with the traditional algorithm [17].

There are not many surveys in UAV indoor navigation, mainly because of the novelty of the topic. A Work in Progress Paper extends a review by considering most promising technological approaches for UAVs indoor localization, providing a comparison table with useful information regarding accuracy, cost, coverage and other important considerations.

While significant advances have been made in visual SLAM techniques for indoor navigation of autonomous vehicles and robots, LiDAR SLAM techniques often provide more robust localization in indoor environments. Various LiDAR SLAM methods have been proposed and comparative analysis can help researchers construct suitable systems for their usage scenarios. For UAVs specifically, tightly integrated positioning methods using MEMS-IMU aided SLAM have shown promising results [17].

In comparison to multi-rotor UAVs, Non-Rigid Airships (NRAs) (Figure 1) exhibit superior operability and present distinct advantages. NRAs operate at lower speeds, eliminating the need for specialized piloting skills due to their controlled nature and helium-based buoyancy, which facilitates hovering. The endurance of NRAs far surpasses that of multi-rotor UAVs, capable of maintaining airborne presence for days once filled with helium, a substantial extension over the limited flight duration of multi-rotor UAVs. In terms of safety, NRAs exhibit inherent advantages over multi-rotor UAVs, primarily due to their lighter mass and slower descent speed, attributed to the buoyancy of helium. The lower probability of causing harm to individuals and nuclear infrastructure sets NRAs apart from their multi-rotor counterparts. Nonetheless, NRAs are not without their challenges. Despite their numerous merits, the payload capacity of an NRA, particularly exemplified in a 2m length and 1.5^3m volume configuration, remains modest at approximately 200g, notably inferior to that of multi-rotor UAVs. This limitation necessitates a focus on lightweight onboard sensors to maintain operational efficacy [18].

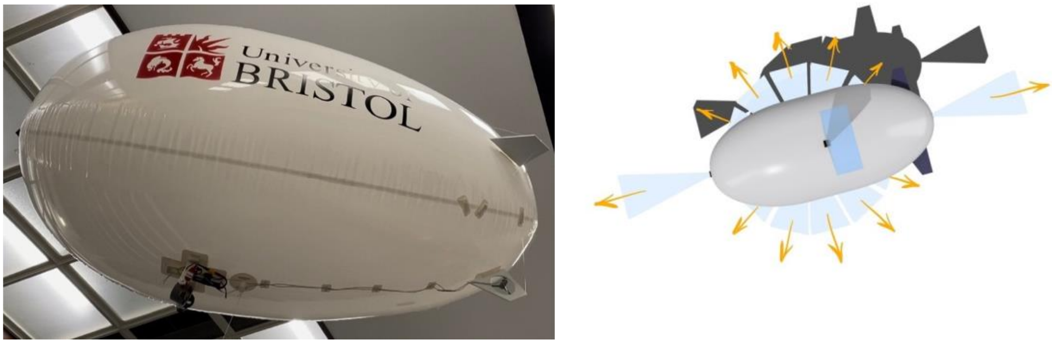

Figure 1: NRA of University of Bristol (left), Schematic diagram of the proposed NRA system (right)

3 RPLIDAR S1- BERRYIMU V4 SLAM SYSTEM

Given the restricted payload capacity of a Non-Rigid Airship (NRA), which typically amounts to approximately 200g for an NRA measuring 2m in length with a volume of 1.5^3m, the incorporation of lightweight sensors becomes imperative. In this study, we used an RPLidar S1 with a 45-degree mirror on one side to gather information from both horizontal and vertical directions (shown in Figure 2). The RPLidar S1 is a low-cost 360-degree 2D laser scanner (LIDAR) solution developed by SLAMTEC. It can take up to 9200 samples of laser ranging per second with high rotation speed and is equipped with SLAMTEC's patented OPTMAG technology, which extends the life of traditional LIDAR systems [19].

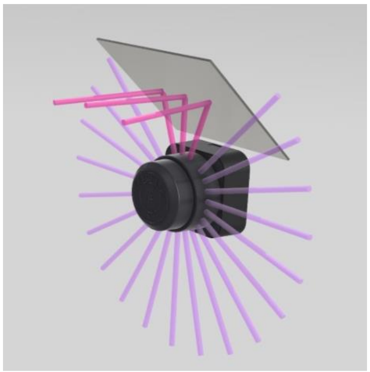

Figure 2: Schematic diagram of RPLidar S1 equipped with mirror

We also used a BerryIMU v4 for SLAM (Simultaneous Localization and Mapping). The BerryIMU v4 is a GPS module specifically designed for the Raspberry Pi Zero that includes all the sensors found in the BerryIMU v3. These sensors include a GPS, accelerometer, gyroscope, magnetometer (compass), barometric/pressure sensor (altitude), and temperature sensor [20].

A Raspberry Pi was used as an onboard microcontroller to run the ROS (Robot Operating System) node. Data was sent from the Raspberry Pi to a laptop for further processing, including the use of Cartographer ROS. Cartographer is a system that provides real-time simultaneous localization and mapping (SLAM) in 2D and 3D across multiple platforms and sensor configurations [21]. The laptop and Raspberry Pi were able to communicate with each other when connected to the same Wi-Fi network [22].

This setup (shown in Figure 3) allowed us to gather detailed information about the environment in both horizontal and vertical directions, while also using SLAM to accurately map and localize the robot within its surroundings. The use of a Raspberry Pi as an onboard microcontroller provided a compact and efficient solution for running the ROS node, while the ability to send data to a laptop for further processing allowed for more complex analysis and visualization of the data.

Figure 3: RPLidar S1- BerryIMU v4 SLAM system

Overall, this methodology provided a robust and effective approach for gathering and analyzing data from the environment using an RPLidar S1, BerryIMU v4, and Raspberry Pi in conjunction with ROS and Cartographer ROS.

4 RESULTS

Using the methodology described above, we were able to successfully generate a point cloud of our office environment (shown in Figure 4). The RPLidar S1, with its 45-degree mirror, provided detailed information about the environment in both horizontal and vertical directions. The BerryIMU v4 allowed us to accurately map and localize the robot within its surroundings using SLAM.

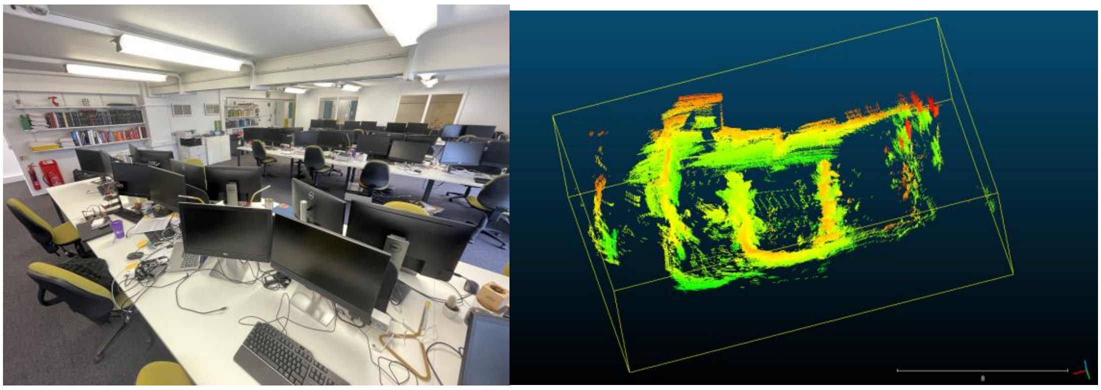

Figure 4: Office environment (left), point cloud of office (right)

The data gathered by the RPLidar S1 and BerryIMU v4 was sent from the Raspberry Pi to a laptop for further processing using Cartographer ROS. This allowed us to generate a detailed point cloud of our office environment, providing a comprehensive representation of the space.

The point cloud generated by our system showed high levels of detail, accurately representing the layout and features of our office environment (Figure 5). This demonstrates the effectiveness of our methodology in gathering and analyzing data from the environment using an RPLidar S1, BerryIMU v4, and Raspberry Pi in conjunction with ROS and Cartographer ROS.

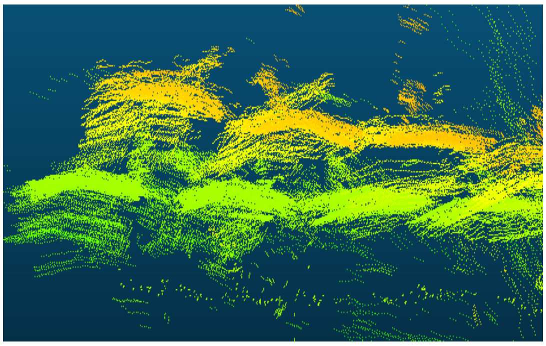

Figure 5: Computer monitors in office shown in point cloud

Further analysis of the point cloud revealed valuable insights into the layout and features of our office environment. In addition, the point cloud provided a detailed representation of the equipment within our office environment. This allowed us to assess the placement and arrangement of these items, as well as their potential impact on movement and workflow within the space.

Overall, our results show that our methodology provides a robust and effective approach for generating detailed point clouds of indoor environments. The insights gained from analyzing the point cloud can provide valuable information for optimizing the layout and use of indoor spaces. Further research could explore the use of this methodology in other indoor environments to improve efficiency and productivity.

5 DISCUSSION AND FUTURE WORK

In this study, we used a combination of an RPLidar S1 with a 45-degree mirror, a BerryIMU v4, and a Raspberry Pi in conjunction with Cartographer ROS to generate a detailed point cloud of our office environment. Our results showed that this methodology was effective in gathering and analyzing data from the environment, providing a comprehensive representation of the space.

One of the key strengths of our methodology is the use of an RPLidar S1 with a 45-degree mirror. This allowed us to gather detailed information about the environment in both horizontal and vertical directions, providing a more complete picture of the space. The use of a BerryIMU v4 for SLAM also allowed us to accurately map and localize the robot within its surroundings.

The use of a Raspberry Pi as an onboard microcontroller provided a compact and efficient solution for running the ROS node. The ability to send data from the Raspberry Pi to a laptop for further processing using Cartographer ROS allowed for more complex analysis and visualization of the data. Our results showed that the point cloud generated by our system was detailed, accurately representing the layout and features of our office environment.

Overall, our methodology provides a robust and effective approach for generating detailed point clouds of indoor environments. The insights gained from analyzing the point cloud can provide valuable information for optimizing the layout and use of indoor spaces. Further research could explore the use of this methodology in indoor nuclear environments, such as nuclear power plants and waste storage managements, to improve efficiency and productivity.

5.1 Future work

In future work, we plan to continue tuning the configuration of Cartographer ROS to achieve the best possible results. Once the configuration has been optimized, we will attach the SLAM system to the bottom of a non-rigid airship. VL53L1X single point laser ranging lidar will be attached to each side of the NRA for collision avoidance. A lightweight radiation detector will also be attached to the non-rigid airship. This will allow us to deploy the entire non-rigid airship system into nuclear sites for long-term indoor inspection.

The use of a non-rigid airship equipped with our SLAM system will provide a unique and effective approach for conducting indoor inspections in challenging environments such as nuclear sites. The ability to gather detailed information about the environment using our methodology will provide valuable insights for improving safety and efficiency in these environments.

Overall, our future work will focus on further refining and optimizing our methodology, as well as exploring its potential applications in challenging indoor nuclear environments such as nuclear power plants and waste storage managements. We believe that this approach has significant potential for improving safety and efficiency in these environments, and we look forward to continuing our research in this area.

6 Conclusion

In conclusion, our study demonstrated the effectiveness of using an RPLidar S1 with a 45-degree mirror, a BerryIMU v4, and a Raspberry Pi in conjunction with Cartographer ROS to generate a detailed point cloud of an indoor environment. Our methodology provided a robust and effective approach for gathering and analyzing data from the environment, providing valuable insights into the layout and use of the space.

Our results showed that the point cloud generated by our system was detailed, accurately representing the layout and features of our office environment. Further analysis of the point cloud revealed valuable information for optimizing the layout and use of indoor spaces.

Overall, our study provides a strong foundation for further research into the use of this methodology in indoor nuclear environments to improve efficiency and productivity. The insights gained from analyzing point clouds generated using this approach can provide valuable information for optimizing the layout and use of indoor spaces.

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