Preliminary Experiments on 3D Localization and Mapping in the Geometrically Repetitive Environments of Nuclear Facilities

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1. Introduction

As the operation of nuclear power plants increases the generation of radioactive waste, the scale of storage facilities has also expanded. To reduce workers' exposure risks and improve management efficiency, robots equipped with radiation sensors are being developed for repetitive monitoring and emergency response in wide-area facilities. The Korea Atomic Energy Research Institute (KAERI) is pursuing this direction through disaster-response robots designed for remote surveillance, radiation measurement, and rapid intervention in hazardous environments (Fig. 1) [1].

Fig. 1. The surveillance robot and the generated map data in the real radioactive waste storage facility. (Reprinted from [Lee et al., 2021])

However, identical storage containers and structures are repeatedly arranged in such facilities, causing sensors to observe similar data at different locations, which leads to localization confusion and undermines long-term reliability. To address this, previous studies have taken two main directions. The first focuses on extracting robust feature points from LiDAR and camera data with prebuilt maps to mitigate localization errors [2], but their high computational complexity remains a limitation. The second leverages non-visual sensors such as Inertial Measurement Unit (IMU) or wheel encoders fused with visual data in filter- and graph-based SLAM to reduce drift, yet large visual sensor errors can still result in rapidly increasing localization errors. Recently, neural network-based approaches have been investigated to learn motion patterns from non-visual sensors and thereby improve long-term robustness [3].

In this paper, a framework is proposed to address localization confusion in repetitive environments. In the proposed structure, IMU data are applied to a neural network-based motion prediction model to enhance the prediction step, while LiDAR observations are used for correction. As a preliminary step, this study investigates the feasibility of using only IMU data to simulate AI-based motion prediction. This work aims to lay the foundation for future practical implementation.

2. Analysis of Conventional SLAM Algorithms in a Nuclear Facility

In radioactive waste management facilities, mobile robots have been developed for periodic monitoring and radiation dose measurement. They patrol along predefined paths, measure radiation levels with onboard sensors, and construct radiation maps for facility safety management [4]. However, because identical storage containers are repeatedly arranged, sensors may generate similar data at different locations, leading to localization confusion, accumulated odometry errors, and incorrect loop closures that undermine long-term autonomous navigation stability.

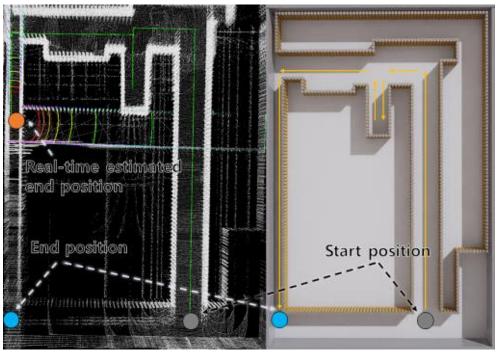

Fig. 2. Illustration of localization drift caused by the repetitive structural layout in a simulated radioactive waste management facility. The gray circle marks the initial position, the blue circle marks the final position, and the orange dot shows the robot's real-time estimated position at that same point.

As shown in Fig. 2, repetitive structures in the simulated environment cause localization drift and distort the generated map. Such errors not only degrade mapping accuracy but also affect path planning and task execution, thereby reducing overall system stability.

In addition, deep geological disposal (DGD) has been actively discussed as a long-term option for high-level radioactive waste. To verify its feasibility, KAERI has constructed the KAERI Underground Research Tunnel (KURT) for demonstration studies. However, this underground facility also suffers from localization instability, particularly in its long linear sections and repetitive structural layouts, which resemble the challenges encountered in nuclear waste storage facilities.

3. AI-based Motion Prediction and Verification

Filter-based SLAM methods such as the Extended Kalman Filter and Unscented Kalman Filter (UKF) integrate IMU measurements during the prediction step to estimate robot states. Although bias correction is applied, accumulated errors remain and grow rapidly in repetitive or visually degraded environments, reducing long-term localization reliability.

To address this, a methodology is proposed in which the IMU integration in the prediction step is replaced by an AI-based motion prediction model. The model directly estimates state changes from IMU inputs, serving the same role as the Kalman filter prediction. In this study, the detailed network design is omitted, and instead, ground-truth-based single-step increments are employed to emulate the expected performance of an AI-based predictor.

Simulations were conducted in the NVIDIA Isaac Sim environment, modeled after a radioactive waste management facility with identical storage drums on one side and a wall on the other. A 16-channel LiDAR sensor with a 30 m range and Gaussian noise was assumed, and the robot traveled ~35 m along a straight path. Conventional UKF-based SLAM was compared with the proposed methodology, where ground-truth-based single-step increments replaced IMU integration to emulate AI predictions.

As shown in Fig. 3, both methods were stable in the initial segment, but the conventional approach exhibited rapid error growth once repetitive structures persisted, caused by accumulated drift exceeding a threshold. In contrast, the proposed methodology maintained stable localization by applying a more reliable motion model, which improved scan-matching alignment. These results indicate that robust motion prediction is a key factor for overall localization and can enhance long-term stability in repetitive environments.

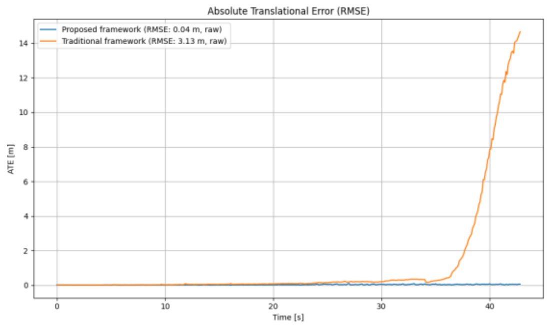

Fig. 3. Absolute translational error (ATE) over time. The blue line (Proposed framework) shows stable localization performance, while the orange line (Conventional framework) exhibits rapid error growth in repetitive structural environments.

4. Conclusion

A method was proposed to mitigate SLAM instability in nuclear facility environments with repetitive structures by replacing the IMU integration in conventional Kalman filter-based SLAM with an AI-based motion prediction model. Through evaluations conducted in the Isaac Sim simulation environment, it was observed that the conventional approach suffered a sharp degradation in estimation performance due to drift in repetitive sections, whereas the proposed method, by applying a more reliable motion model, improved the initial estimates for scan matching and maintained relatively stable localization.

Acknowledgement

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REFERENCES

[1] W. Lee, S. Shim, D. Ryu, and T.-J. Kim, “Preliminary Study of a Surveillance Robot System in the Radioactive Waste Storage Facility,” Proc. of the Korean Nuclear Society Spring Meeting, Daejeon, Korea, May 18, 2023.

[2] D. Choi, S. Lee, H. Lee and J. -H. Ryu, "Vft-Lio: Visual Feature Tracking for Robust Lidar Inertial Odometry Under Repetitive Patterns," 2025 22nd International Conference on Ubiquitous Robots (UR), College Station, TX, USA, 2025, pp. 26-33

[3] Taku Okawara, Kenji Koide, Shuji Oishi, Masashi Yokozuka, Atsuhiko Banno, Kentaro Uno, Kazuya Yoshida, Tightly-coupled LiDAR-IMU-wheel odometry with an online neural kinematic model learning via factor graph optimization, Robotics and Autonomous Systems, Volume 187, 2025, 104929, ISSN 0921-8890

[4] W. Lee, W.-C. Lee, S. Shim, and D. Ryu, ″Development of Spatial Radiation Mapping Framework using Mobile Robot with LiDAR and Radiation Sensor,” Proc. of the Korean Nuclear Society Spring Meeting, Daejeon, Korea, May 10, 2024.