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Experiments on Degeneracy of LiDAR based Localization in an Underground Disposal Facility

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1. Introduction

In nuclear facilities such as underground radioactive waste disposal repositories, the deployment of unmanned robotic systems is essential to minimize workers' radiation exposure [1]. For an unmanned robot to autonomously accomplish a given mission, accurate localization and mapping must be ensured in advance. However, in underground disposal facilities, GPS signals are unavailable, and as shown in Fig. 1, the environment is characterized by the absence of effective landmarks and long featureless corridors.

Fig. 1. Underground Research Tunnel at the Korea Atomic Energy Research Institute (KAERI).

As a result, sufficient geometric constraints cannot be obtained from 3D LiDAR sensors, which in turn may lead to localization failure during the scan matching stage or significant divergence of the state estimate.

Accordingly, in this study, real 3D LiDAR sensor data were acquired using the quadruped robot Unitree Go1 in the Underground Research Tunnel of the Korea Atomic Energy Research Institute. The geometric distribution of the acquired point clouds was quantitatively analyzed using a minimum eigenvalue based metric, and it was confirmed that the geometric constraints contributing to scan matching become insufficient in actual corridor sections.

2. Methods

2.1 Data Acquisition

This experiment was conducted in a long corridor section of the Underground Research Tunnel at the Korea Atomic Energy Research Institute (KAERI). The environment includes both sections with relatively rich structural features, such as corners and intersections, and long corridor sections where features are limited due to repetitive wall structures. Since the tunnel ground surface is relatively uneven, the quadruped robot Unitree Go1, mentioned earlier, was employed in consideration of driving stability, as shown in Fig. 2. The robot was equipped with a 3D LiDAR sensor (Velodyne VLP-16), and three-dimensional point cloud data of the surrounding environment were continuously collected while the robot traversed the facility. The data acquisition path proceeded from sections with relatively abundant features to long corridor sections with comparatively fewer features.

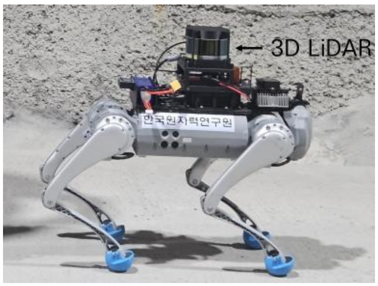

Fig. 2. Quadruped robot platform (Unitree Go1) used for data acquisition in the Underground Research Tunnel.

2.2 Minimum Eigenvalue Based Degeneracy Metric

To quantitatively evaluate the geometric distribution of the acquired point clouds, a covariance matrix was constructed from the distribution of the normal vectors (n_i, total number N) estimated for each frame, and the minimum eigenvalue (λ_3) among its eigenvalues was used as the metric [2]. Letting the mean of the normal vectors be $\bar{n}$, the covariance matrix of the normal distribution is calculated as follows:

$$\mathrm{C}_{\mathrm{normal}} = \frac{1}{N}\sum_{i=1}^{N}(n_i - \bar{n})(n_i - \bar{n})^{\top}$$

Here, if the eigenvalues of the covariance matrix are denoted by $\lambda_1 \geq \lambda_2 \geq \lambda_3$, each eigenvalue represents the variance of the normal direction distribution along a principal axis direction.

When the normal direction distribution is concentrated in one or two directions and thus exhibits a low dimensional structure, the covariance matrix tends to have a low rank structure, and consequently, the minimum eigenvalue tends to approach zero. This suggests that geometric constraints are not evenly provided from multiple directions, and that the solution in certain directions may be weakly constrained. Therefore, in this study, the minimum eigenvalue was used as a quantitative indicator of LiDAR degeneracy, and the variation of the minimum eigenvalue across different sections was compared.

3. Results

Analysis of the point cloud data acquired while traversing the Underground Research Tunnel revealed distinct variations in the degeneracy metric depending on the structural characteristics of the facility. As shown in Fig. 3, in sections with relatively rich structural features, such as intersecting walls, the minimum eigenvalue (λ3) was maintained at a relatively high level. In contrast, as the robot entered long corridor sections with insufficient features, the minimum eigenvalue (λ3) was observed to decrease. This indicates that geometric constraints are relatively insufficient in long corridor sections, which may create unfavorable conditions for LiDAR-based localization.

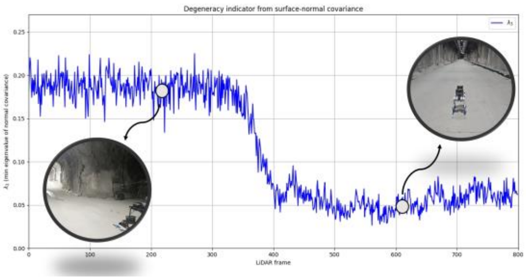

Fig. 3. Variation of the minimum eigenvalue (λ3) along the trajectory in the Underground Research Tunnel.

4. Conclusions

This study quantitatively verified, based on 3D LiDAR point clouds acquired in a real underground nuclear disposal facility, that geometric degeneracy can become more severe in corridor sections by using the minimum eigenvalue. In particular, while the minimum eigenvalue was maintained at a relatively high level in sections with relatively rich structural features, it showed a clear tendency to decrease in long corridor sections with insufficient features. These results demonstrate that LiDAR based localization may become unstable in nuclear facility environments such as actual underground disposal facilities, and they suggest the possibility of degraded scan matching performance and increased state estimation errors. Therefore, further research is required on sensor fusion and robust localization methods that can mitigate such degeneracy.

Acknowledgement

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