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Underground localization using the dual magnetic sensor for embedded directional drilling robot

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ABSTRACT

Conventional drilling systems not only require large equipment but also require a lot of manpower and cost due to complicated processes. In addition, they also have limitations in places where it is difficult to install a drilling system like mountains. To solve this problem, we developed an embedded directional drilling system called “Mole-bot”. Unlike the existing drilling system, the Mole-bot is not connected to the base on the ground. Therefore, a sensor system and an algorithm for underground localization are necessary. However, there are various problems in localization in the underground environment. In the underground environment, vision sensors, range sensors, or wireless sensors cannot be used, and the encoder drifts due to integration errors. In addition, vibration is generated in the process of drilling, which makes it difficult to estimate the position. To solve this problem, this paper proposes a graph-based SLAM (Simultaneous Localization and Mapping) method using two magnetic field sensors. Because the magnetic field sequence has different values for each position of the robot, constraints can be generated when re-measuring the magnetic field sequence. At this time, we use the concurrent normalized cross-correlation (CNCC) method to compare the magnetic field sequences. Through the generated constraints, pose graph optimization was applied to measure the position of the Mole-bot. Experimental results on the actual Mole-bot system proved the validity of the algorithm.

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1. INTRODUCTION

Drilling technology has begun to develop technology to collect various resources buried underground. From collecting oil and gas in the past, it has now collected new resources such as rare earths. In addition, in the future, technology development related to drilling robots for exploration of unknown planets such as the Moon and Mars is required in the future. Drilling system applications are becoming more diverse and various studies have been conducted to overcome the limitations of large and heavy vertical drilling systems used in existing industrial fields. The rotary steering system proposed by Kim (2017) has the advantage of reducing the excavation period and cost. Nevertheless, the large equipment has problems such as a complicated installation process, so it is necessary to develop the technology of a small drilling system. 'Mole-bot' is an embedded system that is developed through the idea of Tirtawardhana (2018) and can be used for directional drilling. It is a robot that imitates the biological structure of the mole like the attached name. Unlike large drilling equipment that is directly connected to the existing base, Mole-bot is not only connected to the base through the wire but also can be controlled. In the case of the mobile robot such as Mole-bot, it is difficult to check its position directly under the ground. To move to the position to be desired, the robot's localization technology is needed. However, it is difficult to use a vision sensor or lidar sensor which is generally used in localization due to the environment in the excavator without light and large vibration. To overcome these limitations, researches have been carried out on localization based on the magnetic field. Park (2014, 2017) proposed a graph SLAM using two magnetic sensors and encoders in a large drilling system. These studies were able to establish enough distance between the two magnetic sensors by using the characteristic that the length of existing drilling equipment is long. The distances between the two magnetic sensors are so large that they can easily generate constraints, but this is not the case for the small robot Mole-bot. Therefore, we will apply a dual magnetic graph SLAM for localization of small embedded directional drilling systems such as Mole-bot.

The contribution of this study is as follows. First, we developed a hardware system for underground localization. Secondly, we proposed a graph SLAM using a dual magnetic sensor for the underground localization of Mole-bot. Finally, through real experiments, we proved that the localization algorithm is suitable for the embedded directional drilling robot system.

2. METHODS

2.1 Embedded directional drilling system

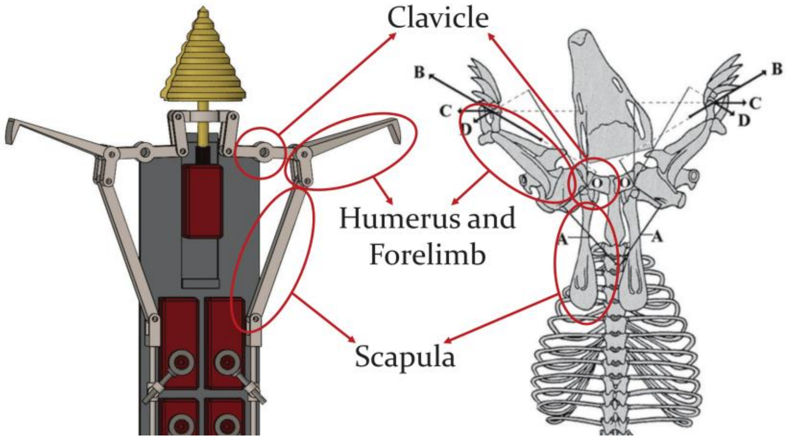

Fig. 1 Mole-bot's biomimetic design (Tirtawardhana 2018)

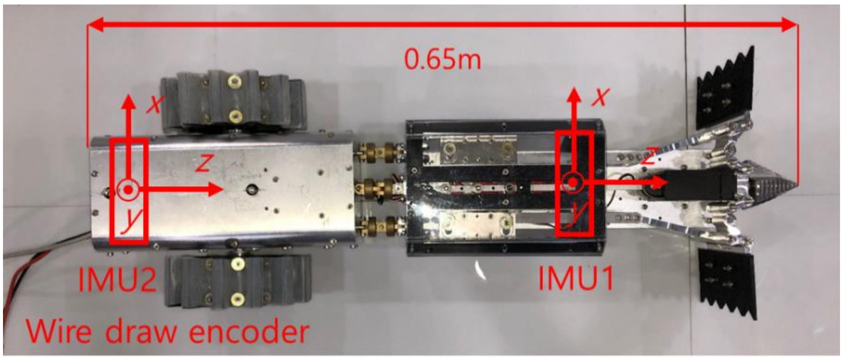

Fig. 2 Mole-bot's sensor system

Mole-bot was developed for the exploration of soft ground with an embedded directional drilling system. Fig. 1 and 2, the biological structure of the mole and the excavation habit of the robot mimics the biology. The Mole-bot consists of a front part and a rear part. The front part consists of two heads for drilling and a drill-shaped head. The rear part consists of a locking mechanism for securing during excavation and two wheels for movement. And one Inertial Measurement Unit (IMU) in the front part and the rear part, respectively. The distance between the IMU sensors is 0.45m and the overall robot length is 0.65m. This is very small compared to existing drilling systems.

2.2 Pose graph SLAM

2.2.1 Node generation and Dead reckoning

Mole-bot uses two IMU sensors and a wire draw encoder for localization. The Mole-bot operates at a distance from the base, unlike a conventional drilling system. Wire draw encoders can also maintain tension on the backward movement of the Mole-bot, so the exact length can be measured. In addition, the current position of the robot can be estimated based on the previous pose through the quaternion measured in two IMUs.

At this time, as the Mole-bot moves, a node including the quaternion and the position of the robot is generated at regular intervals. This node consists of a pose and a magnetic field sequence on the current node, and Eq. (1).

$$\begin{gathered} N_i = \left[X_i, B_{i,1}, B_{i,2}\right] \\ X_i = [x_i, y_i, z_i, q_i] \\ B_{i,k} = [b_{x,1}^k, b_{y,1}^k b_{z,1}^k; \dots; b_{x,l}^k, b_{y,l}^k b_{z,l}^k] \end{gathered} \tag{1}$$

N_i denotes i-th node information, X_i denotes a pose of i-th node, and $B_{i,k}$ denotes a magnetic field sequence of length l in the k-th magnetic sensor. Eq. (2) is applied to estimate the current pose through the pose of the previous node.

$$\begin{gathered} T_i = T_{i-1}T_t = \begin{bmatrix} R(q_i^o) & \begin{matrix} x_{i-1} \\ y_{i-1} \\ z_{i-1} \end{matrix} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I & \begin{matrix} 0 \\ 0 \\ \Delta L \end{matrix} \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R(q_i^o) & \begin{matrix} x_{i-1} + R(q_i^o)_{13}\Delta L \\ y_{i-1} + R(q_i^o)_{23}\Delta L \\ z_{i-1} + R(q_i^o)_{33}\Delta L \end{matrix} \\ 0 & 1 \end{bmatrix} \\ \Delta \mathrm{L} = t_i^o - t_{i-1}^o \end{gathered} \tag{2}$$

The calculated values are used for dead reckoning and include the cumulative error of each measured sensor. The method of minimizing this cumulative error is described in the next section.

2.2.2 Constraint detection

Since the pose of the Mole-bot obtained through dead reckoning contains the cumulative error, the error is minimized by using a magnetic field sequence which is another measurement. When the Mole-bot finds the magnetic field sequence measured earlier, you can calculate the relative position between the nodes and locate the exact robot through the loop closure. There are two cases where loop closure occurs in the applied algorithm. First, the magnetic field sequence measured at the front sensor is measured at the rear sensor. Also, since the drilling system completes the excavation, it returns to the base through the backward movement, and the same measurement as before can be obtained. In the backward movement, almost the same sequence can be obtained when comparing the magnetic field sequences measured by the same sensor. However, in the first case of comparing the measured sequences from the front and back sensors, the magnetic sensors have the different scale or offset differences because they have not been calibrated. Therefore, it is difficult to compare sequences even though they are measured at the same position. We applied the proposed CNCC algorithm in Zhao (2006) to calculate the similarity of two sequences with offset. The coefficient of CNCC is Eq. (3).

$$\gamma(\mathrm{u}) = \frac{\sum_x \left[f(x) - \bar{f_x}\right]\left[t(x-u) - \bar{t}\right]}{\left(\sum_x \left[f(x) - \bar{f_x}\right]^2 \sum_x [t(x-u) - \bar{t}]^2\right)^{\frac{1}{2}}} \tag{3}$$

The higher the similarity between the two magnetic field sequences, the closer the cross-correlation coefficient value to 1. We created a constraint between two nodes if the coefficient value exceeded a specific threshold.

2.2 Pose graph optimization

With reference to Fernández-Madrigal (2012), maximum likelihood estimator was applied to the poses on all graphs for optimization. The cost function intended to be minimized is as shown in Eq. (4).

$$x^* = \arg\min_x \frac{1}{2} \sum_{(i,j)\in\Gamma} r_{i,j}^T(x)\Lambda_{i,j} r_{i,j}(x) \qquad (4)$$
$$x = \{X_1, X_2, \dots\}$$

$r_{i,j}$ is the residual, which means the difference between the pose estimated through dead reckoning and the pose calculated through magnetic field sequence matching, and $\Lambda_{i,j}$ means the information matrix of the sensor measurement. In pose graph optimization, we calculate the pose that minimizes the error defined by the cost function. The change in state, Δx, is given by Eq. (5). We then update the state using Δx and iteratively calculates the optimized state until the state converges.

$$H\Delta x = -g \qquad (5)$$

$$H = \sum_{(i,j)\in\Gamma} J_{i,j}^T \Lambda_{i,j} J_{i,j}$$
$$g = \sum_{(i,j)\in\Gamma} J_{i,j}^T \Lambda_{i,j} r_{i,j}(x)$$

$J_{i,j}$ in the above equation is a jacobian matrix for the residual, and each residual can be calculated by partial differentiation. In our proposed algorithm, optimization was done using Georgia Tech Smoothing and Mapping (GTSAM) proposed by Dellaert (2012).

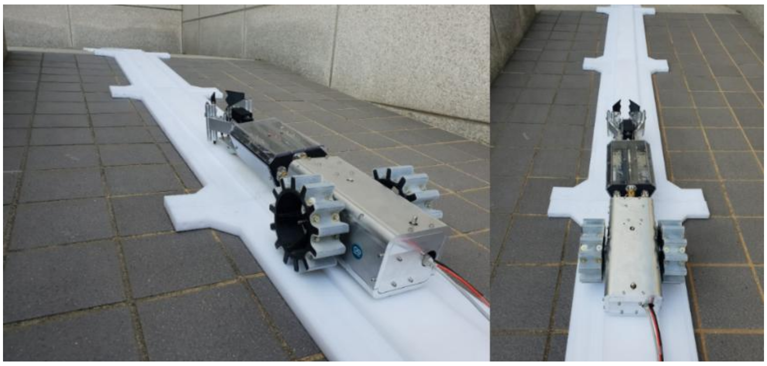

Fig. 3 Experiment environment

3. EXPERIMENT AND RESULTS

For the localization performance and the role of ground truth using a real robot, a guide was installed on a ramp of 5 m length and 6°. After the Mole-bot climbed the guide, the experiment was repeated by returning to the starting position.

The distance between the two IMUs installed inside the Mole-bot is 0.45 m, and the graphs measured on the front and rear magnetic sensors are shown in Fig. 4.

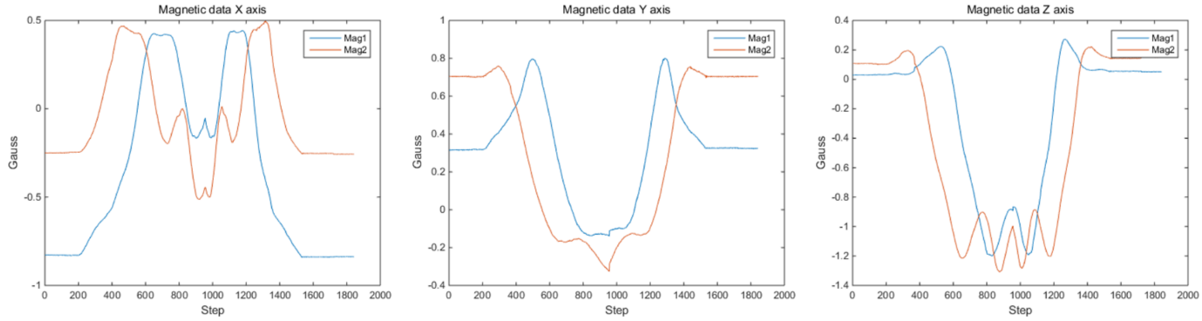

Fig. 4 Magnetic field sequence for each axis

The magnetic data for all axes is symmetric starting from approximately 1000 steps, approximately 5 m. However, as mentioned above, two different magnetic sensors have different scale and offset changes.

Localization results are shown in Fig. 5. In case of dead reckoning, there is an error of about 1 m with respect to the Y axis when returning to the origin again. On the other hand, the result of the proposed algorithm has an error of about 0.13 m. Translation error could be reduced by about 13%.

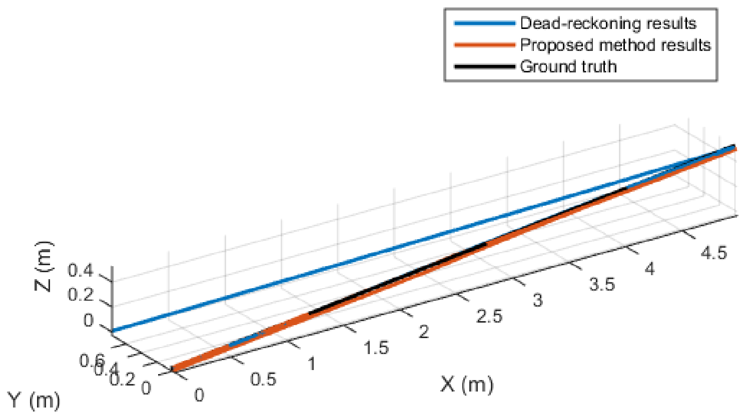

Fig. 5 Localization result

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4. CONCLUSIONS

In this research, we developed a small and novel, directional drilling system Mole-bot which did not existed. To overcome the limitations of using a sensor commonly used for localization in underground environments, we proposed a pose graph SLAM using a dual magnetic sensor. Based on the study that the same magnetic field sequence is measured in the forward movement and the backward movement to make an edge in the graph structure, the magnetic field sequence can be matched through the CNCC method. As a result, the error of dead reckoning using the encoder and gyroscope can be reduced by approximately 13%. However, since the experiments carried out in the research have been conducted on the ground, we have to further verify the algorithm through experiments in the actual underground environment. In addition, for Mole-bot to perform its actual mission, a localization system should be done in real time.

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