Three-Dimensional Localization and Mapping for a Crawler-type Mobile Robot in an Occluded Area Using the Scan Matching Method

Hiroshi Ishida, Keiji Nagatani, Yutaka Tanaka

The Graduate School of Natural Science and Technology,
Okayama University,
3-1-1, Tsushima-naka, Okayama, 700-8530, Japan
Email: keiji@ieee.org

Abstract— In the fields of urban search and rescue (USAR), it is important that crawler-type mobile robots explore occluded areas (collapsed buildings, underground shopping centers, etc.) in preference to rescue workers from the point of view of safety. To map such an occluded environment, it is important for robots to localize their position and pose.

In this paper, we propose two three-dimensional localization algorithms for crawler-type mobile robots. The algorithm is based on "three-dimensional scan-matching" using the three-dimensional laser range finder information. Several experiments using our crawler-type mobile robot verifies the validity and limitation of this method in a simulated disaster environment.

I. Introduction

It is very dangerous and stressful for rescue workers to search for victims in an occluded area of a disaster environment because of the possibility of weakened supports collapsing, which may be caused by after-shocks. There are great expectations that mobile robots would search for victims in such areas instead of rescue workers. Under such a background, "The Special Project for Earthquake Disaster Mitigation in Urban Areas" was launched in 2002 in Japan. Our research group has participated in this project, and we aim to realize the mapping of occluded areas of disaster environments using crawler-type mobile robots.

Localization and mapping of an environment complement each other in any unknown environment because a robot must localize itself in a partially mapped environment. Figure 1 introduces the idea of our localization and mapping method. A robot acquires local information in (1), localizes itself in a partially mapped environment in (2), and expands the environment information in (3). To acquire information about the local environment, we use a three-dimensional laser range finder mounted on a mobile robot.

In this paper, we introduce two algorithms used in mapping and localization methods in a three-dimensional environment. We also report the experimental results to verify the algorithms.

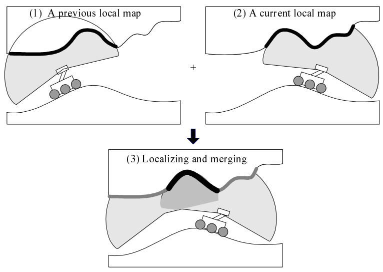


Fig. 1. Introduction to our localization method

II. Related works

"Search and rescue robotics" is related to several research fields. We focus on topics of "localization and mapping for mobile robots," which are relevant to our effort.

Recently, the simultaneous localization and mapping (SLAM) algorithm has gained popularly in the fields of mobile robot research. Thrun et al. systematized the SLAM algorithm for multiple mobile robots using the Bayesian method and successfully implemented it for mobile robots in two-dimensional environments [4]. Choset et al. proposed a SLAM algorithm using a "generalized Voronoi graph" [3], which was also implemented for a mobile robot in a two-dimensional environment. On the other hand, "online scan matching" becomes very popular in the localization and navigation of mobile robots. (e.g.,[6][7]) This method compares patterns of scanned laser range data with an already constructed map to localize the robot in the constructed map.

The basic idea of our approach is SLAM-based scan matching. However, the target environment is three-dimensional space. Therefore, the D.O.F. of the robot's pose and calculation are very complicated. We omit search space using sensing data from gyro sensors for scan matching in three-dimensional space.

III. Hardware

To perform our research experimentally, we set up a sensor unit and a crawler-type mobile robot. In this

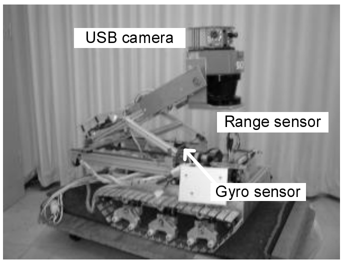


Fig. 2. Target robot (Res-Dog)

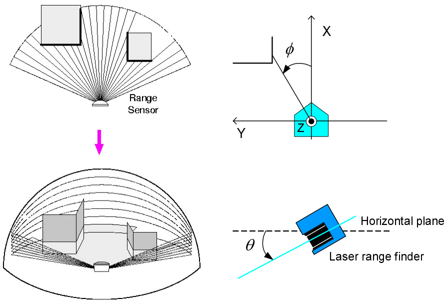


Fig. 3. Acquisition of three-dimensional environment data

section, we introduce our research platform and sensor unit for the acquisition of environmental information.

Figure 2 shows our target robot with a sensor unit. The details of the robot system are described in [8]. This sensor unit, which enables the robot to detect three-dimensional environmental information includes the following sensors:

A. Laser range finder

The laser range finder (SICK LMS200) has a detection capability of range information in a plane parallel to the installation surface. Therefore, the three-dimensional range data is acquired by rotating the sensor about pitch angle. Figure 3 represents this method.

B. Gyro sensor

The gyro sensor (NEC-Tokin MDP-A3U7) detects roll-pitch-yaw angles about the rectangular coordinates. It also includes an electric compass and gravitational sensors to cancel drift errors.

C. Vision sensor

Three USB cameras (produced by I-O Data) are mounted on the laser range finder as vision sensors. They can detect visual information by synchronizing the rotation of the laser range finder.

IV. Outline of the localization method

In this section, we introduce a map representation method and a brief of the SLAM method.

A. Construction of a local map

If we choose a map representation method that employs voxel, considerable computer memory will be required to represent the local map in a three-dimensional environment. (We use the term "local map" as three-dimensional range data at the robot's current position.) In order to save the resources of the computer, a digital elevation map (DEM), a very popular method, is used to represent uneven ground. The map uses two-dimensional (x-y) grids on the horizontal plane of the environment. Each grid has height information to represent the three-dimensional environment. However, a representation of the ceiling is impossible to obtain inside an occluded area (collapsed buildings, etc.) using a standard DEM.

To overcome this problem, the ground surface is represented by θ-ϕ grids instead of x-y grids. Thus, a local map is represented by $r(\theta, \phi)$, where r is the distance of the obstacles from the robot, θ is a tilting angle of the sensor unit, and ϕ is the scanning angle of the range sensor. Using $r(\theta, \phi)$ instead of (x, y, z), we obtain a representation of a building's interiors, which includes ceilings and beams.

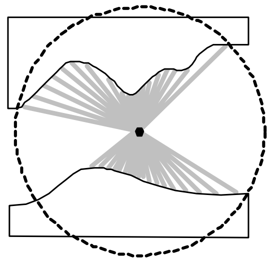


Fig. 4. Construction of local map

Figure 4 shows an example of a local map in a two-dimensional case. This method has an advantage, i.e., we can use the data detected by the range sensor without change. However, it also has a disadvantage that the scatter of the data is concentrated in the neighborhood $\pm\pi/2$[deg] because of our sensor unit's configuration.

B. Localization procedure

In an unknown environment, a mobile robot needs to map a target environment and to simultaneously localize itself in the constructed map (SLAM). Geographical features (such as rubble on uneven ground) are a good source of information for the three-dimensional localization of a robot. Therefore, we apply the following method to mobile robot's localization in three-dimensional space:

1) Build a local map ("a previous local map")
2) Move to a suitable distance
3) Construct a local map ("a current local map")
4) Calculate the correlation between the previous map and the current local map
5) Localize a robot's position in the previous local map
6) Refer to the current local map as a previous local map for the next localization
7) Repeat procedure from 2

We proposed the above localization algorithm that is based on the three-dimensional scan matching method

[8]. However, we observed that the algorithm sometimes resulted in wrong results. One of the reasons for this is large information related to even walls or ceilings prevented correct matching. In other words, the characteristics of the environment are lost by flat plane information the correlation calculations.

To solve this problem, we propose two localization methods in this paper. One is to apply a correction to an environment that has several flat planes in the target environment (method-1), and the other is to apply a correction to an environment that has flat ceilings that are represented as large planes. (method-2) In the following sections, we introduce the details of these methods.

V. Algorithm for localization (Method-1)

In a bumpy environment, information regarding the unevenness of the ground is very useful for localization using the three-dimensional scan matching method. On the other hand, it is difficult to estimate the robot's position using flat-walls or even grounds. Therefore, we propose a localization method that uses only uneven environmental information. This method is performed in two steps: (1) extraction of characteristic information, (2) scan matching using characteristic information.

A. Extraction of feature information

In our detection method shown in section III-A, a plane object is detected as a straight segment at each tilt angle scan of the laser range finder. To remove such plane information from the environment data, straight segments are taken away by Hough transformation (without information of both the end points). As a result, only uneven surface data remains. Using this data, correlation for scan matching can be calculated with lesser data and more speed and precision.

B. Scan matching and localization

Firstly, each range data of a previous local map $r_{pre}(\theta, \phi)$ is transformed into orthogonal coordinates (x, y, z) by the following equations:

$$\begin{aligned} x &= r_{pre} \cos\theta \cos\phi \\ y &= r_{pre} \sin\phi \\ z &= -r_{pre} \sin\theta \cos\phi. \end{aligned} \qquad (1)$$

Secondly, the origin of the previous local map (x_p, y_p, z_p) is moved toward an arbitrary position (x_v, y_v, z_v). Then, a virtual local map $r_v(\theta_v, \phi_v)$, which has its origin located at (x_v, y_v, z_v), is generated by the following transformation:

$$\begin{aligned} r_v &= \sqrt{(x_v - x_p)^2 + (y_v - y_p)^2 + (z_v - z_p)^2} \\ \theta &= \tan^{-1}((z_v - z_p)/(x_p)) \\ \phi &= \tan^{-1}\left((y_v - y_p)/\sqrt{(x_v - x_p)^2 + (z_v - z_p)^2}\right). \end{aligned} \qquad (2)$$

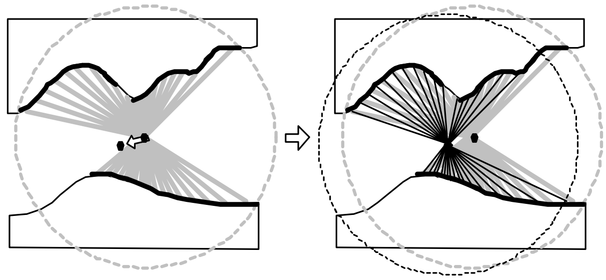


Fig. 5. An example of construction of virtual local map

Figure 5 shows an example of the construction of a virtual local map in the two-dimensional case. In the figure on the left, a local map $r(\theta, \phi)$ is represented by thick black curves. The figure on the right is a virtual local map in the case where the origin of the local map moves toward the lower left.

Finally, the correlation d between a virtual local map and a current local map is calculated by the following equation:

$$d = \sum_{\theta} \sum_{\phi} (r_v(\theta, \phi) - r_{cur}(\theta, \phi))^2 \cos\phi, \qquad (3)$$

where each (θ, ϕ) has range data in both the local maps. A weight coefficient $(\cos\phi)$ is included to reduce the effect in the vicinity of $\phi = \pm 90$[deg].

Once a robot calculates the values of correlation d in (3) at every probable point on the virtual local map, the robot assumes its position to enable it to minimize the value of d.

If the robot uses only range sensor data for localization (and assumes many probable points of positioning and orientation of the robot), calculation cost becomes very high. Practically, we assume that the robot uses a gyro sensor for the detection of an orientation and a pose of the robot to reduce the cost of calculation.

VI. Verification of Method-1

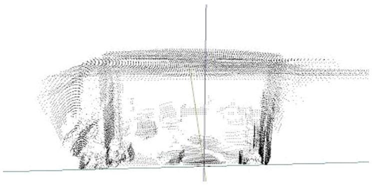
A. Target environment

To verify the validity of Method-1, several experiments have been carried out in a simulated disaster environment in our laboratory, which includes a flat floor and several other obstacles. We set up two types of environments, called Environment-A and Environment-B. The size of Environment-A is about 6 × 8 [m] in length and 3 [m] in height, and the size of Environment-B is about 6 × 2.5 [m] in length and 2.5 [m] in height. Figures 6(a) and 9(a) show Environment-A and Environment-B.

B. Procedure of the experiment

(P-1) Firstly, we place the robot parallel to the ground and note the initial position of the robot. Then, the laser range sensor rotates about the pitch angle (from −120 to 30 [deg]; horizontal direction is considered as 0 [deg]).

(a) Overview



(b) Range data

Fig. 6. A target Environment-A

For every 1 [deg] of the pitch angle, the range sensor measures the range data in the yaw angle (between ±90[deg]) for every 1 [deg]. In this experiment, the pitch angle is detected by the encoder of the motor that drives the rotation of the laser range sensor. The range data is stored as a previous local map $r_l(\theta, \phi)$.

(P-2) Secondly, the robot is moved to a certain distance (about 50 [cm]) and pose (less than 20 [deg] for each angle). Then, the robot scans the local data again. It is the same method as (P-1). The data are stored as a current local map $r_{cur}(\theta, \phi)$. To acquire a pose of the robot, the gyro sensor is used for the detection of the robot's roll, pitch, and yaw angle.

(P-3) Thirdly, the robot calculates a correlation between the current local map and the virtual local maps (These are introduced in section V), and then estimates its position in the previous local map.

C. Experimental result

Figure6(b) represents range data of Environment-A at the initial position. According to the algorithm mentioned in section V, straight segments in the range data of each pitch angle are eliminated by the Hough transformation. Figure7 shows an example of range data at one pitch angle. In this figure, the gray dots are targets to be eliminated as straight segments in our method. The environmental information after eliminating the segments is shown in Figure 8. Thus, the plane information of the ceiling is eliminated.

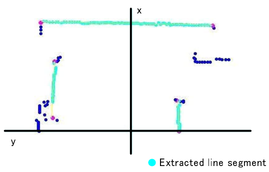


Fig. 7. Extracted segments

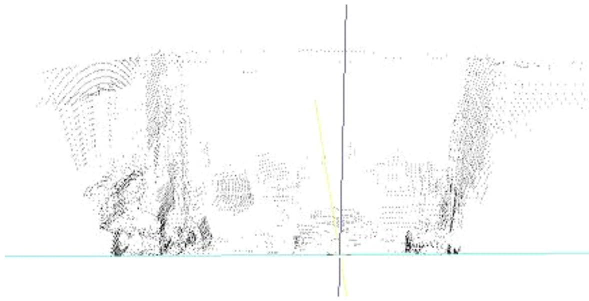


Fig. 8. Range data of environment A (segments are eliminated)

In Environment-A, the robot moved towards the point $(x, y, z) = (35, 30, 5)$, and its pose changed by $(-2, -10, 15)$ [deg] about the x, y, z axes. The estimation results of the localization were $(x, y, z) = (32, 26, 6)[cm]$. From the results and these figures, these are reasonable results from the point of view of accuracy.

However, in Environment-B, there was a problem with regard to accuracy. In this environment, the robot was moved towards the position to $(x, y, z) = (35, 30, 5)$ [cm] and its pose was changed to $(-2, -11, 22)$ [deg] about the (x, y, z) axis. The estimation result was $(x, y, z) = (44, -26, 20)$ [cm], and the z position coordinate seemed incorrect.

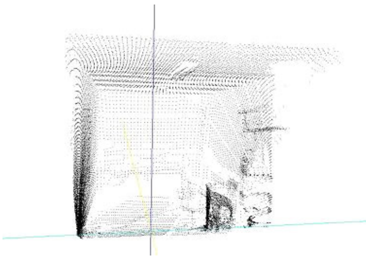
One of the reasons for the incorrect z position coordinate is that the information of several obstacles on the ground was regarded as a plane, and they are eliminated by the Hough transformation. This often occurred in Environment-B. Another reason is the problems regarding accuracy of the gyro sensor. This problem can be solved by replacing the gyro sensor. However, the former reason includes the threshold tuning problem (the threshold value depends on the target environment). At least, height information can be estimated easily by ceiling information if there is a ceiling. Therefore, we propose Method-2 that uses ceiling information in the next section.

VII. Algorithm of localization (Method-2)

In urban search and rescue, it is possible that a crawler-type robot might explore an environment that has flat ceiling (e.g., an underground shopping center). In such an environment, the ceiling can be regarded as the characteristic information for the mobile robot's localization in three-dimensional space. Therefore, we propose the following localization algorithm that uses the flat ceiling information:

1) Estimate the robot's altitude using the displacement information of the ceiling
2) Estimate robot's pose using the ceiling angle

(a) Overview



(b) Range data

Fig. 9. A target Environment-B

3) Estimate the robot's x and y displacement using the scan matching method

This algorithm can be applied to an environment that has a large ceiling as the maximum plane.

A. Estimation of the robot's altitude

Firstly, coefficients $[a, b, c]$ of a plane equation $ax + by + cz + d = 0$ can be obtained by the "Hough transform method" from the three-dimensional range data (x, y, z) detected by the sensor unit. Next, distance h from robot's position $(0, 0, 0)$ to a plane $ax + by + cz + d = 0$ (the robot's altitude) is calculated by:

$$h = \frac{|d|}{\sqrt{a^2 + b^2 + c^2}}. \tag{4}$$

Thus, the difference of h between the previous and the current local map can be denoted by the height displacement of the robot.

B. Estimation of the robot's pose

Comparing the differences of $[a, b, c]^T$ in the previous and current position of the robot, it is possible to estimate the change in the robot's pose. We define the robot's altitude in a local map as shown in Figure 10, and can obtain robot's altitude using the following equations:

$$\begin{aligned} \gamma + \pi/2 &= \tan^{-1}(c/b) \\ \beta &= \tan^{-1}(a/c) \\ \alpha &= \tan^{-1}(b/a) \ . \end{aligned} \tag{5}$$

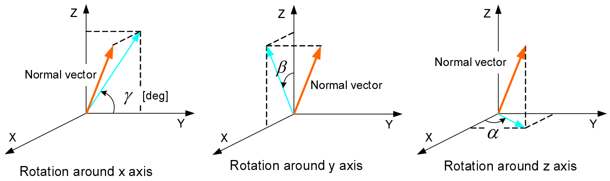


Fig. 10. Roll-pitch-yaw angle

C. Estimation of robot's (x, y) position

We estimate the robot position based on scan matching using the same method as in section V. In this method, only a displacement of the x and y direction should be estimated because the z direction (robot's altitude) is already estimated by the Hough transform method. Then, a virtual local map is constructed by the same technique as in Method-1, however, the number of probable points becomes very small. A correlation between a virtual map and a current local map is calculated by following equation:

$$d = \sum_{\theta} \sum_{\phi} (r_v(\theta, \phi) - r_{cur}(\theta, \phi))^2 / \cos\phi \tag{6}$$

VIII. Verification of Method-2

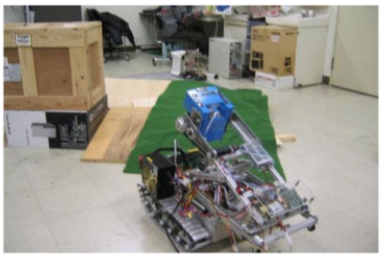
We experiment to verify Method-2 with the same procedure described in section VI. The size of the target environment is about 6×8 [m] in length and 3 [m] in height. The ceiling has several dim bulbs and openings for an air-conditioner. However it is considered to be a flat ceiling, i.e., Hough transform method works robustly.

Firstly, we place the robot at an arbitrary position and assume the initial position. Using (P-1) in section VI, the robot acquires the range data of the target environment. Secondly, we move the robot towards an arbitrary point, and the robot acquires the environmental information again. In this experiment, we set the distance between the positions for which sensing was carried out to be within the range 50-70[cm].

A. Experimental result

Figure 12(a) shows an overwrapped result of range data of the 1st and 2nd position. From these figures, the Method-2 is reasonable because the displacement between the 1st and 2nd position seems very small. However, in figure 12(b) (enlarged view of figure 12(a)), the estimated position does not completely correspond to the actual robot's location that is caused by rounding the errors of r, θ, ϕ in the construction of a virtual local map for every 1 [deg] of θ and ϕ.

Additionally, it is difficult to estimate a robot's yaw pose using a normal vector ($[a, b, c]^T$). The reason for this is that a and b are smaller than the c. Our gyro sensor is also inaccurate, so we measured the robot's yaw angle using a protractor in this case. In our future work, we will estimate the robot's yaw angle by the scan matching method.



(a) 1st position

(b) 2nd position

Fig. 11. Motion of robot and the target environment

In this experiment, the localization is successful even if there are flat obstacles in the target environment. (Actually, it failed in the same environment using Method-1, because the flat information of a box is eliminated.) However, Method-2 assumes strong preconditions (it requires a flat ceiling), so the area of application of the algorithm is limited.

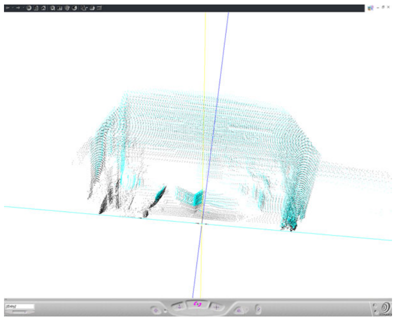
IX. Conclusion and future works

In this paper, we described two algorithms for the localization of the mobile robots on rough terrain. One is that in which the robot eliminates the plane information, and it estimates robot's displacement in the x-y-z direction using the scan matching method. Another one is that in which the robot estimates its altitude using ceiling information, and it estimates the (x, y) direction by scan matching. Moreover, we verified both the localization algorithms in the simulated disaster environment in our laboratory. These results verified the ability and limitation of these algorithms.

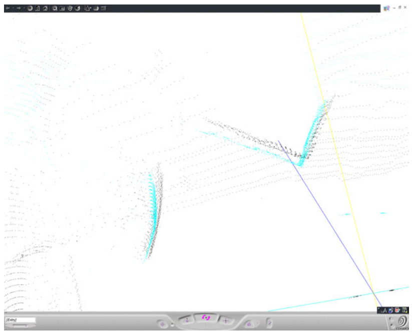
We still have the following problems and discussions:

- We cannot detect the robot's pose using both a gyro sensor and a normal vector of a plane.
- After localization of the robot, we need to construct a three-dimensional environment using range data and vision data from our sensor unit.

Finally, we will try to apply our system to test the "disaster environment" in Kobe and Kawasaki, and carry out further discussions on the effectiveness of our algorithms.



(a) Overall view



(b) Enlarged view

Fig. 12. A result of localization in the 1st and 2nd position

Acknowledgement

This research is fully supported by "The Special Project for Earthquake Disaster Mitigation in Urban Areas" in the Japanese Ministry of Education, Culture, Sports, Science and Technology.

References

[1] S. Hirose, T. Shirasu: Proposal for cooperative robot "gunryu" composed of autonomous segments,Robotics and Autonomous Systems, Elsevier, 17, pp.107-118(1996)

[2] R. Murphy, M. Ausmus, M. Bugjska, T. Ellis, T. Johnson,N. Kelly, J. Kiefer, and L. Pollock: Marsupial-like mobile robot society, IEEE Intelligent Systems, Vol.15, No.3, pp.364-365 (1999)

[3] H. Choset and K. Nagatani: Topological simultaneous localization and mapping(SLAM) toward exact localization without explicit localization, IEEE Trans. on Robotics and Automation, Vol.17, No.2, pp.125-137 (2001)

[4] S. Thrun: A probabilistic online mapping algorithm for teams of mobile robots, Internatinal Journal of Robotics Research, Vol.20, No.5, pp.335-363 (2001)

[5] F. Nashashibi, P. Fillatreau, B. Dacre-Wright, T. Simeon: 3-D Autonomous Navigation in a Natural Environment, IEEE International conference on Robotics and Automation, Vol.1, pp.433-439 (1994)

[6] J. Gutmann and C. Schlegel: Comparison of scan matching approaches for self-localization in indoor environments, Proceedings of the 1st Euromicro Workshop on Advanced Mobile Robots, IEEE Computer Society Press (1996)

[7] F. Lu, and E. Milios: Globally consistent range scan alignment for environment mapping, Journal of Autonomous Robots, Vol.4, pp.333-334 (1997)

[8] K. Nagatani, H. Ishida, S. Yamanaka, Y. Tanaka: Three-dimensional Localization and Mapping for Mobile Robot in Disaster Environments, International Conference on Intelligent Robots and Systems, pp.3112-3117 (2003)

[9] Hough,P.V.C.: Method and means for recognizing complex patterns, U.S. Patent, 306954 (1962)