Continuous Acquisition of Three-Dimensional Environment Information for Tracked Vehicles on Uneven Terrain

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Abstract — Localization and mapping are essential elements in the design of mobile robots used for search and rescue mission. Localization is a key-function of remote control and mapping in an unstructured environment. However, in general, odometry in tracked vehicles is ambiguous because of the track slippage. To solve this problem, we developed a three-dimensional gyro-based odometry that considers the compensation of slippage on the basis of an empirical model. The method was successfully implemented in a tracked vehicle, and its validity was confirmed by initial tests in real environments. Mapping is also very important in a searching task. A small three-dimensional laser range scanner provides operators and rescue crews with a wealth of information for understanding environments. However, to obtain this information, the operators must wait a few seconds and halt the robot's operation. To solve this problem, we propose the continuous acquisition of three-dimensional environment information for tracked vehicles using the three-dimensional gyro-based odometry reported above. In this paper, odometry and continuous acquisition methods are introduced for use by tracked vehicles operating in hostile environments.

Keywords: *Localization, Odometry, Laser range finder, Mapping, Tracked vehicle*

I. Introduction

Following disastrous earthquakes in urban settings, search crews encounter grave dangers and the potential for aftershocks. Therefore, remote-controlled mobile robots are more advantageous than humans for search missions in collapsed buildings or underground cities [1]. To realize such useful search robots in disaster sites or underground cities, we have been developing crawler-type robots. Figure 1 shows one of our recent tracked vehicles, called "KENAF" [2]. Based on former studies, there are three key issues to be considered in the development of remote-controlled mobile robots: (1) traversability, (2) localization, and (3) mapping. In this report, our emphasis is on traversability and localization.

Localization is one of the key functions executing remote control and mapping for search robots operating in unstructured environments. However, it has been generally considered that the odometry measurement of tracked vehicles is useless because of track slippage. One popular method for localization is SLAM (Simultaneous Localization and Mapping). A good summary of this topic is in *Probabilistic Robotics* [3]. A process called scan-matching has recently been shown to be effective and fast for mapping in 2-dimensional environments equipped with laser range scanners (e.g. [4], [5]). However, many such methods rely on odometry for reference location with robots, and odometry of tracked vehicles is less accurate than that of wheeled ones.

Fig. 1. Tracked vehicle testbed Kenaf-II

The first step in our approach to overcome the localization challenge was to improve odometry with consideration of track slippage.

We have developed a useful method, based on an empirical model, to compensate the slippage. The analysis is originally based on the *Theory of Ground Vehicles* [6], and we proposed a new odometry method using a gyroscope with consideration of the characteristics of the tracked vehicle[7]. The validity of the method has been accurately demonstrated in a path tracking maneuver on some kinds of flat surfaces [8]. In this paper, the method is extended to a three-dimensional world with a three-dimensional gyroscope. The first contribution of our study is to propose the three-dimensional odometry with consideration of slippage.

Mapping is another essential element in search missions. When rescue crews enter target environments, three-dimensional information is a significant assistance to understand the environments for the crews. It is also good to support the remote control of mobile robots. In our research project, a small three-dimensional laser range scanner was mounted on a tracked vehicle to obtain three-dimensional information. Although it performed well, it required a few seconds to obtain

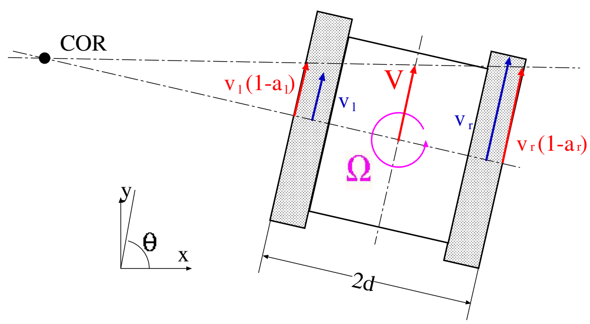

Fig. 2. Kinematic model for tracked vehicles

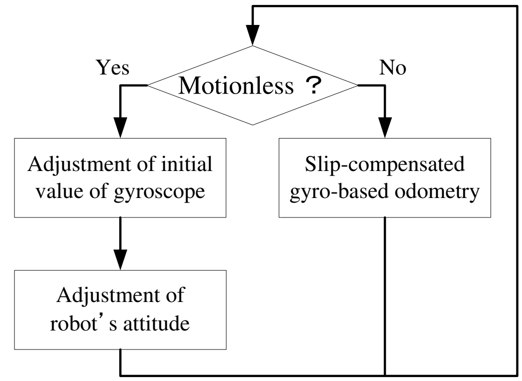

Fig. 3. A concept of compensation of gyroscope's drift

the information. Furthermore, the robot was not supposed to move until the scanning was finished. Such interruptions in the acquisition of environmental information have the potential to impede rescue missions [9]. To solve this problem, we propose the continuous acquisition of three-dimensional environment information. In our current implementation, the method is based on the above three-dimensional gyro-based odometry. The second contribution of our study is to introduce our implementation of the continuous acquisition method.

The above two technologies, three-dimensional gyro-based odometry and continuous acquisition of three-dimensional environmental information, are validated by experiments using our tracked vehicle testbed.

II. Three-dimensional gyro-based odometry

A. Slip-compensation odometry

Odometry is a simple and easy method to estimate the position and orientation of wheeled mobile robots in a planar environment. However, the method requires the assumption that there will be no slippage between the wheels and the ground. Therefore, it is inherently difficult to apply conventional odometry to tracked vehicles. To solve this problem, we developed an odometry for tracked vehicles that compensates for the slippage and improves its accuracy [7][8]. A summary follows.

If the slip ratios of both tracks are quantitatively detected, odometry for tracked vehicles can be expressed by the following kinematic equations (1)–(3),

$$\dot{x} = \frac{v_r(1-a_r)+v_l(1-a_l)}{2}\cos\theta \quad (1)$$

$$\dot{y} = \frac{v_r(1-a_r)+v_l(1-a_l)}{2}\sin\theta \quad (2)$$

$$\dot{\theta} = \frac{v_r(1-a_r)-v_l(1-a_l)}{2d} \quad (3)$$

where v_l and v_r are the theoretical left- and right-track velocities respectively, $2d$ is the tread. a_l and a_r are the terrain-track slip ratios defined as,

$$a_l = \frac{v_l - v_l'}{v_l} \quad (4)$$

$$a_r = \frac{v_r - v_r'}{v_r} \quad (5)$$

where v_l' and v_r' are the absolute velocity of the left and right tracks, respectively. Figure 2 shows the proposed kinematic model of a crawler vehicle.

In practice, v_l' and v_r' are difficult to measure. Therefore, terrain-track slip ratios a_l and a_r should be estimated by other methods. An internal sensor, such as a gyroscope, to measure $\dot{\theta}$ is one good option. However, it is insufficient for determining the two parameters, a_l and a_r, from Equations (1)-(5). Therefore, the following empirical relationship has been suggested,

$$\frac{a_l}{a_r} = -\mathrm{sgn}(v_l \cdot v_r)\sqrt{\left|\frac{v_r}{v_l}\right|}. \quad (6)$$

Now, a_l and a_r are calculated by equations (3) and (6), and finally, $\dot{x}$ and $\dot{y}$ are determined to calculate the odometry of tracked vehicles.

The validity of the model has been confirmed by experiments with good accuracy in path tracking maneuvers on plastic tiles, carpet, and artificial turf[8].

B. Expansion gyro-based odometry to 3 dimensions

The method above was successfully implemented for use with our tracked vehicle, and we confirmed its validity on flat surfaces. However, it was insufficient for rescue missions, in which the target is a three-dimensional environment. Therefore, in this research, we expanded the above algorithm to 3 dimensions using 3 axes of gyroscopes as follows.

We assume that the x-axis corresponds to the robot's orientation and the z-axis is perpendicular to the ground. When the current quaternion of the robot's attitude is expressed as ${}^0q_n$, a quaternion of a small amount of displacement of the robot's attitude, ${}^{n}q_{n+1}$, is expressed by the following vector:

$$
{}^{n}q_{n+1} = \begin{bmatrix} \cos\frac{\Delta\theta_{x,n}}{2} \cdot \cos\frac{\Delta\theta_{y,n}}{2} \cdot \cos\frac{\Delta\theta_{z,n}}{2} \\ \sin\frac{\Delta\theta_{x,n}}{2} \cdot \cos\frac{\Delta\theta_{y,n}}{2} \cdot \cos\frac{\Delta\theta_{z,n}}{2} \\ \cos\frac{\Delta\theta_{x,n}}{2} \cdot \sin\frac{\Delta\theta_{y,n}}{2} \cdot \cos\frac{\Delta\theta_{z,n}}{2} \\ \cos\frac{\Delta\theta_{x,n}}{2} \cdot \cos\frac{\Delta\theta_{y,n}}{2} \cdot \sin\frac{\Delta\theta_{z,n}}{2} \end{bmatrix} \qquad (7)
$$

where $\delta\theta_x$ means a small amount of displacement around the x-axis, $\delta\theta_y$ means a small amount of displacement around the y-axis, and $\delta\theta_z$ means a small amount of displacement around the z-axis. Then, the new quaternion of the robot's attitude, ${}^{0}q_{n+1}$, is expressed by ${}^{0}q_n$ and the equation (7) as follows:

$$
{}^{0}q_{n+1} = {}^{0}q_n \times {}^{n}q_{n+1}. \qquad (8)
$$

On the other hand, a translation of robot body ΔX_n is detected by the method shown in Section II-A. So, a small amount of position displacement vector ${}^{n}p_{n+1}$ is calculated by the following equation:

$$
\begin{bmatrix} 0 \\ {}^{n}p_{n+1} \end{bmatrix} = {}^{0}q_{n+1} \times \begin{bmatrix} 0 \\ \Delta X_n \\ 0 \\ 0 \end{bmatrix} \times {}^{n+1}q_0. \qquad (9)
$$

Finally, a new position of the robot ${}^{0}p_{n+1}$ is calculated by

$$
{}^{0}p_{n+1} = {}^{0}p_n + {}^{n}p_{n+1}. \qquad (10)
$$

According to equations (8) and (10), a robot's attitude and position are updated three-dimensionally.

C. Compensation of the gyroscope's drift

When the encoders of the traction motors of tracks are not changed, and when there is no displacement from its gravity sensor, it is assumed that the robot is in a motionless situation. In this case, the outputs of gyroscope (angular velocities) should be zero, and it is possible to calibrate the drift error of the zero point of the gyroscope on-line. Figure 3 shows the concept of the compensation of a gyroscope's drift. A similar approach was proposed by Prof. Borenstein's group, which is called FLEXnav [10]. Our approach does not rely on Fuzzy Logic to determine whether the robot is moving or not.

When the robot is in a motionless situation and when its estimated attitude is expressed by $(\theta_{roll}, \theta_{pitch}, \theta_{yaw})$, the quaternion of the robot's attitude ${}^{0}q_n$ is,

$$
{}^{0}q_n = \begin{bmatrix} \cos\frac{\theta_{yaw}}{2} \\ 0 \\ 0 \\ \sin\frac{\theta_{yaw}}{2} \end{bmatrix} \times \begin{bmatrix} \cos\frac{\theta_{pitch}}{2} \\ 0 \\ \sin\frac{\theta_{pitch}}{2} \\ 0 \end{bmatrix} \times \begin{bmatrix} \cos\frac{\theta_{roll}}{2} \\ \sin\frac{\theta_{roll}}{2} \\ 0 \\ 0 \end{bmatrix}. \qquad (11)
$$

On the other hand, the gravity vector G is expressed by

$$
G = g \begin{bmatrix} \sin\theta'_{pitch} \\ -\cos\theta'_{pitch}\cos\theta'_{roll} \\ -\cos\theta'_{pitch}\sin\theta'_{roll} \end{bmatrix}, \qquad (12)
$$

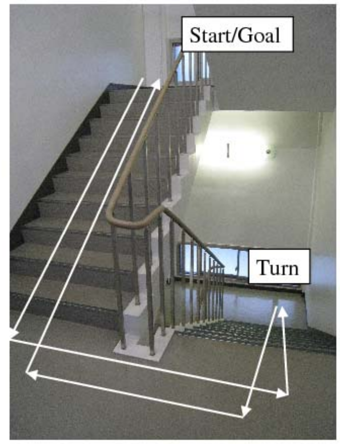

Fig. 4. Target path of our tracked vehicle in an initial test

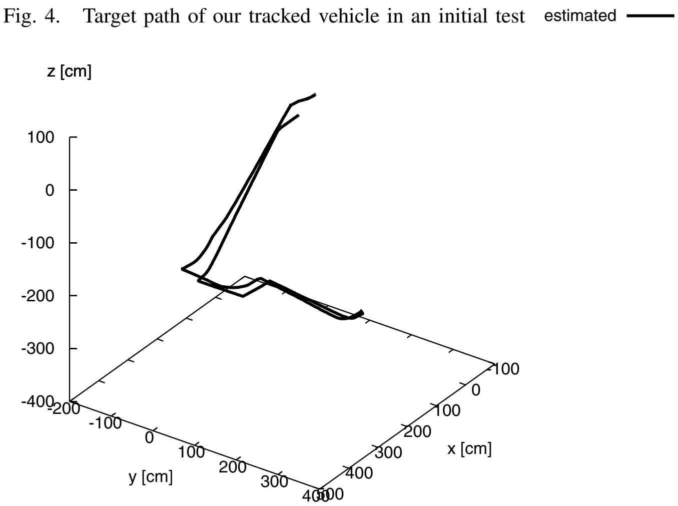

Fig. 5. One typical result of three-dimensional gyro-based odometry

which can be measured by a gravity sensor. Thus θ'_{pitch} and θ'_{roll} are calculated by the above relationship. Finally, the adjusted quaternion of a robot's attitude ${}^{0}q_n$ is expressed by

$$
{}^{0}q_n = \begin{bmatrix} \cos\frac{\theta_{yaw}}{2} \\ 0 \\ 0 \\ \sin\frac{\theta_{yaw}}{2} \end{bmatrix} \times \begin{bmatrix} \cos\frac{\theta'_{pitch}}{2} \\ 0 \\ \sin\frac{\theta'_{pitch}}{2} \\ 0 \end{bmatrix} \times \begin{bmatrix} \cos\frac{\theta'_{roll}}{2} \\ \sin\frac{\theta'_{roll}}{2} \\ 0 \\ 0 \end{bmatrix}. \qquad (13)
$$

D. Initial tests

We implemented the three-dimensional gyro-based odometry and drift compensation method shown in the above sections and performed initial tests. The target environment was the stairs and corridors of the building in which our laboratory is located. The robot is remotely controlled by a joystick with a human operator, and a given path is shown in Figure 4. The robot goes from the 4th floor to the 3rd floor using stairs; it remains on the 3rd floor for 30 seconds (for drift compensation) and returns to its initial position (on the 4th floor). The total length of its path is about 23 meters.

We performed the initial tests note above 5 times, as shown in Table I. One of the typical three-dimensional gyro-based odometry results is shown in Figure 5. If the odometry is accurate enough, the robot comes back to the initial position. However, there is an error of about 70 centimeters on average from the initial position. The error of the z axis is always positive. This means that the tracks sometimes slip when the robot is climbing up the stairs. It is impossible to estimate the degree of slippage with internal sensors.

We also performed the same tests without a drift compensation function. The average of error then became 70 centimeters. In these initial tests, the total time of the experiment was about 200 seconds (excluding the drift compensation time). We assume that the drift error of the gyroscope was not as large in the above cases. However, it is obvious that the three-dimensional gyro-based odometry error accumulates according to time without the drift compensation function.

The function takes some time, which means that the robot must remain stationary for a while; however, stopping to acquire information on a victim's status is typical for tracked vehicles in actual search missions.

III. Continuous acquisition of three-dimensional environment information

A. Introduction to three-dimensional scanning method

The typical acquisition of three-dimensional environmental information is obtained by rotating a conventional 2-dimensional laser range scanner. We chose a Top-URG developed by Hokuyo Automatic Co., Ltd., as a laser range scanner. To rotate the scanner, we use a smart motor, Dynamixel RX-28 (made by Robotis).

Usually, the rotational axis is located parallel with the scanning surface. However, it is a possible to set a scanning surface on any inclination. In our system, we tilted the scanning surface 30 degrees. An overview of our three-dimensional laser range scanner is shown in Figure 6.

There are two advantages of the configuration. The first is that it provides better distribution of the scan points. Convergence points, one of which can be seen at the bottom of the acquired points in Fig.7-(a), do not exist in our sensor configuration. The second is to increase the scanning speed or scanning density.

Figure 7 contains information regarding the trade-off between the scanning speed and scanning density according to the inclination value of the scanning surface. To simplify this discussion, we assume that the angle between two scanning points (the resolution of the scanner) is 1 degree and the angular speed to rotate the scanning surface is variable. Figure 7-(a) shows a conventional scan (the inclination value of the scanning surface is 90 degrees). Figure 7-(b) is the result of a tilted scanning surface (the inclination value of the scanning surface becomes smaller), but the rotational speed of the scanning surface is the same as that in 7-(a). Figure 7-(c) shows the result of the same inclination of the scanning surface as in 7-(b), but the rotational speed of the scanning surface is increased (the angle between two scanning surfaces is 1 degree). Under each condition, a scanning result is added on the right side of the figure.

According to these schematics and examples, (1) the scanning density is increased, and (2) the scanning area is decreased as the value of the inclination of the scanning surface becomes smaller shown in 7-(a) and 7-(b). If we need the same scanning density for 7-(a) with the tilted scanning surface, kinematically, (3) the angular speed ϕ' of the scanning surface should be increased as follows:

$$\phi' = \frac{1}{\cos(\frac{\pi}{2} - \alpha)} \phi \tag{14}$$

where α is an inclination angle of the scanning surface and ϕ is the angular speed in the case of 7-(a).

B. Implementation of continuous acquisition of three-dimensional environmental information

In a conventional method for obtaining three-dimensional environmental information, a robot stops until the scanning is completed. In our case, this time is typically 10 seconds. If the robot does not stop, the center of the scanner's location is moved, and the shapes of objects in the target environment are changed.

If the robot knows each robot's position with a value of exact time (which is called time stamp) and its scanning data with time stamp, the robot will be released from the restriction of stationary scanning. Fortunately, the data coming from the Top-URG includes time stamp information, and, in Section II, we showed a comparatively accurate three-dimensional odometry with the time stamp for tracked vehicles. In this research, on the basis of synchronisation between a robot's position/attitude and laser scanning data, we obtained three-dimensional environmental information without having the robot stop and go.

Figure 8 shows details of the synchronisation method in our current implementation. Each laser range scan has a time stamp, and the odometry information of the robot (when the robot starts scanning) is calculated by a linear interpolation of the odometry's time stamp.

The parameters of this sensor system are as follows:

- The maximum range is 30 meters of Top-URG
- 1,050 points in one scan of Top-URG (every 0.25 degrees)
- 25 milliseconds in one scan of Top-URG

TABLE I
ESTIMATED POSITIONS OF THE GOAL WITH THE THREE-DIMENSIONAL GYRO-BASED ODOMETRY

	x[cm]	y[cm]	z[cm]	norm[cm]
1	-39.1	-49.6	27.6	68.9
2	20.7	-48.4	59.2	79.3
3	-4.9	-21.1	51.9	56.2
4	12.7	10.7	62.5	64.7
5	43.7	23.0	61.7	79.0
ave	-	-	-	69.6

Fig. 6. three-dimensional laser range scanner

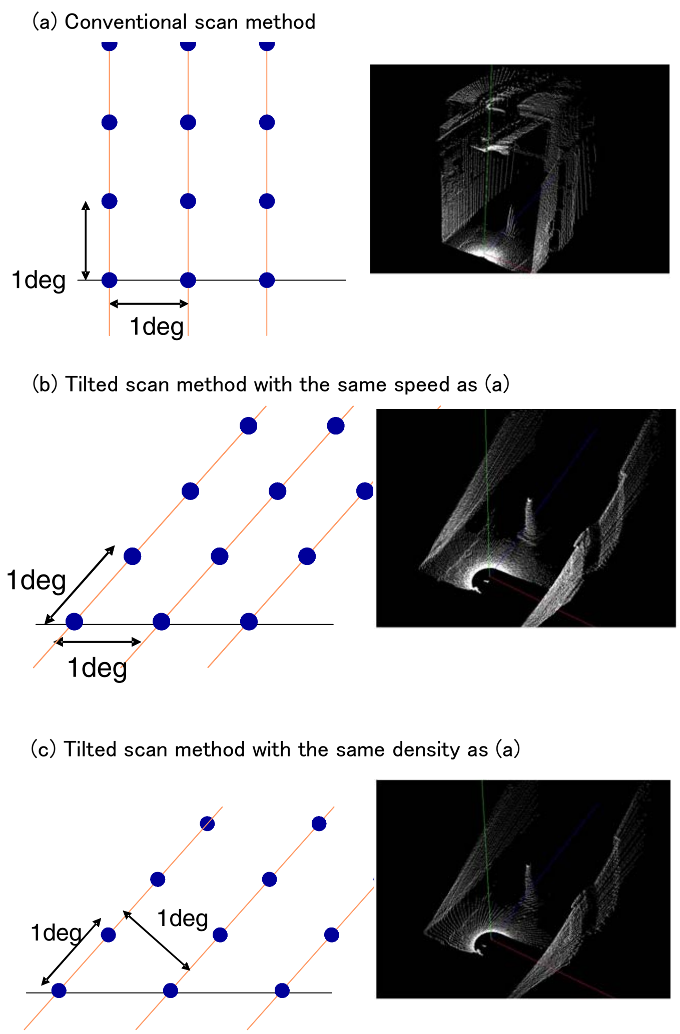

Fig. 7. Comparison of scan-speed and scan-density

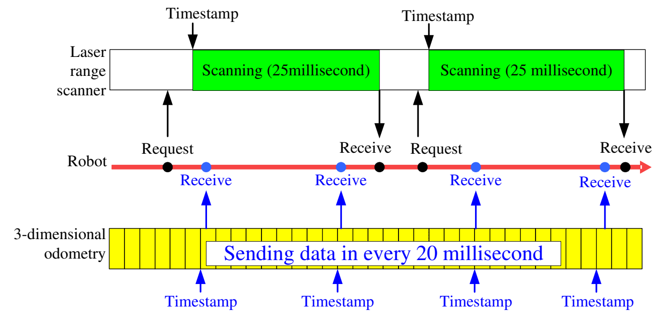

Fig. 8. Synchronization between scanning data and odometry

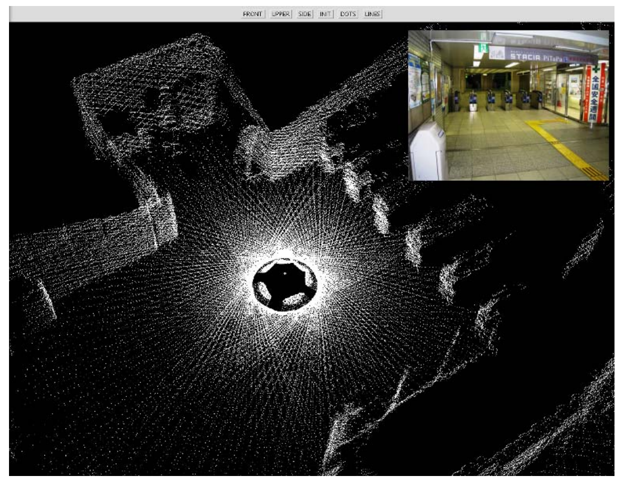

Fig. 9. Scan result with robot's rotational motion

- 8 seconds for the back-and-forth motion of the scanning surface
- 20 centimeters per second for Kenaf's locomotion.

C. Experiments

To confirm the validity of the proposed system, "continuous acquisition of three-dimensional environmental information", we performed continuous scanning experiments in several different environments. In this paper, two of them are presented.

One result is shown in Figure 9. The target environment in the experiment was a space in front of the ticket gates of the metro in San'nomiya, Kobe, Japan. In this place, a robot rotated in the same position by control of both tracks in opposite directions. In the scan result, it was evident that there were several ticket gates, and the result seemed to closely fit with the photograph, which can be seen in the the upper right corner of Figure 9.

If the synchronization between odometry and the laser scanner is incorrect, an angular error affects the modelling error of environments. Therefore, the system seemed to work well on the basis of the experimental results.

Another result is shown in Figure 10. The target environment in the experiment was an artificially bumpy environment, which includes slopes and step fields. An overview of the environment is shown in the photograph at the upper right

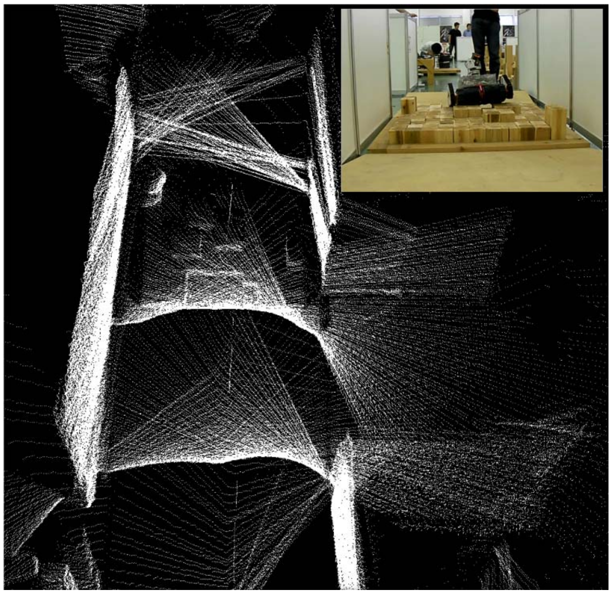

Fig. 10. Scan result with robot's traversing motion on step field

corner of Figure 10. When the robot traversed the bumpy surface, the body roll and tilt angles drastically changed the maximum angle was about 30 degrees, which was selected on a trial basis.) Even under such a condition, the scanning result was acceptable with the aid of accurate three-dimensional gyro-based odometry. However, it is evident that there is a gap in the wall, which is shown at the top center of this figure. Finally, a conventional matching algorithm should be applied in such a case, such as ICP method [11].

IV. CONCLUSIONS

In this paper, we reported our current research involving the remote control of mobile robots for search and rescue missions. We focused on localization and mapping. For localization, we introduced an improved method of three-dimensional odometry for tracked vehicles using a gyroscope and consideration of the characteristics of track slippage. We performed an initial test to confirm its capability in real environments. For mapping, we proposed a continuous acquisition of three-dimensional environmental information using a three-dimensional laser range scanner. Finally, we showed several experimental results that include a continuous acquisition method and three-dimensional gyro-based odometry.

Our objective was to improve the odometry accuracy of tracked vehicles. However, some degree of accumulated error is unavoidable in odometry. Therefore, our next task is to adjust the scanned model and robot position due to a conventional matching algorithm. Furthermore, we would like to confirm the usefulness of the proposed method in hazardous environments. In such situations, our operator's support system with autonomous motion of flippers, which was presented in IROS 2008, should be integrated into our robot system.

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