3-D Mapping of an Underground Mall Using a Tracked Vehicle with Four Sub-tracks

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Abstract —The authors attempted to create a 3-D map of an underground mall and subway station using a tracked vehicle. This paper is a field report of the 3-D mapping of the Sendai subway station by the tracked vehicle in Dec. 2007. From the ticket barriers to the platform, the Sendai subway station consists of three floors. For the 3-D mapping, we developed a tracked vehicle named "Kenaf", a small and light-weight 3-D laser scanner called TK scanner, and a robust 3-D scan matching method. Kenaf can pass through ticket barriers and climb up and down stairs, while TK scanner has a wide view angle and can measure dense 3-D shapes. During the experiment, the robot stopped at different points and collected 3-D scan data. The 3-D shapes were recorded by the TK scanner as point clouds. These 3-D point clouds were integrated into a map on the basis of odometry data on-line. The constructed map was not correct because of the lack of robot position z and the odometry error. The 3-D map was constructed by matching these 3-D point clouds off-line. To increase the robustness of the matching, we used the iterative closest point (ICP) matching method with a gravity constraint.

Keywords: *3-D Mapping, underground mall, tracked vehicle, 3-D laser scanner*

I. Introduction

Studies on rescue robots have progressed rapidly since the Hanshin-Awaji earthquake in Japan and the September 11 attacks in the United States. We have developed a tracked vehicle with sub-tracks named Kenaf. The main tasks for Kenaf are to search for victims and map the structure of disaster areas.

Figure 1 shows Kenaf and its tele-operated control system. Kenaf is controlled by an operator working from a remote location. It has four sub-tracks, and its whole body is covered with a track belt. Kenaf can climb over steps and move across rubble using the tracks [1]. Kenaf is highly mobile compared with other tracked vehicles currently used around the world. Kenaf won the Best-In-Class Mobility at the International RoboCup Rescue Competition in 2007 and 2009. In addition to being highly mobile, Kenaf has other valuable functions, including 3-D mapping capabilities, a 3-D control interface, and a semi-autonomous control system for remote control support. In this paper, we focus on Kenaf's 3-D mapping capabilities. We show the results of measurements taken to construct 3-D map of the Sendai subway station in Japan.

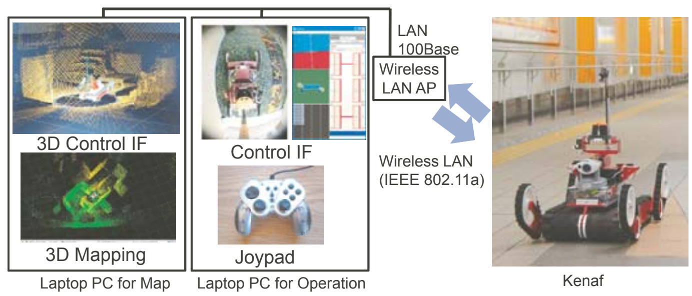

Fig. 1. Kenaf's tele-operation system: This system consists of Kenaf, a laptop PC for control, a laptop PC for mapping and a wireless LAN access point.

Fig. 2. Snapshots of the Sendai subway: 1. Ticket barriers, 2. Stairs, and 3. Platform

Several 3-D map construction methods have been proposed in previous studies [2], [3], [4], [5], [6]. Nagatani and Nuchter et al. [2], [3], [5] used a method based on 3-D scan matching. During their explorations, a robot stops at different points and acquires 3-D scan data. A 3-D map is constructed from these scan data together with odometry data via a scan matching algorithm. This method can be used to construct 3-D maps of buildings, caves, undergrounds, etc. The authors used the same approach to map the Sendai subway station (Sec. II).

Figure 2 shows photographs of the Sendai subway station. There are narrow ticket barriers, stairs, and narrow platform corridors, necessitating a small and highly mobile robot. Kenaf is suitable for exploring such environments as it can pass

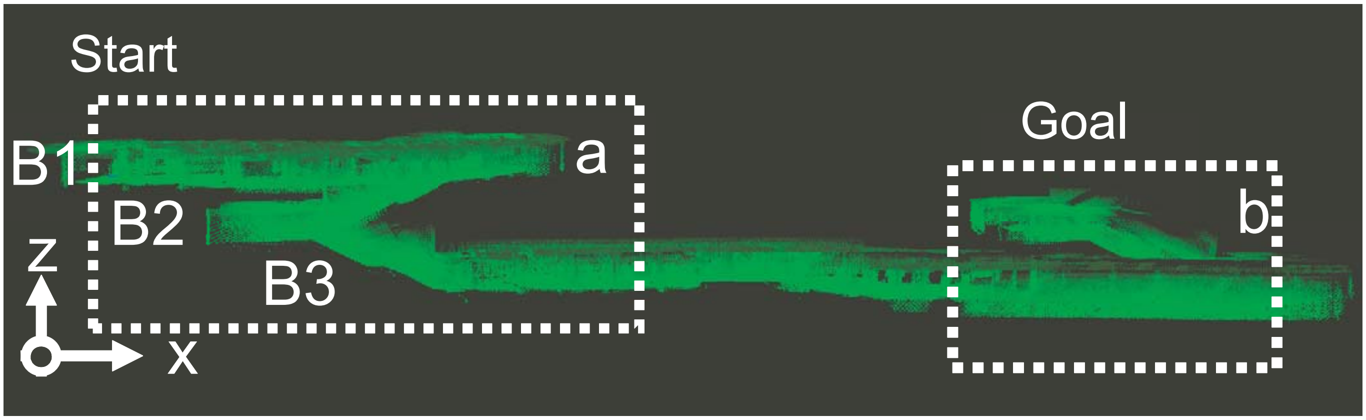

Fig. 3. Result of 3-D SLAM based on 3-D scan matching in the Sendai Subway station: Figure 16 and 17 are the magnified images of areas a and b.

through narrow spaces and climb up and down stairs (Sec. III)

For the 3-D map construction by 3-D scan matching, the scanner requires a wide view angle, and must record the correct 3-D shape in a uniform point density. Therefore, the authors developed a new, small 3-D laser scanner called a TK scanner. In previous research [2], [3], [4], [5], [6], 3-D shapes were ensured by rotating a 2-D laser range finder on the pitch axis. However, this scanning method does not measure a 3-D shape in uniform density and took more than 30s to complete a measurement. The TK scanner can record more uniform 3-D shapes and the measurements do not take as long to complete (Sec. IV).

Thanks to Kenaf and the TK scanner, the authors could record 3-D point cloud data in the Sendai subway station. Correct 3-D maps of Sendai subway station could be constructed using the 3-D scan matching method (Sec. V). Figure 3 shows a constructed 3-D map of the Sendai subway station. The three floors of the structure can be seen in the figure.

This paper is a field report of 3-D mapping experiment performed using a tracked vehicle. The contribution of this paper is description of the details of our experimental setup and our approach to 3-D mapping.

II. Outline of 3-D map construction process using the tele-operated tracked vehicle Kenaf

An operator working from a remote location controls Kenaf using on-board cameras and a 3-D control interface (Fig. 1) to search through rubble. The 3-D control interface shows a model robot in the 3-D map M according to robot movement $P_{r\ t}$ and flipper angles θ_{flipper} (Fig. 1).

Figure 4 illustrates the data flow for 3-D map construction by scan matching. During the search, the operator decides the location to be scanned, and commands Kenaf to stop there and scan the 3-D shapes using the TK scanner (C_{scan} in Fig. 4). The 3-D map M is constructed by connecting the 3-D shapes S_t on the basis of odometry data $P_{r\ t}$. However, $P_{r\ t}$ lacks z information and has a cumulative error. The error is canceled by matching two measured 3-D shapes S_t and S_{t-1}. We used

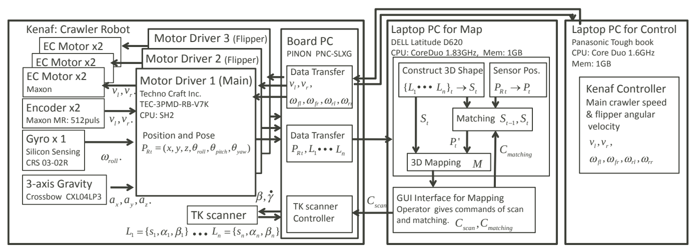

Fig. 4. Data flow for Kenaf's tele-operation and 3-D map construction

the iterative closest point (ICP) algorithm. To achieve robust matching, we added a gravity constraint to the ICP algorithm. In the Sendai subway station experiment, the matching process was executed off-line.

III. Kenaf and its odometry

A. Kenaf

Figure 5 illustrates Kenaf's plan, and Table I shows Kenaf's specifications. Kenaf is a small, light-weight rescue robot used for searching underground. This robot was developed under the NEDO Project for Strategic Development of Advanced Robotics Elemental Technologies, High-Speed Search Robot System in Confined Space. To keep Kenaf small, miniature brush-less DC motors are used. To support the rescue activity, Kenaf can operate on battery power for at least 2 h.

Kenaf has two separate tracks that cover the whole body and four sub-tracks. Each track can move independently. Kenaf can climb over steps as high as 0.3 m and can move robustly, using the tracks to traverse rubble. Because the battery and motor are located lower than Kenaf's center of body, Kenaf does not fall over even if the pitch or roll angle reaches $60°$. However, this depends on the weight of equipment (sensors etc.). Please see [1] for the details of Kenaf's hardware.

B. Odometry of Kenaf

The robot's position and pose $P_{r\ t}$ are represented by $(x, y, z, \theta_{\text{roll}}, \theta_{\text{pitch}}, \theta_{\text{yaw}})$. $P_{r\ t}$ without z is estimated using encoder data from the main track's motors velocities v_r, v_l, angular velocity data from a gyro w_{roll}, and acceleration data from 3-axis gravity sensor $\alpha_{\text{roll}}, \alpha_{\text{pitch}}, \alpha_{\text{yaw}}$.

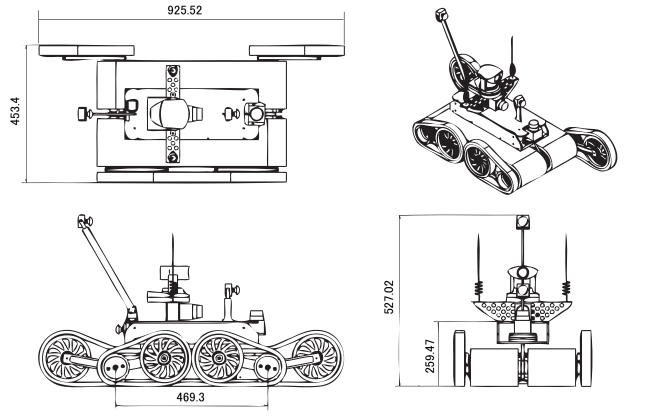

Fig. 5. Kenaf design: whole body tracked vehicle with four tracks. (Units are given in millimeters.)

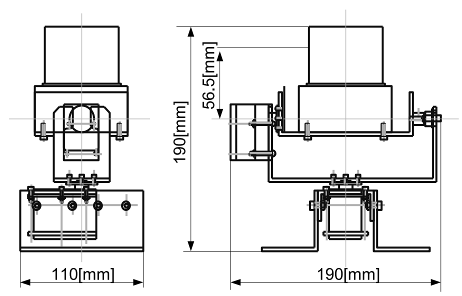

Fig. 6. Size of the TK scanner (3-D laser scanner)

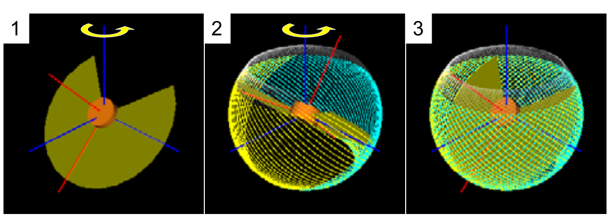

Fig. 7. Trajectory of the laser point during one 3-D scan

$x, y, \theta_{\text{yaw}}$ are estimated by the following equations:

$$\begin{aligned} x &= \int v\cos(\theta)dt + x_0 \\ y &= \int v\sin(\theta)dt + y_0 \qquad (1) \\ \theta &= \int \omega dt + \theta_0 \end{aligned}$$

v and w are estimated from v_r, v_l, and w_{roll}. It is characteristic of the position estimation method to take into account the slip ratio of the main track [8]. $\theta_{\text{roll}}, \theta_{\text{pitch}}$ are calculated from $\alpha_{\text{roll}}, \alpha_{\text{pitch}}, \alpha_{\text{yaw}}$.

TABLE I

SPECIFICATION OF KENAF

Robot size and weight	Length (with flipper)	937(mm)
	Width	429(mm)
	Height	683(mm)
	Weight	22.4 (kg)
	Material	Aluminum alloy
Mobility	Maximum speed	0.4(m/s)
	Maximum step	30(cm)
	Maximum inclination	60°
Main body Track	Length	575(mm)
	Width	148(mm)
	Tread	324(mm)
	Motor	MAXON EC-powermax 22(90W 36V)
	Material	Rubber, Aluminum alloy
Flipper Track	Length	293(mm)
	Width	28(mm)
	Tread	379(mm)
	Motor	MAXON EC 22 (50W 32V)
	Material	Rubber, Aluminum alloy
Sensor	3-axis gravity sensor	Crossbow CXL04LP3
	Gyro	Silicon Sensing Systems CRS 03-02R x1
	Encoder for flipper	MAXON MR Encoder x4
	Range sensor	SHARP GP2D12 x6
Battery	Battery for motors	IDX Power Cube x2 14.8(V) 5700(mAh)
	Battery for control	IDX Power Cube x1 14.8(V) 5700(mAh)
etc.	Motor driver	Technocraft x3 TEC-3PMD-RB-V7K

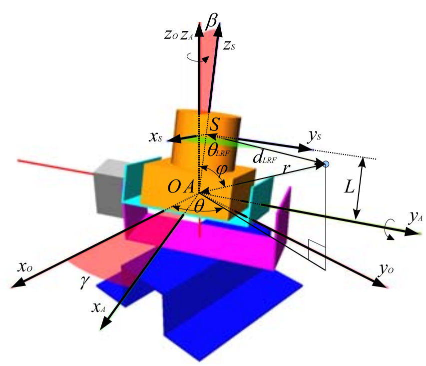

Fig. 8. The TK scanner coordinate system

IV. TK SCANNER

A. Principle of 3-D measurement

The TK scanner is a light-weight 3-D laser scanner with a wide-angle view. A 3-D object can be scanned by rotating a 2D laser range finder (HOKUYO URG-08LX) about two different axes. Figures 6 and 7 illustrate the TK scanner plan and laser point trajectory, respectively, during one 3-D measurement. Table II shows the specifications. Please see [9] for the TK scanner details.

Figure. 8 shows the sensor coordinates and the symbols. O is the base coordinate of the 3-D scanner. A is the coordinate rotated γ upon z axis of O. S is the coordinate tilted β around the y axis of A and translated L along z. S is the sensor

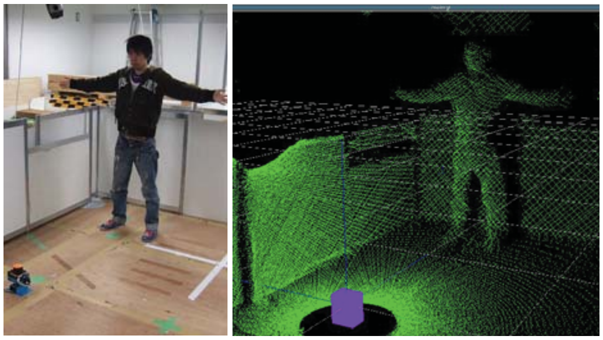

Fig. 9. 3-D scan data measured by the TK scanner ($\beta = -45^{\circ}, t_m = 14.5\mathrm{s}$)

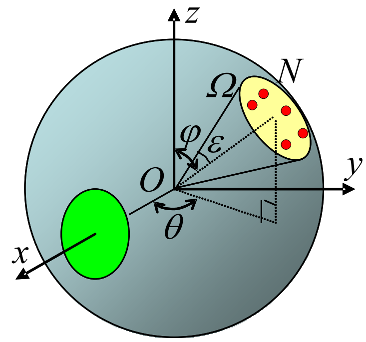

Fig. 10. Definition of measurement density

TABLE II

SPECIFICATION OF TK SCANNER

Range (m)	max 8
Area (degree)	360(H) max 130 (V)
Weight (kg)	0.9
Size (m)	0.19 (W) x 0.11 (D) x 0.19 (H)
Scan Time (s)	Between 5 and 20
Density	Max 20000 (points number /steradian) at β=45

coordinate of URG. θ_{LRF} and d_{LRF} are the direction and the distance of a laser point on S respectively. The position of the laser point on O is presented in Eq. (2).

$$\begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix} = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix} D \quad (2)$$

$$D = \begin{pmatrix} d_{\mathrm{LRF}} \cos\theta_{\mathrm{LRF}} \\ d_{\mathrm{LRF}} \sin\theta_{\mathrm{LRF}} \\ L \end{pmatrix}$$

The polar coordinates of a laser point on O are (r, θ, φ). β and $\dot{\gamma}$ are fixed at constant values during one 3-D scan.

$$\beta = \text{const}, \quad (3)$$

$$\dot{\gamma} = \text{const}. \quad (4)$$

The number of 2D scans m necessary to complete one 3-D scan is presented in Eq. (5).

$$m = \frac{t_m}{T_{\mathrm{LRF}}} = \frac{2\pi}{\dot{\gamma} T_{\mathrm{LRF}}} \quad (5)$$

t_m is the time of one 3-D scan.

The density, area, and time of a 3-D scan can be adjusted by changing the angle β and the angular velocity $\dot{\gamma}$. The details of this adjustment method are explained in [9]. In the Sendai subway station, we used $\beta = -45^{\circ}$, $\dot{\gamma} = 24.8^{\circ}/s (m = 220)$. The 3-D shape can be measured in 14.5 s. Figure 9 illustrates a measurement result.

B. More uniform 3-D measurement

In previous research [2], [3], [4], [5], [6], a 3-D shape was scanned by rotating a 2-D laser range finder on the pitch axis. However, this scanner cannot capture uniform 3-D shapes. Comparing the density of previous scanners with the TK scanner, we can confirm that the TK scanner can perform a more uniform measurement of a 3-D shape.

Density is defined as the number of points contained by a solid angle area on a sphere (Fig. 10). Measurement points during one 3-D scan are projected on a sphere whose center is at the 3-D scanner coordinate O. The density $\eta(\theta, \varphi)$ is presented in Eq. (6).

$$\eta(\theta, \varphi) = \frac{N(\theta, \varphi)}{r^2 \Omega} = \frac{N(\theta, \varphi)}{2\pi r^2 (1 - \cos\epsilon)} \quad (6)$$

$N(\theta, \varphi)$ is the number of measurement points inside a solid angle Ω [sr] at direction (θ, φ), whose angle is ϵ. $\epsilon = 3^{\circ}$ is used in this paper.

Figures 11 and 12 illustrate the density achieved by a previous scanner and the TK scanner respectively. There are two peaks in the graph of the previous scanner. Average density is 2000 m^{-2}, except for these two peaks. The density of the TK scanner is more uniform than that of the previously used scanner. The peak is not more than 20000 m^{-2}. Average density in the area $\phi = 60 \sim 120^{\circ}$ is about 6000 m^{-2}. We confirmed that the TK scanner captures a more uniform 3-D shape than the previous scanner.

V. ICP MATCHING WITH CONSTRAINT OF GRAVITY

We used an ICP matching algorithm with a gravity constraint. Using the constraint, 3-D scan data can be matched even when position z is absent (Fig. 3).

A normal ICP algorithm estimates 6 degrees of freedom (DOF) $(x, y, z, \theta_{roll}, \theta_{pitch}, \theta_{yaw})$ from two 3-D point clouds $\mathbf{S}_t, \mathbf{S}_{t-1}$. However, 3-D ICP matching often failed when the motion between $\mathbf{S}_t$ and $\mathbf{S}_{t-1}$ was large. The lack of z information causes large difference. Without the constraint, the matching often failed. Figure 13 shows the matching result without the gravity constraint. The structure of the three floors cannot be confirmed, and each floor was not flat in shape. Using θ_{roll} and θ_{pitch} angles measured by the gravity sensor, this matching algorithm estimates four DOF (x, y, z, θ_{roll}) instead of six DOF $(x, y, z, \theta_{roll}, \theta_{pitch}, \theta_{yaw})$ from two 3-D point clouds $\mathbf{S}_t$and $\mathbf{S}_{t-1}$. Using this constraint allows us to decrease matching failures because of local minima.

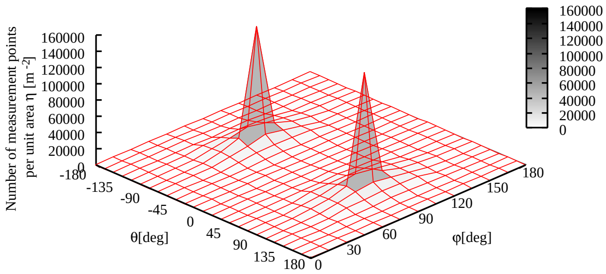

Fig. 11. Measurement density of a 3-D scanner that rotates a 2D LRF on the horizontal axis.

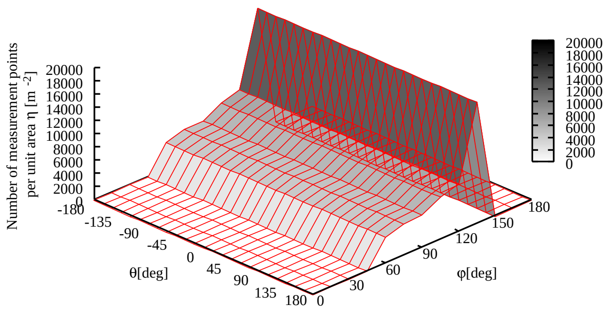

Fig. 12. Measurement density of the TK scanner ($r = 1, \beta = 45°, m = 72$).

The objective of the ICP algorithm is to find the motion $M_t = \{R_t, t_t\}$ between two 3-D shapes $\mathbf{S}_{t-1}$ and $\mathbf{S}_t$ measured by the TK scanner at different viewpoints (see [10], [11] for the details of ICP algorithm). The ICP algorithm derives the robot motion $\mathbf{R}, \mathbf{t}$ and the pair of $\mathbf{x}, \mathbf{y}$ by minimizing $\mathcal{F}$. A pair of closest points in these two shapes $\mathbf{S}_{t-1}$ and $\mathbf{S}_t$, is denoted as $\{\mathbf{x}_i, \mathbf{y}_i\}$, where $\mathbf{x}_i$ is an input data point in $\mathbf{S}_t$, and $\mathbf{y}_i$ is a reference data point in $\mathbf{S}_{t-1}$. The motion is derived by minimizing the following mean-squares objective function $\mathcal{F}$ Shown in Eq. (7).

$$\mathcal{F}(\mathbf{R}, \mathbf{t}) = \frac{1}{N} \sum_{i=1}^{N} \|\mathbf{R}\mathbf{x}_{i_t} + \mathbf{t} - \mathbf{y}_{j_{t-1}}\|^2 \quad (7)$$

where N is the number of pairs (much greater than 3).

$\mathcal{F}$ is minimized by repeating the five following steps:

- **Step 1:** Find the matched point pair between the input scan data $\mathbf{S}_t$ and reference scan data $\mathbf{S}_{t-1}$.
- **Step 2:** Eliminate the mismatched pair.
- **Step 3:** Estimate the motion $\mathbf{R}, \mathbf{t}$.
- **Step 4:** Construct a new rotation matrix $\mathbf{R}'$ from θ_{yaw} calculated from $\mathbf{R}$.
- **Step 5:** Apply the estimated motion $\mathbf{R}', \mathbf{t}$.to $\mathbf{S}_t$.

Step 4 was added to the ICP algorithm as the gravity constraint. These steps are repeated until the estimated motion converges, or the number of iterations exceeds the threshold.

VI. 3-D MAPPING IN THE SENDAI SUBWAY STATION

The mapping experiment in the Sendai subway station was conducted after 23:00 in Dec. 15, 2007. Two kinds of data were collected during the experiment. Due to security reasons

Fig. 13. Matching Result using normal ICP (Without Constraints of Gravity)

the drawings of the experimental environments cannot be shown in this paper.

The first drawing is a map of the underground mall whose perimeter is about 100 m. Figure 14 shows the flat plan and the collected scan data. The ground of the underground mall was flat with poles in the middle of the corridor. During the experiment, control PCs and a wireless LAN access point were set up around the start point. A total of 86 points of scan data were measured by the TK scanner, which took about 45 min.

The middle map in Fig. 14 shows the 3-D map constructed only from the odometry data. The shape was distorted because of the odometry error. The bottom map was corrected by the off-line matching. The distance between the start point and the goal point was about 700 mm. The use of a loop closing technique will decrease the error.

The second drawing is a map of the Sendai subway station. Figures 15 and 3 show the plan and the constructed 3-D map. During the experiment, the control PCs and the wireless LAN access point were carried by the operators because the network could not reach the lower floor. The operator controlled Kenaf using the camera images. The distance was about 120 m. A total of 56 points of scan data were collected, which took about 45 min. Figure 16 and 17 show the magnified view of areas a and b in Fig. 3. The details of the structure can be constructed using our method.

The authors confirmed that 3-D mapping can be achieved using our method. However, there is still room for improvement. To evaluate the accuracy of the 3-D mapping, the true 3-D data or data on the position of the robot is needed. Using a total station, we have to measure the robot position during navigation. Both experiments took over 30 min, suggesting that we have to decrease the time required for 3-D shape measurement. Moreover, we have to develop a method of wireless communication that covers wide areas and is easy to set up.

VII. CONCLUSION

The goal of our research is to develop a 3-D mapping method for a tele-operated tracked vehicle. We successfully created Kenaf and the TK scanner, which together offer robust search and mapping capabilities, which we demonstrated in the Sendai subway station.

In this paper, we explained our experimental setup for the 3-D mapping in the Sendai subway station and the collected 3-D map data. From the constructed maps, we confirmed that our

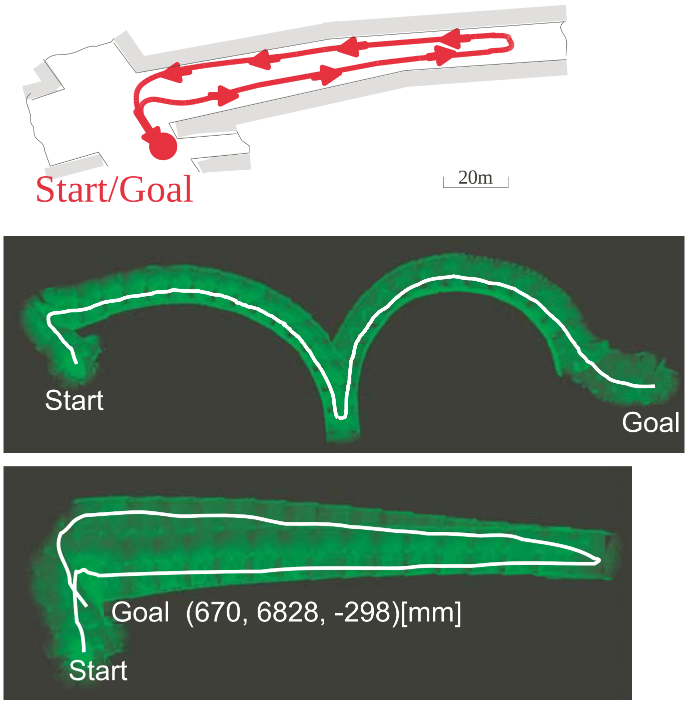

Fig. 14. Mapping in the Sendai underground mall: Flat plan (Upper), 3-D map constructed from odometry and 3-D scan data (Middle), and 3-D map corrected by the matching method (Bottom)

proposed method can be used for 3-D mapping in underground mall and subway environments.

VIII. Acknowledgments

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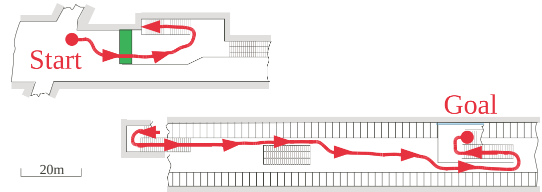

Fig. 15. Plan of the Sendai subway station

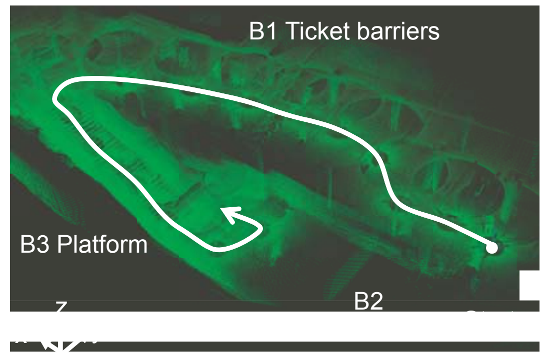

Fig. 16. Constructed 3-D Map of the Sendai Subway: Steps near the start point (area a in Fig. 3)

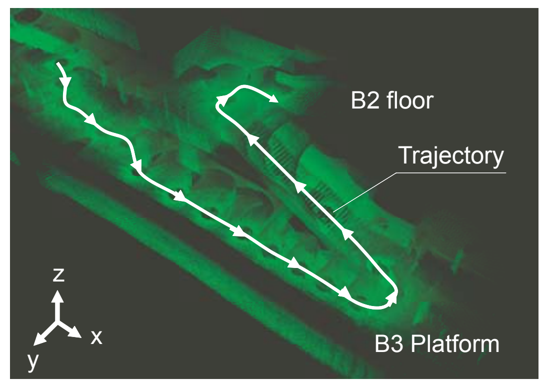

Fig. 17. Constructed 3-D Map of the Sendai Subway: Steps near the end point (area b in Fig. 3)

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