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Trials of 3-D Map Construction Using the Tele-operated Tracked Vehicle Kenaf at Disaster City

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Abstract— **This paper provides valuable information about 3-D map construction using a tracked vehicle at Disaster City. Disaster City is a training facility for the Federal Emergency Management Agency (FEMA) in the United States. FEMA staff used our rescue robot Kenaf to conduct simulated emergency testing. Kenaf is a tele-operated tracked vehicle that has high mobility suitable for use in outside terrains and inside buildings. We equipped Kenaf with a 3-D laser scanner that can measure dense and wide angle 3-D shapes. We collected about 50 3-D mapping data sets during the tests. A part of these data sets can be accessed at our website. In this paper, we explain the Kenaf's tele-operation system, the 3-D mapping system, and the comments about the usability of the 3-D mapping from FEMA staff. In addition, we discuss about the limit of our mapping method on the basis of the trials at Disaster City. This information will be helpful for researchers in the robotics to improve their method of 3-D map construction and their tracked vehicles.**

I. INTRODUCTION

Studies of rescue robots have progressed rapidly since the Hanshin-Awaji earthquake in Japan and the 9.11 attacks in the United States. The main tasks for rescue robots are to search for victims and map construction in disaster areas. For improvement of map construction by rescue robots, it is necessary to reveal the problem of present map construction method in the real environment. In particular, disaster environment is quite different from general experimental environments. The problem of map construction that will be caused by disaster environment is still unclear. This problem is important for researchers in the wide range of robotics because the solutions of this problem will bring new studies about map construction. This paper reports the problem of 3-D map construction caused by the environment that imitates real disaster areas.

We show the results of measurements taken for a 3-D map construction in Disaster City, which is a training facility for the Federal Emergency Management Agency (FEMA) in the United States (Fig. 1). In November 2008, we carried rescue robots "Kenaf" to Disaster City and demonstrated the robot's search and 3-D map construction capabilities at the training facility [1].

We have developed Kenaf rescue tracked vehicles with sub-tracks. Figure 2 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 track belts. Kenaf can climb over steps and move on rubbles using the sub-tracks and the main tracks [2]. Kenaf robots have high mobility on rubbles. Kenaf won the Best-In-Class Mobility at the International RoboCup Rescue Competition in 2007 and 2009. In addition to the high mobility, Kenaf has other useful functions, including 3-D mapping capabilities, a 3-D control interface, and a semi-autonomous control system for remote control support.

This paper describes the results of the demonstration that provides 3-D map data from actual FEMA training drills at Disaster City. This paper also describes the comments of FEMA staff about 3-D laser scanner, odometry, and 3-D mapping. These comments clarify advantages and problems of 3-D map construction by high mobility tracked vehicles and 3-D laser scanners in the disaster areas. Information about the 3-D map data from Disaster City can be accessed at [3]. The collected log data provide a significant amount valuable information. By using the log data, user can evaluate their methods of 3-D mapping and map information display.

This paper is organized as follows. Related works are described in Sec. II. 3-D map construction method using Kenaf is explained in Sec. III, and 3-D mapping at Disaster City is explained in Sec. IV. We discuss the advantages and problems of our mapping method in Sec. V, and conclude this paper in Sec. VI.

II. RELATED WORKS

Our goal was to create 3-D map constructions using tele-operated tracked vehicles in disaster environments. Simultaneous Localization And Mapping (SLAM)) is a hot research topic in the robotics [5], [6], [7], [8], [9], [10]. 3-D map construction in unknown environment is studied in SLAM. In SLAM, the robot position and posture are estimated from internal sensor data (odometry, gyro, etc). Error of the estimated position is corrected from external sensor data (2-D or 3-D laser scanner, ultra sonic sensor etc). The cumulative error can be decreased by solving a loop constraint. The Bayesian model is well used for the estimation and collection. In our research, the robot position and posture are estimated from odometry and gyro sensor. The error was corrected by matching 3-D point clouds. In this paper, we clarify the usability of 3-D scan data and the matching method.

Experiments of 3-D map construction in rough terrain have been conducted in Collapsed House Simulated Facility in Japan [11], RoboCupRescue2004 in Lisbon [12], DARPA Grand Challenge [13] and mine mapping [14]. In [12],

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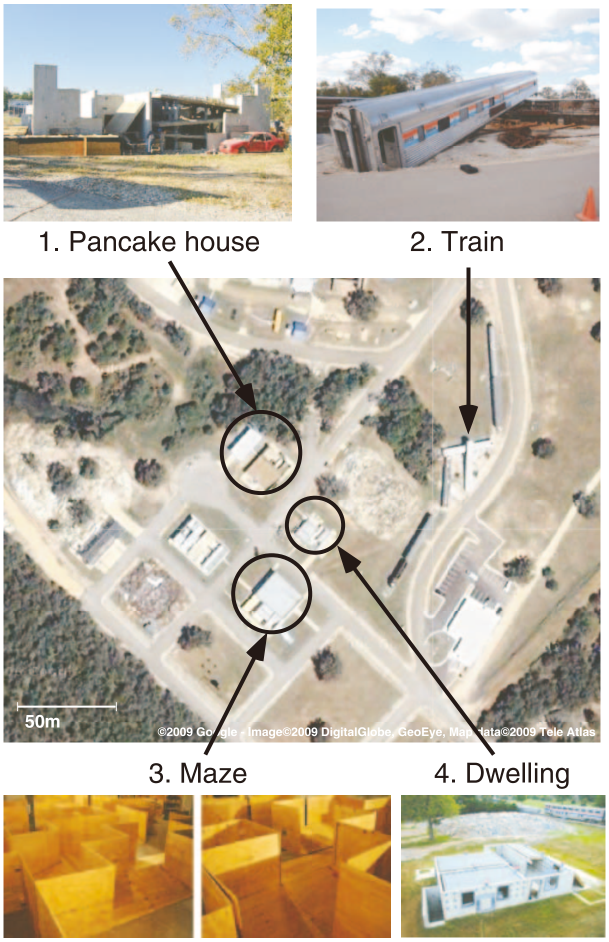


Fig. 1. Google map of Disaster City: We constructed a 3-D map using Kenaf in these four test fields (1) pancake house, (2) train, (3) maze and pipe field, and (4) dwelling.

[13], [14], the robot's position and posture were estimated using odometry or gyrodometry in the wheel-type robots. The position and posture of the wheel-type robots could be estimated well, but their mobility in rubble environments were low compared with that of the tracked vehicles. In our research, tracked vehicle was used, which has four sub-tracks. The tracked vehicles have slip at turn motion, and contact points between the tracks and the ground often change. So, we need a robust position estimation method for the tracked vehicle. The position and posture were estimated by gyro-based odometry [15]. In this paper, we also address both the usability and the limit of the gyro-based odometry.

III. ON-LINE 3-D MAP CONSTRUCTION USING THE TELE-OPERATED TRACKED VEHICLE KENAF

A. *Overview*

An operator working from a remote location controls Kenaf to search a simulated rubble environment using on-board camera images and a 3-D control interface (Fig. 2). The 3-D control interface shows a robot model in the 3-D map M according to robot movement $P_{r\ t}$ and sub-track angles $\theta_{\mathrm{sub-track}}$ (Fig. 3).

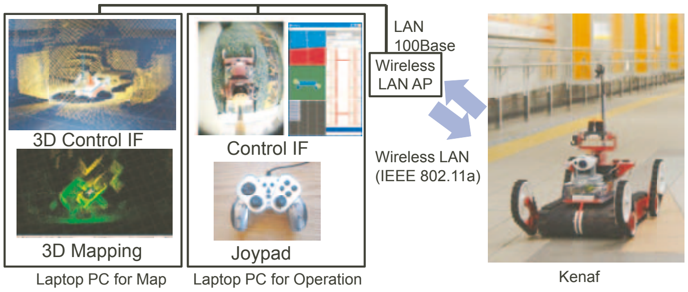


Fig. 2. Tele-operation system of Kenaf: This system consists of Kenaf, a laptop PC for control, a laptop PC for mapping and a wireless LAN access point.

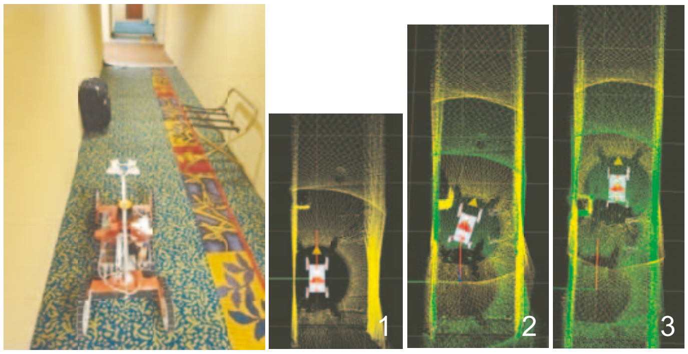


Fig. 3. 3-D map construction based on scan matching in a corridor environment. A 3-D map was constructed by matching scan data in order of numerical number. The mapping GUI was used as 3-D control interface.

Figures 3 and 4 illustrate 3-D map construction based on scan matching and data flow, respectively. In Fig. 3, Kenaf constructed a 3-D map based on scan matching in a corridor environment. During the search, the operator judges the places to measure 3-D shapes, and commands Kenaf to stop and measure 3-D shapes using the TK scanner (C_{scan} in Fig. 4). The 3-D map M is constructed by connecting 3-D shapes S_t based on odometry data $P_{r\ t}$. However, $P_{r\ t}$ has a cumulative error. The cumulative error is canceled by matching two measured 3-D shapes S_t and S_{t-1}. The operator gave commands to match 3-D shapes C_{matching} when the cumulative error increased. We used the iterative closest point (ICP) algorithm. To realize robust matching, we added the constraint of gravity to the ICP algorithm.

The matching process sometime fails to find a correct answer at 3-D mapping and falls into local minimum in monotonous environment (e.g tunnels, corridor). If the program cannot match 3-D shapes, the operator can switch it from autonomous 3-D matching to manual 3-D matching. Usually, S_t data have to be matched with all scan data $\{S_1, S_2 \cdots \cdot S_{t-1}\}$ for more accurate 3-D map construction. However, the program takes a long time to find the correct answer. In addition, the laptop PC (DELL Latitude D620) does not have high computational capability. To shorten the time required to complete the 3-D matching, only S_{t-1} is used for S_t matching.

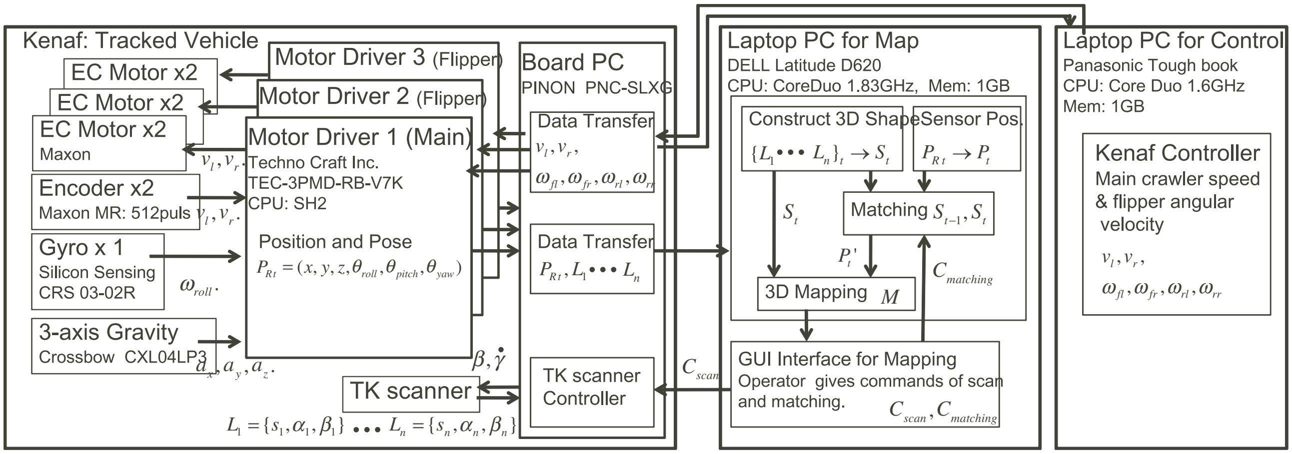


Fig. 4. Data flow for tele-operation and 3-D map construction of Kenaf

B. Kenaf

We summarize Kenaf's hardware. Please see [2] for the details of Kenaf's hardware.

Figure 5 illustrates the plan of Kenaf, 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. Small brush-less DC motors are used to reduce Kenaf's size. To support the rescue activity, Kenaf can operate on battery power for at least 2 hours.

Kenaf has two separate track belts over the whole body and four sub-tracks. Each track and each sub-track can move independently. Kenaf can climb over steps as high as 0.3m using these sub-tracks, and can move robustly using the crawler in rubble environments. 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 becomes $60°$.

An on-board PiNON PC (PiNON Corporation, Tokyo, Japan) and three brush-less DC motor drivers are installed inside Kenaf. The remote control system, semi-autonomous control system and network communication between laptop PCs and Kenaf run on the PiNON, which connects to motor drivers by controller area network (CAN) communication. A laptop PC for remote operation connects to Kenaf via a wireless local area network (LAN).

C. Odometry of Kenaf

We summarize Kenaf's odometry. Please see [15] for the details of odometry.

The robot position and pose $P_{r\ t}$ are represented by $(x, y, z, \theta_{\text{roll}}, \theta_{\text{pitch}}, \theta_{\text{yaw}})$. $P_{r\ t}$ is estimated using encoder data from the main track's motors v_r, v_l, angular velocity data from a gyro $w_{\text{roll}}, w_{\text{pitch}}, w_{\text{yaw}}$, and acceleration data from 3-axis gravity sensor $\alpha_{\text{roll}}, \alpha_{\text{pitch}}, \alpha_{\text{yaw}}$. Characteristic of the position estimation method is to take into account with the slip ratio of the main track.

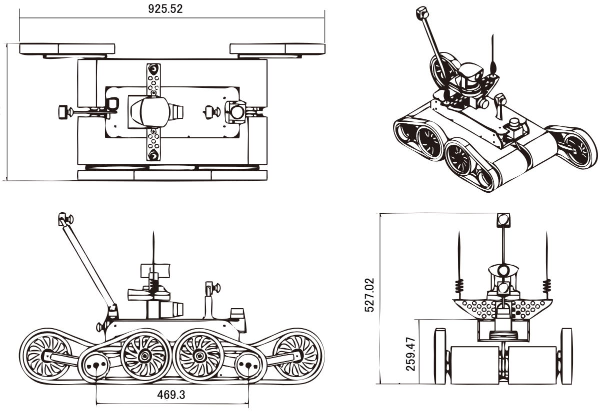


Fig. 5. Kenaf design: Kenaf is a whole body tracked vehicle with four sub-tracks. (Units are given in millimeters.)

P is calculated from integration of differential movements by quaternion. In addition, when the robot stops, the gyro's error caused by drift is canceled using data from the gravity sensor. Nagatani et al. reported that the average position error was about 0.7 m after a 23 m round trip that included stairs. Because the position error was biased to z-axis, they considered that the position error was caused by the track's slip. In Disaster City, we constructed a 3-D map using the method of position estimation developed by Nagatani et al.

D. TK Scanner

The TK scanner is a light-weight 3-D laser scanner with a wide-angle view. The 3-D shape can be measured by rotating the 2-D laser scanner on 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 specification.

The TK scanner consists of a 2-D laser scanner (HOKUYO URG-08LX) and two servo motors (Dynamixel DX-117, RX-64). HOKUYO URG-08LX is a light weight

TABLE I

SPECIFICATION OF KENAF

Robot size and weight	Length (with sub-track)	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 track	Length	575(mm)
	Width	148(mm)
	Tread	324(mm)
	Motor	MAXON EC-powermax 22(90W 36V)
	Material	Rubber, Aluminum alloy
Sub-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 x3
	Encoder for sub-track	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

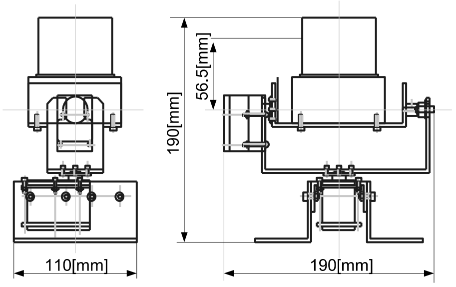


Fig. 6. Size of TK scanner (3-D laser scanner)

(0.33 kg) and small (size 88 × 83 × 83 mm) 2-D laser scanner. URG-08LX can measure 8 m at each 0.36°. The view angle is 270°. The 2-D scan time T_{URG} is 0.068s. The Dynamixel servo-motor is small and powerful. The torque of the DX-117 is 37 kgf.cm. The torque of RS-64 is 64 kgf.cm. Table. II shows the specifications of the 3-D scanner. The 3-D shape can be measured in 14.5 s. Figure 8 illustrates a measurement result.

E. ICP Matching With Constraint of Gravity

We used an ICP matching algorithm with constraint of gravity. 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 $\mathbf{S}_t, \mathbf{S}_{t-1}$ was large. We used the constraint of gravity to reduce the matching failure. Using $\theta_{pitch}, \theta_{yaw})$ angles measured by gravity sensor, this matching algorithm can estimate 4 DOF (x, y, z, θ_{roll}) instead of 6 DOF $(x, y, z, \theta_{roll}, \theta_{pitch}, \theta_{yaw})$ from two 3-D point clouds $\mathbf{S}_t, \mathbf{S}_{t-1}$. Using this constraint allows us to decrease matching failures because of local minimum. We explain the ICP algorithm and the constraint of gravity in the following paragraphs.

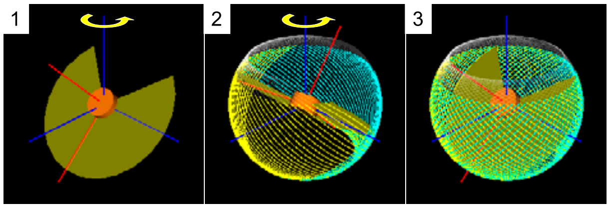


Fig. 7. Trajectory of laser point during one 3-D scan

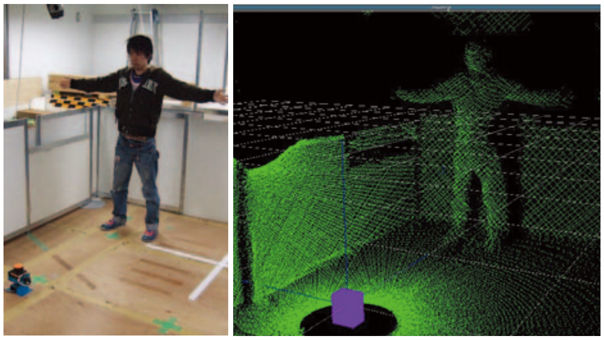


Fig. 8. 3-D scan data measured by TK scanner ($\beta = -45°, t_m = 14.5$s)

The objective of the ICP algorithm is to find the motion $M_t = \{R_t, t_t\}$ between two 3-D shapes $\mathbf{S}_{t-1}, \mathbf{S}_t$ measured by the TK scanner at different viewpoints (see [17], [18] for the details of ICP algorithm).

The ICP algorithm is a technique that derives the robot motion $\mathbf{R}, \mathbf{t}$ and the pair of $\mathbf{x}, \mathbf{y}$ by minimizing $\mathcal{F}$. A pair of closest point in these two shape $\mathbf{S}_{t-1}, \mathbf{S}_t$ is denoted as $\{\mathbf{x}_i, \mathbf{y}_i\}$. $\mathbf{x}_i$ is a point of the input data $\mathbf{S}_t$. $\mathbf{y}_i$ is a point of the reference data $\mathbf{S}_{t-1}$. The motion is derived by minimizing the following mean-squares objective function $\mathcal{F}$ Shown in Eq. (1).

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

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

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

$\mathcal{F}$ is minimized by repeating five steps as follows:

- **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 $\mathbf{S}_t$.

We added step 4 into the ICP algorithm for the gravity constraint. These steps are repeated until the estimated motion converges or the number of iteration exceeds the threshold.

IV. 3-D MAPPING IN DISASTER CITY

From November 18 to 21, 2008, we demonstrated the search capabilities and 3-D map construction function of Kenaf in Disaster City (Fig. 1). The corridor in the test field of Disaster City was narrow (about 1 m wide), and the lighting condition were not suitable for a search using camera images. In this situation, a 3-D control interface was useful for the spatial recognition. By using the 3-D control interface, operators can control the Kenaf from a remote location and can reduce collisions with the surrounding environment. The 3-D control interface was useful when the Kenaf had to climb over steps.

We collected log data for 3-D maps in the following areas: 1) pancake house, 2) train, 3) maze and pipe field, and 4) dwelling. We obtained about 50 log data sets that included more than three sets of scan data. Because it is too difficult to explain all the log data, in this paper, we will explain only a part of these log data collected at the pancake house and train.

A. Mapping in pancake house

Figure 9 shows the outside (right) and inside (left) of the pancake house. The arrow on the left side of Fig. 9 indicates the path of Kenaf during the 3-D mapping experiment. Kenaf started inside the house, went into a dark tunnel, and then left the tunnel. Kenaf measured 3-D shapes and constructed 3-D maps at about 2 m intervals (minimum distance: about 1 m).

Figure 10 illustrates Kenaf's trajectory. The solid line is the trajectory estimated using odometry data, and asterisks on the solid line are the points where Kenaf measured 3-D shapes. Open circles indicate the points where 3-D matching was performed automatically or manually. The odometry log data lacked near points 13 and 14 in Fig. 10 because they were collected via UDP communication. The broken line is the line connecting the corrected Kenaf's positions by 3-D matching. In Fig. 10, Kenaf measured 3-D shapes 16 times, and performed 3-D scan matching 9 times during the trip of about 22.5 m. The left figure in Fig. 11 shows a 3-D map based on odometry, and the right figure in Fig. 11 shows a 3-D map based on odometry and 3-D scan matching.

Fig. 9. Snapshots of the pancake house: Left photo was taken outside the building, Right photo was taken inside the building.

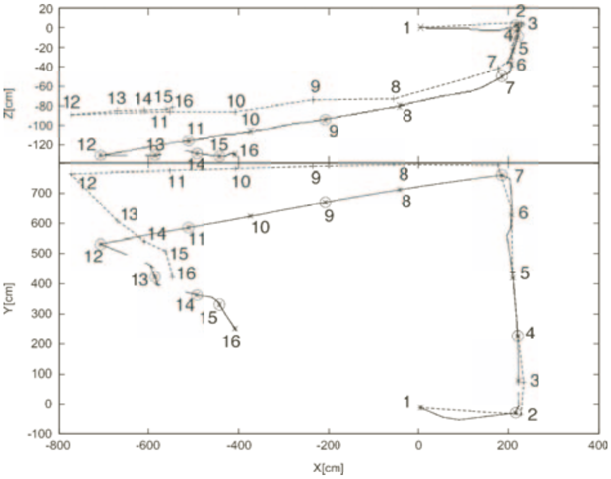


Fig. 10. Trajectory of Kenaf in pancake house mapping.

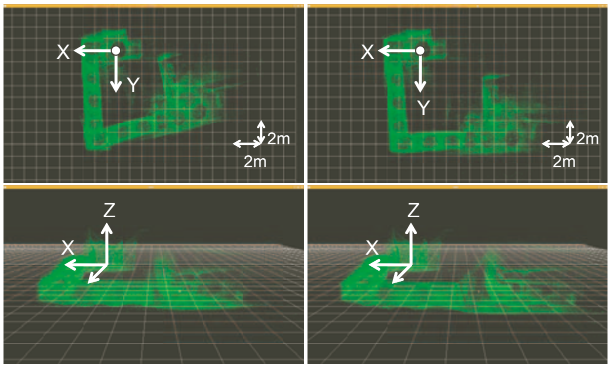
When sub-tracks contact the ground, the robot's turning tends to cause an error in the odometry data. Before the seventh point, Kenaf turned left. At that point, the estimated position based on odometry and 3-D scan matching (cross point) is significantly different from that based on odometry (asterisk) alone.

The operator tended not to give commands for 3-D matching in open spaces because it takes about 15 seconds to measure 3-D shapes, and several seconds to match 3-D shapes. The operator gave more weight to time than accuracy of the 3-D map in open spaces. When the operator needed to recognize more accurate 3-D shapes in narrow spaces to control Kenaf, the operator gave the commands of 3-D matching frequently to see 3-D shapes around Kenaf. In addition, in a dark environment, the operator controlled Kenaf seeing 3-D shapes instead of relying on camera images.

Although the TK scanner can measure correct 3-D shapes inside and outside buildings in normal air conditions, it cannot measure the 3-D shape in smoky conditions. Figure 12 illustrates measured 3-D shapes in a tunnel filled with smoke. Hi-URG measures distance based on phase differences of infrared light. In a space filled with smoke, the light reflected off thick smoke was too strong to measure 3-D shapes. A new tool is necessary to measure 3-D shape accurately in a space filled with smoke.

B. Mapping in train

Figure 13 shows the outside of the train. Arrows in Fig. 13 indicate the path of Kenaf in the experiment. Figure 14 illustrates Kenaf's trajectory. The solid line is the trajectory estimated using the odometry data, and asterisks on the solid



Scan + Odometry Scan + Odometry + Matching

Fig. 11. Constructed 3-D map of the pancake house: Left 3-D map was constructed based on odometry. Right 3-D map was constructed based on odometry and sparse matching. Axes illustrate the origin.

Fig. 12. 3-D scan point cloud measured by TK scanner inside smoke-filled tunnel.

line are the points where Kenaf measured 3-D shapes. Open circles indicate the points where 3-D matching was done automatically or manually. In Fig. 14, Kenaf measured 3-D shapes 20 times, and performed 3-D scan matching 11 times during the trip of about 40 m. Kenaf measured 3-D shapes and constructed 3-D map at every about 2 m. Figure 15 shows the constructed 3-D maps.

In the train experiment, Kenaf started at the inside of the train, went through the corridor, and left the train. Scan data from 1 to 5 in Fig. 14 are measured inside the train. Corridor width is narrow (less than 0.8m). There is a L junction near the start point (1 and 2 in Fig. 14). Kenaf moved using only main track because floor is flat.

In the outside, Kenaf went around the train. Ground is gravel and flat. Hence, the Kenaf also moved using only main track. Scan data from 6 to 18 in Fig. 14 are measured around the train. Under the train, NIST staff put random step fields (Right in Fig. 13). Kenaf got over a random steps using sub-tracks.

When floor is level, odometry can estimate height of robot position Z. Height of robot position Z estimated by odometry alone is similar to one modified by matching at points from 1 to 18 in Fig. 14. However, difference of positing Z increased at points 19 and 20 in Fig. 14 because there were random steps (right photo in Fig. 13). Position correction using the matching is necessary when floor is not level.

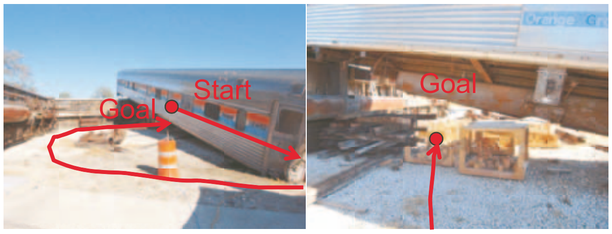


Fig. 13. Snapshots of train environment: Arrow illustrates the path of Kenaf during the mapping.

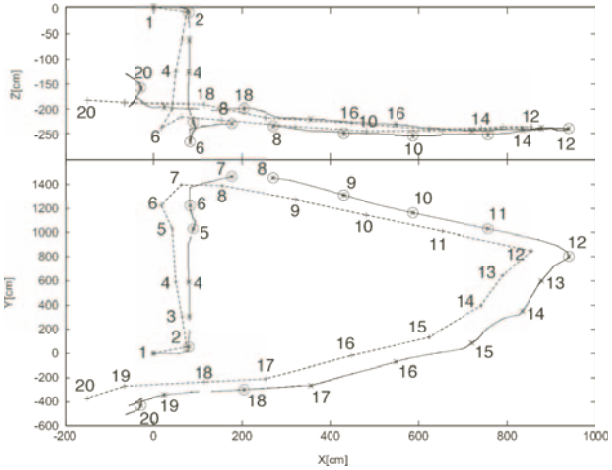
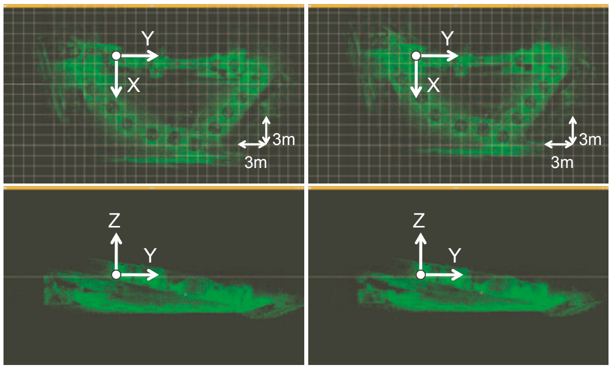


Fig. 14. Trajectory of Kenaf in train mapping.

V. DISCUSSION

Staff members from FEMA provided us many helpful comments about our developed mapping system. We discuss their comments about Kenaf's search and mapping system in the following paragraphs.

1) **TK scanner**
Thanks to its small size and light weight, the TK scanner did not interfere with Kenaf's mobility. Although it takes 15 seconds to measure 3-D shapes by using the TK scanner, the operator can see detailed 3-D shapes around Kenaf. The operator can control Kenaf with-



Scan + Odomery Scan + Odomery + Matching

Fig. 15. Constructed 3-D map of train: Left 3-D map was constructed based on odometry. Right 3-D map was constructed based on odometry and matching. Axes illustrate the origin.

out crashing the robot. FEMA members commented that the resolution of the 3-D shapes was generally satisfactory. However, some members commented that higher resolution was required to recognize victims' body parts (e.g., hands and legs) when they find a victim. We can meet this request by adding a new function to change the resolution of the 3-D shape.

2) **Kenaf's odometry**
According to the 3-D map that was based on odometry data alone, errors in the odometry data were small when Kenaf moved on a level floor. However, when Kenaf moved over unlevel floors, the estimated position based on odometry and 3-D matching differed significantly from data based on odometry alone. This difference was attributed to the effect of the sub-track's contact with the ground. This is an open problem that we have to solve in near feature.

3) **3-D mapping**
A 3-D map constructed based on 3-D shape matching. When the 3-D map was constructed manually, the operator judged to match 3-D shapes based on 3-D control interface image. When Kenaf moved on a level floor in open spaces, the operator did not give commands for 3-D shape matching because the operator did not mind small errors in the 3-D map for such spaces. When Kenaf moved in narrow spaces, the operator frequently gave commands for 3-D shape matching to see 3-D shapes around Kenaf. Hence, detailed 3-D shapes were measured in these narrow spaces. When the operator gives commands for 3-D shape matching, the constructed 3-D map may no be able to show victims' locations for rescue activity. The accuracy of 3-D map construction will increase when the robot measures 3-D shapes at constant frequency automatically. In addition, we need to increase the robustness of 3-D scan matching. In the clutter environment, the matching sometimes failed. These are other open problems. [19] also reported about ICP matching failure and proposed plane segment based matching method. It is an interesting solution for the open problem.

VI. CONCLUSION

The goal of our research was to develop a tele-operated tracked vehicle for search and mapping in rubble environments. For improvement of map construction by Kenaf, it is necessary to reveal the problem of present map construction method in the real environment. So, we demonstrated our method at the Disaster City, and collected log data for 3-D mapping. In the experiment, FEMA staff gave a lot of helpful comments to us. From the comments, we found some open problems that we have to solve in the feature. The information of these open problems will be also helpful for researchers to improve their method of 3-D map construction. The log data will be available to the public at [3].

VII. ACKNOWLEDGMENTS

This research has been partially supported by the NEDO Project for Strategic Development of Advanced Robotics Elemental Technologies, High-Speed Search Robot System in Confined Space. In addition, we borrowed the prototype of URG-08LX from HOKUYO Company.

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