

3D Terrain Sensing by Laser Range Finder with 4-DOF Sensor Movable Unit based on Frontier-Based Strategies

Toyomi Fujita and Toshinori Yoshida

Abstract—The authors have developed a sensing system which consists of a laser range finder(LRF) with 4-DOF arm-type sensor movable unit for a tracked vehicle. The mechanism enables the robot to perform 3D terrain sensing by scanning on horizontal planes and moving the sensor vertically at equal interval, and 3D shape sensings of front and lateral downward area by controlling the angle of sensor properly. Therefore, 3D sensings of steep shape such as mountains and valleys are possible. In this paper, we apply the frontier-based strategies for 3D environment mapping for such terrains by moving a laser range finder with a tracked vehicle. We represent the 3D map using occupancy voxel map which divides the environment space into equal-sized voxels. The frontier is defined as the voxel that can be sensed by the sensor with a motion of the arm or the robot and is adjacent to unmeasured voxels. To select appropriate frontier in surrounding frontiers, we gave the order of priority according to their directions. On the basis of this method, some experiments of 3D environment mapping were employed. The results showed effective performance of presented method.

Index Terms—Laser range finder(LRF), 3D terrain sensing, Arm-type sensor movable unit, Frontier-based mapping, Tracked mobile robot.

I. INTRODUCTION

A 3D terrain sensing is a very important function for a tracked vehicle robot to give precise information as possible to operators and to move working field efficiently. A laser range finder (LRF) is widely used for the 3D sensing because it can detect wide area fast and can obtain 3D information easily. Some 3D sensing systems with the LRF have been presented in earlier studies[1][2][3]. In those measurement systems, multiple LRF sensors are installed in different directions[4], or a LRF is mounted on a rotatable unit[5][6]. However, it is still difficult for those systems to do sensing more complex terrain such as valley, deep hole, inside the gap, or steep downward slope due to occlusions. As the other related work, for example, [7] proposed the combination of 2D LRF and stereo vision for 3D sensing. This method, however, increases the cost of sensing system.

In the previous study, the authors have proposed a new type of LRF sensing system that is able to sense 3D shape of such a more complex terrain: valley, deep hole, inside the gap [8]. The system has a 3-DOF arm-type sensor movable unit which can be mounted on a tracked vehicle robot. A LRF is installed at the end of the unit in this sensing system. The sensor can change position and orientation in a movable area of the arm unit and face at a right angle according to

a variety of configuration. This system is, therefore, capable of avoiding occlusions for such a complex terrain and sense more accurately.

In addition, this sensing system is able to change the height of the LRF by keeping its orientation flat for efficient sensing. In this way, the height of LRF can be changed at equal interval by lifting it up and down vertically by the arm-type sensor movable unit. 3D map can be obtained by combining 2D maps in individual heights of the LRF. This sensing can avoid a problem on accumulation point in conventional 3D sensing method by a LRF with a rotating mechanism. However, if a robot is tilted right or left in roll rotation (rotation around the axis to the forward direction), it may be difficult to apply this kind of sensing method because the scanning plane is also tilted with the tilt angle.

Therefore we have expanded the system to add another revolute joint as a 4-DOF unit so that the robot can keep the LRF flat even on uneven ground [9]. This mechanism enables the robot to sense surround shape of 3D environment with equal interval even in the condition that the robot is tilted horizontally with the roll rotation in uneven ground.

This paper describes the expanded mechanism of sensing system to increase sensing ability of the system even in the situation the robot is tilted. We focus on 3D shape sensings of upward and downward slopes such as mountain and valley which are located in front or lateral of the robot as typical examples of complex shape sensing. We also consider a method for 3D mapping for these terrains based on a occupancy voxel map and frontier-based exploration. In this paper, Section II shows the mechanism of the expanded sensing system. The characteristics of 3D shape sensing by this sensing system is explained in Section III. Section IV describes the method for 3D mapping for these terrains with experimental results.

II. ROBOT AND SENSING SYSTEM

A. Tracked Mobile Robot

Figure 1 shows the tracked mobile robot with proposed sensing system. The robot has two crawlers at the both sides. A crawler consists of rubber blocks, a chain, and three sprocket wheels. The rubber blocks are fixed on each attachment hole of the chain. One of the sprocket wheels is actuated by a DC motor to drive a crawler for each side. The size of the robot is 350 mm in length, 330 mm in width, and 320 mm in height. The total weight is approximately 11 kg.

B. 4-DOF Sensor Movable Unit

The expanded sensing system by 4-DOF sensor movable unit is mounted on the robot as shown in Fig. 1. This unit

Toyomi Fujita is with Faculty of Engineering, Department of Electronics and Intelligent Systems, Tohoku Institute of Technology, Sendai 982-8577, Japan e-mail: t-fujita@tohotech.ac.jp

Toshinori Yoshida is with Celestica Japan Inc.

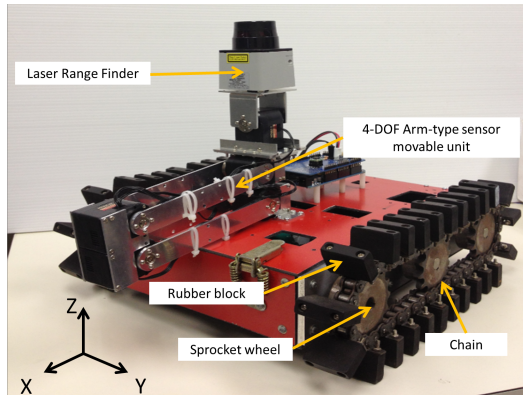


Fig. 1. Tracked mobile robot with 4DOF sensor movable unit

consists of two links, three revolute joints which can rotate around Y-axis, and additional fourth joint rotating around X-axis. The first and second joints and the second and third joints are connected by a link respectively. Two servomotors are used for the second joint to make LRF flat when it is fully down.

The coordinate systems for the joints and sensor is shown in Fig. 2. The coordinate system Σ_1 is set at the base of the arm. Σ_2 , Σ_3 (and also Σ_4), Σ_5 , and Σ_6 are corresponds to the first, second, third, and fourth joints respectively. The sensor coordinate system is represented by Σ_7 .

In this system, the robot can obtain 3D sensing positions from the sensor data of the LRF. When the distance is d_s at a scan angle θ_s by LRF, the 3D measurement position vector $\mathbf{X}$ in the base coordinate system Σ_1 can be calculated by

$$\begin{pmatrix} \mathbf{X} \\ 1 \end{pmatrix} = {}^1\mathbf{P}_6 {}^6\mathbf{P}_7 \begin{pmatrix} \mathbf{X}_s \\ 1 \end{pmatrix} \quad (1)$$

where $\mathbf{X}_s$ shows a position vector of sensor in the sensor coordinate system Σ_7 :

$$\mathbf{X}_s = d_s (\cos \theta_s, \sin \theta_s, 0)^T. \quad (2)$$

${}^i\mathbf{P}_{i+1}$ ($i = 1, \dots, 6$) shows a homogeneous matrix that represents a transformation between two coordinate systems Σ_i and Σ_{i+1} :

$${}^i\mathbf{P}_{i+1} = \begin{pmatrix} {}^i\mathbf{R}_{i+1} & {}^i\mathbf{T}_{i+1} \\ \mathbf{0}_3^T & 1 \end{pmatrix} \quad (i = 1, \dots, 6) \quad (3)$$

where ${}^i\mathbf{R}_{i+1}$ shows a rotation matrix for the rotation angle θ_{i+1} ($\theta_7 = 0$); it represents the rotation around y_{i+1} axis,

$${}^i\mathbf{R}_{i+1} = \begin{pmatrix} \cos \theta_{i+1} & 0 & \sin \theta_{i+1} \\ 0 & 1 & 0 \\ -\sin \theta_{i+1} & 0 & \cos \theta_{i+1} \end{pmatrix}, \quad (4)$$

for $i = 1, \dots, 4$. In case of $i = 5$, it shows the rotation around X-axis:

$${}^5\mathbf{R}_6 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_6 & -\sin \theta_6 \\ 0 & \sin \theta_6 & \cos \theta_6 \end{pmatrix}. \quad (5)$$

${}^i\mathbf{T}_{i+1}$ shows a translation vector from Σ_i to Σ_{i+1} for the translation l_i on z_i axis:

$${}^i\mathbf{T}_{i+1} = (0, 0, l_i)^T \quad (6)$$

for $i = 1, \dots, 6$ ($l_1 = 0$). $\mathbf{0}_3$ shows a 3×1 zero vector.

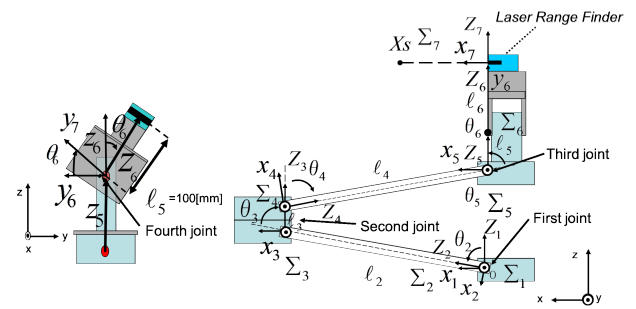


Fig. 2. Coordinate Systems

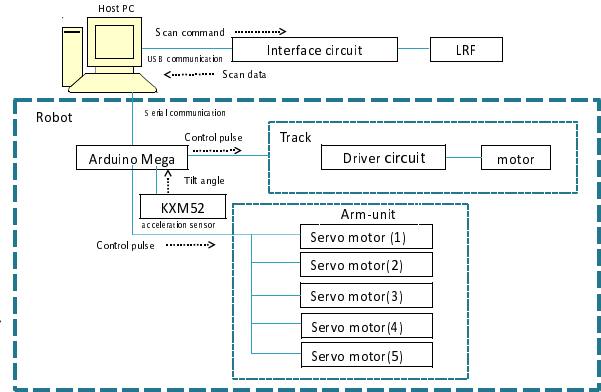


Fig. 3. Control System

C. Control System

Figure 3 shows the control system for this robot. We have used Arduino Mega for the control of the sensor movable unit and tracks driving. This microcomputer board receives desired position and orientation of LRF from the host PC, computes desired joint angles of the unit based on received information and the orientation of robot, then sends the control signals corresponding to the joint angles to each motor. The orientation of the robot is detected by 3-axis acceleration sensor: Kionix Inc. KXM52. The board also manages PWM control of each motor for driving track corresponding to the movement command received from the host PC. The LRF sends the scanned data to the host PC when the host PC requests for the sensing data to LRF. The host PC computes 3D sensing positions from the sensing data of LRF and information of the robot state received from the microcomputer: orientation of the robot and joint angles of the sensor movable unit. We have used MATLAB for the computation and map building from the data.

III. 3D SHAPE SENSING

A. Overview

This presented sensing system has two major advantages. One advantage is that the sensing system enable the robot to perform 3D shape sensing without sparse or dense scanning because this system is able to scan at different heights with equal interval. For example, in case of upward slope located in front of the robot as shown in Fig. 4, presented system can perform 3D shape sensing by moving LRF up and down with equal interval with keeping its orientation flat to the ground. Specifically, it rotates the first, second,

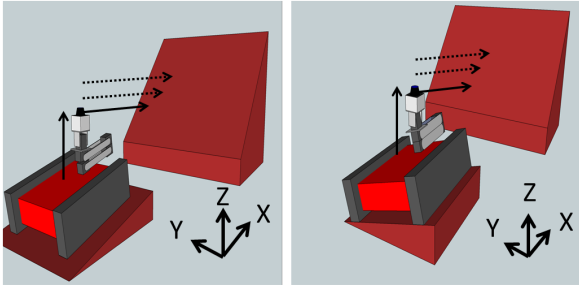


Fig. 4. 3D shape sensings of upward slope at equal intervals

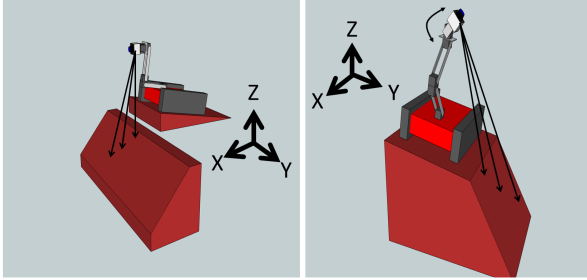


Fig. 5. 3D shape sensings of downward slope in front (left panel) and lateral (right panel) of the robot

and third joints around Y-axis and move LRF up and down. Also, it rotates the third and fourth joints according to tilt angle of the robot which is detected by acceleration sensor so that the orientation LRF is flat to the ground. Therefore, it can perform 3D shape sensing of upward slope by scanning in horizontal planes at equal interval.

Another advantage is that this system reduce occlusions in sensings of steep downward slope and valley shape terrain which are located in front and lateral of the robot. For front downward slope, as shown in the left panel of Fig. 5, the sensing without occlusion is possible by holding the angles of the first and second joints and rotating the third joint around Y-axis. In case of lateral downward slope shown in the right panel of Fig. 5, the occlusion may occur due to mechanical limitation of the sensor movable unit. Nevertheless, it can make the measurement area large by locating the LRF high position as possible and rotating the fourth joint around X-axis.

B. Experiments

We have employed experiments for 3D shape sensing for upward and downward slopes as described in Section III.

1) *3D Shape Sensing of Front Upward Steps*: Upward steps were setup for the experiment of upward slope. Figure 6 shows an overview of experimental setup. The steps were located in front of the robot, at (1150, 0, 310) mm in the global coordinate system which is located as shown in Fig. 6. Each step had 1080 mm in width, 80 mm in length and height. The position of the robot was set so that the origin of the arm-base coordinate system Σ_1 was located at (360, -160, 100) mm. Based on this, three kinds of experiment were proceeded in which the orientation of the robot was changed with upward movement of the LRF by the following manners:

- (1) The rotation angle around X-axis was changed to -15 or -25 degrees as the LRF moved 2.5 mm up. The rotation angle around Y-axis was fixed to be 0 degree.

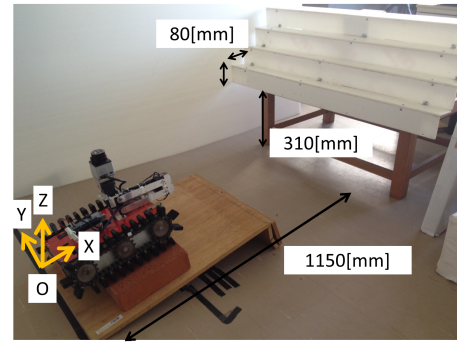


Fig. 6. Experimental setup for 3D shape sensing of front upward steps

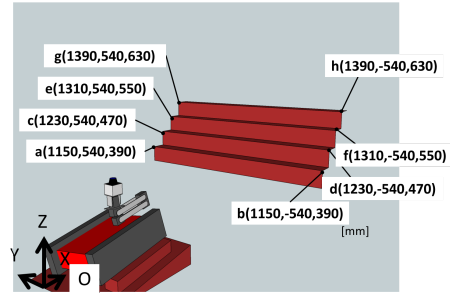


Fig. 7. Reference points for 3D shape sensing of front upward steps

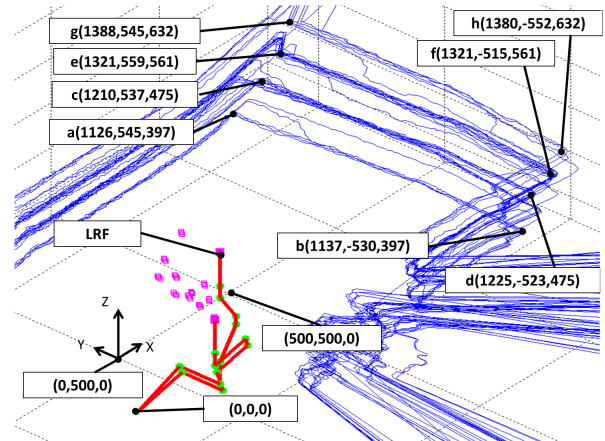


Fig. 8. 3D shape sensing result of front upward steps with measured reference points (unit:[mm])

- (2) The rotation angle around Y-axis was changed to -15 or -25 degrees as the LRF moved 2.5 mm up. The rotation angle around X-axis was fixed to be 0 degree.
- (3) The combination of rotation angles around X-axis and Y-axis was changed to $\{0, -15\}$, $\{-20, -15\}$, $\{-20, -25\}$, or $\{0, -25\}$ degrees as the LRF moved 2.5 mm up in turn.

In each orientation, LRF was kept to be flat to the ground and moved upward. The shape sensing in a horizontal plane was performed at every heights by 0.5 mm interval.

In this experiment, some feature points in the environment were set as reference points to evaluate sensing accuracy. Figure 7 shows the reference points at which positions were represented in the global coordinate system.

Figure 8 shows the result of sensing based on the above experiment (3); the blue lines show the obtained shape and measured position values of reference points are also de-

TABLE I
MEASURED DISTANCES AND ERROR RATIOS ON REFERENCE POINTS FOR FRONT UPWARD STEPS

experiment		(1)		(2)		(3)	
rotation angle around X		0 degree		-15 or -25 degrees		0 or -20 degrees	
rotation angle around Y		-15 or -25 degrees		0 degree		-15 or -25 degrees	
point	actual (mm)	measured (mm)	error (%)	measured (mm)	error (%)	measured (mm)	error (%)
a	1329.0	1335.7	0.5	1328.5	0.03	1312.4	1.2
b	1329.0	1338.1	0.6	1327.7	0.1	1315.8	1.0
c	1423.2	1422.9	0.02	1421.4	0.1	1406.4	1.2
d	1423.2	1426.8	0.3	1431.8	0.6	1414.1	0.6
e	1492.8	1510.3	1.2	1517.0	2.0	1540.2	1.4
f	1492.8	1517.3	1.6	1515.7	2.0	1524.8	0.3
g	1618.8	1617.4	0.09	1622.5	0.2	1619.6	0.05
h	1618.8	1630.4	0.7	1629.1	0.6	1615.1	0.2
average			0.6		0.7		0.7

scribed. We can see that almost accurate shape was obtained. The position errors on reference points were acceptable so that the robot figures out the environment: for example, the position error was (24, 5, 7) mm, its ratio was (2.1, 0.9, 2.0) %, on the point *a*; (13, 10, 7) mm, (1.1, 2.0, 2.0) %, on the point *b*; and the maximum error was 5.0 % on Y-axis of the point *f*.

Table I shows measured distances and errors on reference points for the above experiments. In case of the experiment (1), the average of the error was 0.6 %, the maximum error was 1.6 % on the point *f*, and the minimum error was 0.02 % on the point *c*. In case of the experiment (2), the average of the error was 0.7 %, the maximum error was 2.0 % on the points *e* and *f*, and the minimum error was 0.03 % on the point *a*. In case of the experiment (3), the average of the error was 0.7 %, the maximum error was 1.4 % on the point *e*, and the minimum error was 0.05 % on the point *g*. In all experiments, the average of the error was within 1 %, so these results show that accurate 3D shape sensing is possible for the robot to understand surrounding environment by the presented sensing system.

2) *3D Shape Sensing of Front Downward Steps*: Downward steps were setup for the experiment of downward slope. Figure 9 shows an overview of experimental setup. The steps were located in front of the robot, at (770, 0, -55) mm in the global coordinate system. Each step had 1080 mm in width, 80 mm in length and height. The position of the robot was set so that the origin of the arm-base coordinate system Σ_1 was located at (400, 0, 100) mm. The orientation of the robot was set to the -15 degrees as the rotation angle around Y-axis and 0 degree as the angle around X-axis. The position of LRF was fixed at (531, 0, 432) mm and the angle of the third joint θ_5 was changed from 1 degree to 90 degrees by 1 degree. The measurement was performed in each orientation of LRF. As the previous experiment, some reference points were given and the error of measured distance was computed for each point. The positions of the reference points in the global coordinate system are described in Fig. 10.

Figure 11 shows the result of sensing: the blue lines show the obtained shape and measured position values of reference points are also described. The position errors on reference points were acceptable so that the robot figures out the environment; for example, (5, 4, 1) mm, the ratio was (0.6, 0.7, 2.0) %, on the point *a*; and (11, 4, 1) mm, (1.4, 0.7, 2.0) %, on the point *b*. The maximum error was 19.3 % on Z-axis of the points *e* and *f*.

Table II shows measured distances and errors on reference

TABLE II
MEASURED DISTANCES AND ERROR RATIOS ON REFERENCE POINTS FOR FRONT DOWNWARD STEPS

point	actual (mm)	measured (mm)	error (%)
a	942.1	935.6	0.6
b	942.1	948.8	0.7
c	1008.5	1019.0	1.0
d	1008.5	997.0	1.1
e	1083.8	1082.8	0.1
f	1083.8	1092.6	0.8
g	1165.3	1164.1	0.1
h	1165.3	1174.7	0.8
i	1251.7	1264.6	1.0
j	1251.7	1251.2	0.04
average			0.6

points. The maximum error was 1.1 % on the point *d* and the minimum error was 0.04 % on the point *j*. The average of measured distance was 0.6 %, so this result shows that accurate 3D shape sensing without occlusion is possible for the robot to understand surrounding front downward environment by the presented sensing system.

3) *3D Shape Sensing of Lateral Downward Steps*: Downward steps were setup for the experiment of downward slope as well as previous experiment. Figure 12 shows an overview of experimental setup. The steps were located in the left side of the robot, at (0, 120, -55) mm in the global coordinate system. The position of the robot was set so that the origin of the arm-base coordinate system Σ_1 was located at (0, -160, 100) mm. The following two kinds of experiment were proceeded in which the combinations of the orientation of robot and the position of LRF were set as follows:

- (1) The rotation angle of the robot around X-axis was set to 25 degrees and the LRF was located at (0, -418, 637) mm.
- (2) The rotation angle of the robot around X-axis was set to -25 degrees and the LRF was located at (0, 85, 489) mm.

In each combination, the angle of the fourth joint θ_6 was changed from 90 degrees to 0 degree by -1 degree and the LRF was performed sensing in each orientation. As the previous experiments, some reference points were given and the error of measured distance was computed for each point. The positions of the reference points in the global coordinate system are described in Fig. 13.

Figure 14 shows the result of sensing based on the above experiment (2); the blue lines shows the obtained shape and measured position values of reference points are also described. Although almost accurate shape was obtained, the

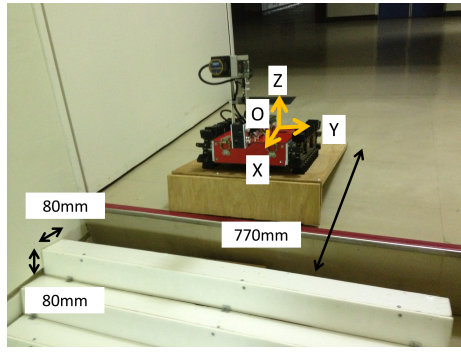


Fig. 9. Experimental setup for 3D shape sensing of front downward steps

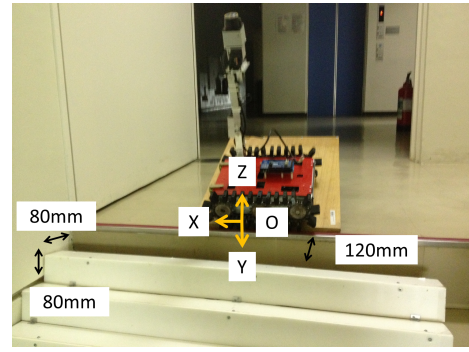


Fig. 12. Experimental setup for 3D shape sensing of lateral downward steps

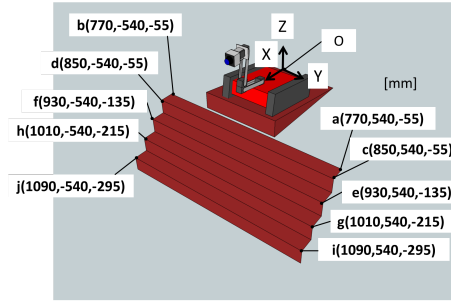


Fig. 10. Reference points for 3D shape sensing of front downward steps

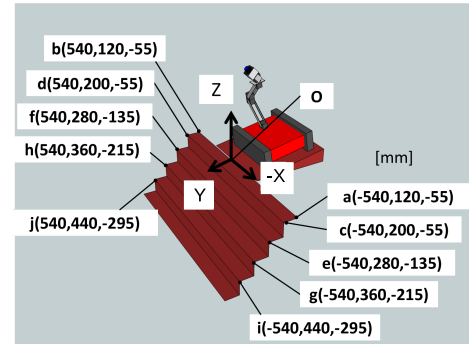


Fig. 13. Reference points for 3D shape sensing of lateral downward steps

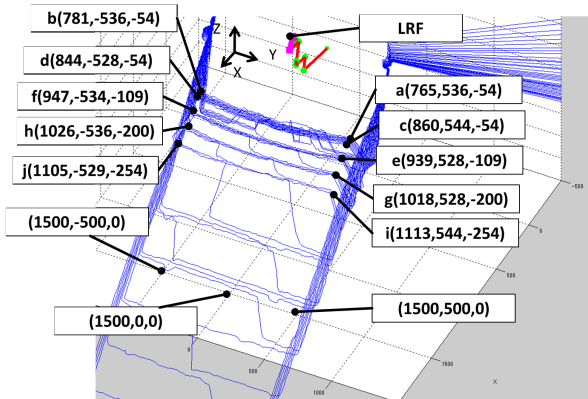


Fig. 11. 3D shape sensing result of front downward steps with measured reference points (unit:[mm])

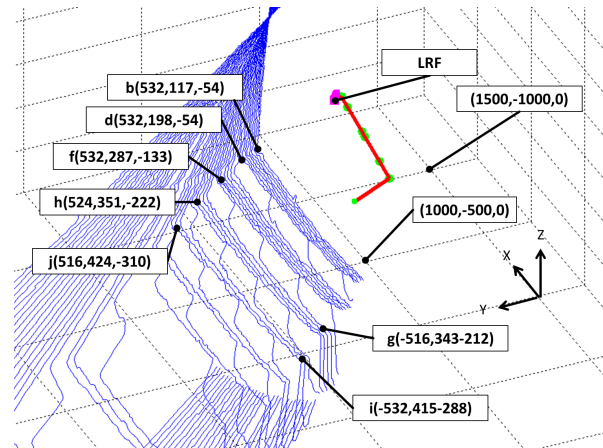


Fig. 14. 3D shape sensing result of lateral downward steps with measured reference points (unit:[mm])

measurement was not performed in a part of area due to occlusion. The position errors on reference points were, for example, (8, 3, 1) mm, the ratio was (1.4, 2.5, 2.0) %, on the point *b*; and (8, 2, 1) mm, (1.4, 1.0, 2.0) %, on the point *d*. With respect to the maximum error of the position, it was 5.7 % on Y-axis of the point *j* in the experiment (2) and 7.2 % of the points *b* and *d* in the experiment (1).

Table III shows measured distances and errors on reference points for each experiment. In case of the experiment (1), the average of the error was 1.3 %, the maximum error was 2.5 % on the point *b*, and the minimum error was 0.1 % on the point *d*. In the experiment (1), however, the robot was not able to obtain enough 3D shape and the data on reference points were insufficient because occlusions occurred in lateral downward area. The points at which the measurement was not made were denoted by a line in Table III. In case of the experiment (2), the average of the error was 2.2 %, the maximum error was 3.0 % on the point *i*, and the minimum error was 0.6 % on the point *f*. The measurement

was not made on the points *a*, *c*, and *e* because these were in the outside of measurement region of LRF. Nevertheless, these results show that accurate 3D shape sensing is possible for the presented sensing system to understand surrounding lateral downward environment, where conventional sensing systems were never able to measure.

IV. FRONTIER-BASED 3D TERRAIN MAPPING

A. Occupancy Voxel Map

We applied occupancy voxel map to represent 3D shape as a map. In this method, the space in the environment is divided into boxes which have same size. This box is called *voxel*. The map is represented by the values which indicates degree of occupancy for the voxels. For simplicity, we represents the values by three kinds of label: *Occupied*, *Unknown*, and

TABLE III
MEASURED DISTANCES AND ERROR RATIOS ON REFERENCE POINTS FOR
LATERAL DOWNWARD STEPS

experiment		(1)		(2)	
rotation angle around X		25 degrees		-25 degrees	
point	actual (mm)	measured (mm)	error (%)	measured (mm)	error (%)
a	555.9	—	—	—	—
b	555.9	541.9	2.5	547.4	1.5
c	578.5	—	—	—	—
d	578.5	579.2	0.1	570.2	1.4
e	623.1	—	—	—	—
f	623.1	—	—	618.9	0.6
g	623.7	—	—	654.9	4.2
h	623.7	—	—	668.6	2.2
i	756.5	—	—	733.6	3.0
j	756.5	—	—	736.3	2.7
average		1.3		2.2	

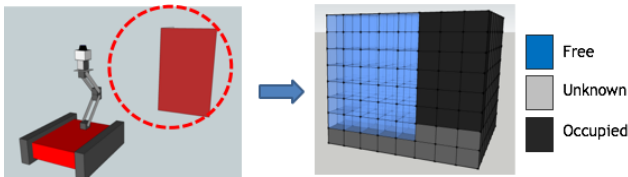


Fig. 15. Occupancy voxel map

Free. Figure 15 shows an example of the occupancy voxel map. A wall which is detected in front of the robot, which is surrounded by dotted line in the left panel, is represented by the occupancy voxel map in the right panel. The *Occupied*, *Unknown*, and *Free* voxels are represented in black, gray, and blue colors in the map.

We applied the run-length encoding to reduce the size of occupancy data for all voxels. In this method, the data are compacted by saving the length of the sequence of the same occupancy voxels rather than the occupancy data for respect voxels.

B. Frontier-Based Mapping

We applied a frontier-based exploration for mapping. Several frontier-based mappings have been presented in previous studies. For example, Yamauchi et al. introduced a mobile robot system that combines frontier-based exploration with continuous localization [10]. Freda et al. have presented a method for sensor-based exploration based on the incremental generation of a configuration-space data structure called sensor-based exploration tree (SET) using the frontier [11]. Pellenz et al. developed a exploration system that combines the frontier-based exploration with the path transform [12]. These frontier-based mappings were performed in 2D environment. Thus we need to expand these kinds of method to the sensing of 3-D environment.

As frontier-based mappings for 3D environment, Dornhege et al. have considered frontier-based exploration and presented a method for 3D space sensing by combining the two concepts of voids, which are unexplored volumes in 3D, and frontiers [13]. However, the sensing with the robot movement has not been considered.

In this study, we define the frontier as the voxel adjacent to a *Unknown* voxel and detectable by the sensor with the movement of the robot and/or the sensor movable unit. First,

the frontiers are detected from the map obtained in the measurement. Then, the next frontiers are selected to get new information.

C. Frontier Selection

In sensing, the frontiers may exist a lot in the upward and downward areas in front of the robot as well as left and right areas. Therefore, the robot needs to select the appropriate frontier to be detected. We thus give priorities for the direction to select the frontier according to the degree of safety for the robot: in the order of front-downward, front, front-upward, and left or right. Then the frontier is selected based on the number of detectable voxel for each direction. The cost of the movement of the sensor by robot and sensor movable unit are also considered.

As examples of the selection of the frontier, two kinds of terrain are described: mountain terrain and valley terrain in front of the robot.

1) *Forward Mountain Terrain:* Figure 16 shows an example of mapping based on proposed method when there is a mountain terrain in front of the robot. Gray voxel shows *Unknown*, yellow one shows *Frontier*, and orange one shows selected frontier. Actually the other frontiers exist around the robot, but they are omitted in this figure so that we see it clearly.

Figure 16(a) shows the voxel map which is obtained by the first scan. In initial state, the arm of sensor movable unit is folded and the sensor is placed horizontally. Thus, the frontiers exist in the upper and lower areas of measured horizontal plane. The number of frontier in the upper area is larger than that in the lower area due to the mechanism of the arm. In addition, the movement cost of the sensor for the sensing of upper area is lower than that for sensing of lower area. From these reasons, the upper frontier area selected for the next sensing.

After that, the selection of the upper area are repeated by the same reason as (a). A mountain terrain is then detected as shown in Fig. 16(b). When the sensor reaches the position where it can not be stretched any more by the arm-type sensor movable unit, the sensor is rotated to direct scanned surface upward further, as shown in Fig. 16(c).

Finally, when the frontier can not be detected in the upper area, the lower frontiers are selected as the next. Figure 16(d) shows this state.

2) *Forward Valley Terrain:* Figure 17 shows an example of mapping based on proposed method when there is a valley terrain in front of the robot.

Figure 17 (a) shows the initial state. The frontiers exist in the upper and lower areas of measured horizontal plane and the upper frontier area selected for the next sensing in the same way as the mapping of mountain terrain. Then the selection of the upper area are repeated, and the sensor is rotated so that the scanned surface directs further upper area when the sensor reaches the position where it can not be stretched any more by the arm-type sensor movable unit, as shown in Fig. 17 (b).

After that, when the frontier can not be detected in the upper area, the lower frontiers are selected as the next as shown in Fig. 17 (c). Then the valley terrain is detected and the frontiers are selected from far to near area on the bottom of the valley by rotating the sensor as shown in Fig. 17 (d).

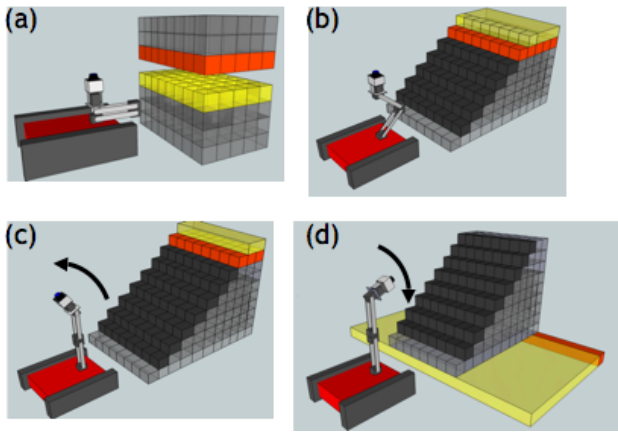


Fig. 16. Frontier selection for mountain terrain in front of the robot

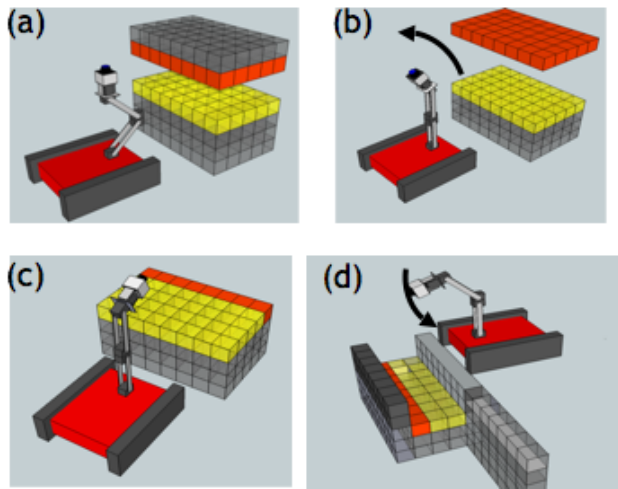


Fig. 17. Frontier selection for valley terrain in front of the robot

D. Experiments

1) *Forward Mountain Terrain*: We conducted an experiment for the mountain terrain mapping based on proposed method described in Section IV-C1. The upward steps used in the experiment of Section III-B1 were also setup as the mountain terrain in front of the robot as shown in Fig. 18. The robot stayed at the same position and the steps were placed 1150 mm ahead of the robot.

Figure 19 shows the result of mapping in this experiment. The blue and green dots show the voxels of *Occupied* and *Free* respectively. The yellow dots show the frontiers and the red dots are selected ones from them at that time. The other areas are the voxel of *Unknown*. The red square mark with bar indicate the position of the LRF with the sensor movable unit. The size of voxel was set to $50 \times 50 \times 10$ mm.

Figure 19 (a) is the map obtained at the first scan. Upper frontiers were selected based on the method explained in Section IV-C1; because the movement cost of the LRF was low and more frontiers was able to be detected at once in the upper area than lower area.

After that, upper frontiers were continuously selected by the same reason in the case of (a). The map obtained in the 50th scan is shown in Fig. 19 (b).

The detection of upper frontiers was repeated further until when the sensor reaches the position where it can not be stretched any more by the arm-type sensor movable unit.

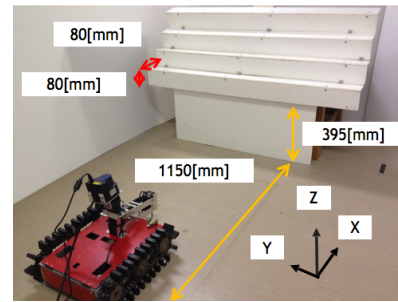


Fig. 18. Experimental setup for mountain terrain mapping in front of the robot

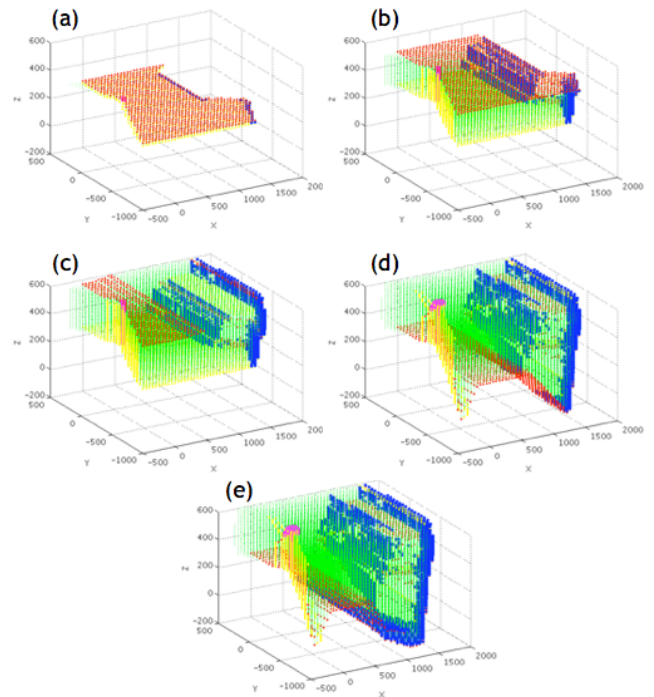


Fig. 19. 3D mapping result when there is a mountain terrain in front of the robot

Then, the sensor was rotated to detect upper area further. The map obtained in the 100th scan is shown in Fig. 19 (c).

When the detection of upper frontier became impossible by this robot, the lower area were selected as the next frontiers. Figure 19 (d) shows the map at that time. This map was obtained in the 240th scan.

The map was finally obtained as shown in Fig. 19 (e). The shape of steps was almost detected. In addition, the size of map data was compacted to 5.3% of the data when full occupancy information for all voxel was saved.

2) *Forward Valley Terrain*: We conducted another experiment for the valley terrain mapping based on the method described in Section IV-C2. The valley shape was setup using two tables which have 600 mm in height as shown in Fig. 20.

The result of this experiment is shown in Fig. 21. The size of voxel was set to $50 \times 50 \times 30$ mm in this experiment.

Figure 21 (a) shows the map obtained in the 40th scan. The frontiers at upper area were selected to upward direction in the same way as the mapping of mountain terrain described above. Then, the sensor was rotated to detect upper area further when the sensor reached the position where it was

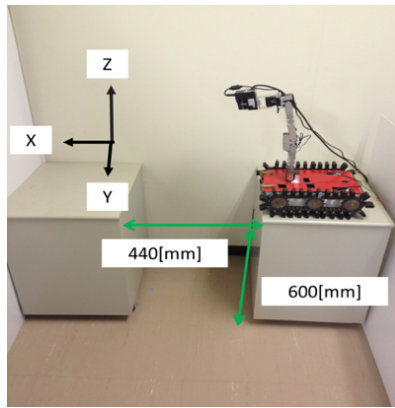


Fig. 20. Experimental setup for valley terrain mapping in front of the robot

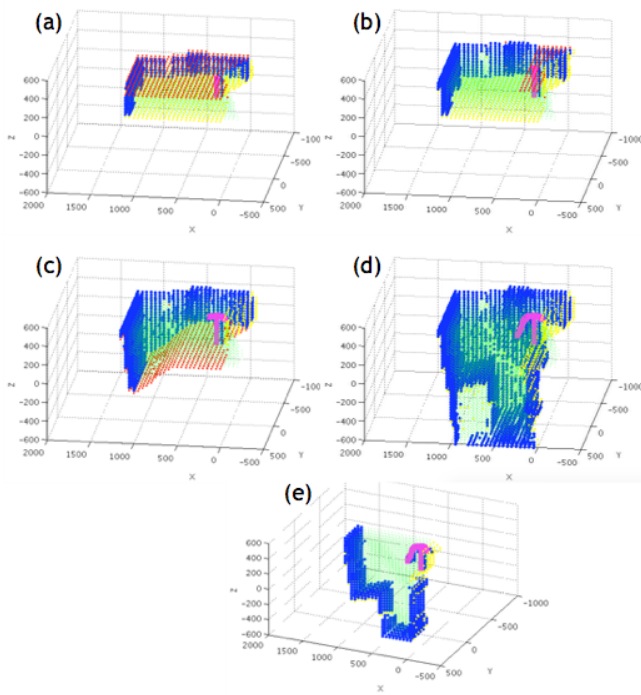


Fig. 21. 3D mapping result when there is a valley terrain in front of the robot

not be stretched any more by the sensor movable unit. The map obtained in the 100th scan is shown in Fig. 21 (b).

After that, because the detection of upper frontier became impossible by any movement of the sensor, the frontiers of lower area were selected. The map obtained in the 230th scan is shown in Fig. 21 (c).

The map finally obtained is shown in Fig. 21 (d). The valley terrain was almost obtained. In addition, the size of map data was compacted to 11.0% of the data when full occupancy information for all voxel was saved. Figure 21 (e) shows a partial cross section between $y = -200\text{mm}$ and $y = 50\text{mm}$ of the obtained map. We can see the valley shape clearly from this result.

V. CONCLUSIONS

This paper presented a 3D shape sensing system by LRF with 4-DOF sensor movable unit. Using the sensor movable unit, 3D shape sensing by flat scanning is possible even in the condition that the robot is tilted. Experiments for front upward steps showed the effectiveness of this sensing. This

sensing system is also able to perform 3D shape sensing of surrounding front and lateral downward environment with less occlusion where conventional sensing systems were not able to measure. In addition, we proposed a method for mapping represented by the occupancy voxels with frontiers. The next frontiers to be detected are selected based on priorities given by the movement cost of the sensor. The robot is able to do mapping safely and efficiently by this method. As future work, we plan to consider a method for more flexible sensing and mapping in the various conditions of the sensor and surrounding environment.

REFERENCES

- [1] M. Hashimoto, Y. Matsui, and K. Takahashi, "Moving-object tracking with in-vehicle multi-laser range sensors," *Journal of Robotics and Mechatronics*, vol. 20, no. 3, pp. 367–377, 2008.
- [2] T. Ueda, H. Kawata, T. Tomizawa, A. Ohya, and S. Yuta, "Mobile SOKUIKI Sensor System-Accurate Range Data Mapping System with Sensor Motion," in *Proceedings of the 2006 International Conference on Autonomous Robots and Agents*.
- [3] K. Ohno and S. Tadokoro, "Dense 3D map building based on LRF data and color image fusion," in *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005.(IROS 2005)*, 2005, pp. 2792–2797.
- [4] J. Poppinga, A. Birk, and K. Pathak, "Hough based terrain classification for realtime detection of drivable ground," *Journal of Field Robotics*, vol. 25, no. (1-2), pp. 67–88, 2008.
- [5] A. Nuchter, K. Lingemann, and J. Hertzberg, "Mapping of rescue environments with kurt3d," in *In Proc. IEEE SSRR 2005*, 2005, pp. 158–163.
- [6] Z. Nemoto, H. Takemura, and H. Mizoguchi, "Development of Small-sized Omni-directional Laser Range Scanner and Its Application to 3D Background Difference," in *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE*, 2007, pp. 2284–2289.
- [7] L. Iocchi, S. Pellegrini, and G. Tipaldi, "Building multi-level planar maps integrating LRF, stereo vision and IMU sensors," in *Safety, Security and Rescue Robotics, 2007. SSRR 2007. IEEE International Workshop on*, 2007, pp. 1–6.
- [8] T. Fujita and Y. Kondo, "3D Terrain Measurement System with Movable Laser Range Finder," in *2009 IEEE International Workshop on Safety, Security, and Rescue Robotics (SSRR 2009)*, 2009.
- [9] T. Fujita and T. Yoshida, "3-D Slope Shape Sensing by Laser Range Finder with 4-DOF Sensor Movable Unit," *Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering and Computer Science 2015, WCECS 2015*, 21-23 October, 2015, San Francisco, USA, pp. 382–387, 2015.
- [10] B. Yamauchi, a. Schultz, and W. Adams, "Integrating Exploration and Localization for Mobile Robots," *Adaptive Behavior*, vol. 7, no. 2, pp. 217–229, mar 1999. [Online]. Available: <http://adb.sagepub.com/cgi/doi/10.1177/105971239900700204>
- [11] L. Freda, G. Oriolo, and F. Vecchioli, "Sensor-based Exploration for general robotic systems," in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, sep 2008, pp. 2157–2164. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4651143>
- [12] J. Pellenz, D. Gossow, and D. Paulus, "Robbie: A Fully Autonomous Robot for RoboCupRescue," *Advanced Robotics*, vol. 23, no. 9, pp. 1159–1177, jan 2009. [Online]. Available: <http://www.tandfonline.com/doi/abs/10.1163/156855309X452494>
- [13] C. Dornhege and A. Kleiner, "A frontier-void-based approach for autonomous exploration in 3D," *Advanced Robotics*, vol. 27, no. 6, pp. 459–468, 2013. [Online]. Available: <http://www.tandfonline.com/doi/abs/10.1080/01691864.2013.763720>