Paper:

Motion Planning of Biped Robot Equipped with Stereo Camera Using Grid Map

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Abstract. Recognizing its surroundings is important for biped robots seeking a destination. In this paper, we propose a motion planning method of a biped robot including path planning and obstacle avoidance. The robot obtains distance information on its surrounding environment from images captured by a stereo camera system, and generates a 3D map, then, builds a 2D grid map that locates flat floor regions, obstacle regions, bump regions, gate regions, and un-measured regions to decide its path by using the 2D grid map. Experimental results confirm the effectiveness of the proposed method.

Keywords: motion planning, biped robot, stereo camera, grid map, 3D measurement

1. Introduction

In this paper, we propose a motion planning method of a biped robot equipped with a stereo camera system.

The growing need for autonomous robots to work in regular living environments, e.g., in housework or nursing robots at home, monitoring or guard robots in non-home facilities, and so on, has expanded the study of biped robots operating in such environments [1, 2]. Biped robots can move flexibly by using many degrees of freedom when there is a restriction in the width and the height of spaces for robot movement.

They need visual function to recognize surrounding environments for biped robots to move to the destination. Therefore, there are a lot of studies about sensing methods for biped robots.

A compact range image sensor is proposed in [3], and a biped robot can move autonomously while avoiding obstacles by detecting flat floor and obstacles using this small sensor [4, 5]. Obstacle avoidance and path planning method for biped robots using stereo vision is proposed in [6]. In this study, a biped robot autonomously moves while generating its path by using a 2D grid map obtained with a stereo camera system. In [7–10] is proposed a 3D navigation method for biped robots as well as a biped robot that can climb stairs. In [11, 12], a biped robot can pass through a gate that has a limitation in height direction.

Table 1. Comparison of related works. O: robot can move, X: robot cannot move, (M): robot can measure, (U): robot cannot measure.

	Flat Floor	Obstacle (Wall)	Bump (Step)	Gate
[4, 5]	O (M)	X (M)	X (M)	X (U)
[6]	O (M)	O (M)	X (U)	X (U)
[7–10]	O (M)	O (M)	O (M)	X (U)
[11, 12]	O (U)	O (M)	X (U)	O (M)
This study	O (M)	O (M)	O (M)	O (M)

Table 1 compares related works. In **Table 1**, O means that a robot can move in that environment, X means that a robot cannot move in that environment, (M) means that a robot can measure and recognize that environment, and (U) means that a robot cannot measure and recognize that environment, respectively.

As to the sensing, there is no study about the sensor-based motion planning for biped robots that can measure all of flat floor, obstacle, bump, and gate. Flat floors, obstacles, and bumps can be measured in [7–10]. However, the height of a ceiling is not considered in these studies. In other words, the robot has no ability to measure and to recognize gates, and gates are treated as obstacles in these studies. In [11, 12], the robot can measure gates. However, the robot does not measure flat floors under the assumption that it always moves on flat floor, and bumps are treated as obstacles.

As to the moving range, the same is true for flat floor, obstacle, bump, and gate. There is no study in which the robot can move in all of flat floor, obstacle, bump, and gate.

In this study, we propose a motion planning method in which a robot can move in floor, obstacle, bump, and gate regions while measuring and recognizing these regions with a stereo camera system (**Fig. 1**). The major contribution of this study is to propose a framework of

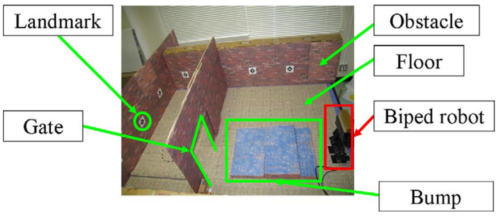


Fig. 1. Biped robot equipped with a stereo camera system and environment including floor, obstacle, bump, gate regions, and landmarks.

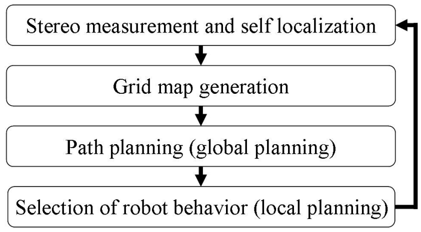


Fig. 2. Flowchart of the motion planning method.

the sensor-based motion planning method for biped robots that can recognize all four environments and take action in response to the sensing results of surrounding environments.

In the sections that follow, Section 2 covers the motion planning method of a biped robot, Section 3 discusses experiments and results, Section 4 describes conclusions and future work.

2. Proposed Method

This study assumes the following three conditions (**Fig. 1**):

1. Objects existing in the environment are classified into:
   - Floor region
   - Obstacle region
   - Bump region
   - Gate region
2. There size and location of landmarks are known.
3. The position of the destination is given to the robot in advance.

Under condition 1, the robot recognizes objects in the environment by distance and shape information. Although the environment where the robot moves is a 3D environment, a generated map is in the form of 2D grids representing positions of objects in each class.

Under condition 2, the robot estimates its position and orientation in the environment.

Under condition 3, the robot plans its path to a destination.

Figure 2 shows the flowchart of the proposed method.

In the first step, the robot measures the distance information of objects from images captured by a stereo camera system. In addition, the robot estimates its position by using landmarks installed all over the environment.

In the second step, the robot updates a 2D grid map which locates floor regions, obstacle regions, bump regions, gate regions, and unmeasured regions that are not yet observed by the robot. In this step, each grid on the 2D grid map is determined whether it is a floor region, an obstacle region, a bump region, a gate region, or an unmeasured region from 3D information.

In the third step, the robot decides its path by using the 2D grid map (global planning). At first, the robot generates the 2D grid map considering interference regions of the biped robot with the obstacle regions. Here, a problem to generate the path to the destination is transformed into that of finding the shortest path along nodes of the 2D grid map. The A* search is used for path planning [13].

In the fourth step, the robot selects its movement sequence based on its path planning result (local planning).

These four steps are repeated until the robot reaches its destination.

2.1. Stereo Measurement

The biped robot acquires 3D information of a surrounding environment by using a stereo camera system installed on the robot itself. **Figure 3** shows the overview of the environment measurement by the robot. **Figure 3**(a) shows an example of an environment, **Fig. 3**(b) shows an acquired stereo image pair, and **Fig. 3**(c) shows a 3D reconstructed shape of the environment.

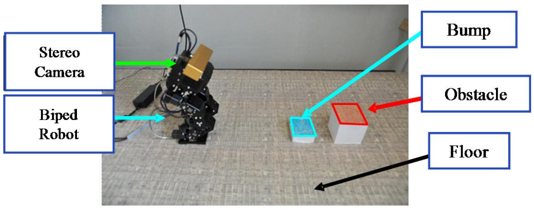
Robot localization error occurs if its position is determined only by odometry alone. It is necessary for the robot to know its position in the map precisely to integrate the on-site measurement data with the already obtained measurement results. Therefore, the robot estimates its position and orientation by using stereo observation with a landmark whose position is known [14].

2.2. Grid Map Generation

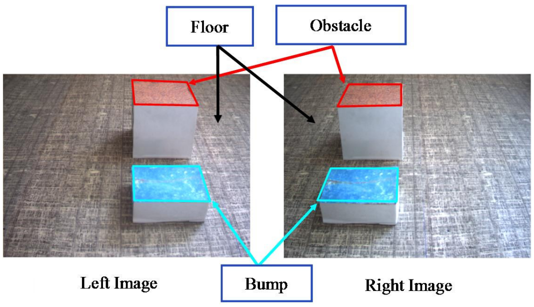
Configuration space (C-Space) [15] is used for representing the robot and the environment. C-Space is the space expressing the robot as a point without size. The biped robot is approximated to a cylinder whose axis coincides with the center of robot's center as shown in **Fig. 4**.

In C-Space, obstacles are enlarged based on robot size, and enlarged objects are called configuration obstacles (C-Obstacles). In this study, the robot is treated in two dimensions without posture and the size of the robot is considered to be the size of a cylinder.

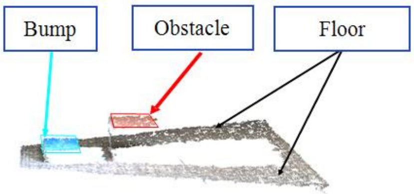
Figure 5 shows an example of grid map generation involving a gate and an obstacle (wall). 3D measurement results (**Fig. 5**(a)) are converted to a 3D grid map (**Fig. 5**(b)) at first, and then C-Obstacle is considered (**Fig. 5**(c)).



(a) Overview.



(b) Stereo image.



(c) Measurement results.

Fig. 3. Stereo measurement.

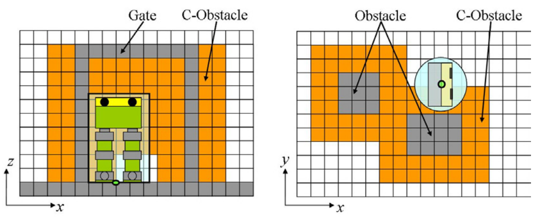
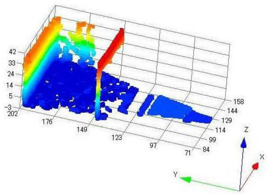


Fig. 4. Configuration obstacle (C-Obstacle).

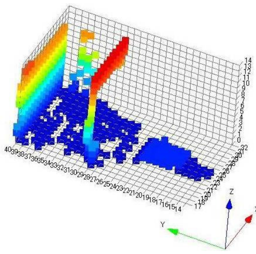
After constructing the 3D grid map in C-space, a 2D grid map is generated. Individual grid cells on the 2D grid map are classified into floor regions, obstacle regions, bump regions, gate regions, or unmeasured regions by projecting the 3D grid map onto the 2D grid map. The obstacle region is the region where the robot cannot go in, the bump region is where there are grids whose heights are different, and the gate region is that the robot can pass through grids by squatting.

Figure 6 shows as a 2D grid map generated with measurement points from **Fig. 3**. Gray grid cells indicate the floor regions, blue grid cells indicate the bump regions, red grid cells indicate the obstacle regions, and white grid cells indicate the unmeasured regions, respectively.

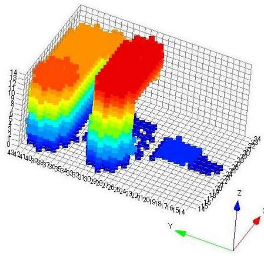
Plural measurement points might be projected to one



(a) 3D measurement result.



(b) 3D grid map.



(c) C-Obstacle.

Fig. 5. Grid map generation.

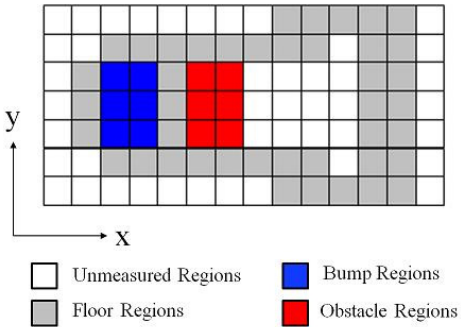


Fig. 6. 2D grid map.

grid in the 2D grid map. When grid information on the same measurement point is different, the majority in the measurement points is selected and the grid is judged whether it is the floor region, the obstacle region, the bump regions, or the gate region. When the measurement point is not projected to the grid, the grid is judged to belong to an unmeasured region. Unmeasured regions exist due to occlusion and the limited field of view of the stereo camera system.

In the proposed method, the measurement procedure is repeated, and then the 2D grid map is updated continuously (**Fig. 7**). As the robot moves, unmeasured regions may be reduced, and the robot moves appropriately to reach its destination.

2.3. Path Planning

The grid map is converted to a 2D graph that consists of nodes and arcs. A path on which the robot can move safely and efficiently to the destination is planned on the generated graph (**Fig. 8**).

Each grid cell of the 2D grid map is first defined as a node connected to neighboring grid cells, and a cost is

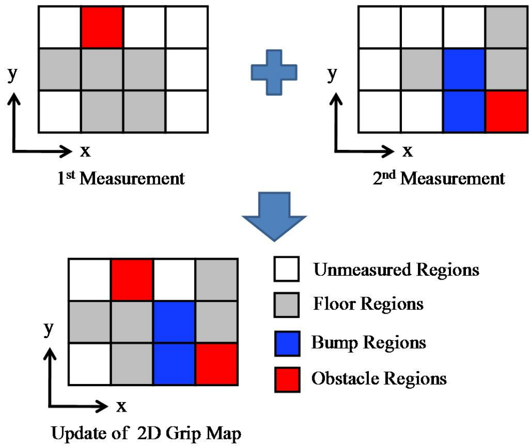


Fig. 7. Update of 2D grid map.

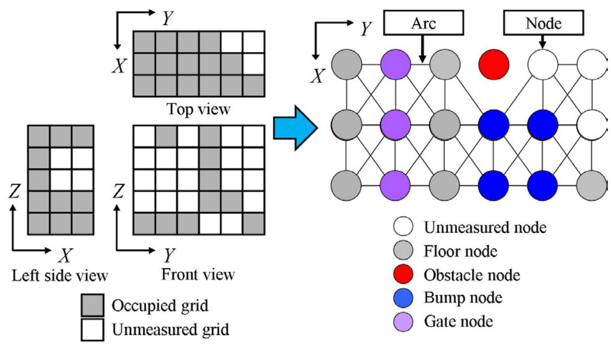


Fig. 8. Graph search.

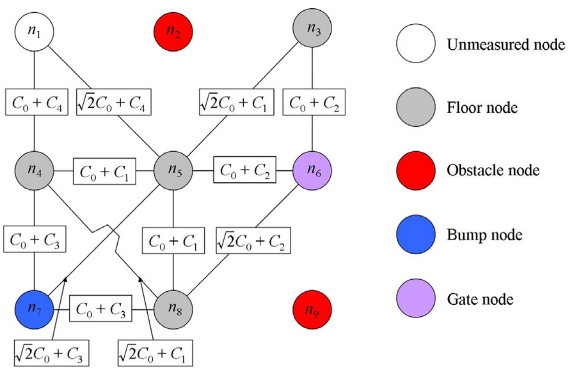


Fig. 9. Costs between nodes in a graph.

given to each set of adjacent nodes. A cost between two nodes is defined as follows:

$$C(n_i,n_j) = C_{distance}(n_i,n_j) + C_{motion}(n_i,n_j) \quad . \qquad (1)$$

where n_i and n_j are adjacent nodes, $C(n_i,n_j)$ is a total cost between nodes n_i and n_j, $C_{distance}(n_i,n_j)$ is a cost of travelling distance between n_i and n_j, and $C_{motion}(n_i,n_j)$ is a cost of movement difficulty (movement time and effort) between n_i and n_j, respectively (**Fig. 9**).

The travelling distance cost between two nodes in a longitudinal direction or in a transverse direction is defined $C_{distance} = C_0$, and that in an oblique direction is defined $C_{distance} = \sqrt{2}C_0$, respectively.

The robot moves easily from a floor node (floor grid cell) to another floor node (floor grid cell). Let the movement difficulty cost C_{motion} in this case be C_1.

The robot passes through a gate, moving from a floor node to a gate node. Let the cost in this case be C_2. Here, C_2 is higher than C_1 because the robot must move while squatting, which takes more time than on a flat floor.

The robot can also move from a floor node to a bump grid cell, and vice versa. Let the cost in this case be C_3. Here, C_3 is higher than C_2 because movement between different heights takes more time than between the same heights.

Movement from a floor grid to an unmeasured grid takes more time than in the above three cases due to additional measurement. Then, the cost in this case, C_4, is higher than C_3.

Paths crossing obstacles are forbidden because the robot cannot move over obstacles.

Finally, the path planning problem is defined as a search problem on the generated graph. Graph search is performed by the A* search algorithm like [13], and the path that has the smallest cost can be obtained.

2.4. Selection of Robot Behavior

The behaviors of the biped robot, in other words, foot step and body motion, in floor walking, gate passing, bump stepping-up, and bump stepping-down are generated in advance. Therefore, the robot behavior is selected from pre-generated patterns (pre-computed motion primitives) in response to the result of path planning.

If the generated path lies on floor regions, for example, the robot moves from the grid cell of the present position to the next grid cell, in one of eight directions. At first, the robot selects the behavior of turning to the direction of the grid cell to move in. Next, by selecting forward motion the robot moves to the next grid cell.

When the grid cell of the present position of the robot is in a floor region and the next grid cell is in a bump region, the robot selects the movement of stepping up on the bump, and vice versa, when the present position of the robot is in the bump region and the next grid cell is in a floor region, the robot selects the movement of stepping down to the floor. In the stepping up and down movement, the robot first measures the direction of the bump edge, changes its orientation to in front of the bump, and then moves in the gate from the perpendicular direction of its edge.

Gate passing motion is also generated. The robot at first squats in front of a gate and then goes through a gate in a squat pose.

Table 2. Pre-computed motion primitives.

Primitive	Speed	Comment
Straight-forward	16sec	5cm
Turn-direction	5sec	45deg
Step-up-bump	96sec	3cm bump
Step-down-bump	96sec	3cm bump
Pass-gate	48sec	37cm gate

3. Experiments

3.1. Experimental Setup

The composition of an experiment system is as follows. A stereo camera system is installed on a biped robot and transmits images to a computer by cable. The computer processes the images and executes path planning and behavior selection. The behavior commands for the biped robot are transmitted from the computer by cable, and the robot moves according to the commands.

We used Point Gray Bumblebee 2 as the stereo camera. The size of acquired images is 512 $\times$ 384 pixels. The baseline length of the camera was approximately 12cm.

The computer had 3GB memory and Intel Core2 Quad 2.4GHz CPU.

The biped robot is a ZMP e-nuvo WALK ver. 3. The size of the robot is approximately 35 $\times$ 16 $\times$ 14cm. The number of degrees of freedom of the robot joints is 6 for one leg, 2 for ankles, 3 for groins, and 1 for knee.

Stereo measurement is unstable and difficult when objects with poor surface texture. Therefore, objects with rich texture were used in the experiment (**Fig. 1**). Note that the robot recognizes flat floors, obstacles, bumps and obstacles only from 3D information acquired from the stereo camera, not from color information.

The two types of landmarks used for self-localization were a 7.5cm radius circle and a square 5cm on a side.

The experimental area was 180 $\times$ 140cm. The black cross is the robot's destination, around which a broken 10cm radius circle was drawn.

The pitch of each grid of a 3D grid map was 5 $\times$ 5 $\times$ 3cm (height), and that of 2D grid map was 5 $\times$ 5cm. Cost between grids in the A* search were set at $C_0 = 1$, $C_1 = 1$, $C_2 = 5$, $C_3 = 10$, and $C_4 = 100$ – parameters were decided based on the execution times of pre-computed motion primitives.

The robot had five pre-computed motion primitives (**Table 2**) generated based on robot dynamics forbidding the robot to move unstably using a dynamics simulator of ZMP e-nuvo WALK ver. 3.

The robot changes direction by selecting a turn-direction primitive, then moves to the next grid cell by selecting a straight-forward primitive when the next grid cell is in an oblique direction. The robot selects step-up and step-down primitives if the next grid cell is a bump and a pass-gate primitive when the next grid cell is a gate. **Figures 10** and **11** show the step-up and step-down primitives.

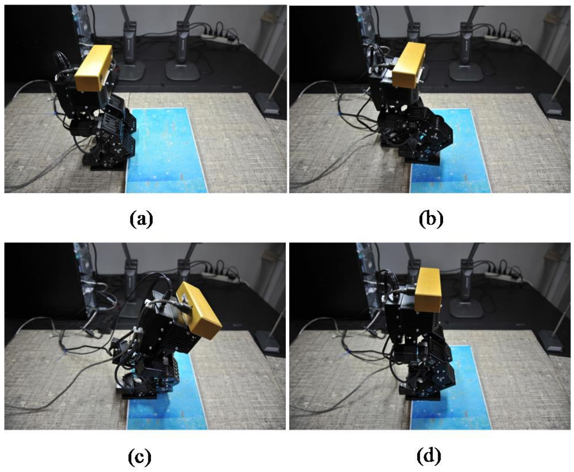


Fig. 10. Step-up primitive.

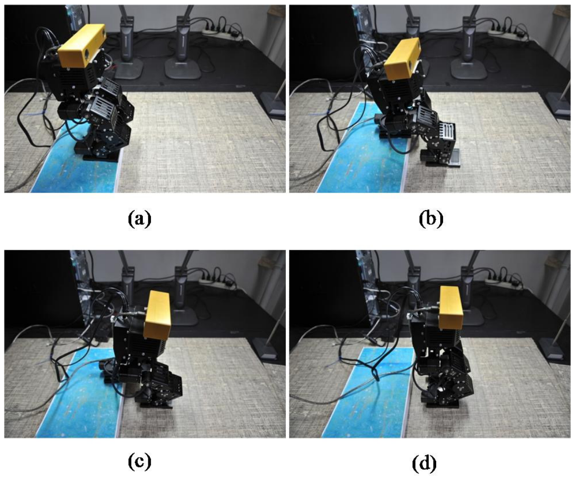


Fig. 11. Step-down primitive.

3.2. Experimental Results

Experiments with the robot moving in the experimental area were executed under the four following conditions[1].

1. Floor and obstacle: experiments 1 (**Fig. 12**) and 2 (**Fig. 13**)
2. Floor, obstacle, and bump: experiment 3 (**Fig. 14**)
3. Comparison of two motion planning strategies: experiments 4 (**Fig. 15**) and 5 (**Fig. 16**)
4. Floor, obstacle, and gate: experiment 6 (**Fig. 17**)

1. Videos are online at the following URLs.
Floor and obstacle (16x):
`http://sensor.eng.shizuoka.ac.jp/~yamasita/movie/research/BipedRobot1Floor16x.wmv`
Floor, obstacle, and bump (16x):
`http://sensor.eng.shizuoka.ac.jp/~yamasita/movie/research/BipedRobot2Bump16x.wmv`
Floor, obstacle, and gate (8x):
`http://sensor.eng.shizuoka.ac.jp/~yamasita/movie/research/BipedRobot3Gate8x.wmv`

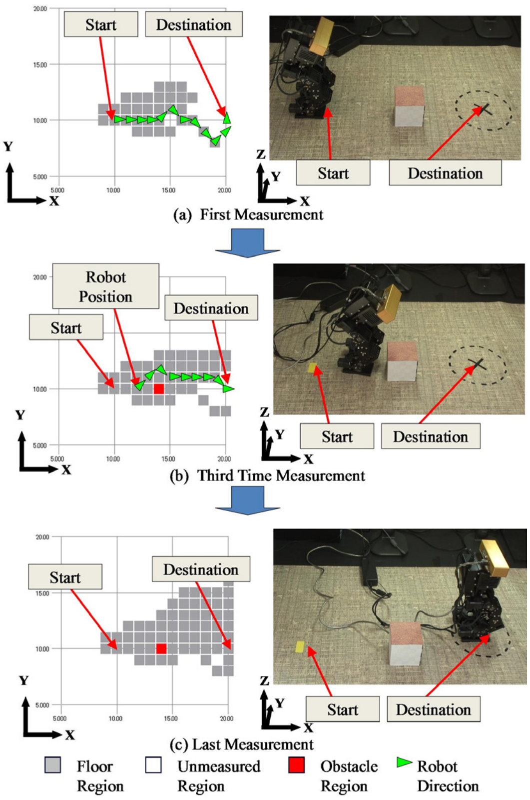
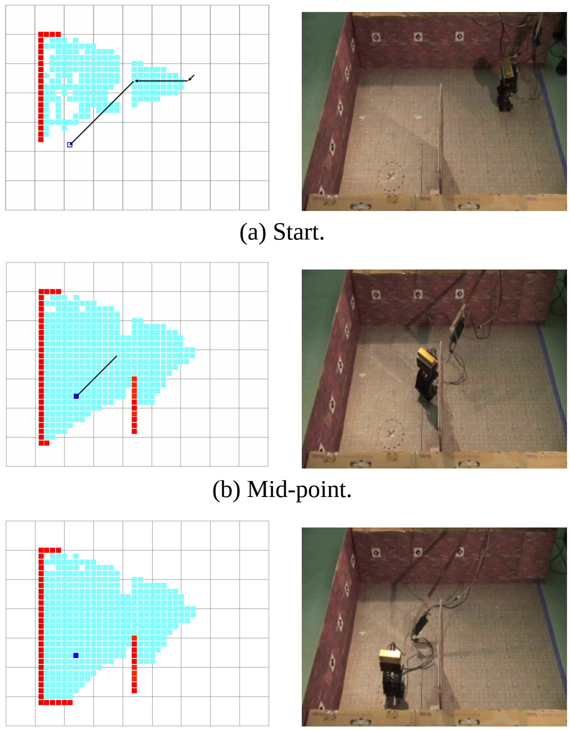


Fig. 12. Experiment 1 (floor and obstacle).



(a) Start.

(b) Mid-point.

(c) Destination.

Fig. 13. Experiment 2 (floor and obstacle).

Table 3. Travelling distances and execution times in Experiments 4 and 5.

Experiment	Distance	Execution time
Fig. 15	133cm	17.0min
Fig. 16 (our method)	85cm	10.0min

Experiments 1 and 2 confirmed that the robot moved to the destination while avoiding obstacles. **Figure 12** shows 2D grid maps at left and the robot measuring the ambient environment at right. In the 2D grid map, gray grid cells are for floor regions, blue for bump regions, red for obstacle regions, purple for gate regions, and white for unmeasured regions. Green arrows are the planned path along which the robot was scheduled to move to the destination. **Figures 12**(a)–(c) show measurement results for the 1st, 3rd, and 16th times. In 1st-time measurement, the robot could not recognize obstacle regions and planned its path to go straight to the destination. By the 3rd time, the robot recognized the obstacle and planned its path again to avoid obstacle regions.

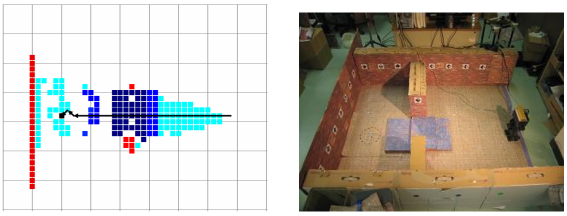
Figure 13 shows results in which the obstacle is taller than the camera. In this case, the robot could successfully reach the destination, too.

In Experiment 3, the robot moved to the destination while stepping up and down between the floor regions and the bump regions. **Figure 14** shows an environment with two different bumps of different height – 3 and 6cm. In this case, the robot could successfully climb up and down the two steps and reach the destination.

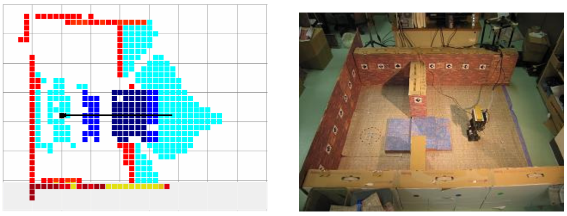
Experiments 4 and 5 were done for comparison of our approach with a reference resulting from path planning where the robot moved only on floor regions. **Figures 15** and **16** show the results of these experiments. **Figure 15** shows the path given by the reference method, and **Figure 16** shows the path given by our approach. The robot judged it faster to go over rather than around the bump. Comparing the two results, movement distance by our approach was approximately 50cm shorter and movement time was approximately 7 minutes shorter (**Table 3**). Consequently, our approach is superior in the movement distance and the movement time to the method which regards bumps as obstacles.

In the last experiment, the robot moved to the destination while passing through the gate (**Fig. 17**). The robot recognized the gate and moved through it while squatting (**Fig. 17**(b)).

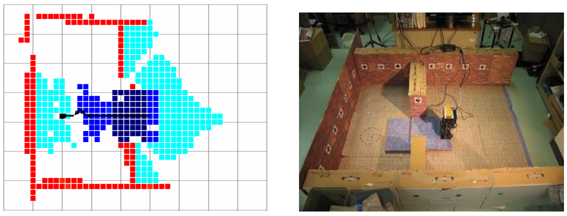
Table 4 shows the execution times of Experiments 3 (**Fig. 14**, floor, obstacle, and bump) and 6 (**Fig. 17**, floor, obstacle, and gate). Distance straight from the initial position to the destination is 100cm in Experiment 3 and 104cm in Experiment 6. The execution time of Experiment 3 is longer than that of Experiment 6, although the travelling distance of the robot in Experiment 6 is longer than in Experiment 3, because the step-up-bump and step-down-bump motions take time (**Table 2**) and there are two step-up motions and two step-down motions in Experiment 3.



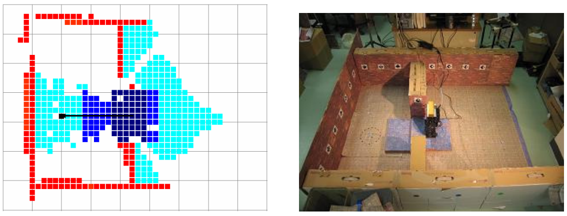
(a) Start.



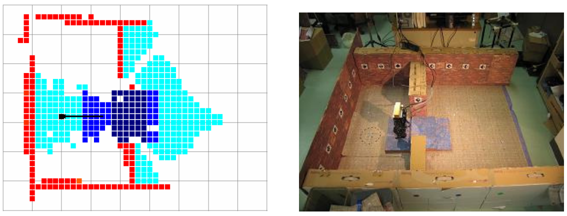
(b) Before bump.



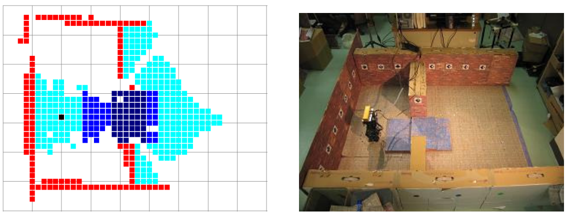
(c) Bump 1 climbing-up.



(d) Bump 2 climbing-up.



(e) Bump 3 climbing-down.



(f) Destination.

Fig. 14. Experiment 3 (floor, obstacle, and bump).

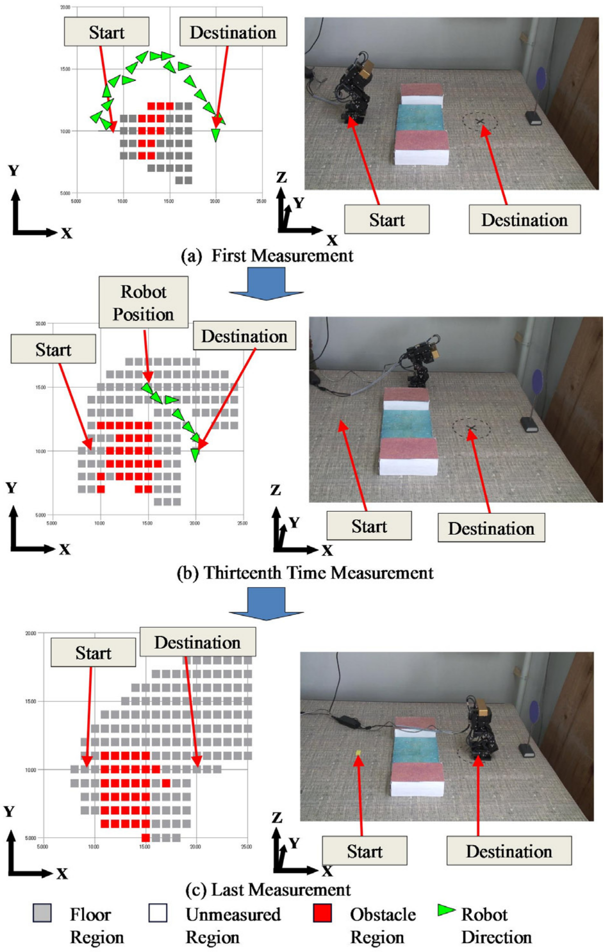


Fig. 15. Experiment 4 (floor, obstacle, and bump). The path was given under the condition that the robot can move only in floor regions.

Table 4. Execution times of Experiments 3 and 6.

Experiment	Execution time
Fig. 14 (floor, obstacle, and bump)	16.8min
Fig. 17 (floor, obstacle, and gate)	9.2min

These results verified that the proposed method could measure 3D environments that contains obstacles, bumps, and gates, express the environment properly, and plan robot motion successfully coping with different situations.

4. Conclusions

In this paper, we have proposed a method for biped robots to move to a destination. The robot obtains distance information from images captured by a stereo camera system. Then, the robot generates a 2D grid map that locates floor regions, obstacle regions, bump regions, gate regions, and unmeasured regions. The robot decides its

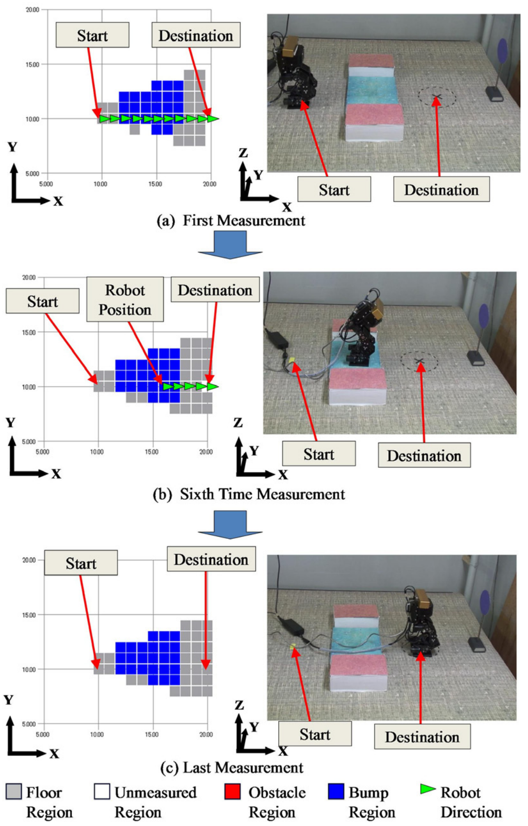


Fig. 16. Experiment 5 (floor, obstacle, and bump). The path was given under the condition that the robot can move in floor regions and bump regions (by our method).

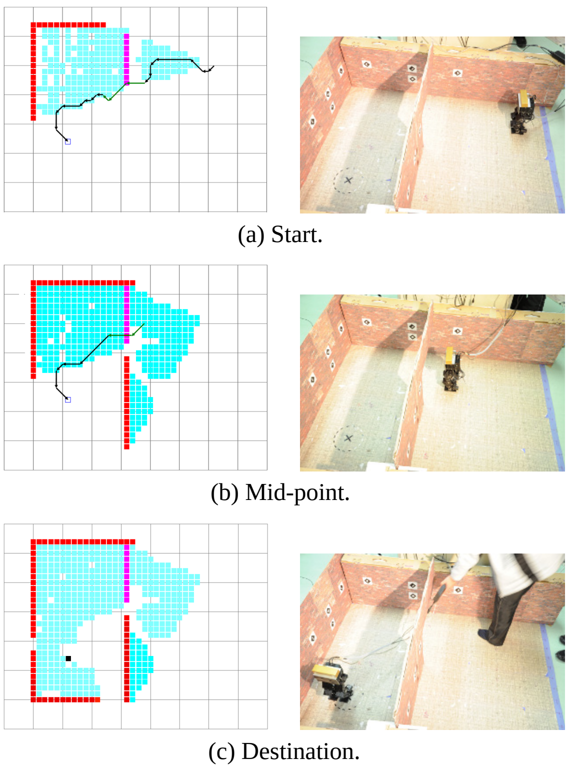


Fig. 17. Experiment 6 (floor, obstacle, and gate).

path by using the 2D grid map, and selects appropriate movement. Experimental results confirmed the effectiveness of the proposed method.

Although the proposed method works well, it has the following limitations:

1. Objects must be richly textured for dense stereo measurement.

2. The robot moves at a constant speed because its movements are combination of the pre-computed motion primitives.

3. Landmarks are required for robot self-localization.

As future work, we plan to execute self-localization without landmarks using a stereo camera [16]. Dynamic foot step planning [17–19] and planning in dynamic environments [20, 21] are also important.

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