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Automatic laser-based geometrical modeling using multiple mobile robots

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Abstract— **This paper presents an automatic 3-D laser measurement system of an environmental structure using the cooperation of multiple mobile robots. The robots are equipped with two types of laser sensors and measure the 3D environmental structure while moving around the environment automatically. To identify the measurement positions by the robots, Cooperative Positioning System (CPS) is utilized which is a highly precise positioning technique of co-operative multiple robots. Since the positions of the robots for 3D laser scanning are identified precisely, the 3D environmental model can be constructed without any post-processing procedure such as the ICP algorithm or manual intervention. Therefore, a fully automatic 3-D measurement system of the environmental model can be realized. This paper presents the manual and automatic planning experiments of measurement procedure using the partially measured structure of the environment. Planning and measurement experiments by three mobile robots are successfully carried out.**

I. INTRODUCTION

Laser-based 3D modeling is a popular technique for constructing a 3D model of a real object. Digital preservation of historical and cultural heritages [1],[2], reverse engineering, search of survivors in collapsed building for rescue operation are good examples of the laser-based 3D modeling.

For constructing a 3-D model of environment using a laser range finder, a number of range images are taken from different viewpoints around the environment since the measured field by a scan is limited. Then, these images are aligned using post-processing procedures, such as the ICP algorithm[3], [4]. After the post-processing procedures, the range images described in the sensor co-ordinate system are transformed to the global co-ordinate system, and the entire shape of the architecture is obtained. However, in general, when sufficiently exact scan pose estimates are not available, a human operator registers the positions before applying the ICP method in order to ensure that the images converge to the proper poses. This procedure is quite time-consuming and is considered to be a significant obstacle for developing an automatic 3-D laser measurement system. Also, all of the images must contain sufficient feature shapes and must sufficiently overlap each other, which requires dense scanning from a number of positions, in order to precisely register the range images using the ICP algorithm.

Another approach that requires no post-processing procedures such as the ICP algorithm can also be considered, which involves the precise identification of the position of the range sensor at each measurement. Since this method can obtain the transformation matrix from the sensor specific co-ordinate system to the global co-ordinate system, local range images are converted directly into the global co-ordinate system with a simple transformation calculation. For this approach, we have proposed a 3-D measurement system of the environment using a group of mobile robots and an on-board laser range finder[5]. The proposed system uses the Co-operative Positioning System (CPS)[6], [7] for multiple robots, which has been proposed as a highly precise position identification technique for mobile robots. The automatic measurement system of the environmental model is realized by combining CPS and an on-board laser range finder. This system can construct a 3-D model of the environment without any post-processing procedure such as the ICP algorithm or manual intervention. In addition, it is possible to register range images even if the number of measurements is few and the data is sparse, e.g., if the range images contain insufficient feature shapes or overlapping regions. It is also possible to construct a 3-D model in environments where GPS is not available, such as inside structures or in an indoor environment.

This paper proposes the extension of the proposed system [5] for an automatic 3-D laser measurement system. The measurement procedure is planned manually and automatically based on the partially measured structure of the environment. Planning and measurement experiments by the mobile robots are successfully carried out. In Section 2, an overview of the previous approaches will be presented. Section 3 will present a short introduction to CPS, which is the highly precise positioning technique for mobile robots in unknown environments, while Section 4 will give a detailed description of the proposed system, In section 5, path generation experiments for mobile robots according to the partially measured environmental model will be described.

II. RELATED WORK

The proposed system is related to the Simultaneous Localization And Mapping (SLAM) method[8], [9], [10], [11], [12], [13], [14], [15], which has attracted a great deal of attention in the robotics community. The 3-D model obtained by the proposed system can be refined by applying ICP. Obviously, the refined measurement position from ICP can also be fed back to the positioning system. This closed-loop control will increase the accuracy of both the 3-D model and the robot position.

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In SLAM, the map is created by performing two processes simultaneously, localization of the robots and measurement of the surrounding environmental information. Thus, the following two elements are essential to create a high-accuracy environmental map with the SLAM system.

(1) High accuracy self-localization system
(2) High accuracy measurement system for surrounding environment

There are several issues to be considered for Item (1). The self-localization method that has been proposed until now, for example, odometry, does not have the ability to measure the self-location of a mobile robot with high accuracy in a bumpy area or in an environment with pitch differences. The SLAM system, which sequentially identifies the location of a mobile robot based on the previous positioning record, requires the characteristic features of the environment and has the same problems as odometry, which is the accumulation of measurement error caused by the measurement device. To reduce error accumulation, loop detection and refinement of the obtained models and paths are the principal, critical issues in SLAM.

Concerning Item (2), systems using a laser range finder are effective and often used from the point of view of cost and accuracy. Originally, laser range finders were large-scale, expensive, and intolerant of vibrations. However, recently, smaller and more inexpensive laser range sensors have been developed and are readily available.

A system that obtains high-accuracy environmental data with laser range finders is used not only in robotics but also in other fields, such as in creating digital archives of cultural heritage. For example, some projects to save accurate 3-D images of vanishing precious cultural heritage as digital data are being carried out at the Angkor monument in Cambodia[16], the Forbidden City in China[17], and the Archaeological Area in Pompeii, Italy. For these projects, high accuracy laser measurement devices or digital cameras are used.

III. Co-operative Positioning System (CPS)

Let us consider the system in which a mobile robot equipped with an on-board laser range finder moves around a measurement target and scans the target from several different positions. If all of the measurement positions are identified with high accuracy, the range data acquired at each position can be converted to the global co-ordinate system by a simple co-ordinate transformation calculation.

Several position identification methods have been proposed, and these methods can be classified into four categories:

(1) Integrate output from internal sensors such as wheel encoders or acceleration sensors.
(2) Observe external landmarks by external sensors such as laser range finders or cameras.
(3) Use the Global Positioning System (GPS).
(4) Use the Simultaneous Localization and Mapping (SLAM) method.

Method (1) is referred to as odometry, or dead reckoning, and is a commonly used positioning technique, especially for wheeled vehicles. However, there are drawbacks associated with this method. For example, the accuracy of position identification in uneven terrain is quite low due to slippage of the wheels, and 3-D positioning including elevation is impossible. Method (2) has high accuracy if the landmarks placed on the moving path can be measured precisely. However, landmarks must be placed beforehand along the moving path, and a precise map of these landmarks must be available. Therefore, method (2) cannot be used in an unknown environment. Method (3) can be considered as a special case of method (2) and has recently become very popular, especially for field robots. However, this method also has several drawbacks. For example, active fields of robots are limited to an outdoor environment with an unobstructed view of satellites, and the accuracy is currently not so high, unless the special techniques described in Section 1 are used. Method (4) is based on matching sequentially observed local features acquired by external sensors such as laser range finders or cameras. When considering the features as landmarks, this constitutes a general case of method (2). Although this method is a prospective technique for precise position identification in unknown and unstructured environments, precise and sufficient information between consecutive observations must be acquired through dense measurements.

To overcome these limitations for the position identification problems and achieve accurate positioning of mobile robots, Kurazume et al. proposed the Co-operative Positioning System (CPS)[6]. In this system, multiple robots with highly precise measurement devices for their mutual positions are controlled co-operatively. This can lead, compared to conventional positioning techniques, to high positioning accuracy, even in unknown and uneven environments.

The basic principle of CPS is as follows: Divide the robots into group A and group B. Group A remains stationary and acts as a landmark while group B moves. Group B then stops and acts as a landmark for group A. This alternating behaviour is repeated until the target position is reached. By using the concept of "portable landmarks," CPS has a far lower accumulation of positioning errors than dead reckoning and can work in three dimensions, which is not possible by ordinary dead reckoning. In addition, CPS can be used in an unknown environment, since there is no need to place landmarks beforehand.

An example of CPS is shown in Fig.1. This example is for a robot system consisting of a parent robot with a sensing device such as a laser range finder and two child robots. The sensing device can measure the relative positions of the child robots from the parent robot. First, assume that the initial position of the parent robot is measured or defined beforehand.

(1) Child robots 1 and 2 are moved and stopped.
(2) The parent robot measures the distance, azimuth, and elevation angles to child robot 1 and identifies the position of child robot 1.

(3) The position of child robot 2 is identified in the same manner as in Step 2.
(4) The parent robot moves and stops. The distances, azimuth, and elevation angles to child robots 1 and 2 are then measured, and the position of the parent robot is calculated using the triangular surveying technique.
(5) Repeat Steps 1 through 4 until the target position is reached.

Though the principle of CPS is simple, a position calculation that suppresses error accumulation is rather complicated[7]. In CPS, although the accuracy is quite high, measurement errors are gradually accumulated with the characteristics of the errors depending on the moving histories of the robots. To minimize error accumulation by taking the moving histories into account, a nonlinear least squared method based on the sequential estimation of error covariance matrices is proposed. The performance of CPS has been tested through many experiments in a variety of environments, such as an unpaved outdoor environment with steep slopes, and confirmed that, compared to odometry, highly precise robot tracking is achievable [7].

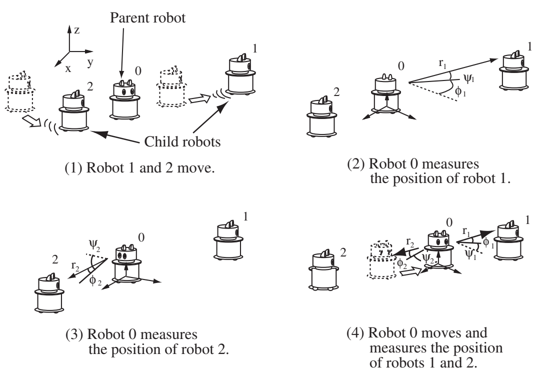


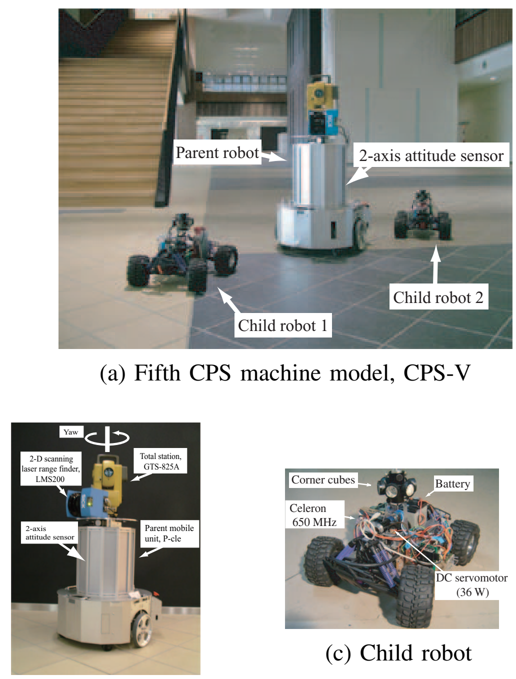
Fig. 1. Co-operative Positioning System (CPS)

IV. Construction of a 3-D environmental map using multiple robots

This section presents a new measurement system for the precise construction of a 3-D environmental map by combining CPS for multiple robots and a laser range finder. In this system, mobile robots move around a large-scale target and scan the target by an on-board 3-D laser range finder from several viewpoints. Each measurement position is precisely identified by CPS using a parent robot and two child robots. First, the fifth CPS machine model, called CPS-V, which is equipped with a 2-D laser range finder and a scanning mechanism, is introduced, and the experimental results for the construction of indoor and outdoor environmental maps by CPS-V are given.

A. Fifth CPS machine model (CPS-V)

Figure 2 (a) shows the fifth CPS machine model, CPS-V. This system consists of a parent robot (P-cle, Parent mobile unit, Fig.2(b)) and two child robots (HPI Japan, Fig.2(c)). The parent robot is equipped with an on-board 2-D laser range finder (LMS 200, Sick), a high-precision two-axes altitude sensor (MD900T, Applied Geomagnetics), and a total station for the survey (GTS-9005A, TOPCON Ltd.)(Table I), which is used to measure the relative positions of the child robots. Even if the body is tilted on a slope, the body inclination is compensated by an altitude sensor, and precise positioning of the robots is achieved. The 2-D laser range finder can acquire 2-D slit-like range data within the range of 80 m and 180 ° , as shown in Table II. The parent robot has a rotating table on the top of its body, and by rotating the table around the vertical axis while scanning using the 2-D laser range finder, 360° 3-D range images as shown in Fig.3 are acquired in 37.8 s.



(a) Fifth CPS machine model, CPS-V

(b) Parent robot

(c) Child robot

Fig. 2. CPS-V is composed of two types of robots

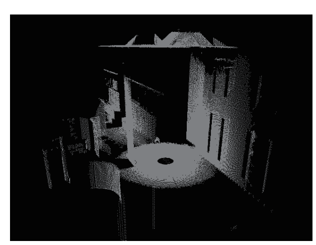


Fig. 3. Range data obtained in one scan

B. Experiment to construct a map of large-scale urban district

Using the proposed system, an urban district environmental map of the Fukuoka Island City area, which is located in the Higashi-ku district of Fukuoka City, Japan, was created. The experiment environment consists of a house and a park,

TABLE I
SPECIFICATIONS OF THE TOTAL STATION, GTS-9005A

GTS-9005A (TOPCON Ltd.)	
Range	1.3 ∼ 2,200 m
Resolution (distance)	0.2 mm
Resolution (angle)	3”
Precision (distance)	± 2+2 ppm mm
Precision (angle)	±5”

TABLE II
SPECIFICATION OF THE LASER RANGE FINDER, LMS200

LMS 200 (SICK Corp.)	
Range	80 [m]
Field of view	180°
Resolution (distance)	10 [mm]
Resolution (angle)	0.5°

where the difference in height is approximately 2 m. Some of the results are shown in Figs.4 and 5. In this experiment, the parent robot measured its surroundings at 45 different viewpoints and moved around up to 115.8 m in x-direction and 131.8 m in the y-direction while traveling a total of 543.4 m. Compared to the 44 movements of the parent robot, the child robots traveled and changed their locations 8 times. The experiment shows that the proposed system has the ability to create a precise 3-D environmental map, even in a large outdoor environment.

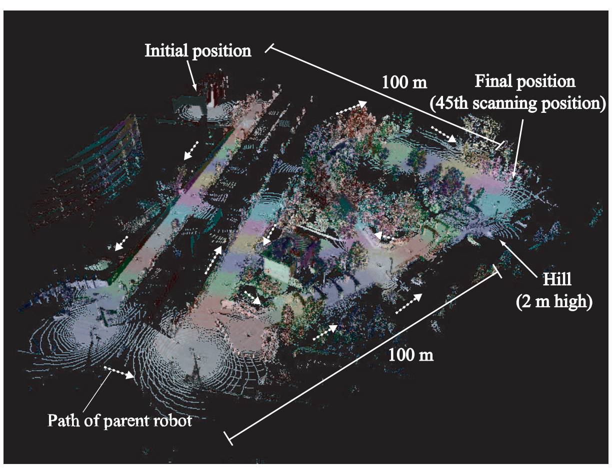


Fig. 4. Obtained 3-D environmental map (overall view)

V. PATH GENERATION EXPERIMENT FOR AUTOMATIC 3-D MEASUREMENT SYSTEM

In the experiments in Section IV-B, the measurement points for the robots were determined previously by a human operator, and the robots were directed to move to those positions. However this is not always possible. For example, consider the case in which the proposed system is applied for the 3-D measurement of the inside of collapsed buildings after a large earthquake. In this situation, a human operator would not be able to visually check where to move the mobile robots. Even if an on-board video camera is available, it would be difficult to plan a safe and global path due to the lack of depth information. On the other hand, the partially constructed 3-D map obtained by the proposed system provides useful information for searching a next measurement position and the pathway to the point. Since the partial architectural structures have been obtained in 3-D, the operator can freely observe the range images from arbitrary viewpoints and figure out the optimal path intuitively. The following sections introduce a path generation experiment using partially obtained 3-D models and an automatic 3-D measurement experiment.

(a) (b)

Fig. 5. Comparison of actual environment with constructed 3-D map

A. Path generation experiments using a partially obtained 3-D model

The environment for the path generation experiment is shown in Fig.6. In this experiment, a 2-D grid map and bird-view images of the partial 3-D model are presented for the operator to determine the next measurement points. The 2-D grid map represents the structure of the environment by cutting the 3-D model at constant height from the ground. The bird-view images of the partial 3-D model are created based on the 3-D environmental data acquired so far, as in Figs.9 and 10.

The 2-D grid map is created as follows. At first, the point data within a certain range of height are extracted from the point clouds of the 3-D environmental model. Next, the extracted data are projected to a planar 2-D grid map with uniform squares with sides of 200 mm. The quadtree format, which has the advantage that less memory is required, is used. The processing time for data conversion is 0.06 s on a Pentium 4 running at 3.00 GHz. The planar map of arbitrary height can be generated almost instantaneously.

The parent robot traveled a total of 220 m around the building, within an area measuring 106 m in the x-direction and 33m in the y-direction. The path of the parent robot is shown in Fig.7. Figures 8 and 9 present the 3-D environmental map. Figure 11 shows the 2-D grid maps and path generation procedures based on the maps. In Fig.11, the square marks show the current position of the parent robot, and the triangular marks indicate the next target position for an environmental measurement. In these experiments, the next target position was determined by a human operator based on the 2-D grid maps and bird-view images. Although the paths to the target positions were generated automatically by assuming that there was no unobserved obstacles in the pathway, the actual motion of the robots was made in manual operation for safety reasons.

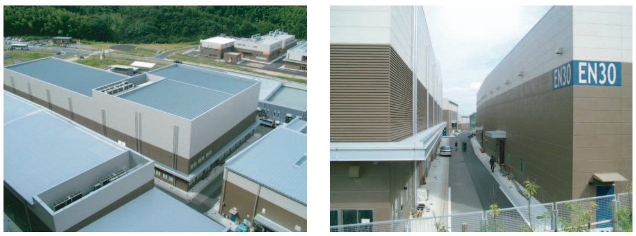


Fig. 6. Experimental environment surrounded by buildings

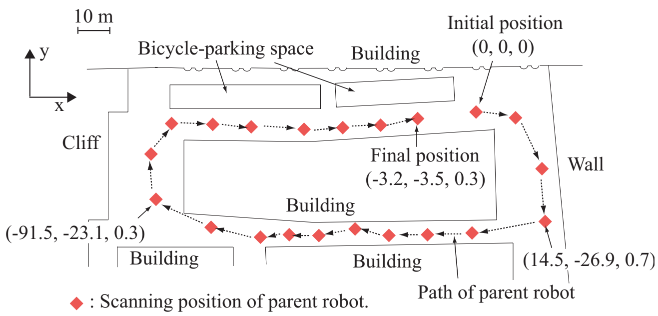


Fig. 7. The path of the parent robotaround the building

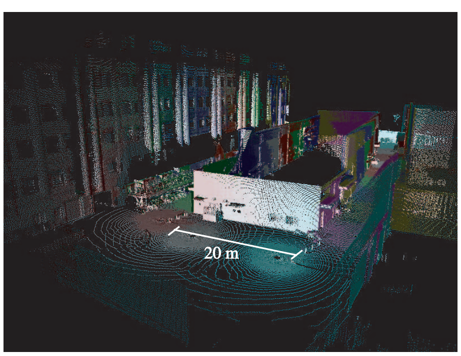
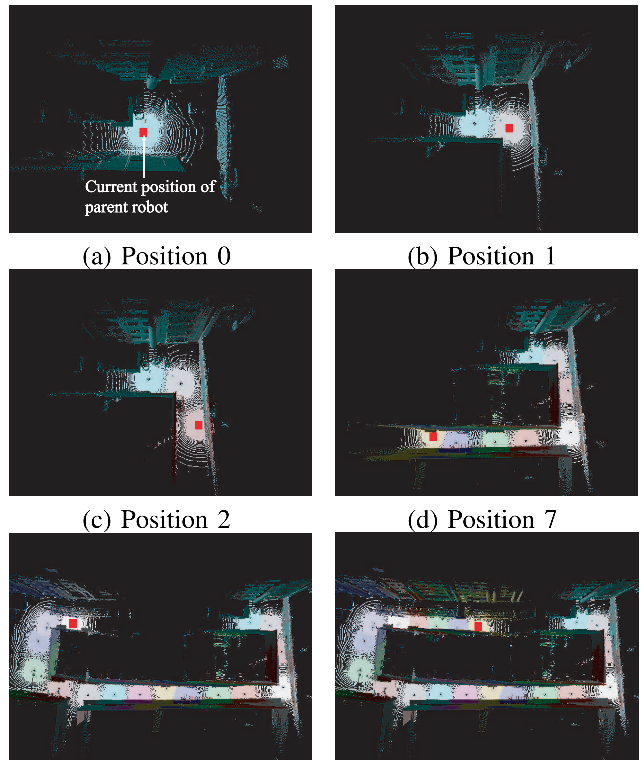


Fig. 8. Obtained 3-D environmental map

The next target position of the parent robot is selected so that the distance from the current position is less than 23 m, which is the maximum distance for adjacent points in range data to be less than the grid width. In other words, if an object is located further than 23 m, some grids covered by the object are not detected as being in the occupied grid, and the robot should not move in this area.

(a) Actual view (b) Obtained 3-D models

Fig. 9. Obtained 3-D model



(a) Position 0 (b) Position 1

(c) Position 2 (d) Position 7

(e) Position 15 (f) Position 19

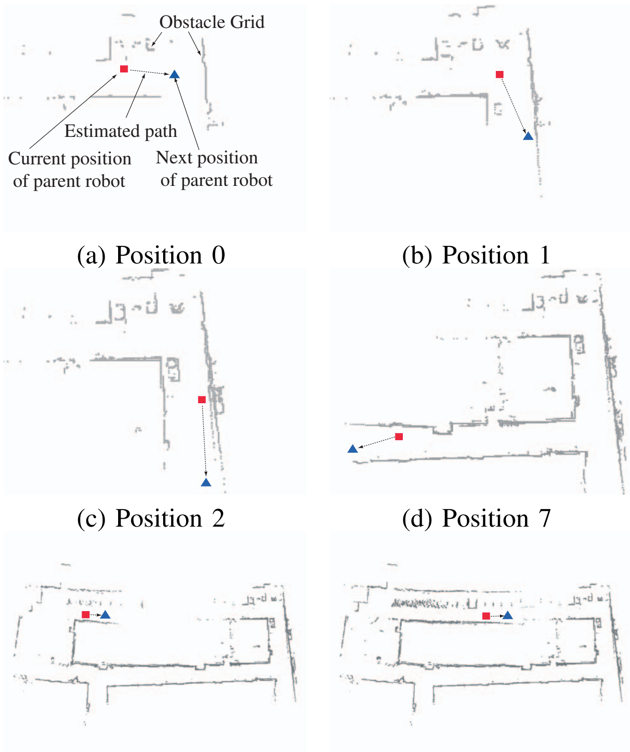
Fig. 10. The partially observed 3-D model presented for the operator

B. Automatic 3-D measurement experiment

The next step is the automatic generation of the target positions based on the 2-D grid map. Figure 12 shows the indoor environment for automatic generation experiments of the target measurement positions. Figure 13 represents the grid map with squares with sides of 500 mm and a virtual CPS-V model.

Figure 14(a) shows the 3-D model of the corridor acquired at the initial position (position 0) and the grid map created according to the point data. The next target position is selected automatically as follows. The distance from the current position is less than 7 m, which is the reliable distance of the laser measurement, the position is one of the furthest points, and there is no obstacle between the point and the current position. Figure 14(b) shows the result of the laser measurement after moving to the new position (position 1).

Figure 15 shows the sequential procedure of the measure-



(a) Position 0 (b) Position 1

(c) Position 2 (d) Position 7

(e) Position 15 (f) Position 19

Fig. 11. Generated 2-D grid map at each parent's position

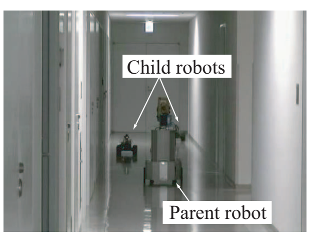


Fig. 12. Experimental environment : corridor

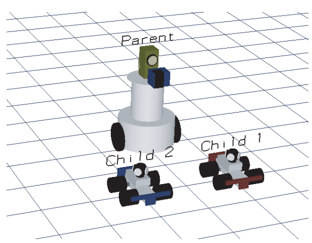
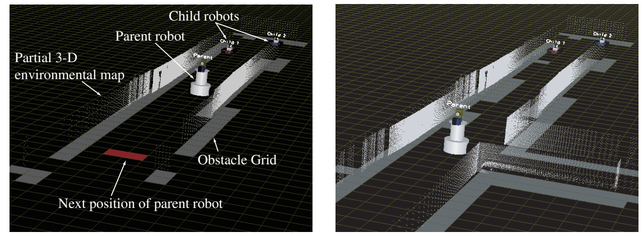


Fig. 13. 2D grid map

ments repeated 6 times. As shown in this figure, the parent robot automatically repeated CPS-positioning based on the laser measurements, determined the next target positions, and moved to the desired position. The parent robot moved 42.2 m in the x-direction and 3.4 m in the y-directions, while the observed environment from the 7 positions is shown in Figs.16. Figure 17 shows the acquired 3-D map of the corridor.

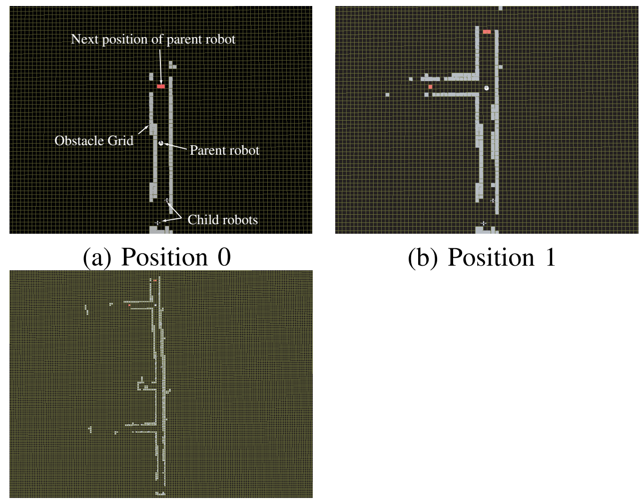
VI. Conclusions

A new 3-D measurement system, 'CPS SLAM', was proposed for large-scale architectural structures. This system is composed of multiple mobile robots and an on-board laser range finder that uses a highly precise positioning technique called the Co-operative Positioning System (CPS) to localize the robots. Measurement experiments in unknown and large indoor/outdoor environments were successfully carried out using the newly developed multiple-robot system, called CPS-V.



(a) Position 0 (b) Position 1

Fig. 14. Calculated next target position



(a) Position 0 (b) Position 1

(c) Position 6

Fig. 15. Generated Grid-based map and the target position

The proposed system has the ability to create a 3-D model without any post-processing procedures. Furthermore, if desired, post-processing procedures, such as the ICP algorithm, can be optionally applied to the 3-D model constructed by the proposed system for a subsequent refinement. Therefore, a fully automatic 3-D measurement system for large-scale architectural structures can be realized based on the proposed system. Useful applications include digital preservation of culturally important structures and search for survivors in underground malls or inside of building collapsed during an earthquake. This paper presented some fundamental experiments for fully automatic geometric modeling based on the partial 3-D model and the 2-D grid map.

In the future, the authors intend to investigate the development of an efficient 3-D laser measurement system that will automatically build an optimal measurement plan. The positioning accuracy of CPS can also be further improved by back-projection, that is, the observation of some stable landmarks before and after movement and the correction of each measurement position by back-projecting the errors. As well, a combination of CPS and the ICP method that can not only be used for refinement of the model, but also for the improvement of accurate positioning, will be considered.

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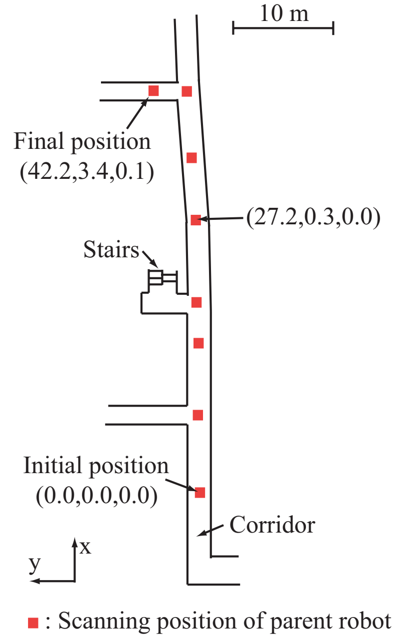

Fig. 16. Path of the parent robot in the corridor

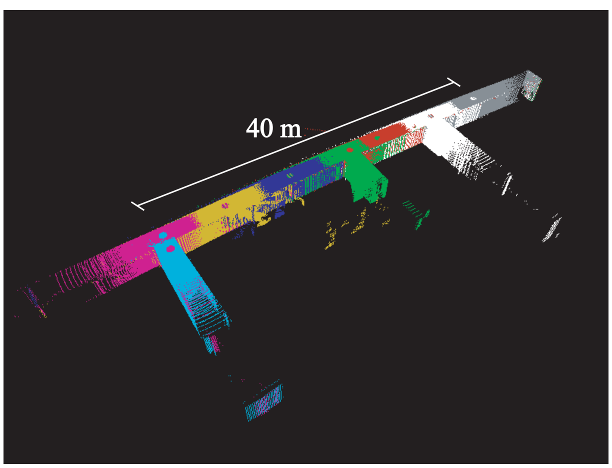

Fig. 17. Obtained 3-D environmental map of the corridor

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