Introduction to the Robot Town Project and 3-D Co-operative Geometrical Modeling Using Multiple Robots

Ryo Kurazume, Yumi Iwashita, Koji Murakami, and Tsutomu Hasegawa

Abstract This paper introduces the author's research project called the "Robot Town Project". Service robots, which co-exist with humans and provide various services in daily life, must have sufficient ability to sense changes in the environment and deal with a variety of situations. However, since the daily environment is complex and unpredictable, it is almost impossible with current methods to sense all the necessary information using only a robot and the attached sensors. One promising approach for robots to co-exist with humans is to use IT technology, such as a distributed sensor network and network robotics. As an empirical example of this approach, the authors have started Robot Town Project. The aim of this research project is to develop a distributed sensor network system covering an area of a block in a town in which there are many houses, buildings, and roads, and manage robot services by monitoring events that occur in the town. This paper introduces currently available technologies including an RFID-tag-based localization system, distributed sensor systems for moving object tracking, and object management systems using RFID tags. For the construction of 3-D geometrical models of large-scale environments, a measurement and modeling system using a group of multiple robots and an on-board laser range finder is also introduced.

1 Introduction

The demand for service robots that can co-exist with humans and provide various services in daily life is expected to increase in the next few decades. These

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robots must have sufficient ability to sense changes in the environment and cope with a variety of situations. However, since the daily environment is complex and unpredictable, it is almost impossible with current methods to sense all the necessary information using only a robot and the attached sensors. One of the promising approaches to develop service robots which co-exist with humans is using IT technology, such as a distributed sensor network and network robotics. The basic idea of this approach is that robots provide a variety of services based on environmental information not only from on-board sensors, but also from sensor networks in the environment. An empirical example of the above approach has been implemented in the research project called the "Robot Town Project" (Fig. 1). The aim of this research project is to develop a distributed sensor network system covering an area of a block in a town in which there are many houses, buildings, and roads, and manage robot services by monitoring events that occur in the town. The sensed events are notified to the "Town Management System, TMS", and each robot receives appropriate information about the surroundings and instructions for proper services. There are several researches for the embedded sensor systems in daily human life environment [25],[9],[4],[15],[21],[27],[19]. However, the most of researches so far are limited to area of a single room or a few rooms.

This paper provides a brief introduction to the Robot Town Project and introduces some technologies developed in this project, including an RFID-tag-based localization system, a distributed sensor system for moving object tracking, and an object management system using RFID tags. For the construction of 3-D geometrical models of large-scale environments, a measurement and modeling system using a group of multiple robots and an on-board laser range finder is also introduced, and large-scale geometrical modeling experiments in indoor and outdoor environments are presented.

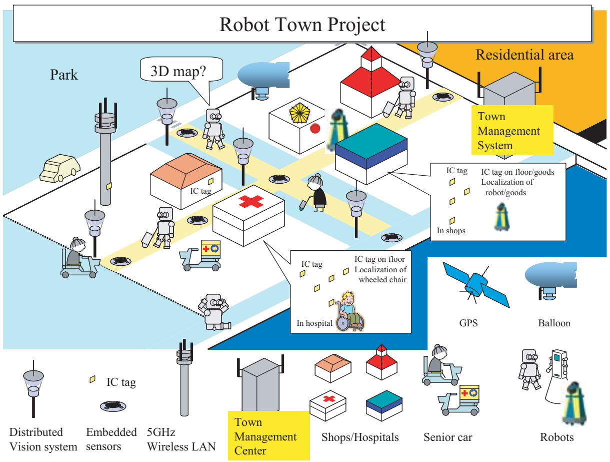


Fig. 1 Concept for Robot Town

2 Robot Town Project

This section introduces the core technologies in the Robot Town Project, including the current implementation of TMS and distributed sensor systems using RFID tags, laser range finders, and cameras.

2.1 *Town Management System, TMS*

TMS is the core technology in this project. A prototype TMS in a home environment has already been developed and tested for human-robot co-operation based on practical scenarios. Figure 2 shows the experimental house for the Robot Town Project.

The TMS consists of a database and API libraries (Fig. 3). The database is developed in MySQL and stores object information acquired using distributed sensors embedded in the environment and the robots: moving object information such as position and velocity of robots and humans; and environmental information including semantic and metric maps. SOAP (Simple Object Access Protocol) is adopted for the interface protocol, and a web-based service is provided. Robots (and operators) are able to access the database using APIs and obtain necessary information for providing service to humans.

Outward

Indoor

Fig. 2 Experimental house

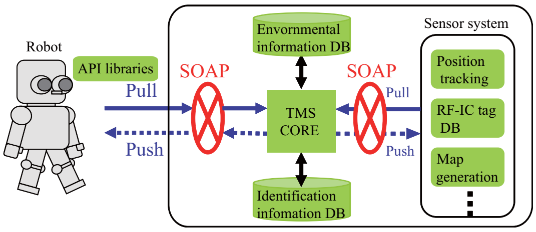


Fig. 3 Town Management System, TMS

2.2 Distributed sensor systems

Information stored in TMS is updated regularly using distributed sensors and robots. In the experimental house of the Robot Town Project shown in Fig. 2, several distributed sensor systems are installed. For example, two types of RFID tags are placed uniformly on the floor. Robots that are equipped with an RFID tag reader can identify their positions by reading the tags and then querying the TMS. To detect the movement of humans, laser range finders and cameras are placed on the floor.

2.2.1 RFID tag system for robot localization

Under the carpet of the floor, 4,000 passive RFID tags are placed as shown in Fig. 4. These tags consist of two types: a high frequency (13.56 MHz) passive RFID tag (Texas Instruments RI-I01-112A, ISO15693) and a low frequency (34.2 KHz) passive RFID tag. The high-frequency RFID tags are placed at an interval of 12.5 cm, while the low-frequency RFID tags are placed at an interval of 25 cm. The yard of the house is also covered by 400 RFID tags.

Robots can identify their positions by reading these tags and querying TMS about their positions based on the tag labels to give a position accurate to within a few centimeters. Detectable areas of the tags are 1 cm for high-frequency tags and 40 cm for low-frequency tags.

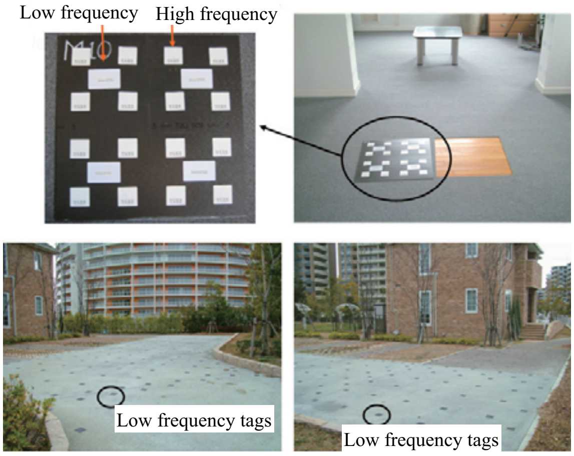


Fig. 4 RFID tag system in and around the experimental house

2.2.2 Laser and vision sensor system

As mentioned above, the position of a robot can be detected by the RFID tag systems if the robot is equipped with an RFID tag reader. However, the position of humans and robots that are not equipped with RFID tag readers cannot be identified using this system. Therefore, the experimental house is equipped with several distributed sensors for detecting the motion of humans and robots [14],[7].

For example, 2-D laser range finders (SICK LMS-200) and cameras (Point Grey Dragonfly2) are placed 1 meter above the floor, and not only the position but also the posture of the humans is tracked [8]. Figures 5 and 6 show the system configuration and the sensor positions in the house. Ceiling pyro-electric sensors are also used for detecting humans in some rooms where privacy should be respected.

Figure 7 shows the position tracking experiment using distributed laser range finders and cameras. Five persons are tracked simultaneously using a single MCMC/SIR particle filter[14]. The posture of the humans is also detected using the cameras (Fig. 8) [8].

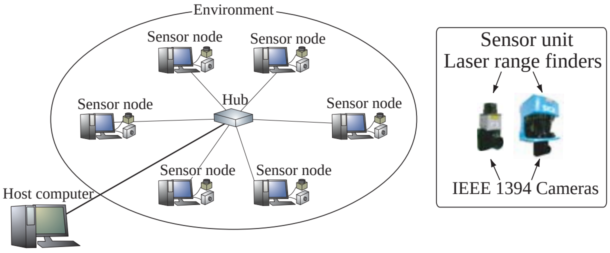


Fig. 5 Tracking system using laser range finders and cameras

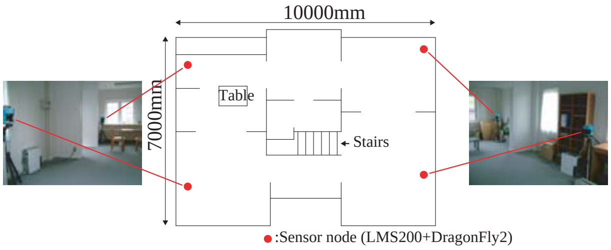


Fig. 6 Sensor positions in the experimental house

2.2.3 Object management system using RFID tags

All of the objects such as drinks, clothes, and shoes in the experimental house are managed by TMS using the attached RFID tags, and robots can identify these objects by reading the tags and querying the identification numbers to TMS. RFID tag readers are placed on the cabinets and refrigerators (Fig. 9) [18] to recognize ob-

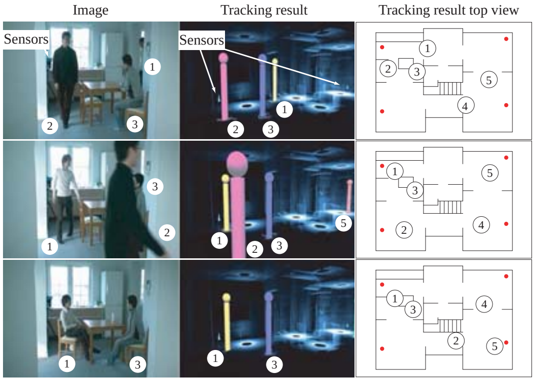


Fig. 7 Tracking experiments of humans in the experimental house

Fig. 8 Posture estimation of humans using captured camera images

jects placed in them. On the other hand, robots query the TMS about the necessary object information and can know their positions and current status, such as in-use or empty.

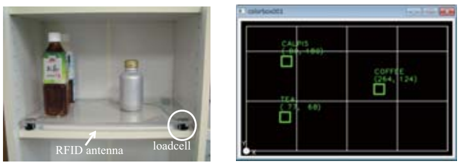


Fig. 9 Intelligent shelf

2.2.4 Experiments for robot service

Experiments using two types of service robots were conducted as shown in Fig. 10. Using voice, a human operator ordered a service robot to bring shoes and cloth (a), the robot queried the TMS about these positions and retrieved them based on the attached RFID tags (b),(c), and then a carrier robot conveyed them to the human operator (d),(e),(f). All the information from the RFID tags on a floor, laser and vision sensors, and service robots was managed centrally by the TMS.

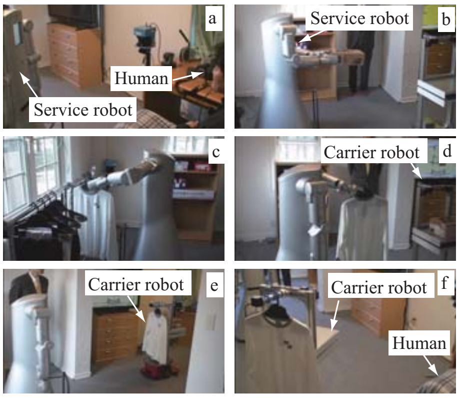


Fig. 10 Robot service experiment

3 Environmental geometrical modeling using mobile robots

3.1 Geometrical modeling of large-scale environments

For a service robot working in a daily environment with humans, an accurate map of a surrounding environment is indispensable. In order to avoid collision with environments and provide various services safely, these maps should contain not only 2-D information which is popular in some robotic applications such as path planning, but also 3-D information such as stair step height or 3-D positions of obstacles. However, most of maps used for a service robot are created by hand currently, and this task, especially for creating detailed 3-D maps, is quite laborious and these maps are not re-created very often. Therefore, from the point of view of efficiency and maintainability, these maps should be constructed using robots themselves automatically.

For constructing 3-D models of large-scale environments using a 3-D range sensor such as a laser range finder, a number of partial range images are taken from different viewpoints around the targets. These images are aligned using post-processing procedures, such as the ICP algorithm[1, 2]. 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. 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. As an example of this approach, several systems that use GPS[33, 23] to determine the position of the range sensor have been proposed. However, special instruments and techniques, such as a Real-time Kinematic (RTK) system or the Virtual Reference Station (VRS) method, are required in order to achieve highly precise position identification using current GPS.

This section introduces a 3-D measurement system for large-scale environments using a group of mobile robots and an on-board laser range finder[13],[12]. The proposed system uses the Co-operative Positioning System (CPS)[11, 10] for multiple robots, which has been proposed as a highly precise position identification technique for mobile robots. This system can construct 3-D models of large-scale environments 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. It is also possible to construct a 3-D model in environments where GPS is not available, such as in an indoor environment.

3.2 Related work

The proposed system is related to the Simultaneous Localization And Mapping (SLAM) method[29, 22, 32, 3, 30, 5, 31, 16], which has attracted a great deal of attention in the robotics community. In the proposed system, the obtained 3-D model can be refined by applying ICP as shown in [12]. 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 like SLAM systems. The following two elements are essential to create a high-accuracy environmental map with 3D measurement robot systems.

(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 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.

Besides these methods, co-operative localization using a team of mobile robots also has been attracting much attention as a highly-precise self-localization technique so far[11, 6, 17, 28, 26, 24, 20]. In this method, robots are localized sequentially and alternatively by observing the positions of other robots in a team instead of natural or artificial stable landmarks. The first idea of the co-operative localization was introduced by Kurazume et al.[11]. Each mobile robot in a team repeats to move and stop, acts as a mobile landmark. The basic algorithm of this method is also introduced in section 3.3 in this paper.

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.

3.3 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.

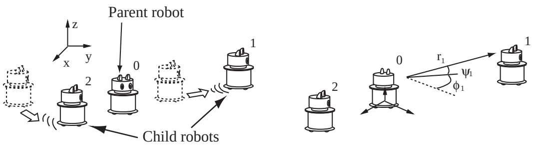
To achieve highly accurate positioning of mobile robots, Kurazume et al. proposed the Co-operative Positioning System (CPS)[11]. In this system, multiple robots with highly precise measurement devices for their mutual positions are controlled co-operatively. This can lead, compared to conventional positioning 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 behavior 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.11. 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.

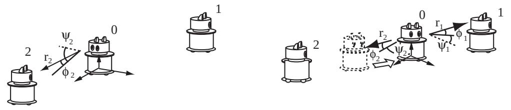
(1) Child robots 1 and 2 are moved and stopped.
(2) The parent robot measures the distance, azimuth, and elevation angles to child robot 1 and identifies the position of child robot 1.
(3) The position of child robot 2 is identified in the same manner as in Step 2.
(4) The parent robot moves and stops. 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[10]. 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. In this method, the error accumulation is repeatedly estimated by calculating the error covariance matrices by taking the accuracy of a sensing device and the relative positions between robots into account. The position of each robot is determined using the accumulated error covariance matrices so that the positioning error is minimized at each positioning. In addition, several optimum moving strategies which minimize the error accumulation are proposed. Note that it is possible to refine the error accumulation after closing a loop by the parent robot using techniques developed in SLAM[29, 22, 32, 3, 30, 5, 31, 16]. The experimental results after applying ICP was reported in [12]



(1) Robot 1 and 2 move.

(2) Robot 0 measures the position of robot 1.



(3) Robot 0 measures the position of robot 2.

(4) Robot 0 moves and measures the position of robots 1 and 2.

Fig. 11 Co-operative Positioning System (CPS)

3.4 Construction of a 3-D environmental map using multiple robots

This section introduces a 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 sixth CPS machine model, called CPS-VI, 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-VI are given.

3.4.1 Sixth CPS machine model (CPS-VI)

Figure 12 shows the sixth CPS machine model, CPS-VI. This system consists of a parent robot and two child robots. The parent robot is equipped with an on-board 2-D laser range finder (LMS 151, Sick), a high-precision two-axes altitude sensor (MD900T, Applied Geosystems), an automatic leveling system (Rizumu, AS-21), and a total station for the survey (GPT-9005A, TOPCON Ltd.), 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 automatic leveling system, 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 50 m and 270°. 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.13 are acquired in 37.8 s.

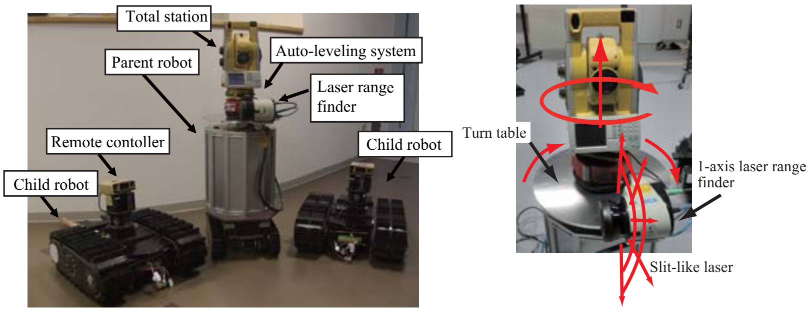


Fig. 12 The developed tunnel shape measurement system

Fig. 13 Range data obtained in one scan

3.4.2 Experiments to construct the indoor and the outdoor environmental maps

Experiments for constructing 3-D maps are carried out using CPS-VI in a long corridor environment (Fig.14). In these experiments, the parent robot and the two child robots moved, stopped, and identified their positions 38, 7, and 8 times respectively,

respectively. Total moving distance of the parent robot was 210 m. After identifying their positions, the parent robot captured 3-D range images at each stationary position by rotating the on-board 2-D laser range finder around the vertical axis. The obtained range images are transformed into the global co-ordinate system by simple co-ordinate transformation calculations using the positioning result measured by CPS. No post-processing procedure is applied. In these experiments, the parent robot repeated the laser scanning from 33 positions and obtained about 40,340,000 points. Figures 14 and 15 shows the total view of the resulting 3-D map.

To verify the accuracy of the obtained 3D model, we compared the measured positions of a same point (door corner) before and after the movements along the corridor with a loop and estimated the modeling error. The error between these points is 0.098 m, compared to the moving distance of the parent robot of 180.9 m, that is, the error is only 0.054% of the total distance traveled.

Fig. 14 Photo and measured shape of corridor

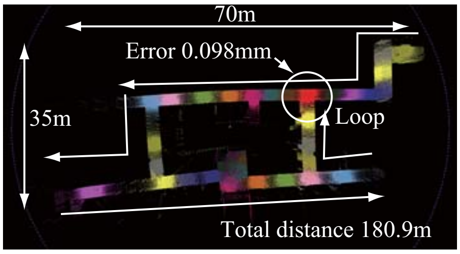


Fig. 15 3D model of corridor

Next, a construction experiment was done to obtain 3-D environmental maps in the outdoor environments with the difference in height of 5 m. The robots moved around buildings and the outer walls of a building were measured from 20 positions and 3-D models were constructed of the building. The path of the parent robot and the obtained map are shown in Figs. 16 and 17. The modeling error in this experiment is 0.116 m, compared to the total travel distance of the parent robot of 343 m, which is 0.034% of the distance traveled.

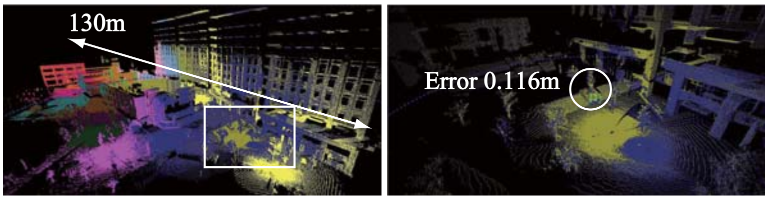


Fig. 16 Measured shapes and errors in outdoor environment

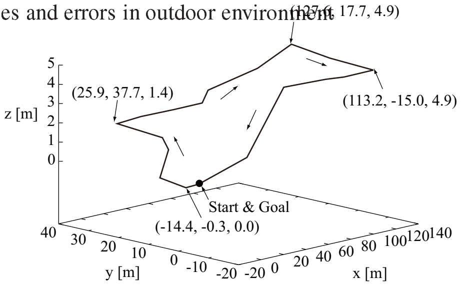


Fig. 17 Path of parent robot

3.4.3 Experiment to construct a map of large-scale urban district

Furthermore, 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, where the difference in height is approximately 2 m. Some of the results are shown in Figs.18. 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. We evaluated the errors of the 3D model in three points (Point A, B, and C) indicated in Fig.18. The errors between the local models measured in the different positions in these points were 57 [mm], 372[mm], and 494 [mm], respectively. The experiment shows that the proposed system has the ability to create a precise 3-D environmental map, even in a large outdoor environment.

3.5 Application for the digital archive of large-scale cultural heritage sites

Finally, an example of the application of the proposed system for the digital archive of a large-scale Japanese cultural heritage site is considered.

The Dazaifu Shrine (Dazaifu Tenmangu) (Fig.19) located in Fukuoka, Japan, was established in 919 in memory of Sugawara no Michizane, a famous Japanese scholar, politician, and poet. The main shrine of the Dazaifu Tenmangu was built in 1591 and is registered as an important cultural property of Japan. The size of the main shrine and the yard are about 250 m × 100 m.

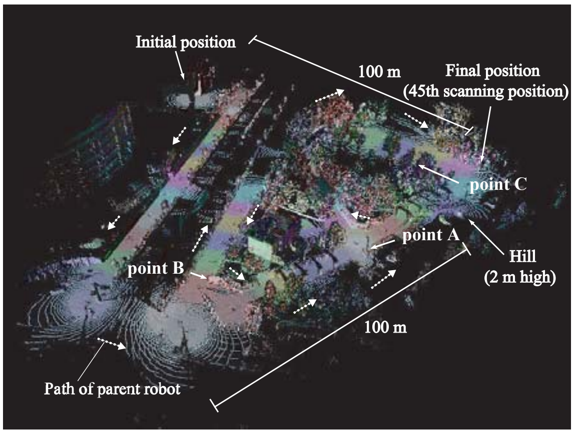


Fig. 18 Obtained 3-D environmental map (overall view)

We conducted a 3-D digital archive experiment on the main shrine of Dazaifu Tenmangu and the vast garden by the robot system proposed in this paper. Figure 19 shows the view of the main shrine of Dazaifu Tenmangu. The parent robot moved and measured the Dazaifu Tenmangu from 76 places on the inside and outside of the main shrine and the garden.

Fig. 19 Main shrine of Dazaifu Tenmangu (Dazaifu Shrine)

4 Conclusions

This paper briefly introduces the research project Robot Town Project. The aim of this research project is to develop a distributed sensor network system covering an area of a block in a town in which there are many houses, buildings, and roads, to manage robot services by monitoring events that occur in the town. The sensed events are notified to the TMS, and each robot receives appropriate information regarding the surroundings and instructions for proper service. This paper introduced the developed systems in this project, including RFID-tag-based localization system, distributed sensor systems for moving object tracking, and object management system using RFID tags.

In addition, a 3-D measurement system using multiple mobile robots was introduced for geometrical modeling of large-scale environments. This system is composed of multiple mobile robots and an on-board laser range finder, and a highly precise positioning technique named the Co-operative Positioning System (CPS) is adopted 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-VI.

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