AN ASSISTANCE SYSTEM FOR BUILDING INTELLIGENT SPACES BASED ON MAPSHARING AMONG A MOBILE ROBOT AND DISTRIBUTED SENSORS

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Abstract- An intelligent space is a space constructed with many networked sensors. Humans and robots in the space are extracted and tracked cooperatively by the networked sensors. The intelligent space can achieve position-based supports to humans and robots according to integration of networked sensors. Generally, the networked sensors are distributed and fixed on the structures in the space such as walls, ceilings and etc. In order to track moving objects such as humans and robots in the intelligent space, all networked sensors have to obtain objects positions in the unified world coordinate. In that case, positions and orientations of the networked sensors must be also known in the unified world coordinate system. However, it is time-consuming to measure positions of many sensors in the world coordinate
accurately and manually. This study aims to develop a system for supporting estimation of positions and orientations of the networked sensors in the intelligent space.

In this paper, a configuration of the proposed system is introduced. The proposed system consists of map building systems of the mobile robot and the distributed sensors. A global map from the robot and local maps from the distributed sensors are compared. Then, the local maps of the distributed sensors are associated with the global map and the positions of the distributed sensors are estimated in the global map. For improvement of map matching, angle differences between maps are evaluated. Some experimental results in an actual environment show that the proposed system achieve sensor position estimation easily.

Index terms: Intelligent Space, Mobile Robot, SLAM.

I. INTRODUCTION

a. Research background

Many kinds of intellect spaces[1] have been studied in recent years. Intellect spaces mainly aim to build robotic systems consisted of various components such as sensors and computers[2]. The systems support humans and robots by integrating local information from the distributed and networked sensors[3][4]. In such systems, tracking and position estimation of moving objects using cameras and laser range sensors can be achieved[5][6]. Also, a human-robot interaction systems was developed as an application of the intelligent space[7][8].

Several sensors are often distributed and fixed in the static strictures of the space for building the intelligent spaces. Especially, more sensors must be distributed for expanding the intelligent spaces more widely. As described above, tracking and position estimation of moving objects are one of the applications in the intelligent spaces integrating many sensors cooperatively. In such applications, sensor positions in the unified world coordinate system must be known because moving objects beyond sensor ranges cannot be tracked without correct position relationships among sensors. Generally, it is time-consuming and difficult to measure accurate positions of all distributed sensors using measurement equipment such as tape measures manually in the unified world coordinate system of the wide intelligent spaces. Convenient position estimation systems of the distributed sensors will facilitate building the intelligent space.
b. Related studies
Several position estimation systems of the distributed sensors in the intelligent spaces have been proposed before. Sasaki et al. introduced a calibration system of distributed sensors based on the moving objects observed at the same time among adjacent laser range sensors with overlapped sensor ranges each other[9][10]. Funia et al. introduced the other calibration system of network cameras automatically by tracking of moving objects with Bayesian filter in the intelligent space[11]. The position relationships among cameras are obtained using moving objects observed at the same time by network camera as same as the former system.

In these systems, specific moving objects were considered as features for obtaining position relationships among sensors. Correspondent errors will often occur in the environments where many moving objects exist and it will degrade the accuracy of position relationships. Also, sensors must be placed with overlapping ranges among sensors to observe common moving objects in the systems. It means that flexibility of sensor placement decreases and construction of the intelligent spaces becomes complicated. On the other hand, position relationships can be obtained using radio field strength emitted from distributed sensors. However, it is not generally accurate to estimate positions.

c. Overview of this study
In this paper, a support system for building the intelligent spaces easily is introduced. The system is consisted of map building systems in a mobile robot and distributed laser range sensors. The laser range sensors are distributed in the space and the mobile robot moves around the space where the laser range sensors are distributed. The robot can build a global map using a SLAM algorithm[12][13]. And each distributed sensor build a local map using laser scan data. The global map and local maps are compared and correspondence among maps is searched. As a result, local maps from laser range sensors are associated in the global map. It means that the positions of the laser range sensors fixed in the space can be estimated in the unified world coordinate system based on the global map. In the system, static structures built by SLAM are used as features for matching not moving objects. Also, distributed sensors are not required to overlap their monitoring ranges.

The paper is organized as follows. In Chapter 2, we introduce a summary of the proposed system. In Chapter 3, we show a comparison method of the local maps from distributed sensors and the
global map from the mobile robot. In Chapter 4, some experiments are performed to evaluate effectiveness of the proposed method. In Chapter 5, the paper is concluded.

II. OUTLINE OF THE PROPOSED SYSTEM

a. Outline of the system

Fig. 1 shows an outline of the proposed system. This system is constructed of a mobile robot and distributed sensors used for object tracking in the intelligent space. In this figure, \( N \) distributed sensors are placed in an environment. In addition, the distributed sensor No.\( i \) shares the map information with the mobile robot as an example in this figure. A laser range sensor is used as a distributed sensor.

In the proposed system, each distributed sensor builds a local map around the sensor independently. A mobile robot has a laser range sensor for monitoring the external environment. A mobile robot performs a self-position estimation and builds a global map by using SLAM. The initial robot coordinate system \((X-Y)\) that is shown in red lines in Fig. 1 is fixed as a coordinate system of the global map. In this system, the coordinate system of the global map is regarded as the unified world coordinate system of the intelligent space. Each distributed sensor No.\( i \) has a local coordinate system \((x_i-y_i)\) as shown in blue lines.

When the mobile robot moves outside of monitoring areas by the distributed sensors, the distributed sensors and the robot work independently. In the cases that the mobile robot enters to the monitoring areas of the distributed sensors, information sharing between the robot and the distributed sensors is performed. The proposed system updates both the positions of distributed sensors and the global map during information sharing. Mainly, map information is shared between the robot and the distributed sensors as described in the following procedures.

Figure 1(i)-(iii) show the procedure of the map sharing. Figure 1(i) shows that the robot enters to the monitoring area of the distributed sensor and starts map sharing. In Figure 1(ii), the local maps and laser scan data in the world coordinate are shared and compared. In Figure 1(iii), the positions of the distributed sensors are updated using correspondences between the local map and scan data based on the global map from the robot. In the system, the robot moves through the monitoring areas of all distributed sensors with executing the SLAM. Then, the procedure as shown in Figure 1(i)-(iii) is iterated in a monitoring area of each distributed sensor.
In the map sharing, the system updates not only the positions of distributed sensors but also the global map and positions of the robot using local maps by the distributed sensors. In this way, improvement of self-position estimation and map building in SLAM by the mobile robot is expected.

Figure 1. Outline of the proposed system

b. Distributed sensors in the intelligent space

In this study, laser range sensors are used as distributed sensors in the intelligent space. Generally, the laser range sensor is suitable for human tracking in the intelligent space. In the proposed system, an initial position of each distributed sensor is unknown. This study aims to develop a support system for building intelligent spaces by simplifying the position estimation of the distributed laser range sensors.

Each distributed sensor estimates own position and a local map around the sensor in the system. Since the distributed sensor is fixed in the space, the actual position does not change. The position of the distributed sensor is updated with map sharing and comparison as described
below. The local map is a grid map using occupancy probability of each grid[12-14]. In each sensor, a local map in the local coordinate system of each distributed sensor is built using laser scan data. The direction of $x_i$ in the local coordinate system of sensor No.$i$ is the center in angular range of the laser sensor. Occupancy probabilities are calculated whether scan points transformed to the local coordinate of the sensor are included in the grids or not. The details of calculation can be found in [15-17]. Fig.2 shows an example of the local grid map and the corresponding environment.

![Sensor placement](image1.png) ![Grid map](image2.png)

**Figure 2.** An example of local grid map by distributed sensors

Figure 2(a) is an environment where a distributed sensor is placed. A laser range sensor is placed in the red circle. Figure 2(b) shows an example of a local map in the environment of Figure 2(a). A red dotted line in Figure 2(a) is structures monitored by the distributed sensor. The same structure can be found in the local map of Figure 2(b). It is possible to build a local map with reducing influences of moving objects by using such an occupancy grid map. In Figure 2(b), the occupancy probability $0 \sim 1$ of each grid is converted to $255 \sim 0$ of pixel intensity.

c. Map building of a mobile robot

A mobile robot has a laser range sensor and builds a global map by using SLAM. The global map is also an occupancy grid map. The mobile robot moves through the monitoring areas of all distributed sensors in the intelligent space.

In the proposed system, Grid-Based-FastSLAM[12] is adopted for building a global map. This is a method of self-position estimation and map building based on FastSLAM with the particle filter. Each grid also has a probability of occupancy calculated using odometry and scan data. The grid probabilities are updated based on comparison between the current scan data and the previous
grid map every sampling time. Matching points between scan data and the grid map are used as weights in the particle filter.

d. Map sharing and comparison among distributed sensor and mobile robot

Figure 3. Processing flow of distributed sensors and robots

Figure 3 shows an outline of map sharing and comparison among the mobile robot and the distributed sensor. The initial positions of the distributed sensors are unknown at first. Actually, random initial positions not so far from the actual positions are given to the distributed sensors. The distributed sensor builds each local map by the method described in Section 2.b. The mobile robot goes through the monitoring areas of the distributed sensors with estimating self-positions and building a global map based on SLAM.

When a mobile robot enters to the monitoring area of the distributed sensor, the proposed map sharing and comparison are performed. During map sharing, it is compared whether the local maps are corresponding in the global map with the unified world coordinate system. The positions of the distributed sensors can be updated with the comparison results. Also, the map sharing and comparison can be used for the likelihood evaluation of the particle filter in SLAM of the mobile robot. As the result, accuracy improvement of the global map is expected.

The judgment that the robot exists in the monitoring area of the distributed sensor is based on both estimated positions of the robot and the distributed sensors. When the robot positions are in the observation range compared with the position of each distributed sensor in the world
coordinate systems, the mobile robot is regarded as existing in the monitoring area of the
distributed sensor. In that case, map sharing and comparison shown in Figure 3 are performed.

e. Problem of map comparison
In map sharing and comparison, corresponding points among maps are considered as the
evaluation results of map comparison. More corresponding points means better map matching.
However, a problem in the map comparison among local maps and the global map is found in a
preliminary experiment. We installed one distributed sensor in an indoor environment. A mobile
robot moved through the monitoring area of the distributed sensor. The distributed sensor and the
robot had their own positions independently before map sharing. In this situation, the positions of
the distributed sensors are not accurate in the world coordinate system. Even if the maps are
shared, enough corresponding points in map comparison cannot be obtained using such
inaccurate positions.
Especially, angular differences are significant for map comparison because small angular
differences make corresponding points fewer as shown in Figure 4. Figure 4 shows an example of
the corresponding points in map comparison in the preliminary experiment. Black points
represent static structures appeared in the local map. Red points represent the scan data obtained
in the mobile robot and transformed to local coordinate system of the distributed sensor. Blue
points are the corresponding points of both.

![Map comparison between the robot and the distributed sensor](image)

Figure 4. Map comparison between the robot and the distributed sensor

This example shows that few corresponding point can be obtained in map comparison. The main
reason of few corresponding points is the small angular difference between maps. Even if the
position of the distributed sensor is close to the actual position, small angular differences will
affects to reduce corresponding points. From above, angular differences among maps in map
sharing and comparison should be considered in position estimation process of the proposed
system.
III. MAP SHARING AND COMPARISON

a. Outline
Comparison in Figure 3 can be detailed as Figure 5. Particle filters are implemented for position estimation of the distributed sensors. Each particle filer works for each distributed sensor independently. In the mobile robot, FastSLAM based on the particle filer is implemented as described above. In the proposed system, local maps and a global map are built as occupancy grid maps by the distributed sensors and the robot respectively. At least, if either of the local maps or the global map is used for map sharing and comparison, the system can achieve map comparison without the influences of moving objects. In this study, scan data from the mobile robot and the local maps of the distributed sensors are compared. The scan data from the robot is transformed to the local coordinate systems of the distributed sensors as shown in Figure 6(a) with using the positions of distributed sensors in the world coordinate system. Figure 6(b) show the local map in this example. In the most cases, angular differences are appeared among transformed scan data and local maps as shown in Figure 6(c).

![Diagram of map sharing and comparison]

Figure 5. Detailed flow of map sharing and comparison
First, when the mobile robot exists in the monitoring area of the distributed sensor, the rough position estimation of the distributed sensor is performed in Figure 5(1) based on slope comparison among the local map and the scan data obtained from the robot and transformed to the local coordinate. Then, the results are used as likelihoods of each particle filter for position estimation of the distributed sensor. A smaller angle difference gives higher likelihood in each particle. Next, map evaluation based on slope comparison is also performed for map matching and position estimation in SLAM in Figure 5(2). These slope comparisons include evaluations on angular differences among maps. At last, the position estimation of the distributed sensor is performed again by comparing the local map with the scan data from the robot in Figure 5(3). In this comparison, corresponding points might be obtained for the evaluation as shown in Figure 6(d) because angular differences are compensated by using the former slope comparisons.

Figure 6. Comparing a local map and scan data
b. Slope comparison in map sharing

This section describes how to evaluate the angular differences among the local map and the scan data from the robot. Dominant slopes of static structures in the local map or scan data are extracted and used for calculation of angular differences. Figure 7 shows the details of the slope comparison.

![Slope comparison diagram](image)

**Figure 7.** Slope comparison between scan data and a local map

At first, two representative points in the local map and the scan data from the mobile robot are selected respectively. Figure 7(a) is an example of a local map. Two yellow grids are two representative points selected in the local map. The grids with the highest occupancy probabilities are selected as the representative points. In this figure, two representative points are named as prob$_1$, prob$_2$. The grids with the highest occupancy probabilities mean using static landmarks that surely exist in the local map. When several grids have equal maximum probabilities, the farthest grid and the closest grid from the distributed sensor positions are selected.

On the other hand, Figure 7(b) shows the representative points in scan data from the robot. The scan data from the robot is transformed to the local coordinate system of the distributed sensor using the estimated global positions of the robot and distributed sensor. Then, the closest two scan points with two representative points in the local map are regarded as the representative points in the scan data.
The slope among two representative points is regarded as the dominant slope in each map or scan data. In Figure 7, \((x_{prob1}, y_{prob1}), (x_{prob2}, y_{prob2})\) in the local map and \((x_{scn1}, y_{scn1}), (x_{scn2}, y_{scn2})\) in the scan data are chosen as the representative points respectively. Then, dominant slopes in the local map or the scan data are calculated using straight lines through two representative points respectively. The difference among dominant slopes is calculated every particle and exploited as likelihood of the particle filter for estimating the position of the distributed sensor. This calculation is repeated for every particle during map sharing when the robot is in the monitoring areas of the distributed sensors. As a result, correspondence points are increased gradually. Although two representative points in the local map and the scan data may not be necessarily correct corresponding points, the problem can be solved after the evaluation shown in Figure 5 (3) as described in the next section.

c. Particle filters in map sharing

In this section, particle filters implemented in the map sharing are described. At first, Figure 8 shows the details of the particle evaluation in Figure 5(1).
The distributed sensor builds a local map using scan data in the local coordinate system. Each particle in the particle filter of the distributed sensor has a different position and orientation in the world coordinate system. This means that each particle has the different local map in the world coordinate system. Scan data from the mobile robot is compared with the local map of each particle of the distributed sensor. In this case, the scan data from the robot is regarded to be acquired in the global position estimated by SLAM. Slope difference explained above is used as the likelihood of each particle of the distributed sensor. Smaller slope differences become higher likelihoods in particles. Then, rough position and orientation estimation of the distributed sensor is performed in Figure 5(1).

Figure 9 shows the details of map comparison in the particle filter for map building and global position estimation of the mobile robot as shown in Figure 5(2).
Every particle estimates a global position and a global map. Although one scan data is obtained in the robot every sampling, the scan data is transformed to the global coordinate system of each particle. This means that different scan data per every particle exists in each global coordinate system. The scan data transformed to the global coordinate system of each particle is compared with a local map of the distributed sensor. In this case, the position of the particle with the highest likelihood in Figure 5(1) is used as the estimated position of the distributed sensor. Then, scan data of every particle is compared with the local map and slope differences are calculated as same as the particle evaluation of Figure 5(1). Also, the particle evaluation in the conventional FastSLAM using odometry and map matching is performed simultaneously. Finally, the likelihood of each particle in the particle filter of the mobile robot is calculated using these two evaluations including the slope differences and the conventional map matching of FastSLAM in Figure 5(2). This evaluation means that the particle which is close to both of the previous global map by the mobile robot and the local map by the distributed sensor has higher likelihood. The position of the mobile robot and the global map is updated by using the evaluation result.

This map sharing process estimates the positions of the distributed sensor and the mobile robot, and the global map in Figure 5(1) and Figure 5(2). As described in the former section, two representative points for slope difference evaluation may not be correct corresponding points. In the final particle evaluation in Figure 5(3), validity of the two representative points is considered. For example, even if two representative points are not correct corresponding between the local map and the scan data from the robot, the particle likelihood will be high in the case of small slope difference with only slope difference evaluation. Then, number of corresponding grids among the local map and the scan data is evaluated in Figure 5(3). Even if small slope differences are obtained by incorrect corresponding, enough number of corresponding grids will not be appeared with this evaluation. This means that the particles with the incorrect corresponding in Figure 5(1) will be removed in this evaluation. Of course, when correspondence of two representative points are correct and the small slope differences are obtained, enough number of corresponding grids are acquired with this evaluation.

In this way, the particle evaluation based on the slope comparison and number of corresponding grids is performed. Finally, the position of the distributed sensor can be estimated using particles with small angular differences and many corresponding grids. This evaluation is iterated while the mobile robot is in the monitoring area of the distributed sensor.
IV. EXPERIMENT

a. Overview of the experiment
In order to evaluate the proposed system, some experiments were performed. We will focus on the following three points especially.

A : Number of corresponding points according to map comparison
B : Improvement of SLAM accuracy using the proposed system
C : Position estimation results of the distributed sensors

“A” represents corresponding points among the scan data of the mobile robot and local maps when the robot moves through monitoring area of the distributed sensors. In this point, increase of corresponding points while map sharing is confirmed. Especially, the proposed map matching based on the slope comparison and the conventional matching are compared. “B” shows that the proposed system affects to improve the position estimation and the map building in SLAM by using the distributed sensors. A conventional FastSLAM, a system using conventional corresponding points matching and the proposed system are compared. “C” aims to show the position estimation results of the distributed laser range sensors in the intelligent space. In the experiments, random initial positions are given to distributed sensors. The results show that the initial positions are updated appropriately to get closer to actual positions.

b. Experiment environment
The experiments were performed in an indoor environment of our university building as shown in Figure 10. Four distributed laser range sensors were placed in the space and numbered from No.0 to 3. The blue square marks show the positions of the distributed laser range sensors. The local coordinate system $x_i - y_i$ ($i = 0,1,2,3$) of each sensor is expressed in blue arrows. Blue circles represent the monitoring ranges of the distributed laser range sensors. The mobile robot moved along the red squared path in Figure 10 from the red dot as the start point. Total travel distance of the robot is approximately 30000[mm]. The robot passes through the monitoring areas of all distributed laser range sensors. The world coordinate axis (X and Y) of the global map built by the robot is set as shown as black arrows in the figure.
Maps built in the system are two-dimensional occupancy grid maps. All of laser range sensors should be the same heights from the ground for appropriate comparison among the distributed sensors and the mobile robot. Since there is little influence on the built maps according to the heights of the sensors in this experiment environment, the installation heights of the sensors were not considered.

As a distributed sensor of the intelligent space, the laser range sensor URG-04LX is adopted. The mobile robot base is Pioneer3-DX and the laser range sensor UTM-30LX is installed for building the global map.

![Figure 10. An experiment environment.](image)

The system exploits the independent particle filters for estimating positions of each distributed sensor and the cooperative SLAM of the robot. Each particle filter uses 30 particles. The grid size of the occupancy grid maps including the global map and local maps is 100 x 100[mm²]. The monitoring range of each distributed laser range sensor is 5000[mm] in 240 degrees. The monitoring range of the laser range sensor installed in the mobile robot is 5000[mm] in 270 degrees. Sensor units were distributed in the experiment environment actually. A sensor unit consisted of a distributed laser range sensor and a computer.

Each sensor unit updates the local map and save it as a text file. The mobile robot with a computer communicated with the sensor unit for information sharing. The robot and sensor units were connected each other via Wi-Fi. When the proposed system judges that the mobile robot
exists in the observation area of the distributed sensor, the comparison between the local map in the text file and scan data from the robot is performed every 500[mm]. In other words, when the mobile robot exists in the observation area of the distributed sensor, the map information sharing is performed about 10 times approximately because the monitoring ranges of the distributed laser range sensors are 5000[mm].

c. Experimental results “A”
Figure 11 to Figure 14 show the actual placements of distributed sensors and corresponding points among map information. The white circles represent the positions where the distributed sensors were installed. Red dotted lines represent static structures expressed in the local maps built by the distributed sensors. The white lines with arrows are orientations of the distributed sensors. The yellow dotted lines with arrows are the moving trajectories of the mobile robot. Results of the distributed sensor No. 0 shown in Figure 14 were obtained when the mobile robot came back to the start point after moving along the trajectory as shown in Figure 10.

Figure 11. Matching in sensor No.1
Figure 12. Matching in sensor No.2

Figure 13. Matching in sensor No.3
(b) and (c) of each figure show the time-series changes of corresponding points while map information sharing among the distributed sensor and the robot. Each (b) represents results of the proposed system. Each (c) represents results of the conventional grid matching. Numbers of corresponding points changed from (i) to (iv) during the passage of time when the mobile robot existed in the monitoring area of each distributed sensor. In (i), the distributed sensor and the mobile robot started the map sharing. Then, corresponding points increased according to time series comparison among maps. The red points represent raw scan data of the mobile robot. The blue points show matched grids of the local maps of the distributed sensors with the scan data from the robot. The figures also show the angle differences between the robot and the distributed laser sensors. In the most cases, angle differences decreased according to the passage of time while map sharing in the proposed system.

As common features of the results, even if there are extremely few blue points at the start time of the map sharing shown in (i), corresponding points increased in the proposed system shown in (b). This means that particles with a few angle differences among the coordinate systems of the robot and the distributed sensor are chosen in the estimation process iteratively because the angle differences are used as one of the likelihood calculation in the particle filters.
Conventional grid matching shown in (c) simply counted the number of blue points while map sharing and the numbers were used as the likelihoods of the particle filters for position estimation. The corresponding points did not necessarily increase while the map sharing. These results mean that more corresponding points can be obtained in the proposed system shown in (b) than simple counting of matched grids shown in (c). The results show that the proposed system worked well in map sharing.

d. Experimental results “B”
In the “B”, effects of the proposed system to global map building of the robot. Figure 15 shows the results of global map building. Figure 15(a) shows the result with the proposed system including the map sharing based on slope comparisons among the robot and the distributed sensors. Figure 15(b) shows the result with map sharing based on simple counting the matched grids among the robot and the distributed sensors. Figure 15(c) shows the result of conventional FastSLAM.

![Figure 15. Map building results](image)

Green dotted lines represent the moving trajectories of the mobile robot. Red dotted lines represent each world coordinate axis in the global map. The built maps look almost similar with the structures shown in Figure.10. However, (b) and (c) have angle distortions and failures in loop closure compared with (a). The results show that positions and orientations of the distributed sensors were estimated accurately using the proposed system and the map sharing also affected to improvement of the global map built in the mobile robot because the angle differences among coordinates in the distributed sensors and the robot were added as one of the likelihood to the particle filter for estimating the global map.
e. Experimental results “C”

Position estimation results of each distributed sensor are shown in Table.1 to Table.4. Initial positions, Actual positions and Estimated positions are also plotted in Figure 16 to Figure 19. Figure 20 shows position estimation results of all distributed sensors. “Estimated position” was adopted from the estimated position in the case that the most corresponding points were provided between the robot and each distributed sensor while map sharing. “Initial position” was the initial position randomly given to each distributed sensor. “Actual position” is the position measured manually, but the positions might have slightly errors because it is difficult to measure the accurate positions in wide intelligent spaces. Especially, accurate orientations of the distributed sensors cannot be measured manually.

Blue points, green points and red points represent “Initial position”, “Actual position” and “Estimated position” respectively in Figure 16 to Figure 20. From these results, the differences between “Estimate position” and “Actual position” are kept within less than 300[mm], even if the “Initial positions” are given to away from the “Actual positions”.

As shown in Figure.15 of experimental results “B”, when the distributed sensors performed map sharing, map distortions become smaller than the cases without appropriate map sharing. This means that the position and orientation results shown in this section are close to actual positions appropriately.
<table>
<thead>
<tr>
<th>No.0</th>
<th>X [mm]</th>
<th>Y [mm]</th>
<th>Θ [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial value</td>
<td>300.00</td>
<td>-800.00</td>
<td>90.00</td>
</tr>
<tr>
<td>Measured value</td>
<td>0.00</td>
<td>500.00</td>
<td>90.00</td>
</tr>
<tr>
<td>Estimated value</td>
<td>143.30</td>
<td>-475.71</td>
<td>89.02</td>
</tr>
</tbody>
</table>

Fig. 16. Positions of Distributed Sensor No.1.  
Fig. 17. Positions of Distributed Sensor No.2.  
Fig. 18. Positions of Distributed Sensor No.3.  
Fig. 19. Positions of Distributed Sensor No.0.
V. CONCLUSION

It is important and complex to know positions of the distributed sensors installed in the space in the unified world coordinate system for building the intelligent spaces easily. In this paper, a support system to build the intelligent spaces was introduced. The proposed system is based on map comparison among a global map built by a mobile robot by SLAM and local maps built by the distributed sensors. Especially, angle differences among the coordinate systems of the global map and local maps are focused on. The angle differences among maps are added to estimation process of the positions of the distributed sensors. That affects to improvement of position estimation and also the global map building by the mobile robot.

Evaluation experiments were performed in the actual intelligent spaces. The proposed system was implemented using actual laser range sensors, computers and the mobile robot. As the results, the proposed system including evaluation of angle differences among maps can improve numbers of corresponding points in map matching, accuracy of the global map and position estimation results of the distributed sensors. That means that easy position estimation of the distributed sensors could be achieved using the proposed system.

As future works, it is necessary for the distributed sensors to detect the mobile robot using the scan data automatically because the current system recognizes that the robot enters into the...
monitoring areas of the distributed sensors when the robot gets close to the random initial position of the distributed sensor. Demonstrations of building larger-scaled intelligent spaces are also expected. For such demonstrations, the system implementation should be sophisticated using component-based implementation such as RT-middleware[18-20].

REFERENCES


