Improved ultrasonic beacon system for indoor localization

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Abstract: One of the most important factors so that mobile objects can achieve their purpose is the information about their positions. In this paper, we propose an improved beacon system, to which ultrasonic sensors are attached, for the indoor localization of mobile objects. We have researched so that it can cover the wider space and estimate more accurate positions than the existent beacon systems. The existent beacon systems have the constraint that one beacon cannot cover wide area since ultrasonic sensors have limits in the angle of signal (beam-angle) on which their signal strength depends. Hence, we used the active beacon which consists of a pan-tilt mechanism and a beacon module. The active beacon system can always aim at mobile objects in order to transmit the strongest signal of the ultrasonic sensors into the objects using the pan-tilt mechanism. In addition, this system is inexpensive because it can decrease the number of beacons by about a half of the beacons of the existent system. Finally, the results show what is the difference between the active beacon system and existent beacon systems, and how accurate it is.

Keywords: active beacon, localization, ultrasonic, pan-tilt, mobile object

1. INTRODUCTION

Improvement of the technology concerning the localization for human or materials is necessary condition to improve the ubiquitous computing and ubiquitous networking appeared the new paradigm of computerization. Especially, localization technology for indoor environment can be defined as basic technology of various technologies such as intelligent robot, intelligent building, guide system, and virtual reality. Hence, many researches about the topic have been taken through various kinds of method. There are dead-reckoning, vision method, laser range finder and beacon (ultrasonic sensor) method, and so on.

Dead-reckoning may be the simplest localization method [1] which is, however, fraught with many factors of error such as slippage and backlash. And vision system can be the only one solution for a new environment with no prior information. But it is expensive since it is required to make high computation possible for the image-processing [2]. And a substantial disadvantage of the vision system is that it is highly dependent on the light condition of environments. It may bring about critical errors unless the environments are properly illuminated with bright and regular lights.

Beacon methods have advantages in cost-saving, easy signal-processing and accurate measurements [3-4]. But several factors remain to be improved for the higher efficiency. First, the existent systems have some constraints that we need the sequential shoot of signals in order to avoid interferences measuring their TOFs (Time-Of-Flight). Using a set of different frequencies for the modulation may be the alternative technology but it is expensive and complex. Second, the area that one beacon can cover is not so wide since the ultrasonic sensors have constraints in the beam-angle on which the signal strength depends [5-6]. Consequently, the area in which we can perform the valid localization with one section of beacons (3 beacons) is strongly limited. Third, in case of the localization of multiple mobile objects, the efficiency of the localization for fast objects would be relatively decreased if the system's sampling time is fixed as the same one with regard to all the objects.

In this paper, we propose two methods to solve the problems of the existent systems.

First, we make active beacons to solve the first two problems by adding pan-tilt mechanism. Providing the pan-tilt mechanism means that the beacons equipped with ultrasonic sensors can face any direction in 3-dimensional space. Hence, we are able to use the strongest ultrasonic signal by turning each beacon toward any object concerned. Then, as the ultrasonic sensors have the limited beam-angle on which the signal strength depends, we can rotate one beacon toward some mobile object while the other beacon toward other object according to the judgment from an RF beacon, which includes the Radio-Frequency module, and can transmit the ultrasonic signals with no interference. In this way, we can transmit the ultrasonic signals to the multiple mobile objects simultaneously. The wider area can be covered with the same number of beacons in the proposed localization as well.

Second, the RF beacon receives the data from each object about its velocity and position via RF communication. Also, the RF beacon gives a priority which object to be faced, which is based on the velocity of the mobile objects: it gives higher priority to faster object. Hence, the sampling time is changed efficiently corresponding to the velocities of mobile objects. As an extreme case, we assume that none of the objects are moving. Then, how often should we perform the localization for the objects? The answer is "Once enough", because they do not move.

This paper describes System configuration (section 2), Inverse kinematics of pan/tilt mechanism (section 3), 3-dimensional localization using Newton method (section 4), Experimental results (section 5) and Conclusion (section 6).

2. SYSTEM CONFIGURATION

2.1 Basic Concept

Fig. 1 shows the usable area when using the existent beacon methods. Each beacon has a fixed angle, and it usually aim at the center of its corresponding section. Also, dotted lines from each beacon show the beam-angles resulting in the recognizable area (dark parts) while there are unrecognized areas beyond the beam angles. Fig. 2 shows the concept of the active beacon system proposed in this paper. At least one RF beacon and two normal beacons without RF module are required for a basic area named a section. Now and after, the beacon without a RF module will be called the beacon. And, the beacon having a RF module will be called the RF Beacon.

Basically, our active beacon system has a structure similar to that of the existent beacon system except some following aspects. Dark parts at fig. 2 express valid areas for the localization in a section. And we can expand the valid areas in the section by rotating the pan-tilt mechanism which is attached the beacon.

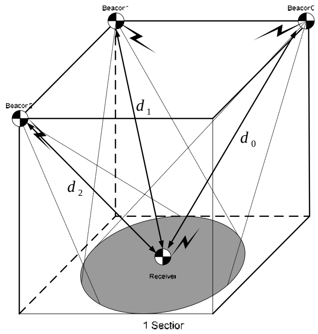

Fig. 1 Simple view of the existent systems

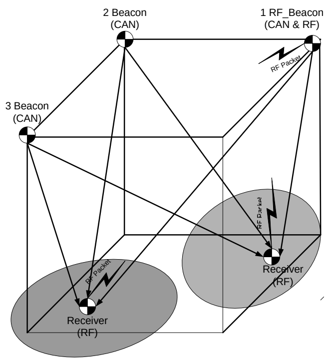

Fig. 2 Simple view of the active beacon system

There is timing synchronization with radio frequency communication between an RF beacon and receivers (installed on top of the mobile objects) while measuring the TOFs. In the existent systems, the radio frequency communication is used only to fire the beacons. But we provide the RF beacon with some information of the receivers such as velocities and positions of the mobile objects. The RF beacon gives a priority based on the velocities of the mobile objects and sends a transmission-permission-packet to them through the RF module. And it transmits the ultrasonic signal which is necessary for the localization of the mobile objects by the priority. In this time, one mobile object obtaining the highest priority becomes a master receiver and the others become the slave receivers. The slave receivers, existing in the same area of reachable range by the ultrasonic sensors, estimate the positions by synchronizing the timing with the master receiver. If we use this method, sampling time is changed corresponding to each velocity of the mobile objects. Therefore, the density of localization for mobile objects is regularly maintained. Also the RF beacon and the other beacons turn to the mobile objects by computing their inverse kinematics before they transmit ultrasonic signals.

When each beacon completes the transmission of the ultrasonic signal, the receiver which is installed to each mobile object calculates the distance from the corresponding beacon. Then, the mobile objects compute their local positions by Newton Method. Also, when the receivers reach the boundary among the sections, they send an information packet to the RF beacon. Then, they wait for a transmission-permission-packet from the RF beacon. As using the above algorithm, the mobile objects can continuously obtain their local positions' information even when moving section to section.

2.2 Configuration of Hardware

Table 1 shows several electronic and mechanical elements included in each module.

Table 1 Configuration of Hardware

	Receiver	RF beacon	Beacon
RF module	O	O	X
CAN Controller	X	O	O
US transmitter	X	O	O
US receiver	O	X	X
Pan-Tilt Mechanism	X	O	O

1) Receiver, RF beacon and Beacon

First of all, most electronic elements are commonly used for receivers, RF beacons and beacons on a common electronic board. All the modules include 8bit microprocessor with CAN controller. Furthermore, receivers include tone decoders for the ultrasonic signal's detection. And radio frequency modules of half-duplex type (447MHz) are included in only both receivers and RF beacons, and ultrasonic transmitters are included in only both RF beacons and beacons.

Receivers are connected with mobile objects via CAN or RS-232 while RF beacons are connected with beacons via only CAN. The major function of beacons is firing the ultrasonic signal when they receive a requesting command of firing from RF beacon. Fig 3. shows the real picture of each module except the normal beacon having no radio frequency module.

Fig. 3 Receiver (upper) and RF beacon (lower) modules

2) Pan-tilt Mechanism

Fig. 4 shows the pan-tilt mechanism, having two degree of freedom, to which RF beacons and beacons are attached. Hence, RF beacons and beacons are possible to target on mobile objects located at any position of current area. Beacons are located at the indoor space with free configuration. But, RF beacons must know the locations of themselves and the beacons in a section because they must furnish the information of the positions to all the receivers.

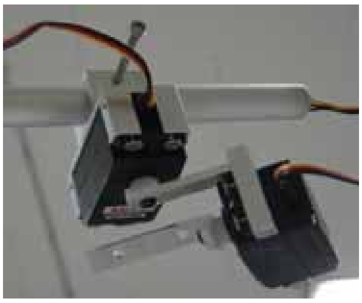

Fig. 4 The Pan-Tilt mechanism

3. INVERSE KINEMATICS OF PAN/TILT MECHANISM

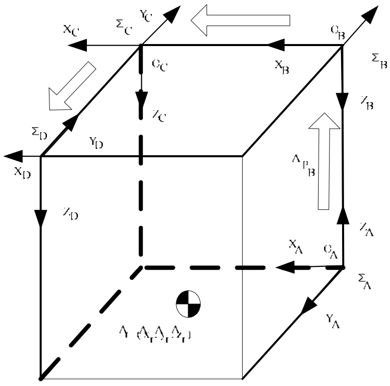

Fig. 5 Reference frame and other frames

Fig. 5 shows several steps of translation and rotation from reference frame A to frames B, C and D of each RF beacon and beacons. For convenience' sake, the reference frame A is denoted by Σ_A having its origin at $\mathbf{O_A}$ and three coordinate axes of X_A, Y_A and Z_A. Similarly, beacon frames such as frames B, C and D are denoted by the same way. The vector from $\mathbf{O_A}$ to $\mathbf{O_B}$, expressed in Σ_A, is denoted as ${}^{\mathbf{A}}\mathbf{P_B}$. Also, the rotation matrix from $\mathbf{O_A}$ to $\mathbf{O_B}$, expressed in Σ_A, is denoted ${}^{\mathbf{A}}\mathbf{R_B}$. ${}^{\mathbf{A}}\mathbf{r}$ is a position expressed in frame A.

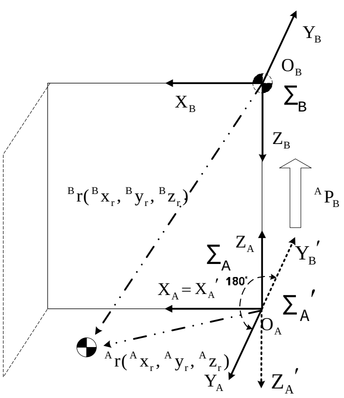

Fig. 6 Relative position of mobile objects

Considering the relative position of a mobile object shown in Fig. 6 we can see that frame B is rotated from frame A as 180 degrees for X_A axis and translated from A as ${}^{\mathbf{A}}\mathbf{P_B}$ for Z_A axis. Consequently, the position of the mobile object through the translation and the rotation from frame A to frame B can be expressed as below equations.

$$ {}^{\mathbf{A}}\mathbf{r} = {}^{\mathbf{A}}\mathbf{R_B}\,{}^{\mathbf{B}}\mathbf{r} + {}^{\mathbf{A}}\mathbf{p_B} \tag{1} $$

Where

$$ {}^{\mathbf{A}}\mathbf{R_B} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos 180^\circ & -\sin 180^\circ \\ 0 & \sin 180^\circ & \cos 180^\circ \end{bmatrix}, \qquad {}^{\mathbf{A}}\mathbf{p_B} = \begin{bmatrix} {}^{A}x_{O_B} \\ {}^{A}y_{O_B} \\ {}^{A}z_{O_B} \end{bmatrix} \tag{2} $$

Eq. (1) can also be expressed in using the Homogeneous Transform as

$$ {}^{\mathbf{A}}\mathbf{r} = {}^{\mathbf{A}}\mathbf{T_B}\,{}^{\mathbf{B}}\mathbf{r}, \quad {}^{\mathbf{B}}\mathbf{r} = {}^{\mathbf{A}}\mathbf{T_B^{-1}}\,{}^{\mathbf{A}}\mathbf{r}, \quad {}^{\mathbf{B}}\mathbf{r} = {}^{\mathbf{B}}\mathbf{T_A}\,{}^{\mathbf{A}}\mathbf{r} \tag{3} $$

where the ${}^{\mathbf{A}}\mathbf{T_B}$ is homogeneous transformation matrix from frame A to frame B defined as

$$ \begin{bmatrix} {}^{\mathbf{A}}\mathbf{R_B} & {}^{\mathbf{A}}\mathbf{p_B} \\ \mathbf{0\ 0\ 0} & \mathbf{1} \end{bmatrix} = {}^{\mathbf{A}}\mathbf{T_B},\ {}^{\mathbf{B}}\mathbf{T_A} = {}^{\mathbf{A}}\mathbf{T_B^{-1}} = \begin{bmatrix} {}^{\mathbf{A}}\mathbf{R_B^T} & -{}^{\mathbf{A}}\mathbf{R_B^T}\,{}^{\mathbf{A}}\mathbf{p_B} \\ \mathbf{0} & \mathbf{1} \end{bmatrix} \tag{4} $$

From Eq. (5), the position vector ${}^{\mathbf{B}}\mathbf{r}$ can be derived from ${}^{\mathbf{A}}\mathbf{r}$ and obtained. by

$$ {}^{\mathbf{B}}\mathbf{r} = \begin{bmatrix} {}^{A}x_r - {}^{A}x_{O_B} \\ -{}^{A}y_r + {}^{A}y_{O_B} \\ -{}^{A}z_r + {}^{A}z_{O_B} \\ 1 \end{bmatrix}. \tag{5} $$

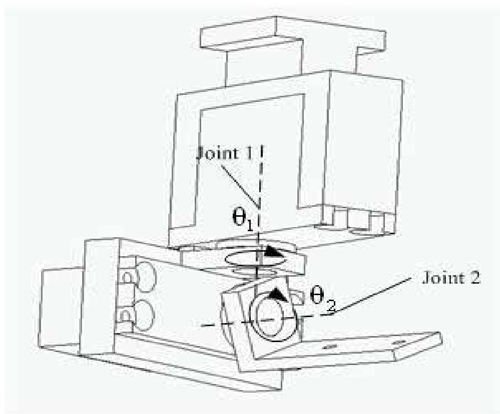

Fig. 7 joint 1 (θ_1) and joint 2 (θ_2)

We are able to calculate angles of joint 1 and joint 2, shown in Fig. 7, using this solution. When θ_1 is the angle of joint 1 and θ_2 is the angle of joint 2, we obtain the solution by Eq. (6) and Eq. (7).

$$\theta_1 = \tan^{-1}\left(\frac{-{}^{A}y_r - {}^{A}y_{O_B}}{{}^{A}x_r - {}^{A}x_{O_B}}\right) \tag{6}$$

$$\theta_2 = \tan^{-1}\left(\frac{\sqrt{({}^{A}x_r - {}^{A}x_{O_B})^2 + (-{}^{A}y_r - {}^{A}y_{O_B})^2}}{-{}^{A}z_r - {}^{A}z_{O_B}}\right) \tag{7}$$

4. 3-DIMENSIONAL LOCALIZATION USING NEWTON METHOD

First of all, a receiver measures the distances, r_i from at least three beacons including an RF beacon. Fig. 8 shows the method of localization.

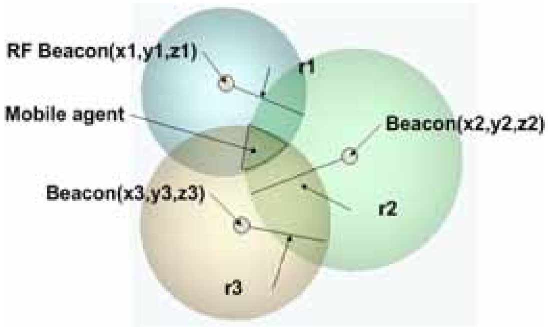

Fig. 8 Relative position of mobile objects

Define a position vector as

$$\mathbf{x} \triangleq [x\ y\ z]^T \tag{8}$$

Given the beacons' positions, $\{\mathbf{x}_1, \dots, \mathbf{x}_n\}$, equations w.r.t receiver's position $\mathbf{x}$ are expressed as

$$\|\mathbf{x} - \mathbf{x}_i\|^2 = r_i^2, \qquad i = 1, \cdots, n. \tag{9}$$

If we define $F(\mathbf{x})$ as

$$\mathbf{F(x)} \triangleq [f_1 \cdots f_n]^T, \quad f_i = \|\mathbf{x} - \mathbf{x}_i\|^2 - r_i^2. \tag{10}$$

then localization problem is equivalent to solving the following equations

$$\mathbf{F(x)} = [0 \cdots 0]^T. \tag{11}$$

Since, given a $\mathbf{x}^{(k)}$ and its neighborhood $\mathbf{x}^{(k+1)}$, the $F(\mathbf{x}^{(k+1)})$ can be approximated by Newton method like

$$\mathbf{F}\left(\mathbf{x}^{(k+1)}\right) \cong \mathbf{F}\left(\mathbf{x}^{(k)}\right) + \mathbf{F}'\left(\mathbf{x}^{(k)}\right)\left[\mathbf{x}^{(k+1)} - \mathbf{x}^{(k)}\right]. \tag{12}$$

Where

$$\mathbf{F}'\left(\mathbf{x}^{(k)}\right) = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} & \frac{\partial f_1}{\partial z} \\ & \vdots & \\ \frac{\partial f_n}{\partial x} & \frac{\partial f_n}{\partial y} & \frac{\partial f_n}{\partial z} \end{bmatrix}. \tag{13}$$

Then, the solution is computed by iteration with a proper tolerance like

$$\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} - \left(\mathbf{F}'\left(\mathbf{x}^{(k)}\right)\right)^* \mathbf{F}\left(\mathbf{x}^{(k)}\right) \tag{14}$$

where the A^* means the pseudo inverse of A.

5. EXPERIMENTAL RESULTS

5.1 Experimental Environment

Fig. 9 shows pictures of the real experimental space. For the flexibility in beacon's position, Several rails are established on the ceiling, also they are designed for being efficiently mounted with pan-tilt mechanism. Red circles in the picture describe the active beacons established on the ceiling. In addition, we use ultrasonic sensors which operate at 40KHz frequency and all their beam-angles are estimated as 100 degree with several experiments.

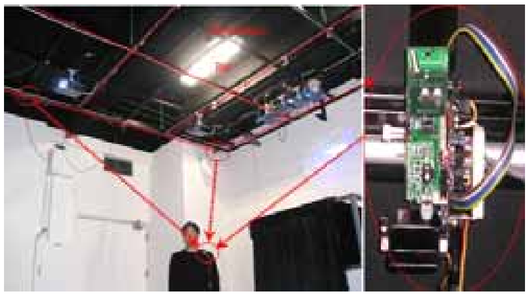

Fig. 9 A Beacon Set on Real space

The experiments were conducted through two ways. One of them is comparing the accuracy and the successful rate of receiving between the fixed angle system (the existent system) and the active beacon system (the proposed system) on static objects. And the other way is comparing the accuracy between the dead-reckoning method and the active beacon method on the mobile robot with its trajectories. The robot is Pioneer 2 made by ActiveMedia Robotics, and the following figures are sampled from its GUI (Graphic User Interface). Fig. 10 shows the pioneer robot to which a receiver is attached. A PDA (Personal Digital Assistants) shown in the figure is used to calculate the absolute positions and send them to a server via wireless LAN (Local Area Network). Also, Fig 11 is a simple top view of experimental space. And Table Ⅱ shows the real positions of our experimental points corresponding to Circles of 1 to 5 in Fig. 11.

Fig. 10 Real picture of Pioneer robot used for experiments

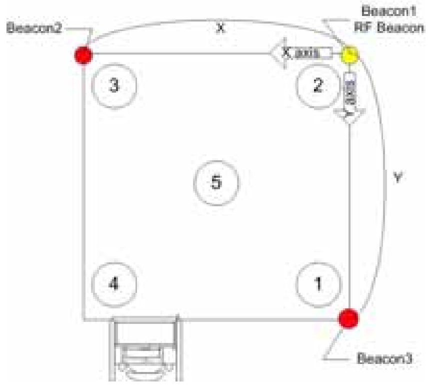

Fig. 11 Simple top view of experimental space

Table 2 Real position of experimental points (3750*4250)

Position of Experiment (x, y, z) unit : mm				
1	2	3	4	5
(500, 3500, 1000)	(500, 500, 1000)	(3000, 500, 1000)	(3000, 3500, 1000)	(1800, 2000, 1000)

5.2 Experiments for Comparison between the fixed angle beacon system and the active beacon system

The comparative experiments between the fixed angle beacon system and the active beacon system were performed in the space as 3750mm by 4250mm. Then, we obtained the results such as Figs. 12 and 13 through experiments using the fixed angle beacon. Experiments have been performed 20 times per each point. Fig. 12 shows the successful rate of receiving of the ultrasonic signal and the average value of errors between the real positions and the measurements. Also Fig. 13 shows each distribution-view of the measured positions at X-Y plane. As shown in Figs. 12 and 13 , the fixed angle system emerges to comparatively inaccurate results, especially at point 4. It is certainly proved that both the accuracy and the successful rate of receiving depend on the distance and the angle between a beacon and a receiver. Also, it means that the stronger ultrasonic sensor's signals are used, the more effective localization can be archived.

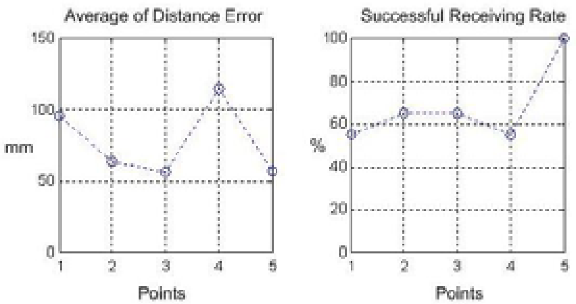

Fig. 12 Average of distance error & successful receiving rate with the fixed angle beacon system

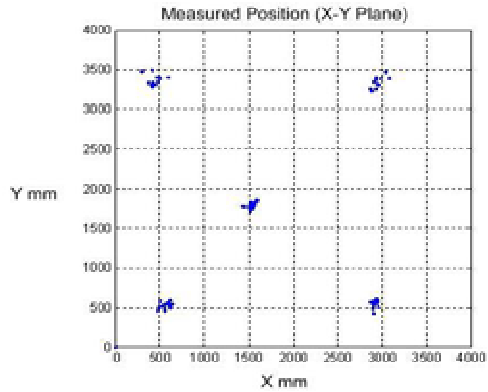

Fig. 13 Distribution-view of real measured positions at X-Y with the fixed angle beacon system

Next, Figs. 14 and 15 show the results from the experiments using the active beacon system.

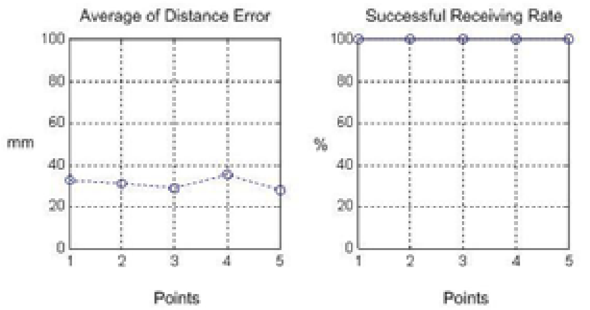

Fig. 14 Average of distance error & successful receiving rate with active beacon system

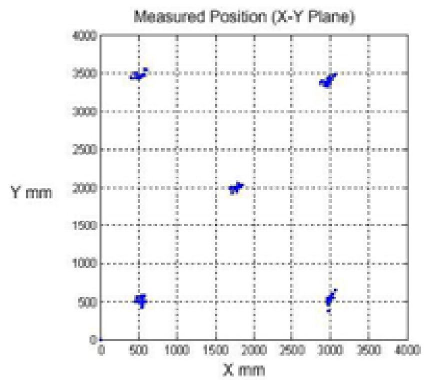

Fig. 15 Distribution-view of real measured positions at X-Y with the active beacon system

By inspecting above graphs, on the contrary, the experiments using the active beacon system show the better results. As for the successful receiving rate, while the fixed angle beacon system shows the results lower than 70% at all points excepted the point 5, the results of the active beacon system are 100% at all points. Eventually, the advantage of the active beacon system emerges to be more obvious in wider space.

5.3 Experiments for Comparison between The dead-reckoning method and The active beacon method

The next experiments are archived in a specific space as

6000 mm by 4500mm, and applied with the multi-section algorithm. The mobile robot is operated by the manual remote control. The experiment is performed as the mobile robot is intended to follow twice the rectangular route that is connected to each green point in Fig. 17. Consequently, we obtain the trajectory such as Fig. 16 through the experiments using the active beacon method. At the same time, the trajectory resulting from the dead-reckoning method is shown in Fig. 17. The real value of the robot's final position was about (1750mm, 800mm).

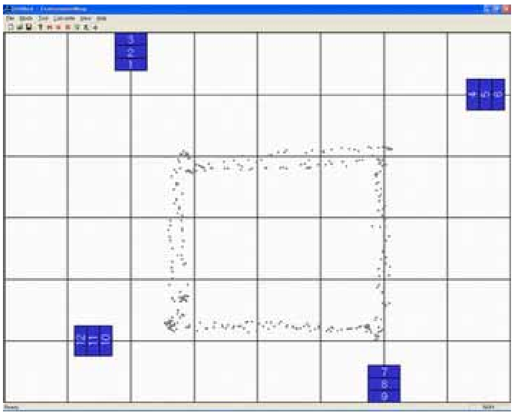

Fig. 16 The mobile robot's Trajectory using the active beacon method (grid : 750mm)

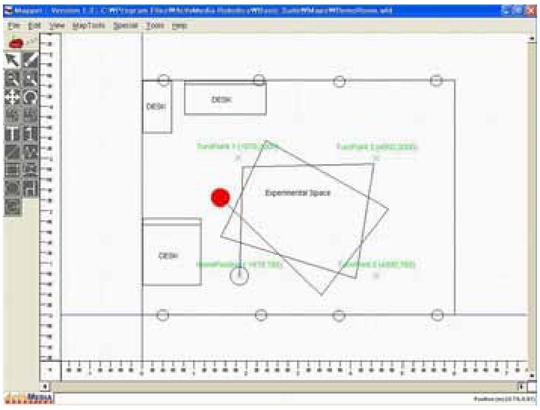

Fig. 17 The mobile robot's Trajectory using the dead-reckoning method (grid : 750mm)

As shown in Figs. 16 and 17, the trajectory using the active beacon method approximately matched up to the real robot's position, while the trajectory using the dead-reckoning method did not.

5. CONCLUSION

Even though the existent beacon systems have the serious constraints, they are often used to find positions of mobile objects because of their inexpensive cost of development. Consequently, we have performed experiments with the existent beacon method which has a fixed angle. Since we found out the problem of the existent beacon method, we proposed the improved systems which are called active beacon system and resolved the problem. As shown in the experimental results, the active beacon system is better than the existent beacon system in two factors – both the successful rate of receiving and the accuracy of localization. Also, it shows the batter results than the dead-reckoning method in case of dynamic objects. Actually, this system is not perfect up to now because the accuracy comes down in some environments which have many obstacles on the line of sights from beacons to receivers. However, we have confirmed its validity for the efficient localization. Following our experiments, the accuracy and the successful receiving rate of beacon systems are considered as being highly dependent on the electronic circuits and software's delay. Most of all, the delay by software is the largest factor of errors in the measure of distance between receivers and beacons.

We will research into autonomous environments for all the mobile objects, and use the active beacon system in order to make the localization possible everywhere at any time for an intelligent building in which the mobile objects can detect their absolute positions by themselves, and also can have the flexibility on their free movements.

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