Mobile Robot Localization based on 96 HF band RFID readers and ID Tag Installed Floor Carpet

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Yasutake Takahashi and Takumi Hashiguchi

Abstract— **Accurate and highly reliable self-localization system is needed for a mobile robot to work in human daily life environment. The studies of a indoor autonomous mobile robot often use visual sensors and laser range finders. Unfortunately, it is difficult to estimate the exact global location if the environment has number of places that have similar shape boundaries or small number of landmarks to localize. Furthermore, it is not robust against environmental changes and unexpected obstacles. Self-localization system based on reading RFID-tags on floor is robust against lighting condition, unexpected obstacles, furniture and doors conditions in the environment. This paper shows RFID-based self-localization system for a omni-directional vehicle and compares its performance to the LRF-based localization.**

I. Introduction

Reliability of self-localization is crucial for a mobile robot works in a hospital or a nursing house. Conventional mobile robots in hospitals or nursing houses often use vision sensors and/or laser range finders and an environment model. It is difficult to estimate the exact global location if the environment has number of places that have similar shape boundaries or small number of landmarks to localize. It tends to take a long time to recover the self-localization estimation if it goes wrong at once. Vision sensors work hard in dark lighting condition. Laser range finder often fails to detect distance to a transparent wall. In addition, the self-localization becomes unstable if unexpected obstacles occlude landmarks that are important to estimate position of the robot. Door opening and closing condition affects the self-localization performance, too. Automated guided vehicles are also popular as transportation system in a hospital or nursing house. However, magnetic taps installed on the floor for the guiding the vehicle are necessary and make the vehicle hard to change the route frequently.

Recently, RFID (Radio Frequency IDentification) system have been studied for autonomous mobile robot self-localization. RFID is a wireless non-contact system that uses radio-frequency electromagnetic fields to transfer data from a tag for automatic identification and/or tracking. As a RFID system uses radio waves, unlike visual sensors, it is robust against change of lighting condition or obstacles.

There are two types of communication in RFID system. One uses radio waves and the other uses electromagnetic induction for communication between reader/writer and IC tags. A RFID system based on radio wave communication using UHF or SHF band realizes long distance communication[1][2][3]. However, in general, the radio wave communication based RFID system often suffers from obstacles between the IC tag and the antennas so that the localization cannot be performed safely in an environment with many obstacles, especially, humans.

On the other hand, RFID systems based on HF[4][5] or LF[6][7] band use electromagnetic induction. The communication distance is short and less than several hundred [mm]. It is hard to estimate the distance between the antenna and the tags but it is quite accurate and reliable to detect the tag if the tag is within the range of the antenna. It rarely suffers from obstacles between the the IC tag and the antennas. Therefore, the position estimation is more accurate than the ones based on radio wave communication with UHF or higher frequency bands.

Conventional self-localization methods based on HF-band RFID systems[8][9] use a single antenna on bottoms of mobile robots to detect the tags on the floor. Unfortunately, it is hard to estimate posture of the vehicle with the tag data detected by one single antenna. Another way to estimate the robot orientation with one antenna is to rotate the antenna with high speed on bottom of the robot and read the tags on the floor[10]. The system needs mechanical rotation mechanism and accurate tag reading system with high speed.

Kodaka et al. [7] proposed a LF-band RFID system for mobile robot self-localization in a home environment. They use one or two RFID readers on the vehicle and tags installed into the floor. The tag is a square, 260 mm on a side, and installed at 300 mm interval. They use a Monte-Calro localization method for the self-localization. The localization error is less than 100 mm and 0.1 rad on average if they chose an appropriate reader's arrangement. Unfortunately, it is hard to increase the accuracy in the configuration because the accuracy depends on the size of tags and communication range of the RFID reader although they developed active self-localization method to increase the accuracy[11]

Takahashi et al.[12] proposed another RFID-based self-localization system which is similar to the [7]. They use 8 RFID reader antennas on the bottom of the vehicle and High-Frequency RFID-tag textile on the floor. The size of tags is about 10×20 mm and the tags are installed on the floor every 100 mm. The size of reader's antenna is 60×60 mm and the interval between the antennas is 80 mm. The localization error is less than 17 mm and 0.12 rad on average. The accuracy is small because of the size of the tag and the tag installation interval. They use a simple kinematics

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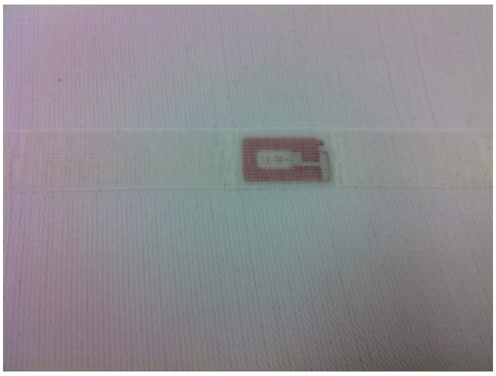
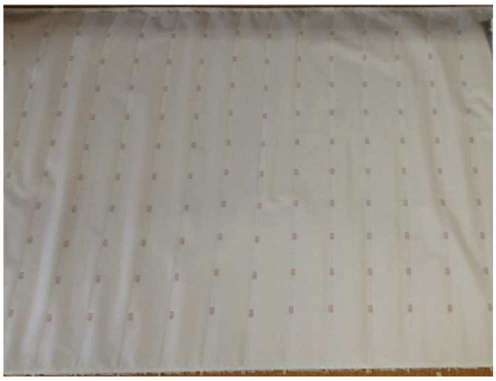
to estimate the localization, however, their method needs synchronization of reading from multiple antennas and shows relatively large localization error if the reader fails to read the tag.

This paper shows more accurate and reliable self-localization method based on HF-band RFID system with small size tags, small antennas, asynchronous RFID readers, and probabilistic approach. The small size tags and antennas of RFID readers improve the accuracy of the self-localization. Integrated RFID system of asynchronous readers enables high frequency of sampling for the self-localization. Probabilistic approach contributes for robust estimation against partially available sensing data, simple computational implementation. Experimental results show the validity of the proposed system.

II. HF band RFID system for Localization



(a) IC Tag

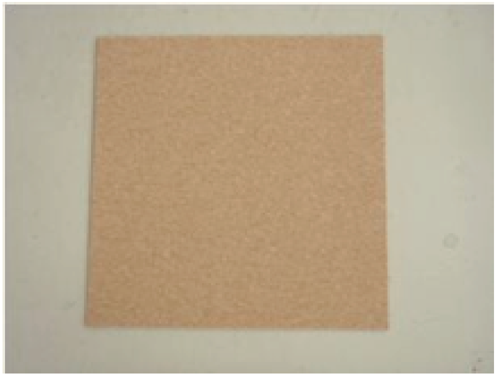


(b) IC Tag Textile

Fig. 1. IC tag textile

Fig.1(a) shows a HF band RFID IC tag we adopt for our experiments. The size of the IC tag is 10×20 [mm]. Fig.1(b) shows a IC tag textile. The IC tags inserted automatically in one polyester sheet while weaving[13]. The interval of IC tags is about 10 [cm] . As the tags are inserted into the textile, there are some errors that can't be avoided. The positions of the tags are measured manually one by one, and then use those data build a IC tag map.

Fig.2(a) shows a carpet which is installed the IC tag textile sheet shown by Fig.1(b). It contains the polyester sheet



(a) IC Tag Textile Carpet

(b) Room installed IC Tag Textile Carpets

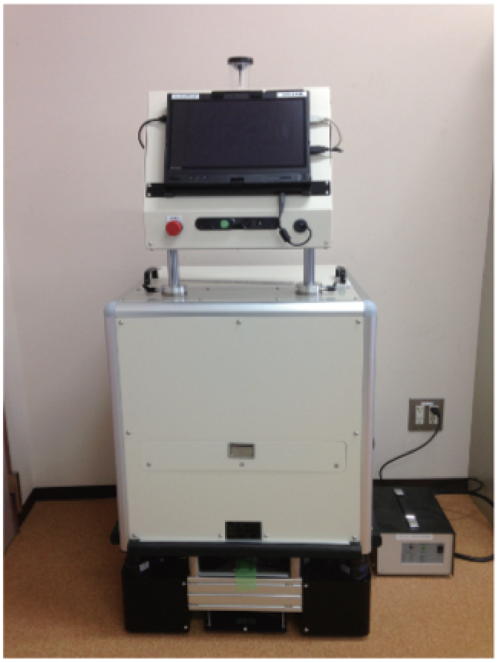
Fig. 2. IC Tag Textile Carpet and Installed Room and Corridor

shown in Fig.1(b). IC tags are not visible because the IC tag textile sheet is covered. We have installed the carpets into a room at a building of University of Fukui as shown in Fig.2(b).

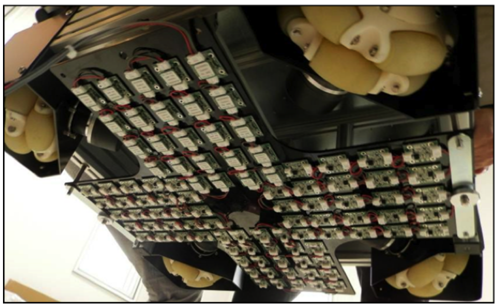
Fig. 3. 96 Multi-Reader

A set of 96 RFID readers is developed by ART FINEX Co.Ltd. Fig.3 The antenna size of each reader is 30×30 [mm]. The intervals between the reader is [37.5] mm in x coordinate and 44.5 [mm] in y coordinate. All RFID readers work simultaneously and asynchronously. Each reader sends the tag's unique ID if it detected the tag immediately.

The 96 RFID readers are installed to the bottom of a omni-



(a) Front View



(b) Bottom View

Fig. 4. Omni-directional Vehicle with 96 Multi RFID readers

directional vehicle. Fig.4 shows the omni-directional vehicle equipped with the 96 RFID readers. It has 4 omni-wheels at four corners as shown in Fig.4(b) and controls its translation and rotation independently.

A mobile robot equipped with the 96 RFID readers runs on the floor installed with HF-band RFID tags as shown in Fig.II. The next section introduce the self-localization method based on the RFID system.

III. Self-Localization based on RFID system

We introduce a Monte Calro Localization method as one of the probabilistic approaches[14]. We define the robot position and posture in world coordinate at time t as ${}^w\boldsymbol{x}_t = ({}^w x_t, {}^w y_t, {}^w \theta_t)$. $\boldsymbol{z}_t = (r_t, tag_t)$ is measurement output at time t while tag_t is the detected tag with RFID reader r_t. A motion model ${}^w\boldsymbol{x}_{t+1} = MotionModel({}^w\boldsymbol{x}_t)$ is defined as it estimates the next robot position and posture ${}^w\boldsymbol{x}_{t+1}$ from the current one ${}^w\boldsymbol{x}_t$. A measurement model $p(\boldsymbol{z}_t|{}^w\boldsymbol{x}_t)$ is also defined to calculate the posterior probability to get the measurement output $\boldsymbol{z}_t$ if the robot position and posture is ${}^w\boldsymbol{x}_t$. A set of particles is defined as a set of hypotheses of the robot position and posture denoted at time t as $X_t = ({}^w\boldsymbol{x}_t^{[1]}, {}^w\boldsymbol{x}_t^{[2]}, \cdots, {}^w\boldsymbol{x}_t^{[M]})$. The algorithm of the Monte Calro Localization is as follows:

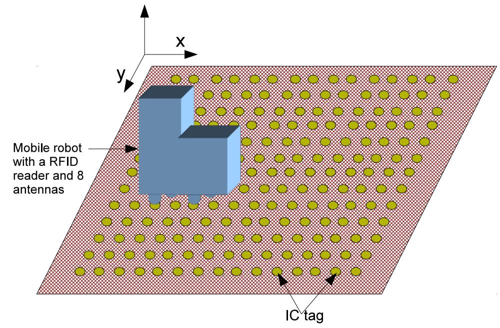


Fig. 5. Self Localization System for a Mobile Robot based on RFID

1) Update particles with the motion model: ${}^w\boldsymbol{x}_t^{[i]} = MotionModel({}^w\boldsymbol{x}_{t-1}^{[i]})$
2) Calculate the belief of each particle with the measurement model : $w^{[i]} = p(\boldsymbol{z}_t|{}^w\boldsymbol{x}_t)$
3) Update the set of particles X_t with probability $w^{[i]}$

The motion model of the omni-directional vehicle is given by Eqs.(1)(2)(3).

$$x_{t+1} = x_t + N(0, \sigma_x)\Delta t \quad (1)$$

$$y_{t+1} = y_t + N(0, \sigma_y)\Delta t \quad (2)$$

$$\theta_{t+1} = \theta_t + N(0, \sigma_\theta)\Delta t \quad (3)$$

Δt and $N(0, \sigma)$ indicate period between time $t+1$ and t and normally distributed random function with standard deviation θ, respectively.

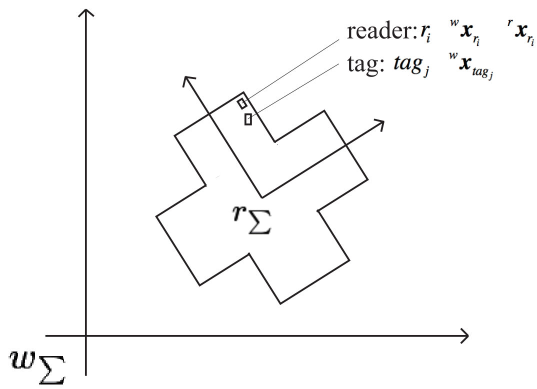


Fig. 6. World coordinate system ${}^w\Sigma$ and robot coordinate system ${}^w\Sigma$

The measurement model $p(\boldsymbol{z}_t|\boldsymbol{x}_t)$ is defined with the sensing model of the RFID reader. We assume that the probability of detecting tag tag_j by RFID reader r_i is defined with a normal distribution as shown in Eq.4.

$$p(tag_j, r_i) = \exp\left(-\frac{1}{2}({}^w\boldsymbol{x}_{tag_j} - {}^w\boldsymbol{x}_{r_i})^T \Sigma^{-1} ({}^w\boldsymbol{x}_{tag_j} - {}^w\boldsymbol{x}_{r_i})\right) \quad (4)$$

where ${}^{w}\boldsymbol{x}_{tag_j}$, ${}^{w}\boldsymbol{x}_{r_i}$, and Σ are positions of tag tag_j and RFID reader r_i in world coordinate, and the variance matrix, respectively. Fig.6 shows world and robot coordinate systems ${}^{w}\Sigma$ and ${}^{r}\Sigma$, the i reader position in world coordinate ${}^{w}\boldsymbol{x}_{r_i}$, in robot coordinate ${}^{r}\boldsymbol{x}_{r_i}$, and the j the tag in the world coordinate ${}^{w}\boldsymbol{x}_{tag_j}$. The position of RFID reader r_i in world coordinate ${}^{w}\boldsymbol{x}_{r_i} = ({}^{w}x_{r_i}, {}^{w}y_{r_i})^T$ at time t is estimated by Eq.(5).

$$\begin{pmatrix} {}^{w}x_{r_i} \\ {}^{w}y_{r_i} \end{pmatrix} = \begin{pmatrix} \cos {}^{w}\theta_t & \sin {}^{w}\theta_t \\ -\sin {}^{w}\theta_t & \cos {}^{w}\theta_t \end{pmatrix} \begin{pmatrix} {}^{r}x_{r_i} \\ {}^{r}y_{r_i} \end{pmatrix} + \begin{pmatrix} {}^{w}x_t \\ {}^{w}y_t \end{pmatrix} \quad (5)$$

After the beliefs of particles are calculated, it estimates the position of the robot as arithmetic weighted mean of the particles.

$$\boldsymbol{x}_t = \frac{\sum_{m=1}^{M} w^{[m]} \boldsymbol{x}_t^{[m]}}{\sum_{m=1}^{M} w^{[m]}} \quad (6)$$

Then the set of the particles is updated from X_t to X_{t+1} with probability proportional to the belief $w^{[m]}$. The pseudo algorithm is shown below:

for $m = 1$ to M **do**
  draw i from X_t with probability $\propto w^{[i]}$
  add ${}^{w}\boldsymbol{x}_t^{[i]}$ to X_{t+1}
end for

IV. Experiments

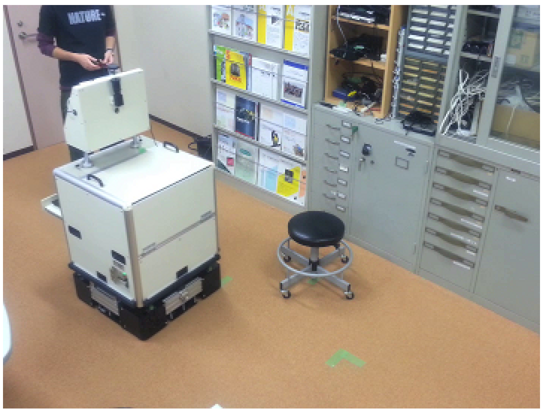


Fig. 7. Omni-directional vehicle embedded with 96 RFID readers on the bottom and experiment environment with RFID tag installed floor

Experiments to evaluate the performance of the proposed method are conducted. Fig.7 shows the omni-directional vehicle with 96 RFID readers on the bottom of the body and experiment environment set up with RFID tag textile on the floor. The vehicle has also 3 laser range finders (LRFs) at left and right corner of the front and center back of the body. We have not only self-localization experiment with the RFID system but also the one with LRFs for comparison. The vehicle is controlled by hand to ensure that it follows a desired route defined beforehand.

The LRF based self-localization uses the outputs of 3 laser range finders. Each laser range finder detects objects around the robot in the range of 4 m with about 3 cm error in measurement and covers 240 degree. One finder outputs the 1024 points for the detected obstacles surroundings. 3072 points in total are used for the self-localization.

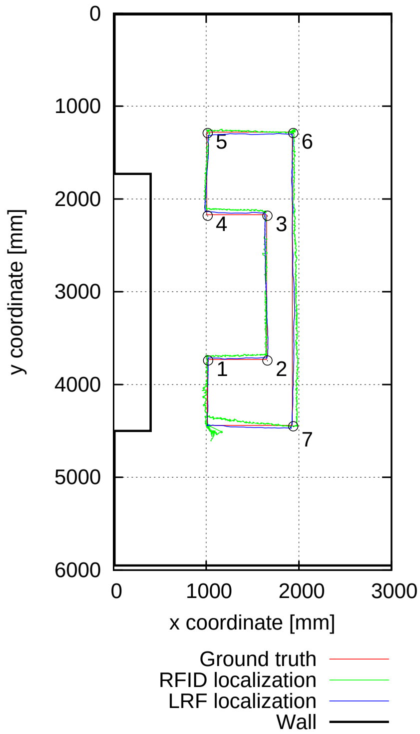


Fig. 8. Estimated trajectories and ground truth

Fig.8 shows the ground truth trajectory of the vehicle. It shows the trajectories estimated by RFID and LRF systems, too. The performances of both localization system are good enough to navigate itself safely. The RFID based self-localization method seems to show a little bit worse performance than the LRF system. The reason is that the RFID system estimates the position and posture of the vehicle with only one pair of the detected RFID tag and the RFID reader which detects the tag while the LRF system uses 360 degree surrounding information. The amount of the information for the LRF system is much bigger than the RFID system, then, the LRF system needs more computational resources to calculate the measurement probability.

Tables I and II show the performances of self-localization methods based on the RFID and LRF systems, respectively. The tables show the mean and variance of the estimated position and posture (x, y, θ). The number of samples at each point is 100. They show that the estimated position errors and variances in x coordinate of the RFID system is competitive with the LRF system while the errors and variance in y coordinate of the RFID system is better than the LRF system. The reason is the vehicle runs near to the wall in x coordinate while the wall is far in y coordinate. The output of LRF has about 1 % error in distance if the obstacle is in from 1to 4 m distance. According to Table I, the RFID self-localization system shows a little bit big error at Points

5 and 6. This is because the positions of RFID tags installed on the floor have some errors and tags are sometimes missing while the textile is installed in the floor carpet.

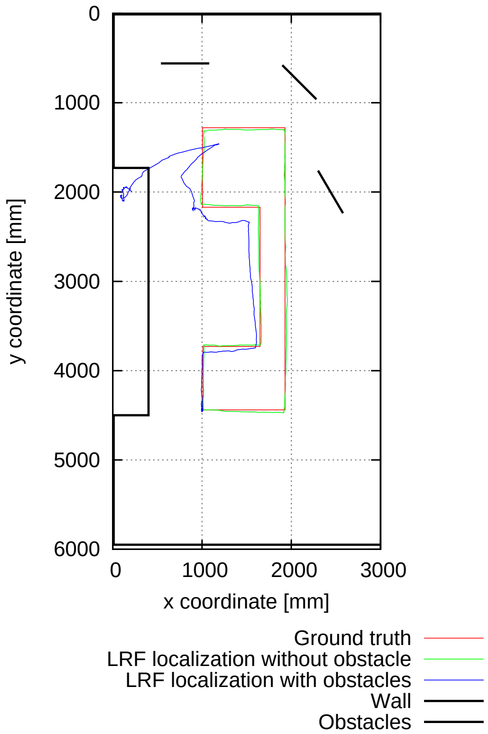


Fig. 9. Trajectories estimated by LRF based self-localization method and ground truth

In order to evaluate the stability of the LRF based self-localization, another experiment is conducted after a few obstacles are set up. The three obstacles as walls are put at about (800, 600), (2100, 800), and (2500, 2000) as shown in Fig. 9. The red and blue lines indicate the ground truth trajectory and the trajectory estimated by LRF-based self-localization. The LRF based self-localization shows good estimation while the vehicle is far from the obstacles, however, it fails to estimate the position of the vehicle if the unexpected obstacles get close to the vehicle. The RFID based self-localization system is not affected by the unexpected obstacles so that it is clear that the the RFID based self-localization system is robust and highly reliable to the unexpected evironmental changes.

V. Conclusions and Discussions

This paper show accurate and reliable self-localization method based on HF-band RFID system with small size tags, small antennas, asynchronous RFID readers, and probabilistic approach. 96 RFID readers with small antennas and RFID tag textile installed on the floor have been developed. The experimental results show its validity. It shows accurate and reliable position and posture estimation performance.

The proposed RFID based self-localization system needs much smaller computational cost for the accurate localization than the LRF based self-localization. The RFID system needs only 4 variables for the self-localization, that is, positions of the detected tags in world coordinate $({}^{w}x_{tag_j}, {}^{w}y_{tag_j})$ and the reader that detects the tag in robot coordinate $({}^{r}x_{r_i}, {}^{r}y_{r_i})$. Number of particles for the Monte-Carlo localization can be small enough to use low computational cost. The self-localization system based on the LRF system needs bigger size of range data to calculate the measurement probability and more number of particles for the Monte-Carlo localization. The localization error of the RFID based self-localization system is less than 5 cm that is small enough for automatic navigation. Furthermore, the RFID based self-localization is more robust against environmental changes than the LRF based self-localization.

Unfortunately, the cost of the 96 RFID reader is too expensive at this moment. Effective arrangement of RFID readers and tags on the floor is one of the future work. The map of the RFID tags on the floor is built by hand at this moment. Automatic map building is another future work.

Acknowledgement

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RFID	mean			variance			error		
	x [mm]	y [mm]	θ [rad]	x [mm]	y [mm]	θ [rad]	x [mm]	y [mm]	θ [rad]
Point1 (1010,3730)	1011.8	3706.8	3.146	4.2	4.1	0.0003	1.8	-23.2	0.005
Point2 (1650,3730)	1636.7	3701.2	3.109	2.5	3.6	0.0001	-13.3	-28.8	-0.033
Point3 (1650,2170)	1618.7	2176.7	3.142	5.8	6.9	0.0003	-31.3	6.7	0.001
Point4 (1005,2170)	1001.6	2183.8	3.180	6.2	11.6	0.0004	-3.4	13.8	0.038
Point5 (1005,1280)	1014.0	1294.7	3.146	11.7	42.4	0.0020	9.0	14.7	0.005
Point6 (1930,1280)	1931.0	1290.2	3.138	41.1	18.3	0.0070	1.0	10.2	-0.004
Point7 (1930,4440)	1906.9	4407.2	3.149	9.0	8.1	0.0006	-23.1	-32.8	0.007

TABLE I

PERFORMANCE OF SELF-LOCALIZATION BASED ON RFID SYSTEM: EACH POINT IS DEPICTED IN FIG.8

LRF	mean			variance			error		
	x [mm]	y [mm]	θ [rad]	x [mm]	y [mm]	θ [rad]	x [mm]	y [mm]	θ [rad]
Point1 (1010,3730)	1033.1	3708.9	3.158	3.9	28.8	0.0000	23.1	-21.1	0.0164
Point2 (1650,3730)	1665.1	3698.1	3.185	4.6	12.1	0.0000	15.1	-31.9	0.0431
Point3 (1650,2170)	1608.1	2199.5	3.199	8.3	27.4	0.0000	-41.9	29.5	0.0574
Point4 (1005,2170)	982.9	2229.2	3.142	7.2	56.6	0.0000	-22.1	59.2	-0.0001
Point5 (1005,1280)	993.5	1336.3	3.149	5.9	10.5	0.0000	-11.5	56.3	0.0078
Point6 (1930,1280)	1931.3	1309.9	3.118	7.5	13.2	0.0000	1.3	29.9	-0.0236
Point7 (1930,4440)	1929.4	4444.4	3.173	13.4	16.2	0.0000	-0.6	4.4	0.0312

TABLE II

PERFORMANCE OF SELF-LOCALIZATION BASED ON LRF SYSTEM: EACH POINT IS DEPICTED IN FIG.8

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