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Improving Position Estimation of the RFID Tag Floor Localization with Multiple Recognition Ranges

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1. Introduction

This chapter introduces the RFID tag floor localization method with multiple recognition ranges and its mathematical formulation to improve position estimation accuracy. Using the multiple recognition ranges of RFID reader, the reader can obtain more information about the distances to the tags on the tag floor. The information is used to improve the position estimation performance. At first, this chapter reviews the RFID tag floor localization method with single recognition range for mobile robots(Park et al., 2010) and The performance measure based on the position estimation error variance for the localization method. For the second, this paper extends the mathematical formulation of the localization method and the performance measure for the case of multiple recognition ranges. This work is related to the previous work(Park et al., 2009) that used multiple powers to improve position estimation performance. However, previous work lacks analysis and mathematical formulation of general RFID tag recognition models. We extend the mathematical formulation and the analysis of the single recognition range RFID tag floor localization method (Park et al., 2010) to the multiple recognition range case. Then the minimum error variance of multiple recognition range is introduced as a lower bound of position estimation error variance. Finally, it presents performance improvement of proposed localization method via the Monte-Carlo simulation and simple experiments. The analysis for the simulation and experimental results and the consideration for real application will be given.

This chapter is organized as follows; This section discusses sensor systems used in the mobile robot localization. Then the advantages of the RFID systems as sensor systems for localization are discussed and the researches on the systems are reviewed. Section 2 introduces the RFID tag floor localization, its mathematical formulation and its performance index. Section 3 represents the motivation of introducing the use of multiple recognition ranges for the RFID tag floor localization method, and extend the mathematical formulation and the error variance for the multiple recognition range case. Section 4 conducts the Monte-Carlo simulation to show the improvement of the position estimation performance when the multiple recognition range is used. Section 5 represents experimental results that support the simulation results. In Section 6, the minimum error variance(Park *et al.*, 2010) as a lower bound of error variance is extended to the multiple recognition range case. Section 7 gives the conclusions, discussions and tasks for the further researches.

1.1 Sensor systems for indoor mobile robots

The localization is essential problem for the mobile robots to navigate a working area and to accomplish their work. For the localization problem, many researchers used various types of sensor systems to solve it.

The dead reckoning systems utilize the movement of actuators by encoders to estimate the relative changes of position and heading angle(Everett, 1995). However, the sensor systems accumulate the errors that induced by the mismatches between real robot and models, slippage of wheels, and variance of wheel diameter due to the air pressure during the navigation.

The localization systems with inertial navigation system (INS) utilize the linear accelerations and angular velocities of the mobile robot(Borenstein and Feng, 1996). The systems integrate these informations to estimate the current position and the heading angle. The cost of the INS systems was very high and the size was large for the indoor mobile robots, until the advances of the micro-electromechanical systems (MEMS). The MEMS based INS have low cost and small size relative to mechanical INS systems. However, the INS suffers from noise and bias that lead to drift of integrated results (Sasiadek *et al.*, 2000). Some INS packages include magnetic sensors to detect the terrestrial magnetism, to reduce the pose or heading angle error. However, there are many sources that can distort the terrestrial magnetism for indoor environments.

The ultra sonic ranging system and the lager range finder (LRF) are range detecting sensors. The mobile robot matches range information with the map which they have, to estimate their positions. These range sensors can measure the range of objects very accurately. But, under some surface conditions, they can't detect objects and can suffer from multipath problems(Everett, 1995).

The ultra sonic satellite systems, such as CRICKET triangulate a moving node's position with distances from fixed nodes by time of flight(Priyantha, 2005). However, the system is hard to scale up for the large work area and the many mobile robots. When the numbers of fixed nodes and mobile robots are increased, the localization takes longer time due to the arbitration processes.

The radio-frequency-based ranging systems such as chirp spread spectrum (CSS) and received signal strength (RSS) are used for localization of the mobile robots(Inácio *et al.*, 2005; Patwari and Hero III, 2003), however, they have relatively large errors for the indoor mobile robot applications. The ultra-wideband (UWB) communication systems are also used for the indoor localization problem and have good resolution, however, the system cost is still high and each fixed nodes needs to be synchronized by wires(Gezici *et al.*, 2005). Moreover, they use the wide frequency bands that can be the reason of the signal interference, therefore, it requires the permission of the relevant government ministries when it is use.

1.2 RFID systems for indoor mobile robots

The RFID based localization systems are also used by several researches to localize the indoor mobile robots. The RFID systems as localization sensor systems for mobile robots have several advantages.

First, the systems are robust to the external environments such as light condition, surface condition of objects, dirts on the landmarks, and distortion of the terrestrial magnetism. Vision-based localization systems suffer from illumination and color changes, bad focused images, image distortions, motion bluer and so forth. The ultra sonic sensor systems and the LRF sensor systems can not detect obstacles or walls, under some surface conditions.

Second, the RFID systems can handle numerous unique landmarks. The landmark is the simplest way to locate the current position, however, the vision sensor based localization

systems have limitations on the numbers of landmarks or features. Moreover, they need heavy image process routines for finding features in images. The RFID tags have their unique identification information in their memories and some of the RFID tags have configurable memories which can be written while or after the landmark installation.

Third, they can handle many tags in a short time. Most of RFID readers are equipped with anti-collision algorithms such as ALOHA, slotted ALOHA, and binary search tree algorithm. It reduces the user's consideration for handling the collisions and arbitrations.

Finally, the installation cost and the maintenance cost of RFID systems are relatively low. The price of tags have been dropping. Nowdays, a 96-bit EPC tags cost 7 to 15 U.S. cents and the EPCglobal tries to reduce the price of tags to 5 cents(RFID journal, nd). After the installation of RFID tags, the efforts to maintain the landmarks are barely needed. These utilize the transmitted power from readers to respond to the reader. They will work normally under harsh conditions.

For these reasons, the RFID systems are used for the mobile robot localization problem by many researchers. Burgard *et al.* (2004) and Kim and Chong (2009) used directional antennas to estimate the current position and target objects. Jia *et al.* (2008) used multiple antennas to locate RFID tags accurately. Ni *et al.* (2004), Shih *et al.* (2006), Zhao *et al.* (2007), and Sue *et al.* (2006) used active RFID tags for indoor localization of target object. Some of them have names such as LANDMARC, VIRE, FLEXOR. Kulyukin *et al.* (2004) and Kulyukin *et al.* (2006) used the passive RFID system with the LRF for guiding visually impaired. Chae and Han (2005) and Kamol *et al.* (2007) used vision information to improve the position estimation performance. Zhou *et al.* (2007) and Zhou and Liu (2007) used active RFID tags that have LEDs on it. Using vision sensors fond the light of tag and aim the laser to the tags to activate it.

2. RFID tag floor localization

The RFID tag floor localization method is one of the RFID based localization method that utilize massive passive tags installed on the working area. The RFID readers are attached under the mobile robot's chassis and the tags are placed on the certain points on a working area. While the mobile robot moves, the reader detects tags near the mobile robot and estimates the position from the detected tags' positions. The RFID tag floor localization method has several advantages. It is easy to scale up the work space and number of robots. Most RFID system still need some arbitration process when multiple readers in a work area. However, the antennas for the RFID tag floor localization face down to the floor. Therefore, they need little consideration for the reader arbitration. Moreover, it rarely require maintenance after installation and does not require power to maintain the tag infrastructure.

The concept of the RFID tag floor localization that called the super-distributed RFID infrastructures, is firstly proposed by Bohn and Mattern (2004). They also propose the criteria to classify the tag placement by the density of tags and the regularities of tag positions. Several researchers managed their works to apply the concept to their application and to improve the position estimation accuracy. Park and Hashimoto (2009a) proposed a simple algorithm that combined rotations and linear movements sequentially to reach the goal position. Lee *et al.* (2007) and Park and Hashimoto (2009b) used weighted mean algorithm to estimate the position of mobile robots. Park *et al.* (2010) investigated the performance of the RFID tag floor localization algorithm with various reader recognition ranges and tag placements. Han *et al.* (2007) used a cornering motion to gather information of robot's position and direction. Senta *et al.* (2007) used support vector machine (SVM) to learn the accurate tag positions from

pseudo table of the tag positions. Choi *et al.* (2008) augmented the ultra sonic sensors and the RFID tag floor localization method for efficient localization.

2.1 Mathematical formulation of the RFID tag floor localization
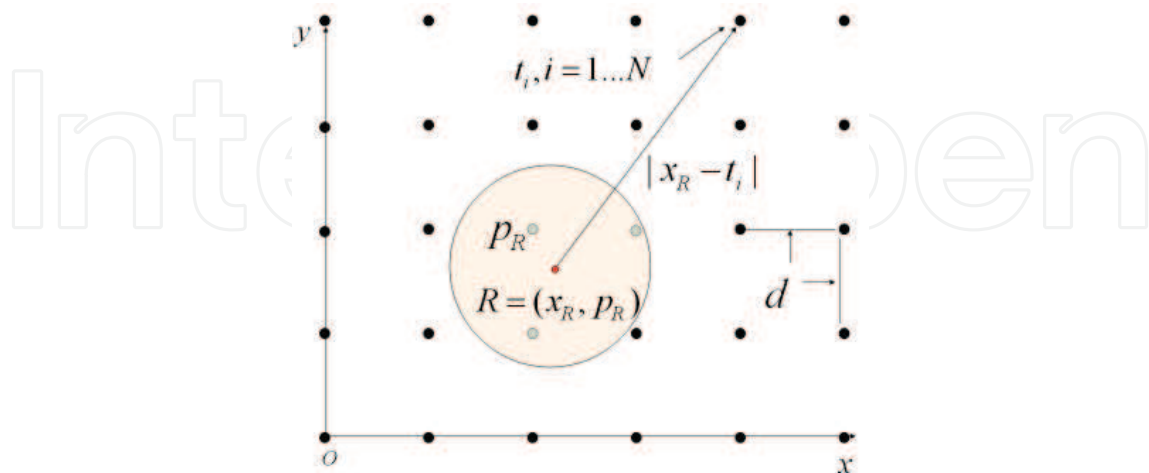

Fig. 1. Concept of the RFID tag floor localization method.

To formulate the RFID tag floor localization (RTFL), it is required to define the representation of the RFID reader and the Tag floor. The RFID reader detects the tags on the RFID tag floor to estimate its position. The RFID tag floor is defined as a set of tags which have their own identities and positions, installed on a work area with some geometric pattern(Fig. 1). The tags are detected by the reader stochastically. The probability of tag recognition can be described as a function of distance and directions between tag and reader. Moreover, the recognition probability is also a function of the RFID reader's transmission power, the number of tags, and other various environmental conditions. Most RFID based localization methods, however, assume that the recognition probability is only a function of distance and the transmission power is fixed for the simplicity of the algorithms.

Therefore, the RFID reader can be described as follows:

$$R = (\mathbf{x_R}, p_R(\cdot)), \tag{1}$$

where $\mathbf{x_R}$ is the position of the RFID reader and $p_R(\cdot)$ is a recognition probability function of distances between the RFID reader and tags.

Tags in tag floor can be described as a tag set T,

$$T = \{t_i | i = 1, \cdots, N\}, \tag{2}$$

where N is the number of tags in the tag floor and t_i is the position of i-th tag.

The result of a recognition process is a set of recognized tags or combination of tags. This set must be one of subsets of T. Y is defined as a set of all subsets of T, and it can be expressed as follows:

$$Y = \{\phi, \{t_1\}, \{t_2\}, \cdots, \{t_1, t_2\}, \cdots, T\}, \tag{3}$$

where ϕ means the empty set that corresponds to the case in which no tag is recognized. The number of elements of Y is 2^N.

However, for a recognition function of a reader, many elements of Y have zero probability, or cannot be happened. For example, in large tag floor, tags in rightmost end and leftmost

end cannot be recognized simultaneously. So, Z is defined as the set of elements of Y, whose elements are the tag set that can be detected at the same time.

$$
\begin{align}
Z &= \{\phi, \{t_1\}, \cdots \} \tag{4}\\
&= \{\phi, z_1, \cdots, z_K\}. \tag{5}
\end{align}
$$

K is the number of elements of $Z - \{\phi\}$. ϕ means the case in which no tag is recognized, but it does not mean that probability is zero. So, ϕ is also a element of set of realizable outputs, Z. The set Z, the set of recognition outputs with nonzero probability, has finite size. In general triangulation problem, there can be additional information such as signal strength, time of flight. However, that the recognition process of RTFL gives only tag's identity and its position. In consequence, only finite number of estimation points can exist. Exactly saying, the number of position estimation points is the same as the number of elements of $Z - \{\phi\}$.
We define the set of mapping or estimation points:

$$
\hat{X} = \{\hat{\mathbf{x}}_1, \cdots, \hat{\mathbf{x}}_K\}, \tag{6}
$$

where $\hat{x}_k$ is position estimation points.
In RTFL, the position estimation using recognition output is mapping from Z to $\hat{X}$,

$$
f : Z - \{\phi\} \to \hat{X}, \tag{7}
$$

$$
f(z_k) = \hat{\mathbf{x}}_k. \tag{8}
$$

This mapping is called position estimation function. In other words, the estimated point $\hat{\mathbf{x}}_k$ is the representative position of the domain where the recognition output z_k occurs.

2.2 Performance index based on position estimation error variance

Main problem in RTFL is making proper position estimation function. To evaluate how proper the function is, performance index is needed. Performance index generally used is average of squared error. The error is difference between the real reader's position and the estimated position. To calculate performance the index, the conditional probability $p(\hat{\mathbf{x}}_k | \mathbf{x}_R)$ should be calculated. This probability function represents the probability of detecting the tags, z_k, corresponding to the mapping point, $\hat{\mathbf{x}}_k$, when the tag is on the position $\hat{\mathbf{x}}_R$. It can be described as follows:

$$
p(\hat{\mathbf{x}}_k | \mathbf{x}_R) = \prod_{t_i \in z_k} p(t_i | \mathbf{x}_R) \times \prod_{t_j \in z_k^c} (1 - p(t_j | \mathbf{x}_R)), \tag{9}
$$

where $p(t_i | \mathbf{x}_R)$ is the probability function in which tag t_i is detected if the reader is on a position $\mathbf{x}_R$. If there is proper number of RFID tags, the recognition probability of a tag is independent of other tags.
Using the conditional probability, the expected value of squared error in position $\mathbf{x}_R$ can be calculated as follows:

$$
V_{\mathbf{x}_R} = \sum_{\hat{\mathbf{x}}_k \in \hat{X}} |\mathbf{x}_R - \hat{\mathbf{x}}_k|^2 p(\hat{\mathbf{x}}_k | \mathbf{x}_R). \tag{10}
$$

The average of squared error, or the error variance, as a performance index is an average of the expected value over the domain of the RFID tag floor. It can be expressed as follows:

$$V = \frac{1}{W} \iint_W V_{\mathbf{x}_R} dx dy \tag{11}$$

$$= \frac{1}{W} \sum_{\hat{\mathbf{x}}_k \in \hat{X}} \iint_W |\mathbf{x}_R - \hat{\mathbf{x}}_k|^2 p(\hat{\mathbf{x}}_k | \mathbf{x}_R) dx dy, \tag{12}$$

where W is the work area. By using the performance index, the optimal estimation position set can be found. Moreover, the accuracy of various position estimation functions can be evaluated by the performance index. In general, mean based or weighted mean based position estimation functions are used in RFID tag floor localization method.

Another aspect of the performance of the RFID tag floor localization is the success rate. The success rate means the ratio of successful localization. The localization fails if there is no detected tag by the reader. The success rate, however, is not dependent on a position estimation function, but the recognition range and distance of grids. For the continuous localization and for avoiding the localization failure, the reader recognition range should contain at least one tag for every position of reader on the work area.

3. RFID tag floor localization with multiple recognition ranges

Most of UHF RFID readers can control power of transmission signal by changing the antenna attenuation of readers Narayanan *et al.* (2005) and it means the reader can change recognition range shown as (Fig.2). We can obtain more information about the distances between reader and tags with multiple power, that is multiple recognition ranges. With low transmission power, only the tags near the reader are detected. The recognition range is increased as the transmission power is increased. By giving more weight for the estimated positions for the lower power, the position estimation error can be reduced.

In previous studies such as the study of Luo *et al.* (2007), multiple power is just used for robust recognition of tag but not used for nearness information. In the studies of Park et al.(2009), they use the nearness information obtained by multiple recognition range to improve the position estimation.

3.1 Mathematical formulation of RFID tag floor localization with multiple recognition ranges

Multiple recognition ranges mean that there are multiple recognition probability functions. We can extend the description of the RFID reader of with single recognition range to the multiple recognition ranges as follows:

$$R = (\mathbf{x}_R, \{p_R^m(\cdot) | m = 1, 2, \cdots, M\}), \tag{13}$$

where M is the number of the ranges and $p_m^R(\cdot)$s are corresponding recognition functions. Also, there exist M sets of recognition outputs with nonzero probability, or Z.

$$Z^m = \{z_0^m, \cdots, z_{K_m}^m\}, \tag{14}$$

$$= \{z_k^m | k = 0, 1, \cdots, K_m\}, \tag{15}$$

where $z_0^m = \phi$ and z^m is a possible recognition output with nonzero probability at m-th recognition range. As like single range case, output of recognition process with m-th range is one of elements of Z^m. K_m is the number of possible elements at the m-th range.
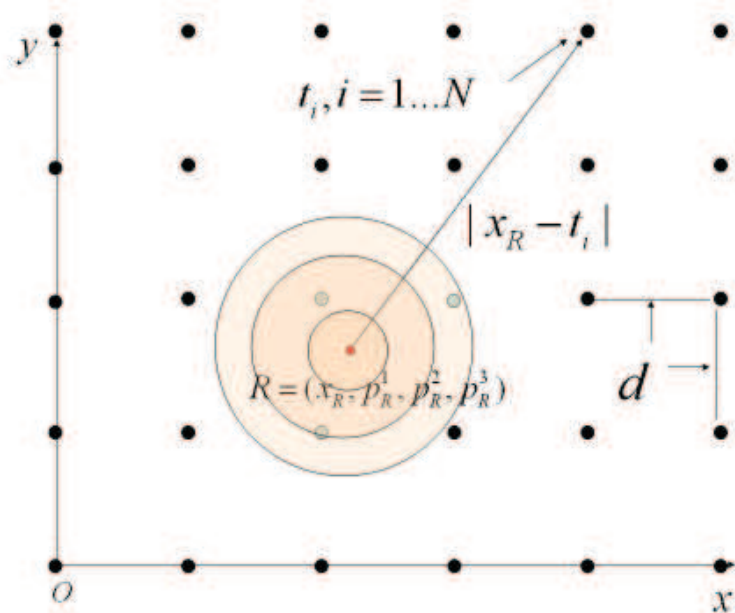
Fig. 2. The concept of the RFID tag floor localization method with multiple recognition ranges.

Define a set $\bar{Q}$ as follows:

$$\bar{Q} = \{(z^1, z^2, \cdots, z^m, \cdots, z^M) | z^1 \in Z^1, z^2 \in Z^2, \cdots, z^M \in Z^M\}. \qquad (16)$$

Hence, recognition output with multiple recognition ranges must be one of elements of $\bar{Q}$. But, some elements of $\bar{Q}$ cannot happen. Q is defined as a sub set of $\bar{Q}$ whose elements are occurred with nonzero probability. Then,

$$Q = \{q_0, q_1, \cdots, q_l, \cdots, q_L\}, \qquad (17)$$

where,

$$q_0 = \{\phi^1, \phi^2, \cdots, \phi^M\}. \qquad (18)$$

q_0 means that there is no recognized tag in recognition process for all recognition ranges. L is the number of all possible combination of tags for the multiple recognition ranges.

In RTFL with multiple recognition ranges, elements of Q instead of Z are the outputs of recognition process. The others are the same as the things in recognition process with single recognition range as follows:

$$\hat{X}_M = \{\hat{x}_1, \hat{x}_2, \cdots, \hat{x}_l, \cdots \hat{x}_L\}, \qquad (19)$$

$$f_M : Q - \{q_0\} \rightarrow \hat{X}_M, \qquad (20)$$

where M is the number of recognition ranges .

Generally, the size of Q is much larger than the size of Z. So, there are much more estimated points in multiple ranges case and each estimated point is representative to narrower area. In result, error variance is smaller than error variance of single range, it means accuracy of position estimation is improved.

3.2 Performance indexes for position estimation performance

In multiple ranges case, definition of error variance is the same as the definition in single range case as follows:

$$V \quad = \quad \frac{1}{W} \sum_{\hat{\mathbf{x}}_k \in \hat{X}_M} \iint_W |\hat{\mathbf{x}}_k - \mathbf{x}_R|^2 p(\hat{\mathbf{x}}_k | \mathbf{x}_R) dx dy. \tag{21}$$

However, as using Q instead of Z, calculating $p(\hat{x}_k | x_R)$ need modification as follows:

$$p(\hat{\mathbf{x}}_l | \mathbf{x}_R) = \prod_{z^m \in q_l} (\prod_{t_i \in z^m} p_R^m(t_j | \mathbf{x_R}) \quad \times \prod_{t_j \in (z^m)^c} (1 - p_R^m(t_j | \mathbf{x_R})), \tag{22}$$

Multiple recognition ranges give good success rate as well as accuracy improvement. The accuracy improvement will be verified by simulations and experiments in Section 4 and Section 5.

4. Simulation for the two RFID tag floor localization methods

This section provides and compares the simulation results for the tag floor localization method and the method with multiple recognition ranges to show the performance improvement of the proposed method. The Monte-Carlo method is used for the simulation and the position estimation error variance is used as a performance index.

4.1 Simulation settings
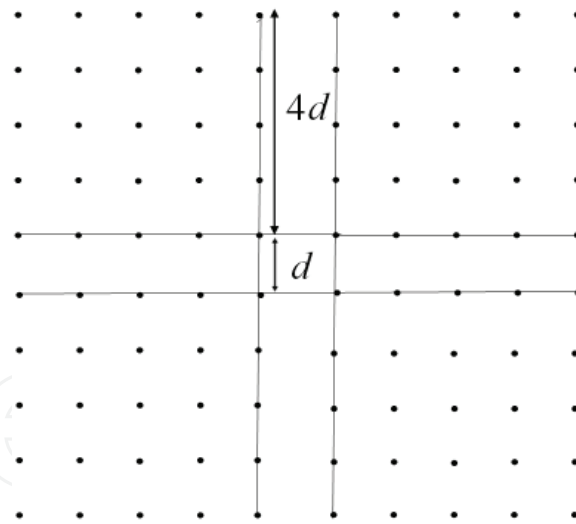
Fig. 3. The tag grid used for the RFID tag floor localization simulation.

For this simulation, 9×9 tag grid is used as shown in Fig. 3. To compare the two type of RFID tag floor localization methods, 400,000 sample points are generated in the 1×1 center grid cell. The approximation of the position estimation error variance is calculated as following equation:

$$\hat{V}(\mathbf{x_R}) = \frac{1}{M-1} \sum_{j=1}^{M} | \mathbf{x_{R,j}} - \mathbf{x_{k,j}} |^2. \tag{23}$$

The M is the number of samples that succeed to detect at lease one tag. If the recognition range is small, there may be no detected tag, and we call that the sample is failure point. The rate of failure is also one of the performance index for the position estimation as mentioned before.

If the sample point succeed to detect a tag set or tag sets with multiple recognition ranges, the estimation point is determined by the position mapping function. For the single recognition range case, the estimation point is determined by $f(z_{k,j}) = \hat{x}_{R,j} = x_{k,j}$. In this simulation, we take mean of the detected tag positions to estimate the reader position. For the multiple recognition range case, we use following position estimation function: $f_M(q_{l,j}) = \hat{x}_{R,j} = x_{k,j}$. In this simulation, the mean value of the mean position of recognized tags for each level is used for position estimation function.

In general, the recognition range of a tag from the position of RFID reader can not be defined clearly, since the probability of a tag recognition gradually decreases from a certain range near the recognition boundary. However, the recognition model $p_R(\cdot)$ used in this section is circular model as follows, for simplicity of the simulation:

$$p_R(\mathbf{x_i} \mid \mathbf{x_R}) = \begin{cases} 1 & \text{for } \mid \mathbf{x_i} - \mathbf{x_R} \mid \leq r \\ 0 & \text{for } \mid \mathbf{x_i} - \mathbf{x_R} \mid > r. \end{cases} \tag{24}$$

The recognition ranges r changed from 0.5 to 4.0. For the multiple recognition range case, the number of recognition ranges is 3 and the recognition range set (r_1, r_2, r_3) is defined $(0.3r, 0.7r, r)$.

4.2 Simulation results

Figure 4 and 5 shows the simulation results. Figure 4 represents the error variances of position estimation. The line and broken line respectively represents the approximation of position estimation error variance of the RFID tag floor localization method and the method with multiple recognition ranges. It shows the improvement of the position estimation performance when the multiple recognition ranges are used. Both error variances are
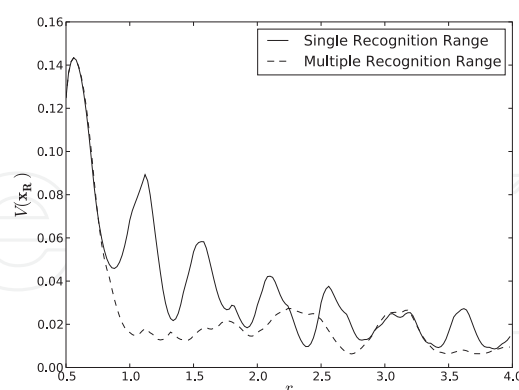

Fig. 4. The position estimation error variance of the RFID tag floor localization methods.

decreasing as the recognition range is increasing. The reason of the decrease of the error variance is the increase of the number of the estimation or mapping points. For the larger recognition range, the more tags are detected by the RFID reader. Figure 5 shows the number of the mapping points. The numbers of mapping points increase as the recognition range increase. Each mapping point corresponds a partition that divided by the recognition boundaries. If the number of partitions increases, the error variance is decreased. In Fig.
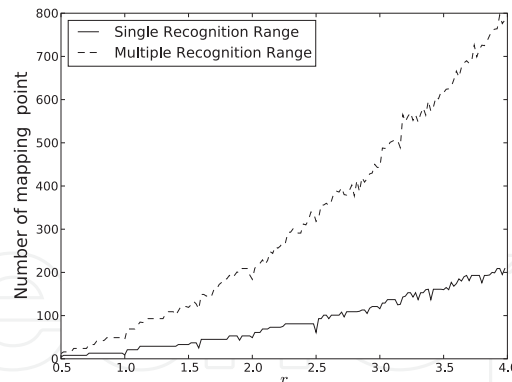
Fig. 5. The number of mapping points that corresponds the number of the detected tag combinations.

5, we can find the fluctuations on the error variances. The reason of the fluctuations is the balance between each partitions. If the partitions are relatively even, the error variance is low, otherwise, the error variance is high. More illustrative explanation will be given in Section 6.

5. Experimental results of multiple recognition range RFID tag floor localization

This section provides the experimental results that support the performance improvement of the proposed RFID tag floor localization method with multiple recognition ranges. The settings for the experiment of the tag floor localization methods are explained. Then, the result of experiment is processed with random sampling algorithm to get meaningful data. Finally, the meaning of the results are discussed.

5.1 Experimental settings
In this experiment, 9×9 tags were placed with the 20cm$\times$20cm grid. And the reader detected the nearby tags at every 2cm grid points inside the 65cm$\times$62cm work area of the experimental equipment. At each point, the reader changed the transmission power from 15dBm to 25dBm by 1dBm and read the tags 10 times for each power.

After gathering the sample data, we used random sampling algorithm to process the data. For each point, the recognition probability of each tag was defined by the data. Then, at each sample point, tags were detected with the recognition probability and conducted the position estimation process based on it. It was repeated 1000 times at each sample points.

Figure 6 shows the equipments and setting that we used in this experiment. Figure 6(a) is the experimental equipment. It was made by wood to avoid the effects of metallic objects on the RFID reader performance. It can move the reader along x and y direction with 2mm accuracy in the 65cm$\times$62cm work area. Figure 6(b) shows the tag placement and Fig. 6(c) represents the tags used in this experiment. All of the tags were aligned with one direction to reduce directional difference of tag antenna sensitivity. However, the directional sensitivity of the tag in this experiment was not significant and was ignorable. Next subsection will illustrate the recognition of the tag and other sticker type tags. Figure 6(d) is the small portable type RFID reader that can alter its transmission power from 15dBm to 30dBm. The antenna was 8cm$\times$8cm ceramic antenna and faced down to the floor at the 10cm above the floor.

(a) The experimental equipment. (b) Tag placement for the experiment.

(c) The UHF RFID with casing tag(CONFIDEX MICRO).

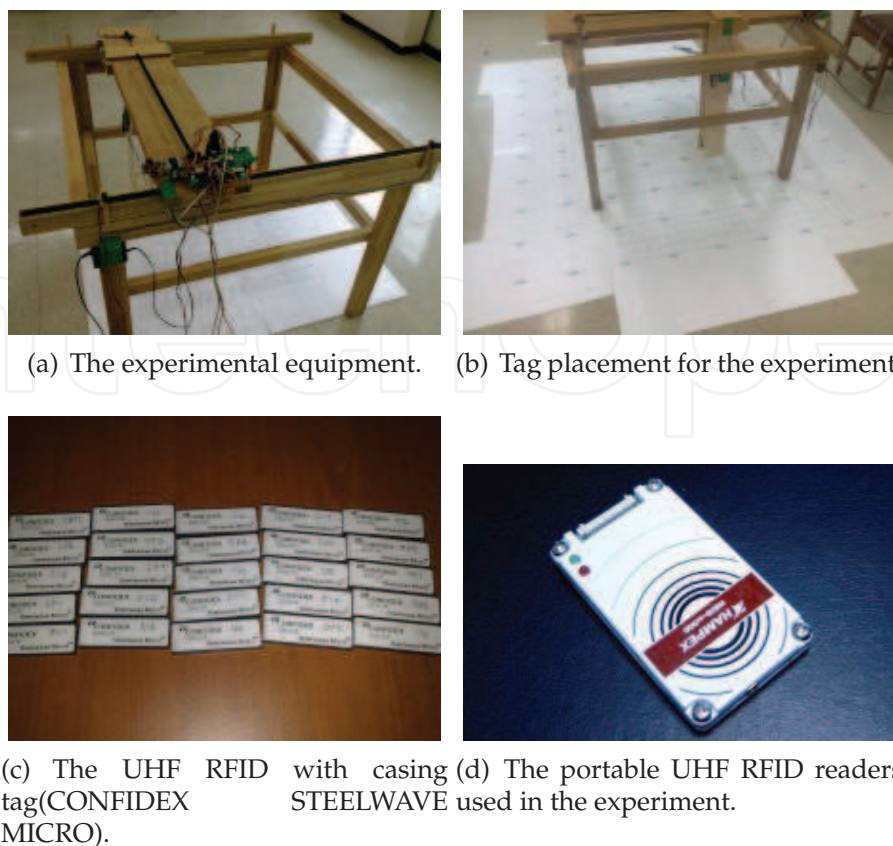(d) The portable UHF RFID readers STEELWAVE used in the experiment.

Fig. 6. The experimental settings.

5.2 Experimental results for localization

Figure 7 shows the recognition ranges of a tag used in the experiment with different RFID reader transmission powers. We can find that the recognition range increases according to the power. The patterns are slightly ellipsoidal shape, however, we fit these patterns to circles and estimate the recognition ranges. Figure 8 represents the fitting result. The relation between the reader transmission power and the reader recognition range seems to be linear, but we can not have strong confidence to the linear relation in this experiment. Moreover, under the different conditions such as different tags, antennas and height of antenna from the floor, different relation can be found.

However, due to the relation linear like relation, Fig. 9, the error distance which is the square root of the error variance can be interpreted without additional works. The relative recognition range with respect to the tag grid (20cm) is (0.25,0.9). The simulation results that we conducted have the data from recognition range is 0.5. Therefore, we can find the trend of the position estimation error variance in Fig. 9 shows similar trends of the position estimation error variance in Fig. 4 only in the range of 0.5 to 0.9. But the rest of recognition range need more investigation. However, due to the relation linear like ship, Fig. 9, the error distance which is the square root of the error variance can be interpreted without additional works. The relative recognition range with respect to the tag grid (20cm) is (0.25,0.9). The simulation results that we have starts from 0.5. Therefore, we can find the trend of Fig. 9 shows similar trends of the position estimation error variance in Fig. 4 in the range of 0.5 to 0.9. But the rest of recognition range need more investigation.

Figure 11 and Fig. 12 show the recognition ranges of other tags. The tags placed each conner of the work area of the experimental equipment . The recognition data is sampled with

(a) 15dBm   (b) 16dBm

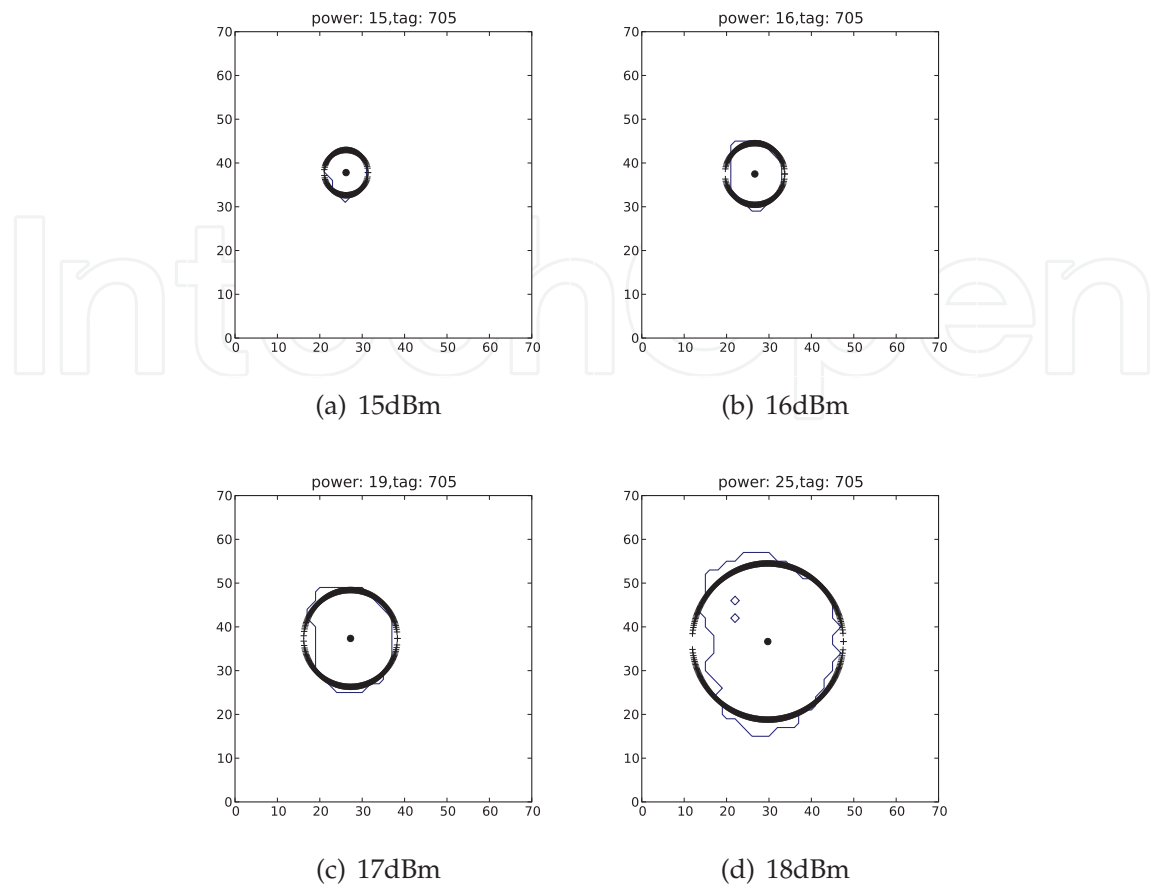(c) 17dBm   (d) 18dBm

Fig. 7. A Recognition range of a tag with different transmission powers.
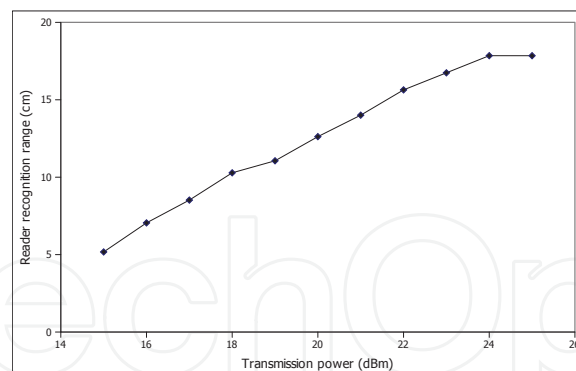

Fig. 8. Experimental result of the relation between reader transmission power and reader recognition range

5cm×5cm grid. These are "Inray" sticker type UHF RFID tags with 7cm×1.7cm dimension. The tags have supreme recognition ranges. At the power of 15dBm, their recognition range are already over 50cm. Long recognition range is good for the tag installation cost. However, these tags have irregular recognition patterns and large difference of recognition ranges between each tags. Tags of "Inray" types are hard to used for the RFID tag floor localization. Figure 10 represents the fail rate which is the ratio of the number of samples that failed to recognize tags, to the sample points. For the small powers, due to the small recognition
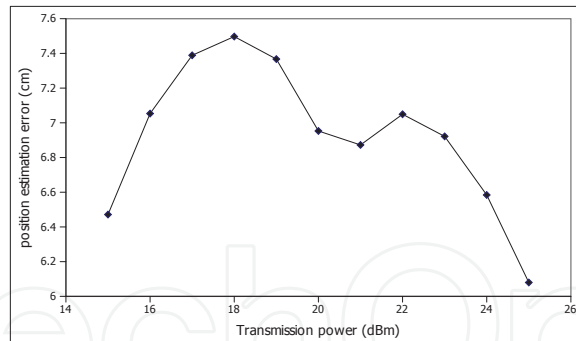
Fig. 9. Experimental result of the relation between the position estimation error(square root of the position estimation error variance) and the reader transmission power.
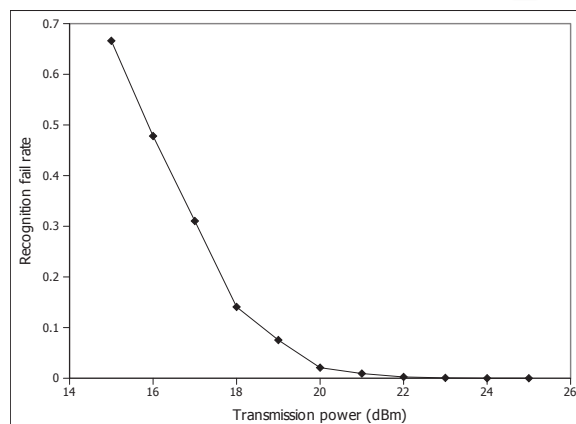
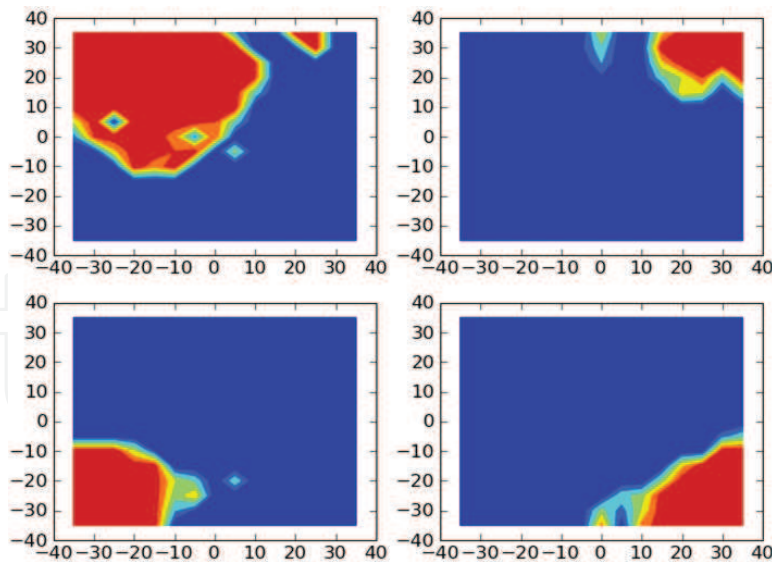Fig. 10. Experimental result of recognition fail rate for the experiment.

Fig. 11. The recognition patterns of a "Inray" type tags with 15dBm transmission power of RFID reader

ranges, the fail rate is high. High fail rate reads to error accumulation during the mobile robot navigation application .

Table 1 shows the results of the random sampling post process of the acquired data previously mentioned. We use three power levels for the multiple recognition ranges. However, in
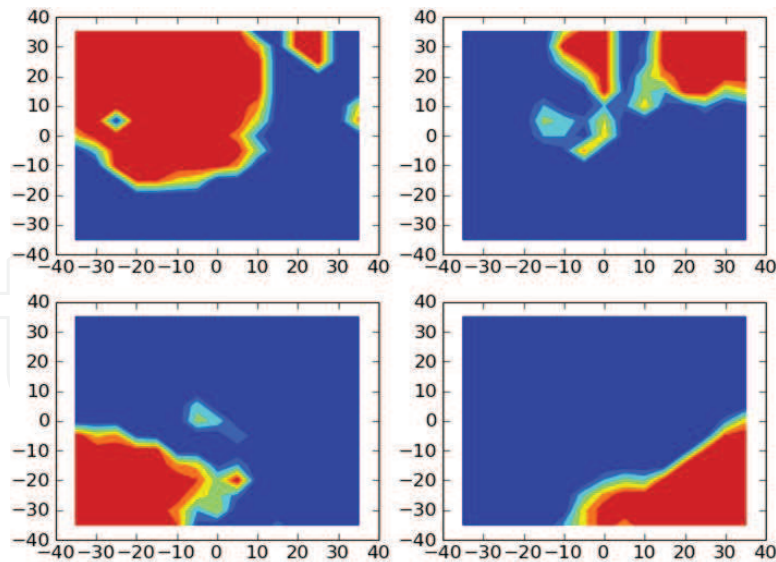
Fig. 12. The recognition patterns of a "Inray" type tags with 17dBm transmission power of RFID reader

Power combination(dBm)	Position estimation error(cm)	fail rate
(15,15,15)	6.471	0.6661
(16,16,16)	7.053	0.4781
(17,17,17)	7.389	0.3104
(18,18,18)	7.497	0.1407
(19,19,19)	7.367	0.0754
(20,20,20)	6.953	0.0209
(21,21,21)	6.872	0.0093
(22,22,22)	7.049	0.0025
(23,23,23)	6.922	0.0007
(24,24,24)	6.584	3.9E-005
(25,25,25)	6.080	2.7E-005
(16,19,25)	5.590	0.0009
(15,20,25)	5.634	0.0005
(15,19,25)	5.650	0.0011
(15,18,25)	5.674	0.0012

Table 1. The experimental results after the random sampling post process of the acquired data. The position estimation errors are shown in cm.

real applications, the number of power levels and the combination of powers should be determined with various considerations. The first eleven rows in Table 1 can be seen as the result of the RFID tag floor localization with single recognition range. Since the multiple sampling reduces the sample error variance, we used three same power levels for the single power case, for the fair comparison with multiple recognition range case. The last four rows represent the RFID tag floor localization method with multiple recognition ranges. The combinations of the powers are selected by the position estimation errors.

We can see that the position estimation errors with the multiple recognition ranges are smaller than the position estimation errors with single power. The recognition fail rates are smaller than single recognition range cases with powers under 23dBm. The improvement of position

estimation error of (16,19,25) case with respect to (25,25,25) is about 8%. Moreover, it can save the energy of the RFID reader.

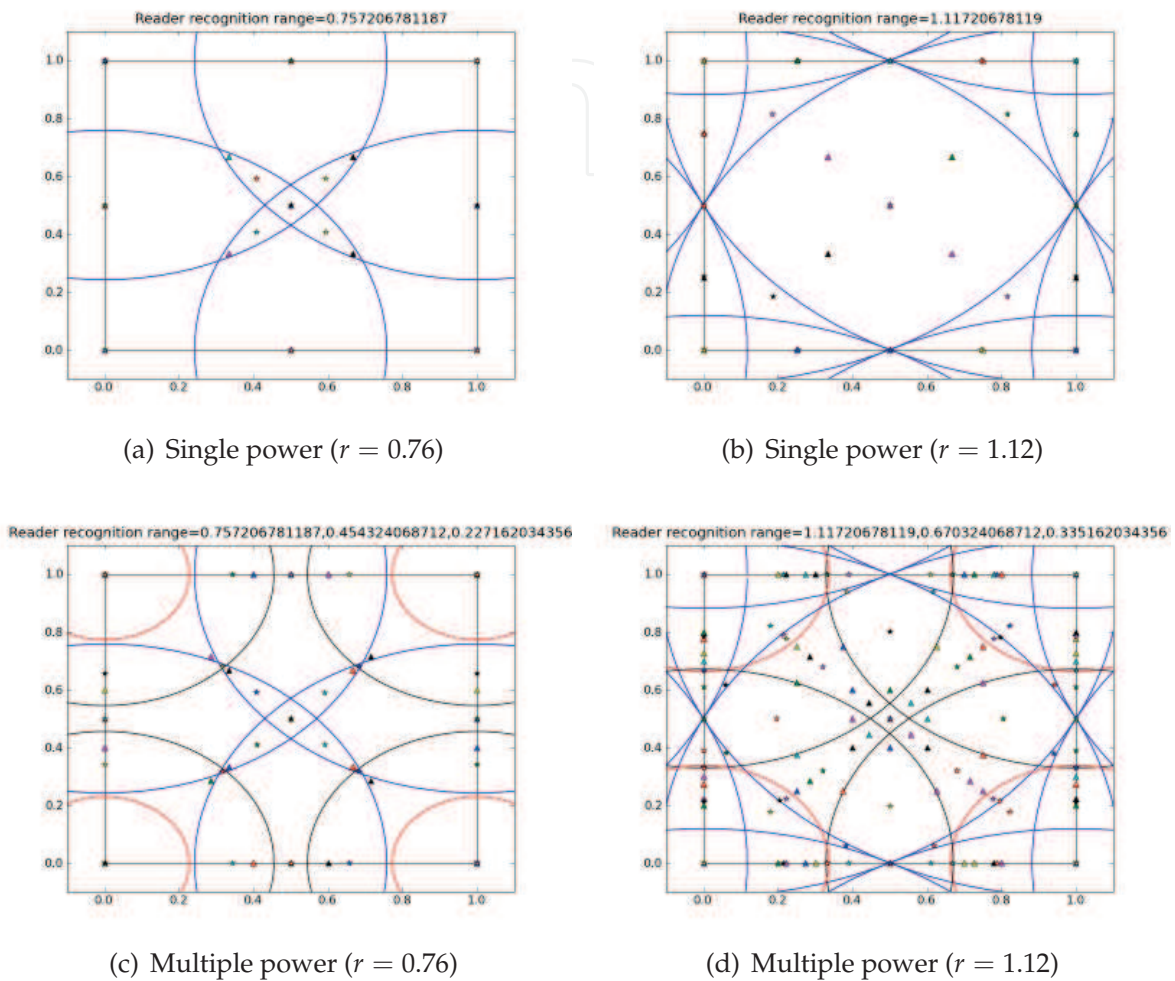## 6. Minimum variance of position estimation as a bound of error

(a) Single power ($r = 0.76$)

(b) Single power ($r = 1.12$)

(c) Multiple power ($r = 0.76$)

(d) Multiple power ($r = 1.12$)

Fig. 13. Mapping points by the mean method and minimum variance method.

In this section, we will introduce the minimum variance of position estimation as the bound of the position estimation error and extend it to the multiple recognition range case. Figure 13 shows the motivation of introducing the minimum variance of position estimation. As the recognition range also grows, the number of mapping points that correspond to the partitions is grows. As the number of partitions grows and the balance between each partitions are more even, the position estimation error variance gets smaller.

In each figure in Fig 13, the △ marks represent the mapping points produced by the mean algorithm and the ⋆ marks represent the mapping points produced by the minimum variance criteria. The mapping points based on the mean algorithm does not changed even if the recognition range is changed. Moreover, for the some recognition ranges such as $r = 1, 12$ in Fig. 13(b), the mapping points are out of their corresponding partitions. It leads to increase of the error variance. If the mapping points are on the center of mass of the each partitions,
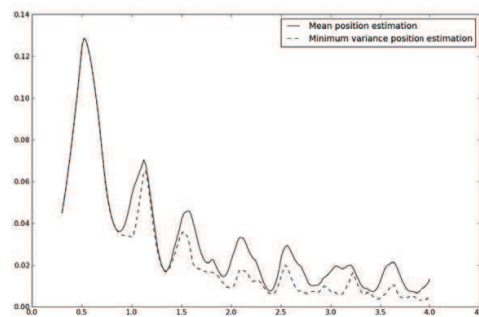
Fig. 14. The error variance and the minimum error variance of single power case.
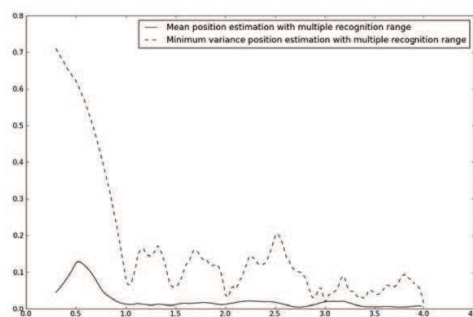

Fig. 15. The error variance and the minimum error variance of multiple power case.

the position estimation error variance will be minimized and it is the motivation of minimum error variance of position estimation.

However, in general, to find the minimum variance error bound analytically is not easy. We used the Monte-Carlo simulation to find the minimum variance of position estimation of RFID tag floor localization methods. The simulation setting is the same as Section 4.1. In addition, we calculate the center of mass and the variances of the sample point of each partitions. The results are represented in Fig. 14 and Fig. 15.

The minimum error variance can be used for the bound of position estimation error. The position estimation based on the minimum variance mapping point has lower error variance than the mean based position estimation. However, to find the minimum variance mapping points, we should know exact recognition model of tags and properties of tags in the tag floor must be even. The approximation of the dual problem of the minimum variance position estimation can be found in (Bouet and Pujolle, 2009a;b). They estimated the moving RFID tag with the fixed tags by approximating the center of mass with the virtual RFID tags.

7. Conclusion

In this chapter, we reviewed the researches on the RFID based localization methods, especially the RFID tag floor localization methods. Then we introduced the mathematical formulation of the RFID tag floor localization method and its performance index based on the position estimation error variance. Moreover, we extend it to the multiple recognition range case. Then, the improvement of the RFID tag floor localization system with multiple recognition ranges is shown by the simulation results and the experimental results. And we extend the error bound to the multiple recognition range case.

However, for the practical application of mobile robots, we need to solve some problems. There are still little researches on the effects of chassis, wheels, and metallic object on the floor on recognition. Antenna emission patterns of the tags and the readers need to be studied more and controlled for some ranges. Moreover, researches on effects of and counter plans to irregularities of tags are required.

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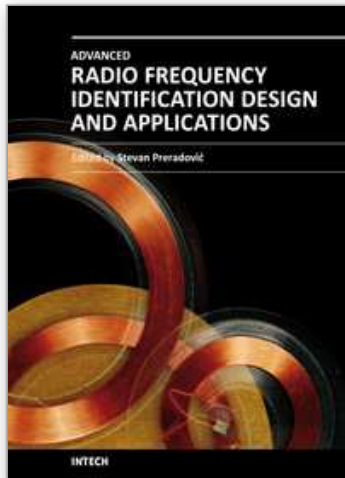
Advanced Radio Frequency Identification Design and Applications

Edited by Dr Stevan Preradovic

Radio Frequency Identification (RFID) is a modern wireless data transmission and reception technique for applications including automatic identification, asset tracking and security surveillance. This book focuses on the advances in RFID tag antenna and ASIC design, novel chipless RFID tag design, security protocol enhancements along with some novel applications of RFID.

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