

# RFID-Based 3-D Positioning Schemes

Chong Wang, Hongyi Wu, and Nian-Feng Tzeng

**Abstract**—This research focuses on RFID-based 3-D positioning schemes, aiming to locate an object in a 3-dimensional space, with reference to a predetermined arbitrary coordinates system, by using RFID tags and readers. More specifically, we consider a hexahedron which may be a shipping container, a storage room, or other hexahedral shape spaces. A number of RFID tags and/or readers with known locations are deployed as reference nodes. We propose two positioning schemes, namely, the active scheme and the passive scheme. The former scheme locates an RFID reader. For example, it may be employed to locate a mobile person who is equipped with an RFID reader or an object that is approached by an RFID reader. The passive scheme locates an RFID tag, which is attached to the target object. Both approaches are based on a Nelder-Mead nonlinear optimization method that minimizes the error objective functions. We have carried out analyses and extensive simulations to evaluate the proposed schemes. Our results show that both schemes can locate the targets with acceptable accuracy. The active scheme usually results in smaller errors and has a lower hardware cost compared to its passive counterpart. On the other hand, the passive scheme is more efficient when locating multiple targets simultaneously. The effectiveness of our proposed approaches is verified experimentally using the IDENTEC RFID kits.

## I. INTRODUCTION

The Radio Frequency Identification (RFID) has gained increasingly widespread adoption recently for automatic operation and tracking. An RFID system consists of two components, the transponder (or tag) and the detector (or reader). The RFID tags are categorized as either active or passive. The passive tag possesses a coupling element and a small, inexpensive electronic microchip, which is programmed with a unique set of data (up to several kilobits) that cannot be modified. It operates without a separate external power source. The transponder is only activated when it is within the response range of a reader, which supplies required power to the transponder through the coupling unit. The active RFID tag is powered by an internal battery and its data can typically be rewritten. The battery supply gives active tags a longer read range. But such a tag exhibits a larger size, higher price, and limited lifetime. Unlike the traditional bar code, the RFID system doesn't need line-of-sight and thus the tags can be embedded into the objects and deployed in harsh environments.

Object tracking and localization is one of the most important applications of the RFID system. The traditional approaches are to deploy either tags or readers with known positions to determine the possible range of a target object. For example, the readers may be deployed in strategic locations in a warehouse or workshops. When an object with an RFID tag passes the reader, the system detects the rough location of the object, which is within a circle centered at the reader and with a maximum radius equal to the response range. Alternatively, a number of RFID tags with known coordinates may be

deployed inside a building. When a person or a robot with a reader passes through the area, the nearby tag is activated, showing the rough location of the person or robot within a circumstance bounded by the response range from the tag. Such traditional approaches may provide location information with coarse granularity useful, for example, to determine the rough trajectory of a moving object or the presence of an object within a certain range.

Our objective is to develop RFID-based 3-D positioning schemes that provide location information with a finer degree. More specifically, we consider a hexahedron which may be a shipping container, a storage room, or other hexahedron-shaped spaces. A number of RFID tags and/or readers with known locations are deployed as reference points, in order to determine the three-dimensional coordinates of the target object placed inside the hexahedron and attached with a tag or a reader. We aim to limit the error of the coordinates to less than 5% of the longest edge of the hexahedron for meeting the accuracy requirement of applications such as 3-D packaging and tracking in containers or storage rooms. We propose two positioning schemes, namely, an active scheme and a passive one. The active scheme locates an RFID reader, possibly employed to pinpoint a mobile person who wears an RFID reader or an object that is approached by an RFID reader. The passive scheme locates an RFID tag, which is attached to the target object. Both approaches are based on nonlinear optimization methods that minimize the error objective functions. We have carried out analyses and extensive simulations to evaluate the proposed schemes. Our results show that both schemes can locate the target with acceptable accuracy. The active scheme usually results in smaller errors and has a lower hardware cost compared to its passive counterpart. On the other hand, the passive scheme is more effective when locating multiple targets simultaneously. Furthermore, experiments are carried out using the IDENTEC RFID kits to demonstrate the effectiveness of our proposed 3-D positioning schemes.

The rest of this paper is organized as follows. Sec. II discusses related work. Sec. III introduces our proposed 3-D positioning schemes. Simulation and experimental results are presented in Secs. IV and V, respectively. Finally, Sec. VI concludes the paper.

## II. RELATED WORK

Tracking RFID tags is an inherent function of the RFID system, where the reader is employed to activate nearby tags and report their existence (and perhaps their contents as well). Such an approach can usually detect the target tags when they approach strategic locations only, where the readers are deployed. In order to provide precise location information anywhere, a large number of readers have to be deployed,

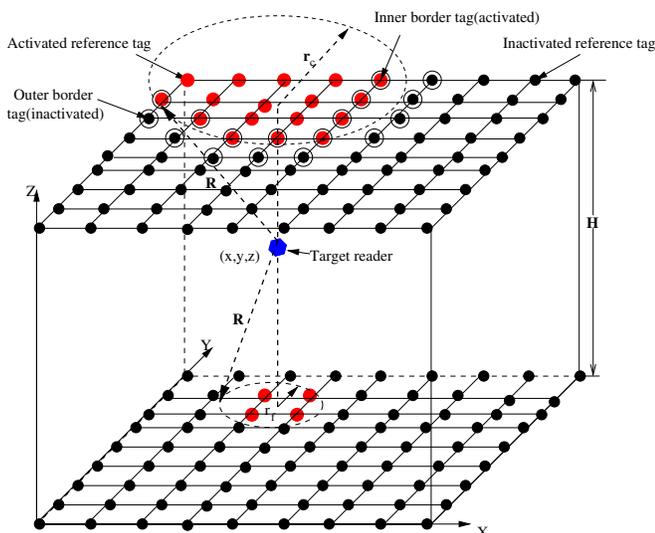


Fig. 1. Active positioning scheme.

significantly increasing the cost of the system. A series of efforts have been carried out recently to enable a cost-effective system that can locate the tags anywhere. For example, [1] proposes to deploy reference tags inside a building and equip the robot with an RFID reader, which scan nearby reference tags to obtain location information. [2] studies the same problem with similar system setup. The support vector machine scheme is employed to reduce the inaccuracy resulted from signal transmission dynamic due to the environment. A location sensing prototype system, called LANDARC (LocAtioN iDentification based on dynaMic Active Rfid Calibration), is presented in [3]. The basic idea of LANDARC is to deploy a set of reference RFID tags and a small number of readers. Each reader has several transmission power levels. Based on signal strength information, a k-nearest neighbor approach is taken to estimate the location of the tracking tag. These approaches, however, can only provide coarse location information, which may not meet the requirement of applications such as 3-D packaging/locating in containers or warehouses. In addition to the above approaches based on RFID, several non-RFID-based approaches have been proposed for indoor localization. The Cricket Location Support System [4] and Active Bat Location System [5] use the ultrasonic technology to provide location information. Since the time-of-arrival scheme is used to measure the distance, they exhibit high accuracy but incur expensive hardware.

With their importance in routing and information gathering, a number of positioning/localization schemes have been proposed recently for ad hoc networks and sensor networks. The readers are referred to [6] for details. While those approaches address different problems than our study here, they offer insights into the localization problem and provide guideline for our research.

### III. PROPOSED 3-D LOCALIZATION SCHEMES

We propose two RFID-based 3-D localization schemes, namely, *active scheme* and *passive scheme* discussed in the following subsections. The proposed schemes are for locating

an object in a hexahedron, with reference to a predetermined arbitrary coordinates system by using RFID tags and readers.

#### A. Active Scheme

The active scheme aims to locate an RFID reader. For example, it may be employed to locate either a mobile person who wears an RFID reader or an object which is approached by an RFID reader. In the rest of this subsection, we first introduce the system setup needed for the active scheme, and then discuss our basic procedures for coordinates calculation, followed by error analysis and discussions.

1) *System Setup*: The basic idea of the active scheme is illustrated in Fig. 1. A number of reference tags with known coordinates are placed on the floor and the ceiling of a hexahedron (e.g., a storage room or a container)<sup>1</sup>. The length, width, and height of the hexahedron are  $L$ ,  $W$ , and  $H$ , respectively. Both passive and active RFID tags can be deployed as reference tags. For a large hexahedron, active tags are preferred due to their longer transmission range. An arbitrary local coordinates system is assumed, as shown in Fig. 1. The placement of those reference tags is fine-tuned so that their coordinates are highly accurate. The coordinates of the reference tags can be stored either in the tags or in a database maintained by a local server. The RFID reader is located inside the hexahedron and has a fixed transmission power. As to be discussed later, the active scheme doesn't rely on the signal strength-based radio range estimation. Thus it is neither necessary to fine-tune the transmission power nor to estimate the distance according to the received signal strength, which could result in considerable errors.

2) *Coordinates Calculation*: In order to determine its location  $(x, y, z)$ , the RFID reader shall activate the reference tags within its transmission range and obtain their responses. If the reader has sufficient computing power, it may perform the following coordinates calculation by itself. Otherwise, it sends the information of activated reference tags to a computer for coordinates calculation. Assume signal transmission from the RFID reader forms a sphere<sup>2</sup>, which covers the reference tags in two circles centered at  $(x_f, y_f, 0)$  and  $(x_c, y_c, H)$  with radii  $r_f$  and  $r_c$  on the floor and the ceiling, respectively (see Fig. 1). One needs to determine the centers  $((x, y, 0)$  and  $(x, y, H))$  and the radii ( $r_f$  and  $r_c$ ) of the two circles in order to calculate the coordinates  $(x, y, z)$  of the reader.

However, finding the centers and the radii of the two circles is nontrivial, especially when the reader is at the border of the hexahedron, resulting in partial circles on the floor, the ceiling, or both. We have considered three approaches to address this problem. All of them are based on the same principle, but use different sets of reference tags in calculation.

*Inner Border Method (IBM)*. The basic idea of IBM is to first identify the "inner border" nodes of the circles and then determine their center and radii via a nonlinear optimization

<sup>1</sup>Note that this is the minimum requirement. One may deploy more reference tags on other sides of the hexahedron to improve accuracy.

<sup>2</sup>In practice, radio transmission is not a sphere due to different signal gains at different directions. This will be discussed in Sec. III-A.4.

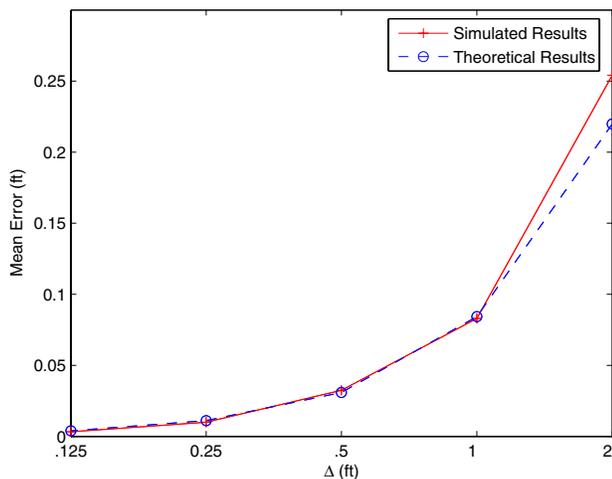


Fig. 2. Comparison of simulation and analysis for active scheme.

method. More specifically, an inner border node can be identified by the status of its neighboring reference tags. An inner border node is an activated reference tag that has inactivated neighbors. Otherwise, if a reference node is not activated or if the node and all of its neighbors are both activated, then it is not on the inner border of the circle (see Fig. 1). Assume  $N_f$  inner border nodes are identified on the floor, which are denoted as the *effective reference tag set*,

$$\Psi = \{(x_i^f, y_i^f, 0) \mid 1 \leq i \leq N_f\}. \quad (1)$$

We employ a Simplex method to find the center  $(x_f, y_f, 0)$  and radius  $r_f$  of the circle on the floor. More specifically, we define an error objective function

$$\epsilon_f = \sum_{i=1}^{N_f} (r_f - \hat{L}_i^f)^2, \quad (2)$$

where

$$\hat{L}_i^f = \sqrt{(x_i^f - x_f)^2 + (y_i^f - y_f)^2}. \quad (3)$$

A Nelder-Mead Simplex method [7] is used to minimize the error objective function  $\epsilon_f$  and obtain  $(x_f, y_f, 0)$  and  $r_f$ . The Nelder-Mead Simplex method is a nonlinear fitting procedure for function minimization. It uses the nonlinear adjustment of parameters (in our case, the coordinates variables  $(x_f, y_f, 0)$  and radius  $r_f$ ) until some convergence criterion is met (i.e.,  $\epsilon_f$  becomes lower than a threshold). The Simplex method has been implemented by many software codes. Our simulation (to be discussed in Sec. IV) adopts the Nelder-Mead module available in Matlab [8] to minimize the error objective function.

The center  $(x_c, y_c, 0)$  and radius  $r_c$  of the circle on the ceiling can be derived in a similar way. Consequently,  $x$  and  $y$  of the reader's coordinates are determined by the average of  $(x_f, y_f)$  and  $(x_c, y_c)$ , i.e.,

$$x = \frac{x_f + x_c}{2}, \quad (4)$$

and

$$y = \frac{y_f + y_c}{2}. \quad (5)$$

$z$  is determined based on  $r_f$ ,  $r_c$ , and  $H$ . Specifically,

$$z = \frac{r_c^2 - r_f^2 + H^2}{2H}. \quad (6)$$

Thus, the coordinates of the reader,  $(x, y, z)$ , are obtained.

**Full Border Method (FBM).** It is similar to IBM, but its reference tag set (i.e.,  $\Psi$  in Eq. (1)) includes both inner border nodes and outer border nodes. The inner border nodes have been discussed above. The outer border node is a non-activated node that has activated neighbors. The calculation of  $(x, y, z)$  follows the same routine (Eqs. (2)-(6)), as discussed above. We expect that the use of both outer border and inner border tags will improve the accuracy of  $r_c$  and  $r_f$ , which are estimated as smaller values by IBM.

**Solid Circle Method (SCM).** In SCM, the effective reference tag set (i.e.,  $\Psi$  in Eq. (1)) consists of all activated reference tags. With more reference tags taken into consideration, SCM may result in more accurate  $x$  and  $y$  values, when the activated tags form full circles on the floor and the ceiling. When the target is at the corner of the hexahedron, partial circles may be formed by the activated tags, giving rise to large errors.

3) *Accuracy Analysis:* We now establish a mathematical model to analyze the accuracy of the proposed active scheme. The following discussion is based on the full border method, which yields the smallest errors, as shown by our studies to be discussed in Sec. IV. Similarly, the other two methods can be analyzed.

Let's consider a circle formed by the activated reference tags on the floor (or the ceiling) with a radius of  $r$ . The average distance of a pair of border nodes to the center of the circle can be found as:

$$\hat{r} = \int_0^\Delta \frac{2}{\pi\Delta} \left\{ (R-x) \text{EllipticE}\left(\frac{\pi}{4}, -\frac{4rx}{(r-x)^2}\right) + (r-\Delta+x) \text{EllipticE}\left(\frac{\pi}{4}, -\frac{4r(\Delta-x)}{(r-\Delta+x)^2}\right) \right\} dx, \quad (7)$$

where  $\Delta$  denotes the minimum distance between two adjacent reference tags, and *EllipticE* is the incomplete Elliptic integral of the second kind, which is defined as:

$$\text{EllipticE}(\phi, m) = \int_0^\phi (1 - m \sin^2 \theta)^{1/2} d\theta. \quad (7)$$

Thus the expected error of the radius based on one pair of border nodes is:

$$\delta_r = |r - \hat{r}|, \quad (8)$$

where  $r$  is the actual radius.

Let  $N_b$  denote the total number of pairs of border nodes. If the target reader is not close to the sides or corners of the hexahedron, we expect a full circle with  $N_b$  pairs of border nodes,

$$N_b \approx \frac{2\pi r}{\Delta}. \quad (9)$$

Therefore the average error of the radius based on all pairs of border nodes is,

$$\bar{\delta}_r = \frac{\delta_r}{\sqrt{N_b}}. \quad (10)$$

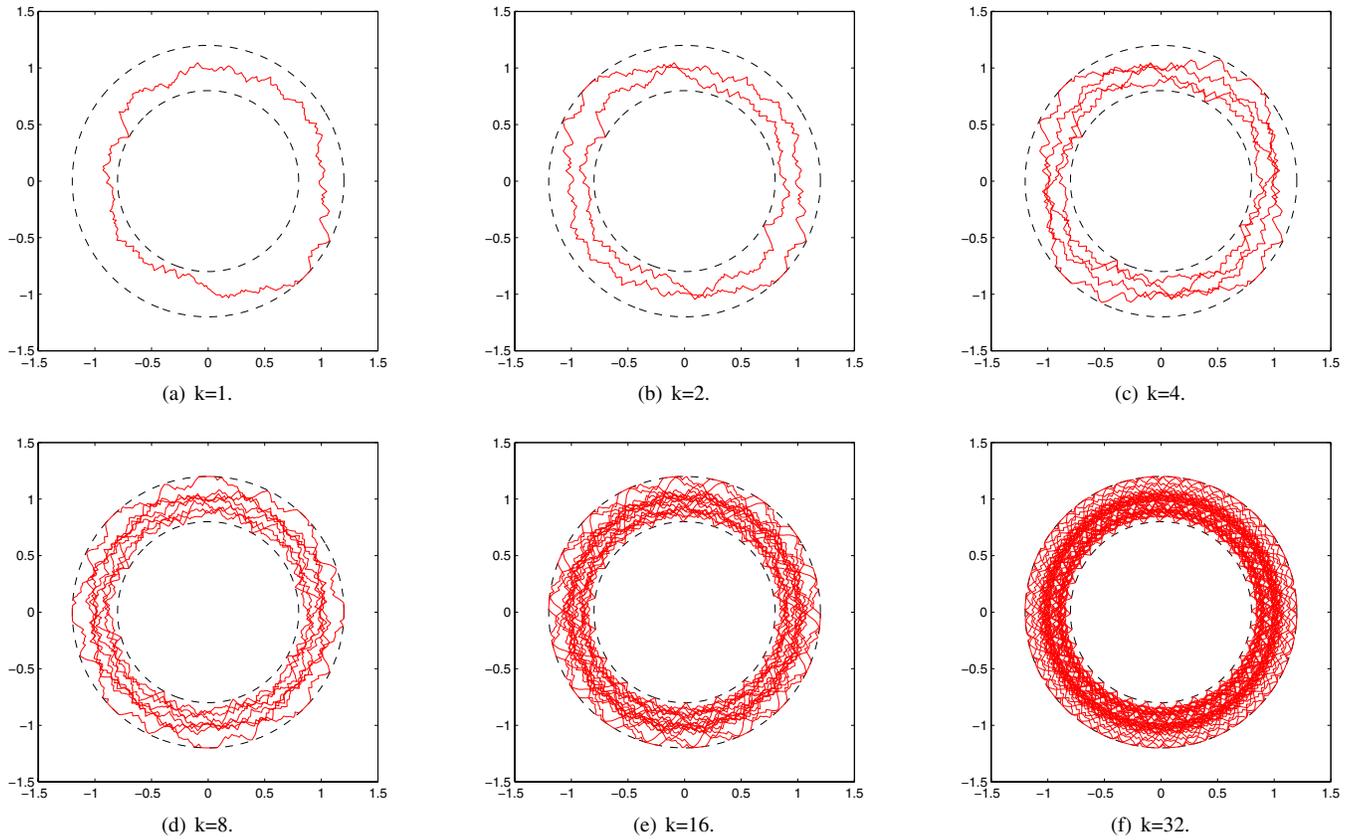


Fig. 3. DOI under the antenna array with various number radiation elements ( $k$ ).

The above calculation can be applied to both  $r_c$  and  $r_f$ , yielding their average errors,  $\bar{\delta}_{r_c}$  and  $\bar{\delta}_{r_f}$ .

According to error propagation theory, the joint average errors of  $x$  and  $y$  are estimated as:

$$\bar{\delta}_{xy} = \sqrt{(\bar{\delta}_{r_c})^2 + (\bar{\delta}_{r_f})^2}. \quad (11)$$

Then, we can deduce the average error of  $z$  based on Eq. (6). More specifically,

$$\bar{\delta}_z = \frac{1}{H} \sqrt{r_c^2 \bar{\delta}_{r_c}^2 + r_f^2 \bar{\delta}_{r_f}^2}. \quad (12)$$

Finally, the total average error of the coordinates is

$$\bar{\delta} = \sqrt{(\bar{\delta}_{xy})^2 + (\bar{\delta}_z)^2}. \quad (13)$$

The above analytic model has been verified via simulations as shown in Fig. 2. The details of simulation will be discussed in Sec. IV.

**4) Accuracy Improvement:** The accuracy of the proposed schemes depends on the following two factors. First, it is affected by the density of the reference tags. Low density (i.e., large  $\Delta$ ) tends to result in coarse granularity and high errors (see Fig. 2). To achieve complete accuracy in theory, an infinite number of reference tags should be deployed. In practice, more reference tags yield higher accuracy, with a higher cost at the same time. Second, while we have assumed in the above discussion that signal transmission from the RFID reader forms a sphere, this is usually not true due to different signal

propagation attenuation amounts and different antenna gains in different directions. To quantitatively study this problem, we define a Degree of Irregularity (DOI). More specifically, we assume an upper bound ( $R_u$ ) and a lower bound ( $R_l$ ) of the reader's signal transmission range. DOI is the maximum variation of the reader's transmission range per unit degree change. For example, Fig. 3(a) shows the transmission range of a reader with DOI=0.03. The inner circle is the lower bound, while the outer circle is the upper bound of the transmission range. The irregular curve between them illustrates the actual transmission range of the reader over  $360^\circ$ . Clearly, DOI has a negative impact on accuracy. Larger DOI results in a more deformed circle specified by the activated reference tags, and accordingly lowers accuracy.

While it is difficult to perfectly compensate different antenna gains and path losses in different directions, a low cost antenna array with multiple radiation elements may be employed to minimize the effect of DOI. The calculation of coordinates (in particular, the identification of border nodes) is based on all reference tags activated by the antenna array. Figs. 3(b)-3(e) show the superimposed transmission range of an antenna array with 2, 4, 8, and 16 radiation elements, respectively, where  $R_u = 1.2$  units,  $R_l = 0.8$  units, and DOI=0.03. Clearly, more radiation elements result in a set of activated tags closer to a circle and accordingly more accurate results, at the expense of an increased hardware cost. We also employ an "optimized method" in our implementation, where the calculation is based only on the set of nodes that are

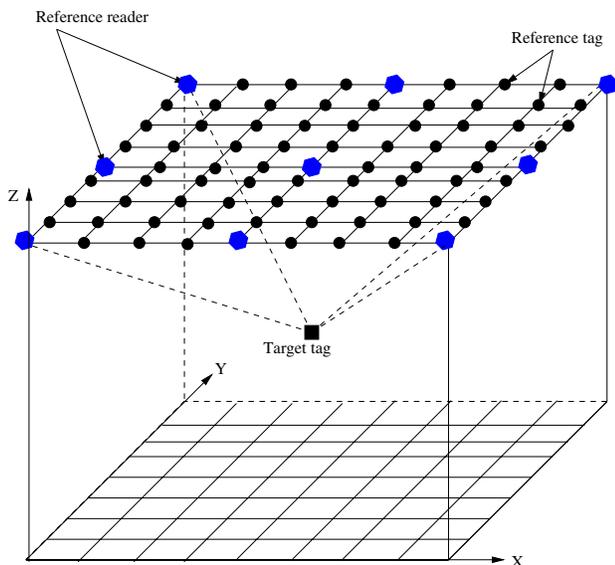


Fig. 4. Passive positioning scheme.

activated by all radiation elements, in order to more effectively filter out the irregularity. Further discussion and simulation results of the above approaches for improving accuracy will be provided in Sec. IV.

### B. Passive Scheme

The proposed passive scheme aims to locate an RFID tag, which is attached to the target object.

1) *System Setup*: The passive scheme for 3-D localization is illustrated in Fig. 4. Unlike those in the active scheme, the reference tags with known coordinates are now placed only on the ceiling (or the floor) of the hexahedron<sup>3</sup>. In addition to the reference tags,  $N$  ( $N \geq 4$ ) RFID readers are deployed on the ceiling (usually at the vertices or edges). As to be discussed later, deploying more readers may increase the accuracy, while it may result in a longer computing time and higher cost. The passive scheme requires the readers capable of multiple transmission power levels. While many readers have only one fixed transmission power, readers with multiple (up to 38) tunable transmission power levels have been available in the market [9]. Here each RFID reader is assumed to have  $K$  transmission power levels, and the transmission power levels are calibrated so that there is a linearly increasing response range with the increase of power level. The coordinates of reference tags and readers are determined similarly as discussed in Sec. III-A.

2) *Coordinates Calculation*: Upon receiving the request for locating one (or several) RFID tag(s), all readers scan the target tag(s), and report the gathered information of activated tags to a computer for coordinates calculation. More specifically, the readers start with the lowest power level and gradually increase the transmission power until they receive the response from the target tag<sup>4</sup>. At the same time, each reader

<sup>3</sup>Similar to our discussion for the active scheme, this is the minimum requirement only. One may deploy more reference tags on other sides of the hexahedron to improve accuracy.

<sup>4</sup>Linear searching is employed here for illustration purpose. Fast search schemes (such as binary search) may be employed to improve efficiency.

also receives the responses from reference tags. Let  $\Phi_k$  denote the set of RFID tags which send responses when the reader uses power level  $k$ . Let's consider a reader  $i$  and a target tag  $j$ . If  $j \notin \Phi_k$  and  $j \in \Phi_{k+1}$ , the distance between  $i$  and  $j$ , denoted by  $L_{ij}$ , can be estimated by averaging the distances from the reader to all reference tags that are in  $\Phi_{k+1}$  but not in  $\Phi_k$ . After a set of approximate distances from the target tag  $j$  to the  $N$  readers, i.e.,  $L_{1j}, L_{2j}, \dots, L_{Nj}$  are collected, the location of the tag  $j$  is determined by minimizing the error function, which is defined as

$$\epsilon = \sum_{i=1}^N \left( \frac{L_{ij} - \hat{L}_{ij}}{L_{ij}} \right)^2. \quad (14)$$

Here we denote  $(x_i, y_i, z_i)$  and  $(x_j, y_j, z_j)$  as the coordinates of reader  $i$  and target tag  $j$ , respectively. Thus the distance from reader  $i$  to the tracking tag  $j$  is represented by

$$\hat{L}_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \quad (15)$$

If a reference reader does not receive response from the target tag even by using its maximum transmission power, its term is eliminated from Eq. (14). Similar to the active approach, the Simplex method [7] is used to minimize the error objective function  $\epsilon$  to determine the coordinates for the target tag  $j$ ,  $(x_j, y_j, z_j)$ .

The methods for identifying border nodes (as discussed in the active scheme) are not employed in the passive scheme, because the activated tags in  $\Phi_{k+1}$  but not in  $\Phi_k$  already form a narrow ring. In addition, the two issues discussed in Sec. III-A.4 (i.e., the density of the reference tags and the DOI) have a similar impact on the accuracy of the passive scheme and can be addressed similarly.

3) *Accuracy Analysis*: In the passive scheme, the error of  $L_{ij}$  (i.e., the estimated distance from the target tag  $j$  to a reader  $i$ ) is dominated by the granularity of the power levels. Let  $R$  denote the maximum response range of a reader, and  $N_r$  denote the total number of readers that can receive responses from the target RFID tag, given the maximum response range of  $R$ . Since each reader is assumed to have  $K$  transmission power levels, which are calibrated so that there is a linearly increasing response range with the increase of power level, the response range per power level is  $R/K$ . Since the coordinates of the target tag are obtained by minimizing the error objective function based on the estimated distances from the target tag to the set of  $N_r$  readers, the average error of the final result is

$$\delta = \frac{R/K}{\sqrt{N_r}}. \quad (16)$$

Fig. 5 compares the analytic results and the simulation results. The former result values are slightly less than the latter, because we have ignored the errors introduced by the reference tags with finite density in our analysis.

### C. Further Discussion

Comparison between the active scheme and its passive counterpart is summarized in Table I and elaborated as follows. First, the targets being tracked by these two schemes are

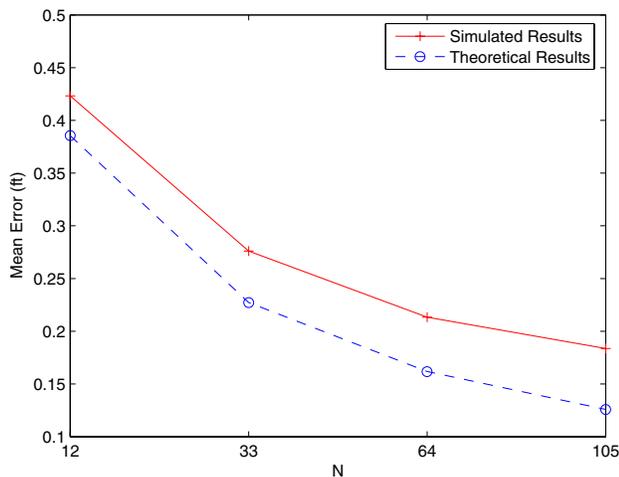


Fig. 5. Comparison of simulation and analysis for passive scheme.

different. The active scheme locates an RFID reader, while the passive scheme locates the RFID tag(s). Second, both RFID readers and tags are deployed as reference points in the passive scheme. The active scheme, however, uses only RFID tags to serve as the reference points. Third, both schemes are range-free. In other words, it is not necessary for either scheme to estimate a distance according to wireless signal strength. Thus, accuracy is not materially affected by the types of readers possibly with different radiation patterns. The passive scheme requires a reader to have multiple tunable power levels. In contrast, a reader in the active scheme needs one fixed power level only. Fourth, the passive scheme usually results in a longer time for localization due to its gradual increase in the transmission power. Meanwhile, it may locate multiple targets simultaneously, thus reducing the average tracking time per target. The active scheme locates only one target at a time. Finally, the average accuracy of the active scheme is usually one order of magnitude higher than that of the passive scheme. The errors are location-dependent. More specifically, the active scheme performs very well when the target is at the center but suffers from large errors when the target is at a corner. On the other hand, the accuracy of the passive scheme is less sensitive to the target location.

#### IV. SIMULATION RESULTS

We have carried out extensive simulations in Matlab to evaluate our proposed 3-D positioning schemes. In particular,

TABLE I  
COMPARISON BETWEEN ACTIVE AND PASSIVE SCHEMES

	Active Scheme	Passive Scheme
Target	Reader	Tag
Reference Nodes	Tags	Tags and Readers
Reference Node Deployment	Ceiling and Floor	Ceiling (or Floor)
Range Free	Yes	Yes
Power Level	One	Multiple
Multiple Tracking	No	Yes
Positioning Time	Short	Long
Hardware Cost	Low	High
Error (ft)	0.2 – 0.5	0.3-3.0

we study the impact of several parameters of interest, such as the radio propagation irregularity, the number of radiation elements of the antenna array, the number of power levels, and the reference node density, which may dictate the accuracy of the positioning schemes. We simulate a hexahedron of the size of a typical container (about  $40' \times 8' \times 8'$ ). The error is defined as the absolute difference between the actual coordinates and the calculated coordinates of target objects. The active scheme and the passive scheme are discussed next in sequence.

##### A. Active Scheme

To employ the active scheme, a number of reference tags with known coordinates are placed on the floor and the ceiling of the hexahedron. The placement of the reference tags are fine-tuned so that their coordinates are highly accurate. The density of the reference tags is represented by a parameter  $\Delta$ , which is the distance between two adjacent reference tags.  $\Delta$  equals 1 foot by default. The target RFID reader is located inside the hexahedron and has a fixed transmission power which results in  $R_u = 7.2$  feet and  $R_l = 4.8$  feet. The default value of DOI is 0.03. The results are based on an antenna with four radiation elements, unless specified. We vary  $\Delta$ , DOI, and the number of elements  $k$  to observe their impacts on the accuracy of the active scheme. The results are the average of 2560 sample points uniformly distributed in the hexahedron. In average, it takes no more than 100 millisecond to locate a target.

The impact of DOI on the accuracy of the active scheme is shown in Fig. 6(a). As can be seen, the errors increase almost linearly with DOI. This is reasonable because higher DOI results in a more deformed circle of the activated reference tags and accordingly larger errors in finding the center of the circle. All methods yield fairly accurate results, given  $\Delta = 1$  foot. The optimized full boarder method (where the calculation is based only on the set of nodes that are activated by all  $k$  radiation elements) achieves the highest accuracy. It locates the target with errors less than 0.5 feet even when DOI is high. The full border method (without optimization) performs slightly worse than the optimized one, because the latter can more effectively filter out the irregularity of radio transmission. The inner border method has a higher error as it tends to estimate smaller values of  $r_f$  and  $r_c$ . The solid circle method results in the highest error, because it is heavily affected by the partial circles when the target is around the corner of the hexahedron which may dramatically decrease the accuracy.

Employing more radiation elements can effectively reduce the negative impact of DOI. Fig. 6(b) shows the results of the optimized full border method under various numbers of radiation elements. The results of other methods show a similar trend and thus are omitted. As we can see, the error is the highest with a conventional antenna. The errors are reduced sharply when the antenna array deployed is with two and four radiation elements. With more radiation elements, the error reduces resulting from a set of activated tags closer to a circle and accordingly more accurate  $x$  and  $y$  coordinates.

Figs. 6(c) and 6(d) show the errors of the proposed active positioning scheme at various locations in the hexahedron. As the outcomes of all methods show a similar trend, only the

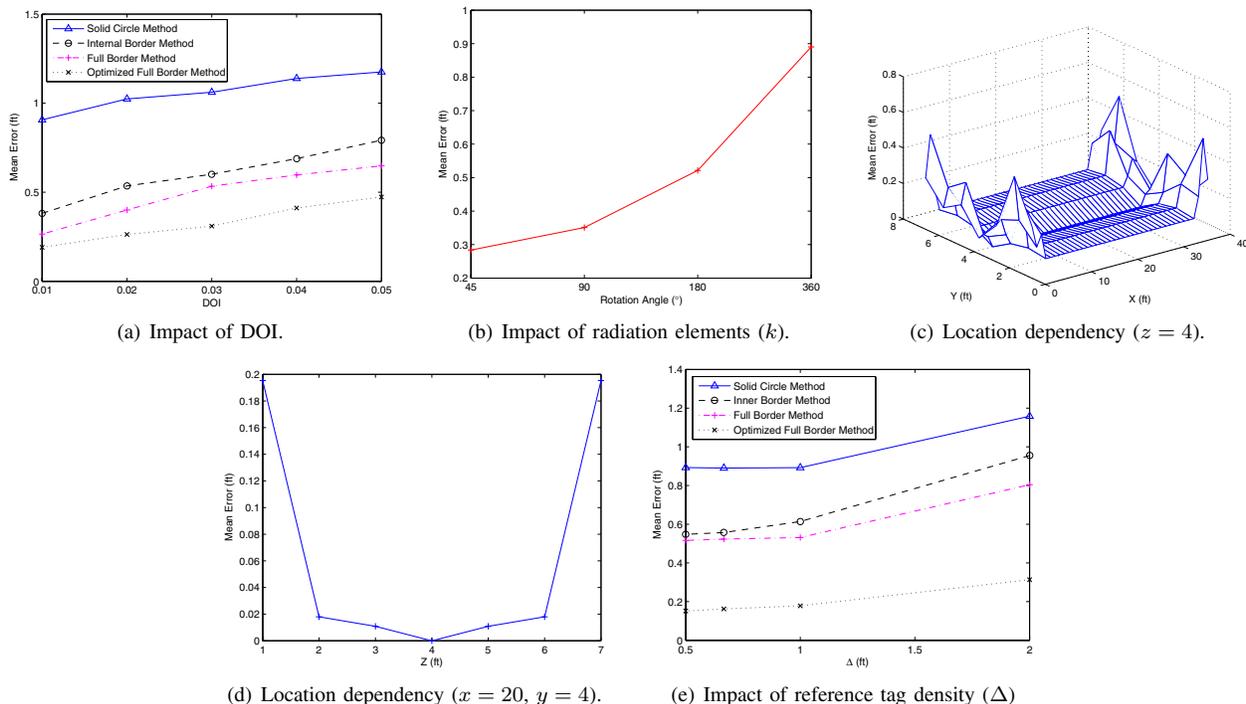


Fig. 6. Simulation results under the active scheme.

optimized full border method is illustrated here. We observe that the highest accuracy is achieved when the target is at the center of the hexahedron (i.e.,  $x = 20, y = 4$ , and  $z = 4$ ), where the errors of  $x, y$  and  $z$  are all about 0. When the target RFID reader moves to the corner of the hexahedron, the errors grow because partial circles are usually formed by the activated reference tags. Though the results are not shown here, we also observe that the solid circle method is more vulnerable when the target is at the corner, resulting in noticeably higher errors than other methods.

The density of the reference tags ( $\Delta$ ) also affect the accuracy. As shown in Fig. 6(e), higher density (i.e., smaller  $\Delta$ ) largely results in smaller errors. When  $\Delta$  becomes 1 foot or smaller however, it has no significant impact on the accuracy of the active scheme. Specifically, the performance of the optimized method improves only marginally with the increase of reference node density, while the accuracy of the solid circle method, the inner border method, and the full border method is not noticeably improved. This is reasonable because, when  $\Delta \leq 1$  foot, the density of the reference tags is no longer a dominating factor and the errors are mainly introduced by DOI. Given that  $\Delta \leq 1$  foot is sufficient to achieve high accuracy (with error less than 0.2 foot in the optimized full border method), a typical large container with a size of  $40' \times 8' \times 8'$  needs only 640 reference tags. As the price of an RFID tag is expected to drop to below ten cents eventually, a positioning system can be established with a reasonably low cost.

### B. Passive Scheme

As we have discussed in Sec. III-B, a number of reference tags and readers need to be deployed on the floor and the

ceiling of the hexahedron for the passive scheme. In our simulation,  $N = 12$  readers are deployed by default. Similar to our discussion on the active scheme, the density of the reference tags is represented by a parameter  $\Delta$ , which equals 1 foot unless specified. Each reader has  $K$  transmission power levels with a maximum transmission range of 16 feet. We assume the transmission power levels are calibrated so that there is a linearly increasing response range with the increase of power level, in order to improve the accuracy. In other words, the transmission range per power level is  $16/K$  feet. We vary the values of  $N, \Delta$ , and  $K$  to observe their impacts on the accuracy of the passive scheme.

We have observed from our simulation that there is a trade-off between the accuracy and the cost in the implementation of the passive scheme. We first study the impact of the number of reference readers ( $N$ ). As can be seen in Fig. 7(a), the errors decrease with more readers deployed, because more readers result in a more accurate error objective function (i.e., with more terms in Eq. (14)). At the same time however, deploying more readers clearly increases the system cost and leads to a higher computing complexity and longer time to locate the target.

Besides the number of readers, the number of power levels ( $K$ ) available to each reader is usually a dominating factor on the accuracy of the passive scheme. Our results show that more accurate coordinates are yielded with more power levels (see Fig. 7(b)). This is reasonable, because a larger  $K$  results in a finer increase in the readers' transmission power and thus more accurate estimation of distances from the target tag to the readers. However, the reader with many power levels is usually unavailable off-shelf or prohibitively expensive.

Figs. 7(c) and 7(d) show the impact of target locations on

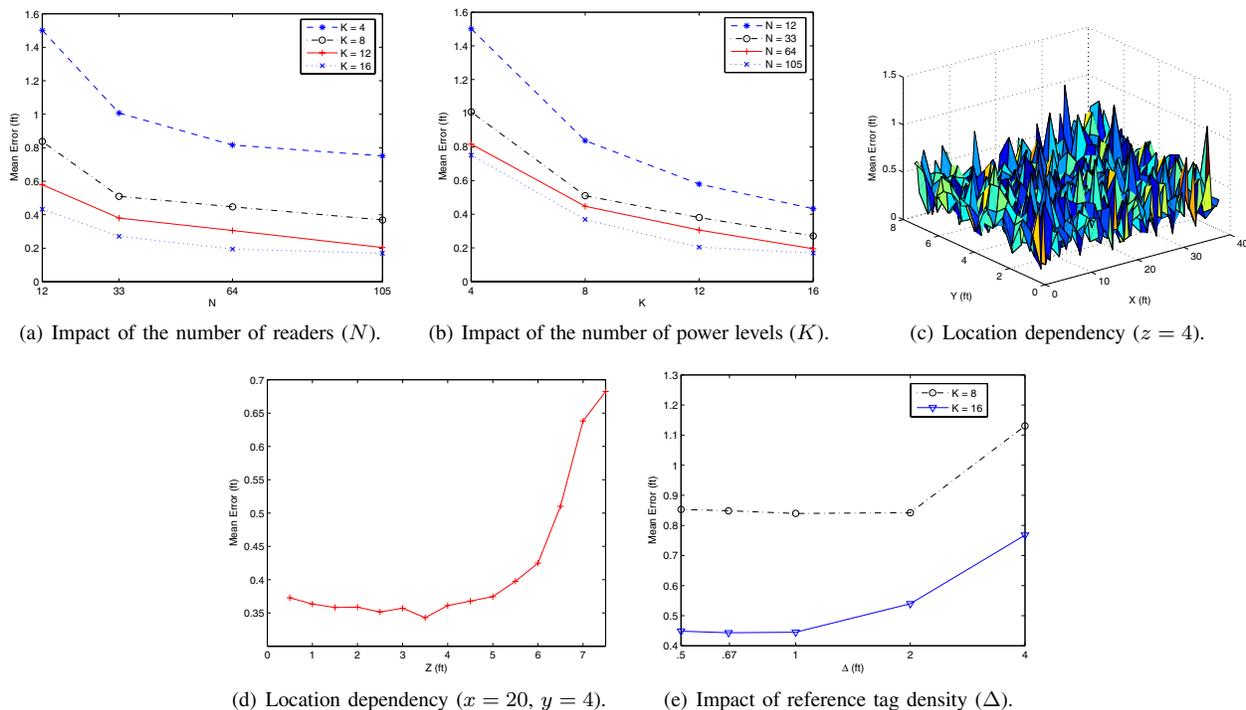


Fig. 7. Simulation results under the passive scheme.

the accuracy of the passive scheme. It is observed that the accuracy of  $x$  and  $y$  is insensitive to the location of the target. The errors vary only marginally with the location. At the same time, the error of  $z$  is not affected much by the location when the target is below 5 feet. While the target becomes very close to the ceiling, the error of  $z$  increases significantly because the relative error becomes high.

In addition, we observe that the density of reference tags has less impact on accuracy compared with  $N$  and  $K$  (see Fig. 7(e)). This is because the density of the reference tags is often sufficiently high, leading to a much finer granularity, compared with the readers' transmission power levels. In particular,  $\Delta$  doesn't noticeably affect accuracy when  $\Delta \leq 16/K$ , because, with the reference tag density so high, the power level granularity completely dominates the errors.

### V. EXPERIMENTAL EVALUATION

To further demonstrate the effectiveness of our proposed 3-D positioning schemes, we have conducted experiments by using the IDENTEC RFID kits [9], including the i-card RFID reader and the i-Q RFID tags as shown in Fig. 8. Given the limited resource, we have experimented the active scheme only. Our experiments were done in an apartment room of 18.5 ft long, 11 ft wide, and 7 ft high. The i-card reader connects via the PCMCIA III slot to a laptop, on which basic utility software to control the reader (e.g., to adjust its transmission power) and to obtain the results (e.g., to acquire the ID's of responding tags) and our 3-D positioning algorithm were run. An antenna is attached to the i-card, which is put roughly at the center of the room. Its height is fixed at 5 feet below the ceiling, permitting our studies on the  $X$  and  $Y$  coordinates only during experiments. Without loss of



Fig. 8. IDENTEC RFID kits used in our experiments.

generality, an arbitrary coordinate system is assumed, with its origin at the reader's antenna in each experimental setup. The reference tags are put at grid points across the ceiling, with the distance between two adjacent grid points equal to one foot, as depicted in Fig. 9.

We first carried out experiments using i-Q tags and readers (which suffer from considerable DOI), with the reader's transmission power set to be -15dbm. Based on the responses of the tags, our proposed algorithm results in the coordinates with errors of 1.5 ft (or 8%) along  $X$ -axis and 0.78 ft (or 7%) along  $Y$ -axis. As can be seen from Fig. 9(a), our algorithm works reasonably well in locating the target, despite that the responding tags don't form a circle due to high DOI.

Without a suitable antenna array at hand, we then emulated

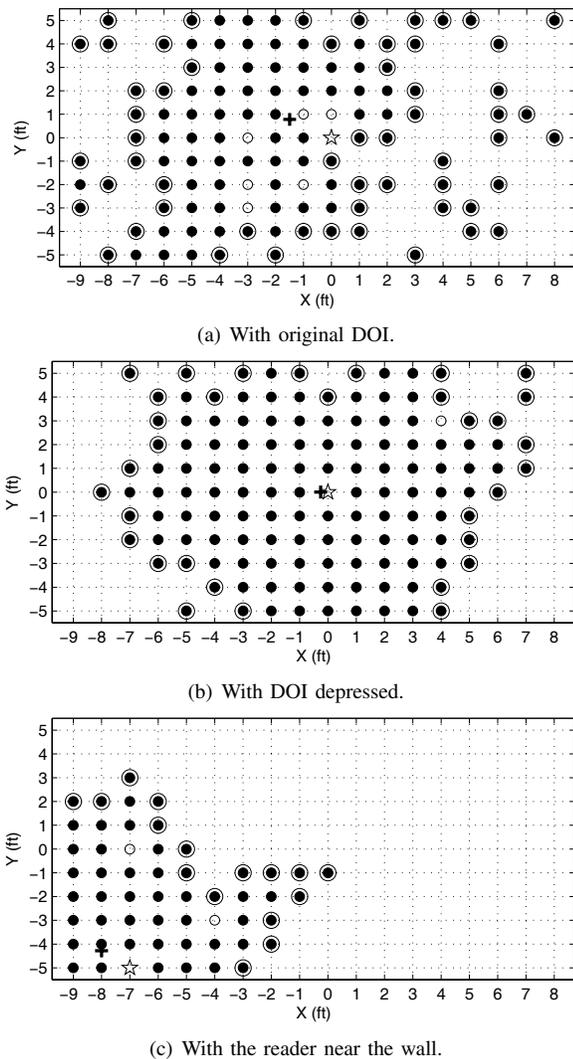


Fig. 9. Experimental results (active scheme). The star at center is the actual position of the reader, while the bold cross is its estimated position. The solid circle indicates the tag that responds to reader. The solid circle enclosed with an outer circle is the border tag identified by our algorithm.

the effect of using an antenna array by rotating the reader during experiments to reduce the DOI effect. Based on the accumulated tag responses after rotations (every 15 degrees), our algorithm yields far more accurate coordinates, with errors on  $X$  and  $Y$  coordinates shrinking respectively to only 0.26 (or 1.4%) and 0.01 ft (or 0.1%), as demonstrated in Fig. 9(b). The actual position (denoted by the star at the center) and the calculated position (marked by a bold cross) of the target reader are then very close to each other.

When the reader is moved to the corner or near the walls of the room, the errors become larger due to decreasing numbers of border nodes and the stronger interference introduced by signal reflections from the walls. Fig. 9(c) is obtained by rotating the reader every 90 degrees to emulate a less expensive antenna array (compared with the one employed the above experiment). The results still show acceptable accuracy, with errors on  $X$  and  $Y$  coordinates being 1.00 ft and 0.72 ft, respectively.

## VI. CONCLUSION

We have proposed two RFID-based 3-D positioning schemes, namely, the active scheme and the passive scheme, aiming to locate a target in a 3-dimensional space. In the active scheme, a number of RFID tags with known locations are deployed as reference points for locating a target RFID reader. For example, it may be employed to locate either a mobile person who wears an RFID reader or an object that is approached by an RFID reader. The passive scheme locates an RFID tag, which is attached to the target object. Both schemes are range-free (i.e., distance estimation based on signal strength is not required). In contrast to the active scheme where the reader needs to have one transmission power level only, its passive counterpart requires a number of readers with multiple power levels to serve as reference points. The coordinates calculation of both schemes is based on nonlinear optimization methods that minimize the error objective functions. Several approaches, such as border node identification and reader rotation, have been developed to improve positioning accuracy. We have carried out analyses and extensive simulations to evaluate the proposed schemes. Our results show that both schemes are effective. The average accuracy of the active scheme is usually one order of magnitude higher than that of the passive scheme. The errors are location-dependant. The active scheme performs very well when the target is at the center of the 3-D space but yields higher error when the target is at the corner. The accuracy of the passive scheme is less sensitive to the location of the target. In addition, the passive scheme usually takes a longer time for completion due to its gradual increase in the transmission power. On the other hand, it may locate multiple targets simultaneously, thus reducing the average tracking time per target. The effectiveness of our proposed approaches has been verified via experiments based on IDENTEC RFID kits.

## REFERENCES

- [1] D. Hahnel, W. Burgard, D. Fox, K. Fishkin, and M. Philipose, "Mapping and localization with RFID technology," in *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1015–1020, 2004.
- [2] K. Yamano, K. Tanaka, M. Hirayama, E. Kondo, Y. Kimuro, and M. Matsumoto, "Self-localization of mobile robots with RFID system by using support vector machine," in *Proceedings of IEEE/RSJ Int'l. Conference on Intelligent Robots and Systems*, pp. 3756–3761, 2004.
- [3] Y. C. L. Lin, M. Ni, Yunhao Liu and A. P. Patil, "Landmarc: Indoor location sensing using active RFID," in *Proceedings of IEEE Conference on Pervasive Computing and Communications*, pp. 407 – 415, 2003.
- [4] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The cricket location-support system," in *Proceedings of the Sixth Annual ACM International Conference on Mobile Computing and Networking (MOBICOM)*, pp. 32–43, 2000.
- [5] R. Want, A. Hopper, V. Falcao, and J. Gibbons, "The active badge location system," *ACM Transactions on Information Systems*, vol. 10, no. 1, pp. 91–102, 1992.
- [6] H. Wu, C. Wang, and N. Tzeng, "Novel self-configurable positioning technique for multi-hop wireless networks," *IEEE/ACM Transactions on Networking*, vol. 13, no. 3, pp. 609–621, 2005.
- [7] J. Nelder and R. Mead, "A simplex method for function minimization," *Computer Journal*, vol. 7, pp. 308–313, 1965.
- [8] Matlab. <http://www.mathworks.com/>.
- [9] IDENTEC SOLUTIONS. <http://www.identecolutions.com/>.