RFInD: An RFID-based System to Manage Virtual Spaces

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Abstract

We present RFInD, a cost-effective utilitarian system for locating objects using RFID technology. RFInD separates the notion of location from that of physical co-ordinates by using the abstraction of a Virtual Space. A virtual space is created by using RFID tags to label entities and locations in the physical space as references. RFInD manages the virtual space by using the references to create a spatial map, over which objects can be tracked and located. The target objects are labeled and embedded in a virtual space by associating them with proximate reference tags. RFInD creates the technology to automatically and efficiently manage these associations. In this work, we first characterize the capabilities of a commercially available RFID reader. We show how to use these capabilities for two tasks, namely Proximity Detection and Tag Association. RFInD uses these capabilities as primitives to create virtual spaces, embed objects in the virtual space, and navigate the space to track the embedded objects. Further, our experiments establish the effectiveness of our approach in managing virtual spaces.

1 Introduction

Keeping track of objects is an intrinsic requirement in several scenarios. These scenarios include critical business settings like supply chain management to more relaxed settings like finding objects in homes. The method of choice for this purpose involves assigning co-ordinates to tracked objects using one or more of current technologies like Wi-fi, ultra-sound, Radio Frequency Identification (RFID), etc. However, they require setting up costly infrastructures and may still be quite inaccurate in their measurements.

We take an alternate approach in this problem space. We utilize a novel resource in form of human cognizance to be able to locate objects at a substantially lower cost. This advantage that cognizance gives us is evident from the following examples: If Alice is looking for a book, a tracking system only needs to tell her that the book is on the Desk in Room 101. She does not need the system to give her the exact co-ordinates of the book. If Bob is looking for a printer near his location, he does not need the co-ordinates of the printer. A simple description like “The printer is in Room 102” suffices.

The fact that these examples highlight is that unlike robots, humans need not be guided at micro-levels. Knowing sufficiently proximate objects suffices for human beings to locate things. We utilize this insight as the motivating factor in designing the RFInD system described in this paper. RFInD uses RFID technology to track objects. It recognizes that the costly component in an RFID-based system is the reader. The cost of the RFID tags is minuscule. Thus, while the existing RFID-based location tracking and localization systems use a network of readers to locate the objects, RFInD tries to minimize the cost by having an ability to function using even one reader. This is the fundamental design guideline for RFInD. This is attained by exploiting the human cognizance as a resource to locate a proximate object in the vicinity. Our focus is on attaining the object location functionality by using a single RFID reader. It is obvious that using multiple readers only enhances the capabilities of the RFInD system. However, we do not focus on that aspect and comprehensively evaluate the ability of a single reader in providing human-navigable trackability.

The key concept in RFInD is to relax the notion that the location of an object is defined by its physical co-ordinates. Instead, we identify an object using its associations with other proximate objects. Collectively, we term the space of objects (defined by the associated RFID tags) as Virtual Space.

2 Related Work

In the recent past, significant research has been conducted in devising accurate ways of determining indoor location. Of these, the location-centric systems such as Cricket [3] and Radar [2] try to solve the problem of creating a geographical coordinate system in an indoor setting. Recently,
Tables in RFInD Database

(a) Virtual Space Creation

(b) Tables in RFInD Database

Figure 1. Creating Virtual Space over an office’s floor plan and the entries in the RFInD Database.

various RFID [6] based location tracking systems have been developed. RFID-Radar [4] proposed the use of low cost transponders to provide location information. Landmarc [7] proposed a multi-reader, multiple tag approach for localization. RFInD does not depend on finding the absolute locations of objects and creates a proximity and containment space that is human-navigable.

An object motion detection algorithm which allows unobtrusive detection of human interactions with RFID tagged objects using a long range RFID reader has been proposed in [9]. The authors characterize a commercial reader and use the estimated signal strength variation to find whether an object was moved. Further, [10] shows how to combine multiple passive RFID tags to form a 3D tag and use it to find the position and orientation of an object. [8] does simultaneous localization and mapping using robot-mounted mobile RFID antennae. This paper also gains similar insights regarding reader characteristics and tag-grouping as a preliminary step. However, since the purpose of RFInD is entirely different, we use these insights in designing novel algorithms for tag association and proximity.

3 Architecture Overview

The RFInD system is build upon the cost-effective RFID technology. Fundamentally, RFInD aims to do three thing: 1) Create a Virtual Space, and 2) embed objects in the virtual space, and 3) find objects in the virtual space. RFInD creates this virtual space merely using cheap passive RFID tags and a single RFID reader. RFInD aims to identify the physical space with RFID tags that are referred to as reference tags. The locations of the target objects is identified by affixing RFID tags (called object tags) and using the reference tags in their vicinity. Effectively, RFInD uses each reference tag to identify a Containment Space with the reference tags collectively defining a Virtual Space. The target objects are embedded in this virtual space and are associated with one or more containment spaces. Subsequently, when a user wishes to locate an object, the RFInD system can navigate her through the virtual space to the location of the object.

In our RFInD prototype implementation, we use a computer connected to the RFID reader that allows us to control the reader’s gain settings and communicate with RFInD database machine through its wireless interface (using XML, with SOAP as the underlying protocol). A GUI at the same computer allows users to manage and navigate the virtual space. Since RFInD creates a virtual space by associating object tags with reference tags, it is important to clarify the notion of the following associate sets used by RFInD:

Physical Associate Set: This set comprises of the associate tags that are identified by the RFID reader as the tags that are close to the target tag.

Logical Associate Set: This set contains the tags which may not be in the physical proximity of the concerned object tag but are associated to the tag by the user based on the description of the tagged object or for efficiently locating it.

For efficient user navigation, our prototype requires prior construction of the virtual space and embedding of target objects in it. The creation of a virtual space involves a user setting up reference tags at the positions that are to be part of the virtual space. The associate set for each of the reference tags is found using the Tag Association Operation. XML messages are constructed with each of the tag’s id, it corresponding location (using a text description e.g. “Shelf”) and sent to the RFInD database host which populates the Virtual Space Table. Further, additional information like Logical Associate Sets for each tag may also be added. For example, if all the target objects in the virtual space are stored in a store-room in a large building, a tag can be affixed to the building entrance and added it to the logical associate set of the tag identifying the store-room entrance. The description for this link could contain the actual physical description of the path between these two tags. Relatively moveable objects (e.g. “Book”) are affixed with an object tag and placed in the virtual space. For embedding an object tag, the associate set is first found using the Tag Association Opera-
The RFID reader in the RFInD system identifies the characteristics of the virtual space using two primitives: 1) Tag Association, and 2) Proximity Detection. As mentioned earlier, we can not rely on absolute values that a reader generates. Hence, we only use the trend values for designing these primitives. We used a commercial off-the-shelf RFID reader [5] provided by Symbol Technologies. The gain control on the reader is used explicitly in implementing the primitive operations. The gain refers to the power level of the transmit signal from the RFID reader. We perform extensive set of experiments to properly characterize the behavior of the RFID reader and use out findings in designing the primitive operations that underlies the RFID system.

4 RFInD Implementation

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4.1 Tag Association

This operation is used to find a set of reference tags which are “around” a target tag. These reference tags are collectively termed as the associates of the target tag. The basic idea is to isolate $T$ from the other tags in the vicinity and identify the other tags that are read along with it. To approximate the position of $T$, the area is scanned at the maximum gain of the reader. The approximate straight line at which $T$ resides is estimated by identifying the phase at which $T$ can be read at minimum gain ($g_{min}$). Possibly at $g_{min}$, a large number of tags can be read ($T'$) along with $T$. While reducing the gain in steps, the unread tags from $T'$ are eliminated and added to $T_{assoc}$ until $T_{assoc}$ has some members. Lastly, the reader’s antennae are rotated in both directions away from the straight line to $T$ in steps of 10 degrees at $g_{min}$ and $g_{min}+1$ until $T$ is not read or some new tags that weren’t visible during the previous steps are found. These tags are added to $T_{assoc}$ to obtain the associate set of $T$. The detailed algorithm for Tag Association is shown in Figure 2. The procedure $\text{Min\_Readable\_Gain}(Tag\ T)$ returns the minimum gain at which $T$ could be read.

For example, in Figure 3, the shaded regions show the zones the reader is capable of reading for gains $G_1$ and $G_2$. The dashed regions show the read zone at gain $G_1$, when the reader’s antennae are rotated by a certain angle. The tags $R_1$, $R_4$, $R_6$, and $R_7$ would form the associates of tag $T$. However, as is also evident that treating $R_1$ and $R_4$ as associates of $T$ would be a mistake as they are relatively far off. We note that this case is unlikely to occur since from our experience, with decrease in gain the read-zone shrinks more in the length rather than phase. So the non-overlapping regions of the read-zones of two consecutive gain values are likely to be closer to $T$ (the farther edge) rather than at different phases.

In certain cases, no tags within two levels of gain of $T$ could be associated with it. In this case, we associate the
closest tag to the current tag as its associate. We do this using a simple relation that the signal strength of a radio signal goes down with the square of the distance. Thus, the distance of a tag from the reader would be proportional to the square root of the minimum gain required to read it. Using this information and the relative angle of a tag with respect to the target tag, we compute a their relative distance in terms of gains. The distance \( D_T \) of the tag \( T \) from the reader is given by \( \sqrt{g_{\text{min}}} \) and the distance \( D_X \) of a candidate tag \( X \) is given as \( \sqrt{\text{Min}_{\text{Readable Gain}}(X)} \). Using the relative angle between \( T \) and \( X \), it is straightforward to compute the distance (in terms of gain) between them. The target tag is then associated with the candidate tag which has the minimum gain-distance from it. We note that this approach is likely to be inaccurate in some scenarios.

### 4.2 Proximity Detection

The proximity operation returns the id of the closest tag to the current location of the reader. This is essential to answer the simple question: “Where am I?”. Thus, while association identifies a set of tags located near another tag (possibly at a remote location from the reader), proximity detection identifies one tag that is closest to the current location of the reader.

In order to find the closest tag to the current location, a binary search is performed on the reader’s gain values until the minimum gain value \( (g_{\text{min}}) \) is reached at which a set of tags can be read \( (T_{\text{min}}) \). At \( g_{\text{min}} \), the reader’s antennae are rotated to find if some other tags can be read at any other angle (these tags could already be in \( T_{\text{min}} \)). If at some phase such tags are found, the binary search is resumed from the reader’s minimum gain value to a maximum of \( g_{\text{max}} \). If some tags are read at a gain \( g' \) less than \( g_{\text{min}} \) at some phase, \( g_{\text{min}} \) is set to \( g' \) and a new \( T_{\text{min}} \) is created for these tags. Figure 4 shows our algorithm for proximity detection. The procedure \( \text{Min}_{\text{Readable Gain}}(\text{low}, \text{high}) \) returns the minimum gain in the range low–high at which some tags could be read. The procedure \( \text{Tags}_{\text{Read At}}(g_{\text{min}}) \) returns the set of tags which are read at the given gain.

### 4.3 Experimental Results

We now show how the tag association technique performs in actual experiments. For these experiments, we have one target object tag placed between two reference tags. We refer to the reference tags as Closer Tag and Further Tag based on their distance from the reader’s antennae. The goal is to identify the reference tag closer to the target object tag. For the same gain and distance settings, we calculate the probability of reading a tag over 25 iterations. We define a threshold that a tag is read at a given gain if the probability of reading it is more than 0.5.

For the first set of experiments, we first place all three tags on the straight line perpendicular to the reader, directly facing the antennae. The reference tags are placed at distances of 5 feet and 15 feet from the reader. The target tag’s position is varied from 8 feet to 11 feet in increments of 1 foot. The aim of this experiment is to identify how effectively our algorithm can perform in the case when it needs to identify an associate tag which is closer. Figures 5(a), (b) and (c) plot the probability of identifying the closer, middle (denoting the object) and farther tag at different gains. The distance of the object tag \( (D) \) from the reader is varied at 8, 9 and 11 feet. Since our system threshold for identifying the minimum gain at which a tag is read is a reading probability of 0.5, we can see that in Figure 5(a), the three tags are identified at minimum gain levels of 6%, 8%, 22%. Using the square root of gains as notions for distances, we observe that the middle tag is considered closer to the Closer Tag.
which is the correct deduction. Similarly, in Figure 5(c), when the middle tag is at a distance of 11 feet, it is identified correctly to be closer to the Farther Tag. However, for the case in figure 5(b), the middle tag is identified as closer to the Farther Tag, which is incorrect (based on the gains at which the three tags are identified as 6%, 13%, 18%). Note that the farther tag was earlier identified at 22% gain but in this experiment, it is identified at a gain value of 18%. These fluctuations could occur not just due to interference between tags, but also due to changes in environmental conditions.

The second experiment looks at a similar scenario when the farther tag is at a phase with the reader. In this case, the farther tag is at a distance of 15 feet but is at a phase of around 10 degrees from the line of sight. For this experiment, the object tag is at 11 feet from the reader (where it was comfortably associated with the Farther Tag in the previous experiment).

Table 1. D=11 ft. at 10 degrees

<table>
<thead>
<tr>
<th>Gain (%)</th>
<th>Closer Tag</th>
<th>Object Tag</th>
<th>Farther Tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1 shows the gains at which the three tags are identified in this case. The three tags are isolated at gains of 6%, 16% and 28%. Using the square root of gains as indicators of distance, we find that now the target object tag is associated with the Closer Tag which is incorrect. We shall remedy this effect in the next section.

The third experiment in this set looks at the impact of interference on the correctness of tag association. In this case, we attach one extra tag approximately 6 inches from each of the previous three tags and all the tags are in a straight line. This causes interference and reduces the probability that a tag may be read correctly. Table 2 shows the gain values for this case. We see that now the distinguishing gain values are 6%, 16%, and 32%. Obviously, this is an erroneous situation where the target tag is deemed closer to the Closer Tag. Next we define a simple refinement that helps in these situations.

4.4 Improving Reliability with Clustering

Due to various conditions described above, the association decisions might get skewed. To alleviate this problem, we propose the use of tag clustering, where instead of one tag identifying a reference point, a bunch of tags can identify the same reference point. If an object tag is found to be associated with any one of the tags in the cluster, it is said to be associated with the entire cluster. The intuition behind this approach is the results from the previous section where the probability of reading at least one out of two tags placed close to one another is more than the probability of reading either one of them individually. We see the effect of clustering on the experiments shown in the previous section in Figures 6(a), (b) and (c) respectively. Looking at the distinguishing gains for each of the cases, we find that in each case clustering helped in correctly identifying the associate tag for the target.

5 RFInD Applications from User Experiences

While the real-life applications of RFInD may be left to the user’s imagination, we provided our prototype to mem-
numbers of Administration and Information Technology Support groups working in our organization. RFInD was found to be an useful tool for the following:

**System Administration**: System Administrators found a natural use of RFInD in locating servers across several racks in the machine room. The location of the server was located using the racks as references. RFInD was particularly helpful in the scenario when servers had to be hard-rebooted.

**Locating Peripheral Devices**: It not very uncommon for someone to use a network printer for printing material and not know the exact location of the device. RFInD was helpful in locating the areas where Printers and Plotters were placed.

**Asset Tracking**: Personnel in the Finance Administration found a good use of RFInD in tracking purchased items such laptops and monitors to keep their inventory updated. RFInD was also helpful in tracking borrowed equipment such as projectors. Further, RFInD was useful for tracking equipment that was temporarily provided to interns.

**Locating Objects in the Supply Room**: Another use of RFInD was found in locating lost carts in the supply room.

### 6 Conclusion

We presented the design of the RFInD system that uses a single RFID reader to locate objects. RFInD relaxes the notion of a location of an object being tied to its physical location. Instead, it bases the location of an object by its proximity to other objects. Using this relative notion of location allows RFInD to find the middle ground of using a single reader and still creating a object-location map of a large space of objects. We showed how to associate locations with objects in the RFInD system using two primitive operations called proximity detection and tag association. Our experiments performed using a commercially available RFID reader indicate the effectiveness of RFInD in locating objects.

### References


