RFID-BASED LOCALIZATION AND TRACKING TECHNOLOGIES

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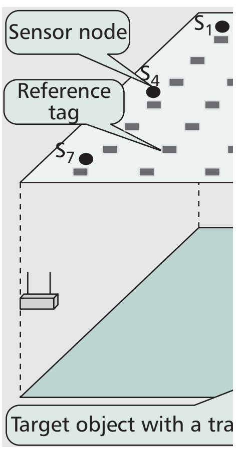

The authors present an overview of RFID-based localization and tracking technologies, including tag-based, reader-based, transceiver-free, and hybrid approaches. These technologies mainly use the resource of radio signal strength information or RSS change information to localize the target objects.

ABSTRACT

Radio frequency identification usually incorporates a tag into an object for the purpose of identification or localization using radio signals. It has gained much attention recently due to its advantages in terms of low cost and ease of deployment. This article presents an overview of RFID-based localization and tracking technologies, including tag-based (e.g., LANDMARC), reader-based (e.g., reverse RFID), transceiver-free, and hybrid approaches. These technologies mainly use the readily available resource of radio signal strength information or RSS change information to localize the target objects. A number of well-known approaches and their limitations are introduced. This article also indicates the challenges and possible solutions in the near and long terms. The challenges include multipath propagation, interference, and localizing multiple objects, among others. Most of these challenges exist not only for RFID-based localization, but also for other RF-based localization technologies.

INTRODUCTION

Localization of objects and tracking of moving objects are essential to many location-based services. Many technologies, such as WiFi, wireless sensor networks (WSNs), ultrasound, infrared, and video camera, have been proposed or used as the mechanism for localization and tracking. Radio frequency identification (RFID) is a promising technology for the purpose of identification and tracking of objects using RF signals. Among its many applications, RFID is widely used in enterprise supply chain management to improve the efficiency of inventory tracking and management. The relatively low cost of RFID technologies — an RFID tag can cost under 50 U.S. cents, much less than general-purpose wireless sensor nodes — makes RFID a popular candidate for localization and tracking.

There are two major types of RFID tags: active tags and passive tags. Passive tags have a very limited read range, on the order of 1 m from the reader. An active tag powered by a battery can be read up to about 300 m from the reader (or less without line of sight), which implies a broad range of location-based applications with a small number of readers. This, however, also raises a serious challenge in terms of the accuracy of localization. The focus of this article is on localization and tracking using mostly active but also passive RFID technologies.

RFID localization (as well as tracking) systems usually consist of three main components, *RFID tags*, *RFID readers*, and the *data processing subsystem*, as depicted in Fig. 1.

- RFID tag: An active RFID tag is battery powered and contains its own transmitter. It is able to actively send out beacon messages (i.e., the ID of the tag) at certain time intervals. Some RFID tags are associated with a motion sensor, so they will emit the beacon message when the tag is moved (e.g. RF Code [2]).[1] Battery lifetime can be as long as 7 years.
- RFID reader: An RFID reader reads data from the tags using a defined radio frequency and protocol to transmit and receive data. Depending on the antenna design, read range can exceed 100 meters (e.g., RF Code [2] claims a range of up to 300 m and Savi [3] claims a range exceeding 100 m).
- Data processing subsystem: The data processing subsystem utilizes the data from the readers to execute localization algorithms and make localization results available to various applications.

When a reader receives an ID message from a tag, the reader not only identifies the tag, but can also obtain the received signal strength (RSS) information from the tag. RSS information is a measure of power, usually represented in dBm (decibels referenced to 1 mW). By placing a number of readers in known locations, different readers will receive their own RSS

[1] *Certain commercial equipment, instruments, or materials are identified in this article in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.*

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readings from the same tag. Combining all the RSS information from all the tags, the target location can be estimated. The major advantage of using RSS information from readers for localization is that it is readily available without additional cost. However, RSS information is not always reliable as its value varies due to environmental factors. Figure 2 shows the RSS measurement of one tag taken in a laboratory at a fixed distance from the reader. The RSS information varies somewhat with the passage of time even in a static environment. However, a minor environmental change can cause a significant fluctuation in RSS. Furthermore, multipath propagation and interference in the environment increase the variability. Accordingly, localization accuracy is easily influenced by these factors.

In the following sections, this article aims to explain in detail the technologies, the challenges, and the opportunities of ubiquitous RFID localization systems.

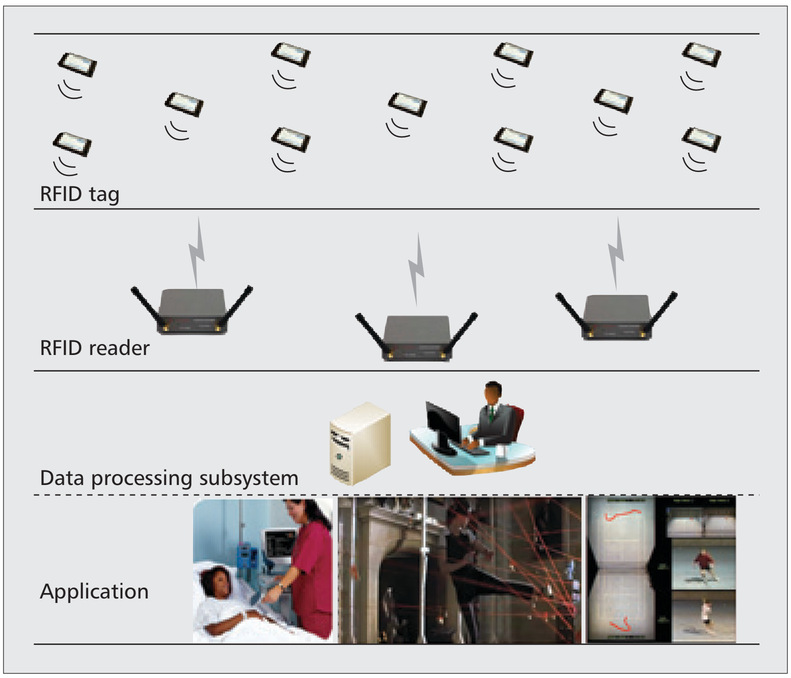

Figure 1. *Components used in RFID-based localization systems.*

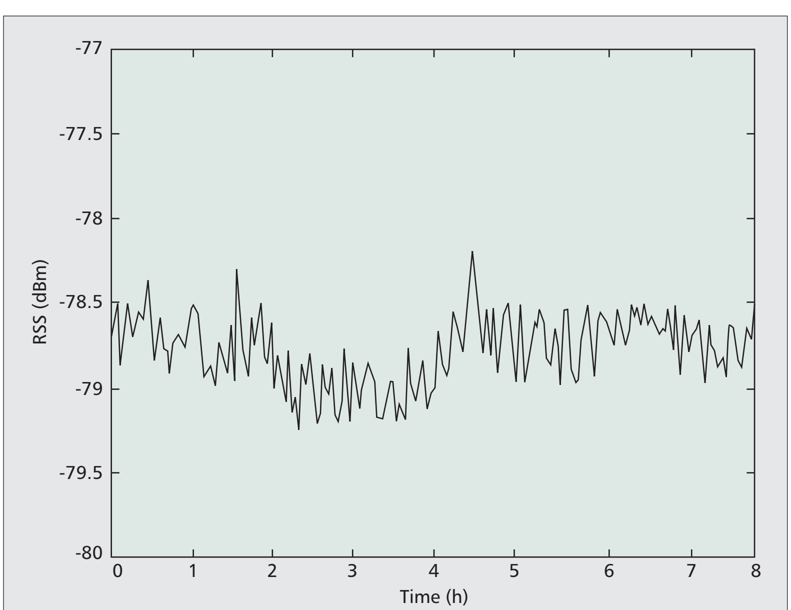

Figure 2. *RSS variation of a given tag over time.*

Performance Metrics

Different applications present different requirements on localization systems. In view of this, designers may optimize the systems towards various performance objectives. Typical performance metrics are listed as follows.

Accuracy

Accuracy is a key metric to evaluate the localization result. In general, it is measured by localization error, which is the distance between the actual location and the estimated location. Different applications have different accuracy requirements.

Latency

Latency is also an important metric to evaluate a localization system, especially for real-time tracking applications. In general, it is defined as the time between when an object moves to a new location and when the new location information is obtained. In real-time tracking of moving objects, low latency is required.

Cost

Cost is another metric for localization systems. In RFID localization systems, the cost includes the number of tags and readers needed.

Other Practical Concerns

In addition to the above metrics, there are other practical concerns. For example, suitability to different deployment settings should also be considered. Moreover, robustness to node failure is a concern in evaluating a localization system.

Classification of RFID-Based Technologies

RFID-based localization technologies can be classified into four categories: tag-based, reader-based, transceiver-free, and hybrid technologies. Tag-based technologies require the target to carry a tag, e.g., an active RFID tag, to periodically transmit beacon messages. Reader-based technologies require the target to carry a portable RFID reader, to gather information from nearby tags. In transceiver-free technologies, target objects can be localized without carrying any device, neither readers nor tags. Hybrid technologies integrate RFID technologies with other technologies such as inertial navigation systems (INSs) [4] and WSNs [5]. In the following we elaborate on these technologies.

Tag-Based Technologies

LANDMARC [6] was among the first RFID tag-based technologies. Besides consisting of RFID readers and a data processing subsystem, LANDMARC uses two different types of RFID tags:

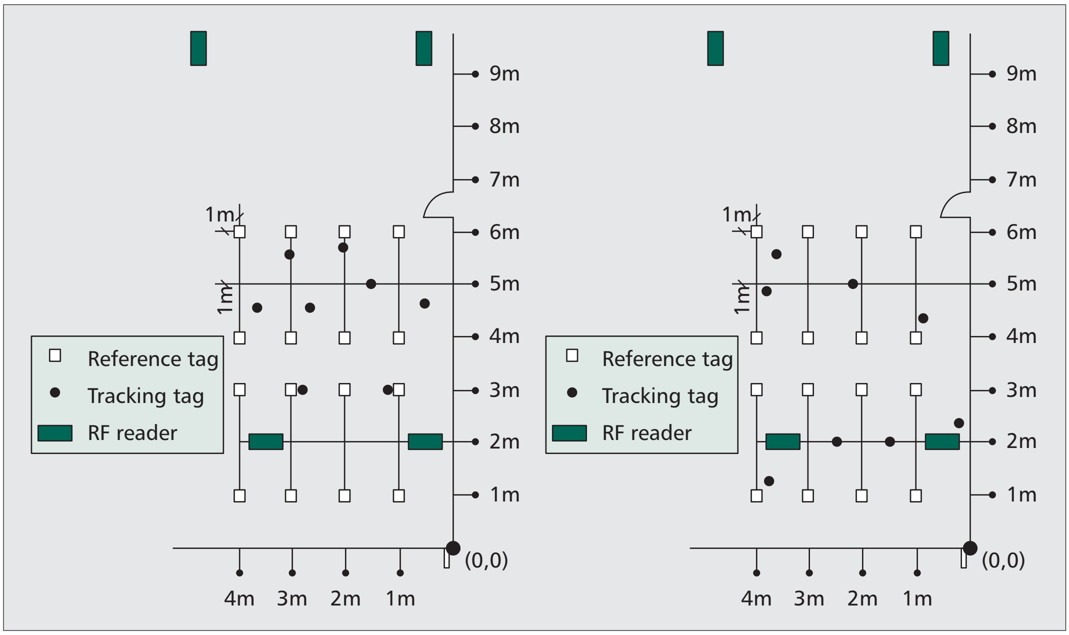

Figure 3. *Tag-based example (LANDMARC).*

The motivation behind Reverse RFID is to remove the dependence on an infrastructure of networked readers. Its applications include tracking public safety personnel responding to a natural or man-made disaster in which a pre-existing infrastructure of networked RFID readers might be rendered inoperative.

reference tags and tracking tags. The reference tags are deployed to the field prior to localization, while the tracking tags are attached to the target objects. The reference tags have fixed and known locations that cover the whole tracking area. When the objects are present in the area, readers receive the RF signal from both the target tags and reference tags. Due to correlation of radio propagation, the tags nearby will generate similar RSS to the readers. LANDMARC uses the reference tags with the closest RSS values to the tracking tags as the candidate reference tags. These candidate tags are used to compute the locations of the tracking tags.

Figure 3 provides an overhead view of an example system to illustrate the localization procedure. The left and right subgraphs show different scenarios of tracking tag locations. In each case, 16 reference tags and 4 readers are employed with 8 tracking tags for target objects. All tags have a read range of 46 m (150 ft), and the target objects are assumed to be on the ground. The reference tags are deployed on the ground with accurately known locations. The readers are deployed at the corners of the room. Both reference tags and tracking tags send out beacon messages periodically. The readers can obtain the corresponding RSS information. By comparing the RSS values, LANDMARC chooses K reference tags with the closest RSS values to the tracking tag. Here, K is a system control parameter and its optimal value is empirically observed to be 4 in 2D plane environments. Reference tags with closer RSS value to the tracking tags are assigned a higher weight. The target object location is computed by weighted average of the K reference tags.

The accuracy of LANDMARC in this example was observed to be about 1 m on average and as high as 2 m in an area of 24 m^2. The latency was about 7.5 s, mainly due to a hardware limitation (a fixed tag beacon interval). Data processing time was negligible. Nowadays, this latency can be improved to 2 s due to hardware improvements by vendors.

LANDMARC is relatively easy to implement and is used in a variety of applications. Although interference and multipath effects may influence the RSS signal from the tracking tag, the signals from the reference tags are also influenced. Thus, choosing the nearest K reference tags (i.e., nearest in the sense of signal strength) to estimate the target location yields respectable accuracy.

Reader-Based Technologies

In most RFID applications, including the aforementioned tag-based system, a tag is attached to the mobile tracked object, and the readers are at fixed locations. In reader-based localization systems, the traditional roles of tag and reader are reversed: tags are placed at fixed, known locations (much like the reference tags in LANDMARC), and a portable reader is carried by the mobile user or object being tracked [4]. The location of the mobile user is determined from the tag IDs (and possibly the RSS values) detected by the portable reader. This approach to RFID-based localization is sometimes referred to as *reverse RFID*.

The motivation behind reverse RFID is to remove the dependence on an infrastructure of networked readers. Its applications include tracking public safety personnel responding to a natural or man-made disaster in which a preexisting infrastructure of networked RFID readers might be rendered inoperative. The assumption is that the inexpensive tags, or enough of them, are more likely to survive an incident than a network of installed readers.

Reverse RFID can be used in conjunction with either active or passive tags. With active tags, the portable reader is likely to detect multiple tags simultaneously and therefore provide continuous tracking. When used with lower-cost passive tags, which have a much shorter read range, a portable reader is likely to detect at most one tag at a time, and location information would be provided at discrete steps with a resolution determined by the spacing of the tags. The discussion of hybrid RFID-INS technology below describes how inertial navigation can be used to supplement tag-location updates and provide tracking between tags.

An important issue with reverse RFID solutions is how to communicate the tag information obtained by the portable reader to a centralized tracking system. In conventional RFID-based localization systems, this information is communicated through the network of installed readers. When such a network is unavailable (e.g., due to damage in an emergency response), alternate means must be used.

Transceiver-Free Technologies

Transceiver-free technologies (e.g., [7]) aim to detect the object's trajectory pattern without requiring the target to carry any device. The idea originated with transceiver-free object tracking [8]. It is based on a simple observation that in a *static environment*, wireless signals are quite stable. When links are disturbed (e.g., signal strength changes dramatically), very likely there are moving objects nearby. In the implementation of [7], an array of reference tags and a few readers are deployed on the ground. The distance between tags is 1 m. Tags periodically send out beacon messages and the readers obtain the RSS value from each tag. In a static environment, the RSS values of tags are relatively stable. When a moving object appears in the array, it causes the RSS values of some nearby tags to change. This RSS change information is utilized to identify the moving object's trajectory patterns. Data mining techniques are employed as detailed below.

In the example in Fig. 4, the green dots represent the tag array and the circle represents a moving object. In this example, the RSS values from tags a, b, c, and d are very likely to be affected, while those from the tags in area A, such as h, are unlikely to be affected. Such information is utilized, and data mining approaches are applied to monitor the target activity.

The data mining consists of two phases: training and monitoring. In the training phase, the RSS values of tags are collected in a period of time. With the training phase frequent moving trajectories are identified as the model of normal activities in the field. In the monitoring phase, activities are detected and compared with the frequent trajectories by applying an approximate sequence matching algorithm [7]. When an activity matches a trajectory, it is treated as normal. Otherwise, an alert is sent out.

Since this approach only aims at detecting moving object traces, its accuracy is measured by the ratio between the length of a correctly detected trajectory and that of the real one. When the activities of the target are not complex, the accuracy is quite high, up to 100 percent. The latency is again dependent on the beacon interval of the tags, 2 s. Moreover, it requires an additional training step, which increases the calibration cost. In addition, there is the cost of deploying tags with sufficient coverage density (e.g., 25 tags in a 16 m^2 area in the example of Fig. 4).

Clearly, the advantage of a transceiver-free solution is that the target is not required to carry a device. However, it only performs well in finding the normal trace. Also, the trajectory patterns of multiple objects are still hard to obtain.

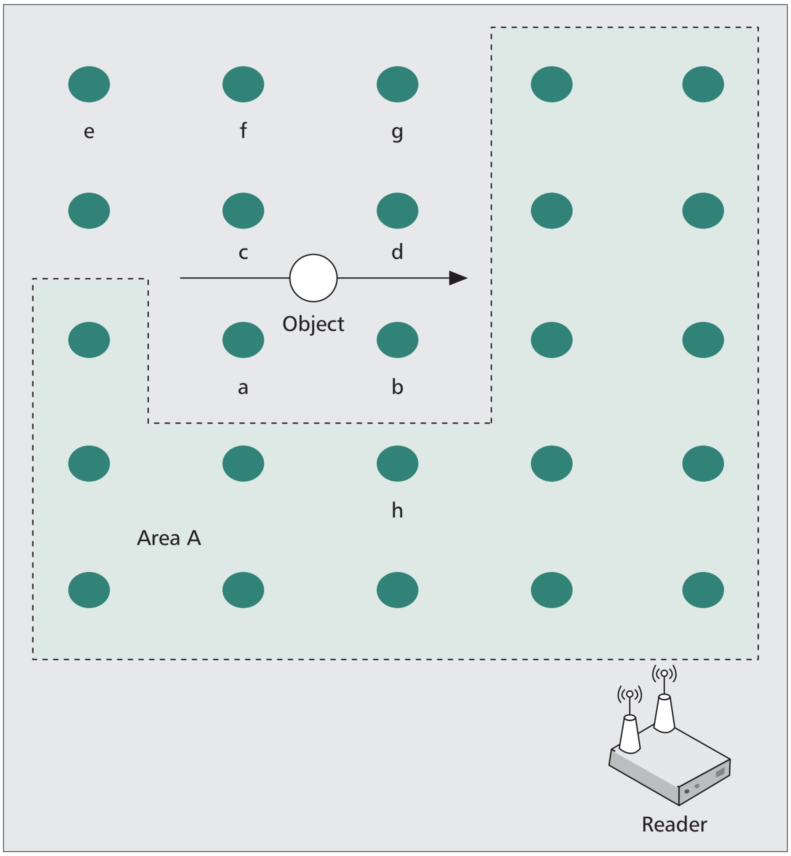

Figure 4. *Transceiver-free example.*

Hybrid Technologies

Hybrid technologies can improve the performance of a localization system by leveraging the advantages of different technologies. In this section we introduce two examples. RFID/WSN outperforms traditional pure RFID localization technologies in a very large indoor area. RFID/INS provides tracking when the target is out of RFID range.

RFID/WSN — Localization schemes for wireless sensor networks have used connectivity information to localize nodes within the network (e.g., [9]), exploiting the bidirectional nature of WSN links. RFID-based localization systems, on the other hand, are based on unidirectional links (information transfer from the tag to the reader). Hybrid RFID/WSN solutions seek to take advantage of both the richer connectivity (and RSS) information of WSNs and the lower cost of RFID.

An example of a hybrid RFID/WSN implementation is Cocktail [5]. The objective of Cocktail is to improve localization accuracy in a large indoor area. In traditional RFID localization approaches, the accuracy drops dramatically when the system is deployed in a large field. The reason is that in traditional approaches, the candidate tags are selected from all the tags. However, in a large field of applications, many more tags are employed with severe multipath and interference effects (discussed in the latter part of this article). These effects cause the RSS values to vary widely, making it possible for a distant tag to have a similar RSS value as the tracking tag. As a result, an inappropriate reference tag can be selected as the candidate tag, dramatically lowering localization accuracy.

To solve this problem, in addition to a tag-based RFID infrastructure, Cocktail employs a very sparse WSN network to cover the same area. RFID uses RSS information from tags and the WSN uses RSS change information from sensors. The RSS change information is more robust to environmental changes and sensitive to moving objects [5, 8]. Moreover, since sensor node links are bidirectional, for a given number of nodes the sensors can provide more RSS values than RFID. Although sensor nodes are more expensive than RFID tags, the sensors have a sparse grid deployment. Initially, RSS change values detected by the sensors are utilized to choose a group of tags which are very close to the target. Then this selected group of tags is used for localization.

In the example of Fig. 5, the sparse sensor array is set 3 × 3 on the ceiling or the floor, and labeled s_1, s_2, …, s_9. The distance between sensors is 3 m, and the nine sensors divide the field into 4 sub-areas, $s_1\, s_2\, s_4\, s_5$, $s_2\, s_3\, s_5\, s_6$, $s_4\, s_5\, s_7\, s_8$, $s_5\, s_6\, s_8\, s_9$. The dense tag array is set 7 × 7 on the ceiling covering the same area. The four readers are deployed at the corners. Since sensors and tags operate in different bands, 2.4 GHz and 303.825 MHz respectively, no interference between RFID and the WSN is introduced. When the target comes into the field, it causes RSS values to change for some sensor links. These affected links are called *influential links*, illustrated as red lines in Fig. 5. The influential links tend to be clustered around the object [8]. Since most influential links occur in the sub-area $s_5\, s_6\, s_8\, s_9$, only the tags in this sub-area are selected. Then, traditional LANDMARC or Support Vector Regression (SVR) [10] is applied.

Cocktail is able to improve the localization accuracy in a large indoor area. In the example above employing 9 sensors and 49 RFID tags in a 36m^2 area, average accuracy reached 0.45 m, a 55 percent performance improvement over LANDMARC. The latency of Cocktail is also bounded by the beacon interval of the tags, which is 2 s. Moreover, it provides a potential method to track multiple objects. Multiple objects can be identified by different groups (sub-areas). However, tracking multiple objects becomes more challenging when they are very close to each other.

RFID/INS — An inertial navigation system (INS) uses inertial sensors (accelerometers, gyroscopes) as well as non-inertial sensors (magnetometers, pressure sensors) to track the position of the target object. However, the tracked position inherently drifts over time resulting in growing errors in position; this is especially true of

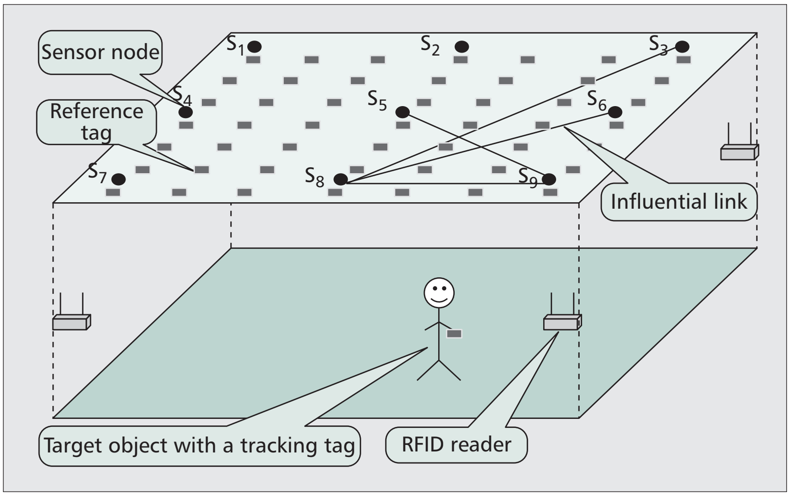

Figure 5. *RFID/WSN hybrid example (Cocktail).*

the more portable and less expensive systems. Periodic corrections are needed to limit the error to an acceptable level.

In a hybrid RFID/INS system, pre-deployed RFID tags serve as known waypoint locations at which the position error of the INS is zeroed out. INS is a natural complement to Reverse RFID. In hybrid Reverse-RFID/INS, the target object or user carries a portable INS integrated with a portable RFID reader. When the user is out of range of a tag, the INS provides continuous tracking estimates. As soon as the user comes within read-range of a tag, the known coordinates of the tag (either stored in the tag's memory or mapped from the tag's ID) are used to correct any drift in the INS estimate.

Experimental tests of a hybrid RFID/INS prototype highlight the benefits and challenges of this technology. Sample results of these tests are shown in Fig. 6. The prototype is based on Honeywell's (formerly Point Research Corporation's) Gyro Dead Reckoning Module and SkyeTek's SkyeModule portable UHF reader. Figure 6a illustrates results for an indoor environment, on one floor of an office/laboratory building. The user started in the southwest corner, walked counter-clockwise around all four corridors, returned to the starting point, and continued past the starting point until stopping inside an office. The green circles represent the locations of passive UHF tags. The red dots indicate the trajectory estimate provided by the hybrid RFID/INS prototype, which is corrected at the tag locations. One observes the INS drift, especially along the southern and western corridors. On the other hand, along the eastern and northern corridors, the estimated trajectory is relatively accurate. These results highlight the sensitivity of the azimuth estimate of the INS to structural steel, pipes and electromagnetic interference (EMI), the effects of which can be greater in some parts of the building than others.

To test the system in the absence of these structural influences, the experiment was repeated at an outdoor location approximately 200 m from the nearest building. Figure 6b shows results of a user walking around a baseball field starting at home plate (northwest corner). In this experiment, no RFID tag corrections were made to the INS-estimated trajectory. In contrast to the indoor experiment, the estimated trajectory is fairly good, with some drift observed around third base (northeast corner). Contrasting these results with those of the indoor experiment suggests that metal and EMI, indeed, are likely the greatest sources of error in the INS estimate indoors, and points to the importance of drift correction using a complementary technology like Reverse RFID.

Practical Considerations

Multipath Effect of RF Signals

Multipath is the radio propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. It occurs almost everywhere. The causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from mountains and buildings. Severe multipath occurs indoors, since the structure, objects, and humans also cause the reflection, refraction, diffraction and absorption of radio signals.

In theory, if there is no multipath or shadow fading, the signal strength is a function of distance [11]. As distance increases, the RSS decreases monotonically. However, in real environments, the RSS results from the signal summation of all the paths, including the multipath reflections, and therefore easily varies. For those localization approaches that are based on signal strength, accuracy is affected.

Some approaches attempt to solve this problem by trying to differentiate the main propagation path's signal, such as the line-of-sight path, from the other paths. But as far as we know, these solutions have limited value in practice. This issue affects not only RFID-based localization, but all RF (Radio Frequency)-based localization.

Interference

Interference occurs when unwanted signal(s) alter, modify or disrupt the signal of interest and naturally presents a challenge to RFID localization. In general, the received RF signals are apt to change due to interference. Again, for those localization schemes based on RSS information, the deviation of RSS results in localization error.

Interference is difficult to eliminate. Since most bands for RFID are unlicensed, different users may interfere with each other. Even in a clean environment, in which no other emitters occupy the same or neighboring channels, a large number of tags in the same system communicating at the same time will generate multiple access interference.

One approach to reduce multiple access interference is to use carrier sense plus randomized transmission. This policy can reduce the chance of concurrent beacons. Another approach is to utilize different channels; for example, Cocktail uses different channels for the sensors and tags [5]. Thus, the impact of interference on localization performance can be reduced, though not eliminated.

Multiple Objects

Localization of multiple objects is always a tough issue not only for RFID localization systems, but also for many RF-based localization technologies. If multiple objects are sparsely distributed, they can still be accurately localized. Hybrid technologies are particularly suitable for localizing multiple objects. For example, Cocktail is easily able to recognize how many objects there are. It also contains a grouping step, which first determines the sub-area of each target, improving localization accuracy.

However, when the number of multiple objects grows very large (dense objects), RF signals are much more easily influenced, and localization accuracy is apt to suffer.

Hardware Limitations

As mentioned previously, the beacon interval of an active RFID tag is a fixed value set by the vendor. For example, the beacon interval of the RF code [2] active tag is 2 s. The localization latency is bounded by this value. If RFID vendors were to provide a mechanism that would

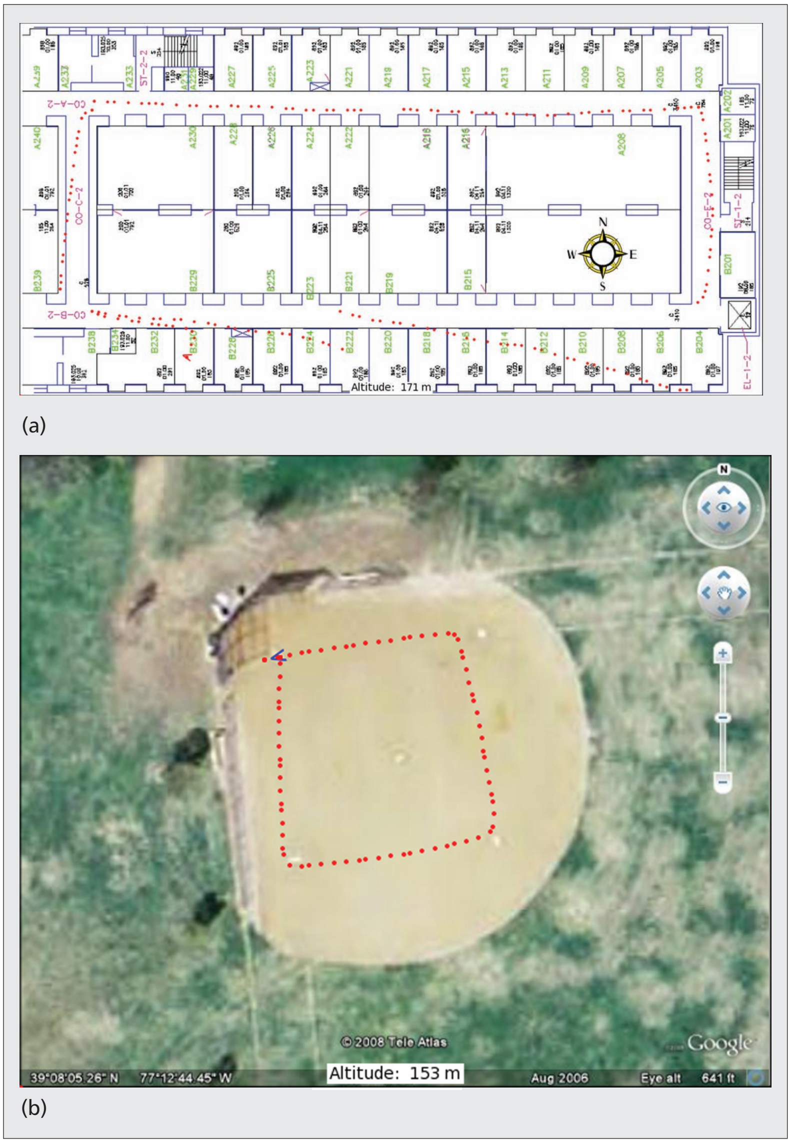

Figure 6. *Experimental results of hybrid RFID/INS prototype: a) indoor; b) outdoor.*

allow users to reconfigure the time interval, system performance could improve appreciably.

Another limitation is the variation of tag characteristics. Most RFID localization approaches (e.g., LANDMARC) assume all tags emit roughly the same signal strength. Variation in signal strength introduces localization error. Accordingly, if emitted signal strength can be made more uniform, localization accuracy can improve.

Communication of Reader-Based Location Information

In public safety and certain industry applications, there is a need to track users' locations from a centralized system. For example, the locations of public safety personnel responding to an emergency inside a building typically need to be known by the incident commander outside of the building. In addition, underground mine operators in the United States have recently been required by law to make implementation plans for tracking the locations of underground miners from the surface [12]. For some of the technologies described earlier, such as LANDMARC and transceiver-free, the communications capability is an inherent part of the system; the network connecting the installed RFID readers can be used to communicate location information elsewhere. However, part of the motivation of reader-based technologies like reverse RFID, which gather the necessary information locally at the target object, is to lessen the dependence on pre-installed infrastructure and support post-incident emergency response when any existing infrastructure may have been rendered inoperative.

One of the challenges in sending location information collected at the target object to a centralized system is the difficulty of communicating wirelessly and reliably into and out of large structures (e.g., high-rise buildings, tunnels, underground mines). The signal loss propagating into and within such structures can be severe, rendering traditional wireless technologies ineffective. Approaches to establishing communication paths for location information include extending coverage with high-gain directional antennas, the use of a multihop wireless ad hoc network, and rapid deployment of a wireless mesh network of repeaters [13].

Embedding Location Information in Tags

Since many RFID localization approaches involve advance deployment of a large number of reference tags, efficiently managing their location information becomes important. Economically feasible methods are needed for embedding accurate location information in tags and updating this information when necessary [14].

Conclusion

This article presents an overview of RFID-based localization schemes. These schemes use low-cost approaches to localize the target object with or without a device attached to the target. Moreover, some hybrid technologies were also put forward to handle localization problems in certain environments. However, the use of RF technologies presents a set of challenges that are as daunting as the benefits are great. While using RSS may be cost effective, it introduces challenges posed by multipath and interference. If these challenges are overcome, the performance of RFID localization technologies, and that of RF-based localization technologies in general, will improve.

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