Proximity Detection with RFID:

A Step Toward the Internet of Things

RFID systems will help enable the Internet of Things by performing proximity detection and localization. The authors investigate an RFID device that facilitates these functionalities—the device can passively detect and decode backscatter signals from tags in its proximity.

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The Internet of Things (IoT) vision merges the physical world of things with the Internet.[1] It's defined as a dynamic global network of physical and virtual things that have identities, physical attributes, and intelligence. A key ingredient of the IoT will be the ability of things to know their immediate neighbors—that is, the ability to sense the proximity of other things. Current RFID tags don't have this functionality, which is a significant hurdle in making RFID a fundamental pillar of the IoT. Here, we address one of the main weaknesses of today's ultra-high frequency (UHF) RFID systems as part of the IoT infrastructure.

In previous work, we introduced and studied a novel RFID system, which, in addition to tags and readers,[2] contains components called *Sense-a-Tags* (STs). An ST can passively detect and decode backscatter signals from RFID tags in its proximity, perform basic processing tasks, and communicate the acquired information to an RFID reader by backscattering according to standard RFID protocols. STs can be deployed throughout the space of interest or placed on objects or people. An ST can sense the communication of other tags and STs with readers only if it's physically near these tags. If the STs' locations are known, an RFID system with a network of STs can offer fine-grain localization and real-time tracking and monitoring—features traditional systems can't offer.

Here, we describe the potential and usefulness of ST-based systems in applications where proximity detection is a key requirement. First, however, we survey other potential RFID solutions.

Survey of RFID Solutions

Researchers have explored various approaches for integrating RFID and the IoT and have studied several RFID-based techniques for localization and proximity detection.

RFID and the IoT

Passive UHF RFID tags don't have batteries, so their cost is low—making them the main candidate for tagging a large number of things.

Various researchers have proposed different concepts for improved RFID systems suitable for the IoT. One RFID-enabled IoT solution is based on UHF RFID readers placed in a building and passive UHF RFID tags attached to people and objects of interest.[3] The system was extended with several software applications that let it search for things, integrate with social applications, and track personal trends.

Other work describes tags that can power themselves and communicate based on ambient

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RF. These tags communicate using backscattering and, in outdoors settings, can detect proximity up to 70 cm.[4] The solution isn't based on UHF RFID and doesn't support UHF RFID passive tags and protocols.

Efforts that base proximity detection on short-range communication of ultra-wide band (UWB) devices include the EnHANTS (Energy Harvesting Active Networked Tags) project,[5] which focuses mainly on energy harvesting. Because the communication isn't based on backscattering, this solution consumes more power than solutions based on passive RFID.

Localization

State-of-the-art solutions for localization based on passive UHF RFID rely on received signal strength (RSS), the phase of the RF signal returned to the reader from the tag, landmark tags, and a combination of RFID with some other technology.

Range estimation from RSS is unreliable, especially when the system operates in complex propagation environments. Furthermore, as pointed out elsewhere,[6] the tag backscatter loss varies with the power incident on the tag because the input impedance of an RFID tag's IC is power dependent. The RSS is also angle dependent. Therefore, different techniques are used to improve the localization accuracy of RSS-based systems. They include fusing the tag detection rate with RSS values or employing neural networks to train the system based on previously collected RSS values.[7]

Landmark-based systems rely mainly on comparing the RSS values of the tags placed at known locations with RSS values of a tag that must be located. Due to the previously mentioned RSS problems, calibrating these systems is difficult.

Phase-based techniques can be used to improve the localization accuracy for RFID readers that provide phase information.[6] However, it has also been shown that the performance of phase-based and RSS techniques in non-line of sight (NLOS) environments decreases significantly.

Solutions also exist that enhance passive RFID systems with other technologies, including ultrasound or cameras. Such solutions outperform RFID-only approaches in localization accuracy. For example, Wireless Identification and Sensing Platform (WISP) tags are extended with LEDs that allow for optical localization of tagged items with millimeter accuracy.[8] Another example is a camera and UHF RFID reader with a steerable antenna to localize items tagged with standard passive RFID tags within a cubic meter.[9]

Proximity Detection

Several solutions have been introduced to augment existing UHF RFID systems, including the ST-based system presented here, the software-defined radio Gen2 Listener,[10] and an augmented RFID receiver (ARR).[11] These systems use detected communication of passive RFID tags for localization, proximity detection, protocol analysis, or data collection. The ARR has a lower cost and lower detection range than the Gen2 Listener, but it's still too expensive for the ubiquitous deployments required for IoT applications. Also, the ARR and Gen2 Listener aren't mobile and can be used only as landmark tags, which is too expensive for localization applications.

In other work,[12] a UHF component called a *reader tag* (RT) was implemented. The RT has a circuitry that modulates the continuous wave signal from an external exciter. The RT's read range was 25 mm and, as such, this system wouldn't be useful for the applications we propose here.

OpenBeacon is an active RFID solution that can detect proximity and social interaction among people.[13] The OpenBeacon active tags can detect signals from other active tags in their proximity, decode them, and report the acquired information to a reader.

There's also a proximity-detection application for monitoring people's daily activities.[14] The system is based on a miniature HF RFID reader that's attached to a wrist or glove and can detect when tagged objects are touched.

Sense-a-Tags

None of the systems just described provide cost-effective support for localization or for detecting other tags' proximity—both necessary requirements for the IoT. Here we describe an UHF RFID system with STs that performs these tasks.

Functionality

The system is composed of standard tags, readers, and STs. Using STs is useful for the IoT for several reasons.

First, an ST can decode backscattered signals from nearby tags and communicate with the reader as a regular tag using backscattering communication. In other words, it's an IoT tag that can sniff the communication link between EPCglobal's Class 1 Generation 2 UHF RFID readers and tags.

Second, an ST can store the detected tags' ID numbers, which it then uses to associate with those tags. Based on this information, the system can infer proximities among tags and STs.

Finally, an ST can have situational sensitivity, because it can be programmed to detect and sense only particular tags.

System-Level Design

The ST is a semipassive device, compliant with EPCglobal Class 1 Generation 2 tags, that operates in the range of 902 to 928 MHz. It uses a battery to power the digital and analog electronics. Specific ST components include an omnidirectional antenna with 3 decibel isotropic (dBi) gain, FPGA Xilinx Spartan 3AN, and an alkaline 9 V 2100 mAh battery.

The ST's detection range for passive tags is approximately 1 meter. It has been extensively tested with the Impinj Speedway R1000 reader and with

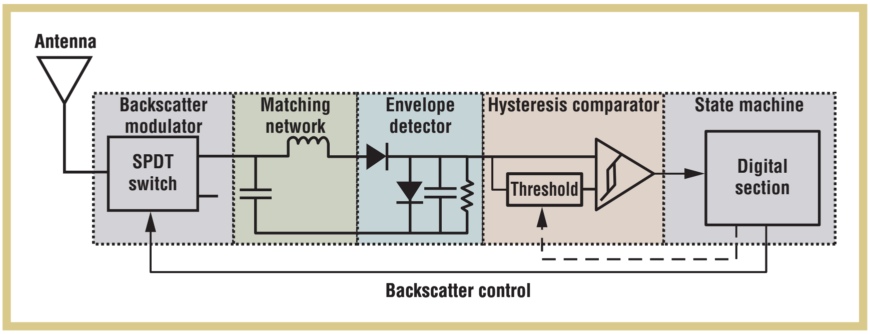

Figure 1. The Sense-a-Tag (ST) architecture that consists of an antenna, a modulator, a passive envelope detector, digital electronics, and variable filtering and threshold generation circuits to reliably digitize the reader signal as well as the tag backscatter signal.

different commercial tags. Figure 1 shows a block diagram of the ST hardware (more details appear elsewhere[2]). The antenna is followed by a backscatter modulator, a conventional matching circuit, and an envelope detector. The detector's output is fed to a comparator that acts as a one-bit A/D converter. The comparator's output is the input to the ST tag's digital section, which implements the ST protocol. A threshold circuit is used to adjust the analog section for detection of signals from both the reader and tags. These two types of signals are modulated differently and have disparate power levels; thus, the threshold for their detection is computed in real-time in the digital section.

Next, we describe the functionalities of the host and ST so that proximity detection can be accomplished. An ST can act as a tag, which means that it can respond to all the commands from a reader in the same way as regular tags. However, the ST can also listen to particular reader commands for addressing tags; if the ST detects these commands, the tag's response, and the reader's acknowledgment, it has detected the tag. The ST then stores the information about the detected tag. When the reader singulates an ST, this ST transfers its acquired information to the reader.

Because STs are viewed as ordinary tags by the readers, the host must specify a procedure for reading the tags and STs. Also, the host understands the ST's operations, and it controls the reader using standardized commands. The host's first task is to make sure that the reader reads only tags in several query cycles. During these cycles, the STs listen to tag responses and store the information acquired from the detected tags. Subsequently, the reader selects and reads only STs. The host analyzes the information provided by the STs to implement the intended application.

Advantages

Table 1 summarizes the ST's main advantages over the localization and IoT solutions described earlier. An additional advantage of the ST-based system in comparison to other systems is the operation of indirect localization or localization by association. When an ST is localized, it can detect other nearby tags, which are thus localized, too. Furthermore, the ST can be used to implement accurate gateways (portals).

Limitations and Disadvantages

The main disadvantage of the ST-based system in comparison with traditional UHF RFID systems or those that use phase-based localization (see the first two rows in Table 1) is that it requires landmark tags for localization applications. Furthermore, the ST is semipassive and requires battery changes. However, the landmark tags can be passive UHF RFID tags that are inexpensive and maintenance-free. As for the batteries, the prototype's most power-consuming component is the Spartan FPGA. Based on experiments, our ST can keep working continuously for up to 10 days. Currently, we're working on migrating from an FPGA design to a low-power microcontroller that can potentially increase the battery's lifetime by up to one year.

Other features of the current ST version also need improvement. The detection range between the ST and the tags depends on the orientation between the ST and the tags. We can improve the detection range with dual-dipole passive tags, two tags per object, or semipassive tags.

The ST's detection range depends on the reader's distance from a tag (the detection range decreases with distance). In localizations with fixed reader antennas and fixed passive landmark tags, this weakness can be corrected by designing an ST with an adaptive detection threshold.

The current ST listens to five reader query rounds and reports in the sixth. Therefore, the ST's reporting speed is limited with this design decision and the implemented parameters of the protocol. This can readily be changed.

In the current design, demodulation is based on envelope detection, and the ST might not be able to detect the backscattered ASK-modulated signal from a tag at some places, resulting in read nulls. This could affect the ST's performance in static settings. However, we consider applications where there's always relative movement between the tag and the ST (tracking, portal, proximity detection), which means that there's small probability that the ST doesn't detect the tag at least once. The effect of read nulls can be significantly reduced by implementing an ST with more than one antenna, an adaptive threshold of the comparator based on the reader signal's observed amplitude at the ST, or an improved envelope detector.

TABLE 1
Summary of the Sense-a-Tag (ST)-based RFID solution's advantages.

System	ST advantages
Traditional UHF RFID systems[3]	• Allows for proximity detection among tagged objects • Provides fine-grained localization • Has potential to link an RFID system with other wired or wireless systems (such as with Ethernet[11])
Traditional UHF RFID systems for localization that are phase[6] or RSS based[7]	• Enables proximity detection among tagged objects • Allows for improved localization that's more robust and depends less on fading and non-line of sight (NLOS) conditions in indoor environments
HF RFID solutions[14]	• Offers scalability (HF systems aren't scalable because they require reader-to-tag proximity detection, but in UHF systems, many STs and tags can operate in a single reader's reading zone) • Allows for detection of person-to-person interactions
Active RFID solutions[13]	• Reduces costs because active tags are more expensive in general • Doesn't require batteries for localization applications when passive UHF tags are used as landmark tags (OpenBeacon tags used as landmark tags have batteries that must be replaced)
RFID systems enhanced with other technologies[8,9]	• Doesn't require modifications of off-the-shelf components

Applications

Here, we briefly explain how the STs can be used in two IoT applications.

Proximity detection. For proximity detection, the location of the STs (or tags) isn't known in advance and is irrelevant. Many applications must detect interactions of objects or proximity between objects/people without knowing their exact locations. This is particularly true for the IoT, where the interaction between things and people and among people will be a core issue.[1] Object-to-object proximity detection can be used to determine if the object moves from a particular place. People-to-object proximity detection can be applied for tracking people's daily activities and for tracking interaction with sensitive objects, such as blood samples, dangerous chemicals, or explosive devices. People-to-people proximity detection can be employed for tracking interactions at social events.

Preventing unwanted reads. Reliable localization and detection of entrance and exit events are important for RFID-based IoT applications. However, using RFID for these applications produces problems with read-accuracy (the percentage of correctly identified tags) and cross-reading of tags (unwanted reads of tags that don't go through the portal). With RFID passive tags, the read-accuracy depends on the amount of power the reader delivers to passive tags. To improve read accuracy, a reader antenna's output power is increased, but this increases the number of cross-readings. Clearly, high read accuracy and zero cross-reads are two conflicting requirements.

Using STs makes it possible to transmit signals from a reader antenna at full power. The STs are deployed to sense tags only in the portal area by properly positioning and shielding them. When tags outside the portal area are read by the readers, they won't be sensed by the STs and therefore the system won't register them.

Experimental Results

Here, we present results of three experiments. In the first experiment, the objective was to track human actions. Next, we aimed to investigate the possibility of locating a moving ST and performing indirect localization. In the third experiment, we evaluated the feasibility of ST-based solutions in portal applications.

In the experiments, we used our ST and the Impinj R1000 Speedway reader. The reader power for transmission was set at 30 decibel-milliwatts (dBm). The gain of the reader antenna was 6 dBi.

Tracking Human Interactions

The experiment's purpose was to demonstrate that the ST is suitable for tracking the daily interactions of people and objects. In this experiment, we investigated whether it's feasible to detect a person moving an object. We attached UHF tags with the Philips MF1S70 chip to several boxes. To improve system performance, each item was tagged with two tags placed on the top and side of the object. An ST was used as a wristband worn by the person.

Figure 2a shows the experimental setup. The person who wore the ST approached an object placed on the right desk, grabbed the object, and put it on the left desk. The distance between the desks was 2 m. The reader antennas were separated by 2.5 m and placed in front of each desk. The RFID reader switched between the antennas every second. The UHF tags on the boxes could be read by both reader antennas,

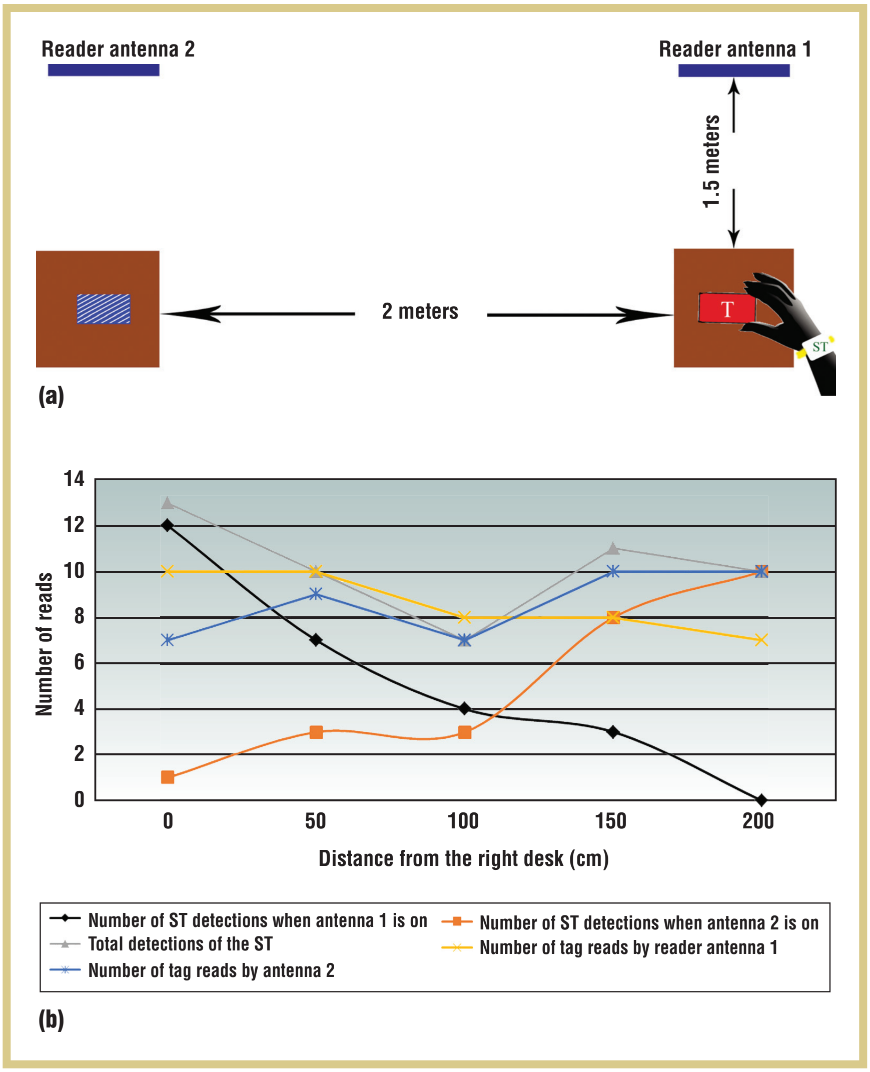

Figure 2. Tracking interactions between a person and an object. (a) The experimental setup and (b) the number of tag reads by the reader and the ST (for reader antennas 1 and 2). The grey line represents the total number of ST reads.

so it was difficult to detect the movement without STs. Figure 2b shows the number of reads of the target object's tags by reader antennas 1 and 2 (the yellow and blue lines, respectively).

Figure 2b shows the ST's number of detections when reader antenna 1 and antenna 2 were on, as well as its total number of reads. We're mainly interested in the number of times the ST detected the tag (the gray line in Figure 2b). We consider the person to be interacting with the object when the number of ST detections is more than one per second. Therefore, for the current scenario, we could always detect when there was an interaction between the person and the object.

When the person picked up the item from the right desk, the ST detected the tag only when the reader antenna 1 was on. About 2 m away from the right desk, the number of ST detections of the tag when antenna 1 was turned on was very small, but the number of detections when antenna 2 was turned on was large. The results suggest that the ST allows for the possibility of detecting movement of a tagged object from one desk to another.

The experiment was repeated for the following situations:

- with a human body between the reader antenna and the ST/tags,
- with 10 other tags on different objects, and
- with only one tag attached on the tracked object.

In the first case, the system wasn't reliable. We believe this was due to the drop in ST performance in proximity of the human body and the reduced power of the tag's backscattered signal caused by the human body. In the second case, the other tags didn't affect the performance. However, in the third case, although the number of times the tag was detected by the ST dropped more than three times, it still indicated that this system could be used with one tag per object. We aim to improve the ST so that it performs better in settings similar to the first and third cases.

Locating Moving and Static Objects

This experiment's goal was to determine whether it's possible to locate a moving object that carries an ST as well as to indirectly locate static objects tagged with passive tags. We used a robot that was tagged with an ST and was moving along a trajectory (the black line in Figure 3). The area was 4 m × 2 m and was covered with passive UHF RFID landmark tags. Software was developed in C# to process the received data from the ST, control the reader, and log the activity (Figure 3). The ST's position was estimated using the weighted centroid method.[2]

In Experiment 1, we had 24 landmark tags; in Experiment 2, we had 12 (we removed every second tag in the *y*-direction). Two boxes with UHF passive tags were in the area with coordinates of box 1 (100, 125) and box 2 (100, 300). We used one RFID reader with one antenna placed at the coordinate (1 m, 2 m). The antenna's height was 2.6 m. We performed additional experiments in which we added 10 more tags to the environment and had two people stand between the boxes and the moving robot. The estimate of the ST's location is presented on the screen using red dots. The green circles represent the position estimates of box 1, and the blue circles the position estimates of box 2.

The system's accuracy in estimating the ST's location in Experiment 1 was better than 32 cm (Figure 4); in Experiment 2, it dropped to 48 cm in the *y*-direction. Because the reader antenna is placed in the path's middle and the number of landmark tags at the path's beginning and end is smaller, the localization error is different throughout the path.

In order to test the indirect localization capabilities of the ST-based system, our goal was to determine whether it's possible to locate unknown tags' positions based on the estimated ST position. Our results show that when an ST was close to a tagged box, the box could be detected and located. The ST detected boxes in both experiments and located the boxes in all the cases. It reported approximately every second but didn't detect the boxes in each report. The number of reports when the STs were in the range of the boxes was between 40 and 66 percent, which was enough to locate boxes every time. The proximity of people or other tags didn't affect the localization performance or box detection and localization.

Similarly, we can design a system to track people carrying STs and determine if they carry tagged objects. This can be used to identify in real time if someone moves and carries important, dangerous, or expensive objects.

Preventing Cross-Reading

An RFID system with STs can readily be used to rectify problems with cross-readings. In this experiment, we sought to demonstrate the feasibility of an ST solution in which the ST detects the tag's proximity only inside a portal area. In the experiment, a person wore a wrist tag (a passive UHF tag with the Philips MF1S70 chip) and passed

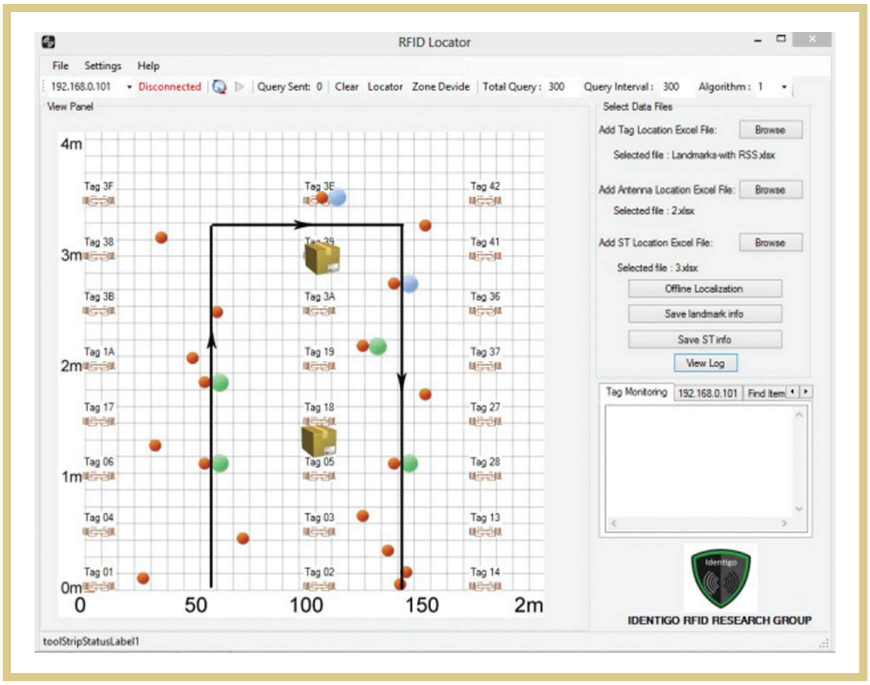

Figure 3. The GUI of the software for ST localization in real-time for Experiment 1. Tags 1 through 42 represent positions of the passive landmark tags. The black line is the trajectory of the moving object with the ST that needs to be located, and the red dots are the estimated locations. The system also estimates indirectly the location of the two tagged boxes. The estimates are presented using green and blue circles.

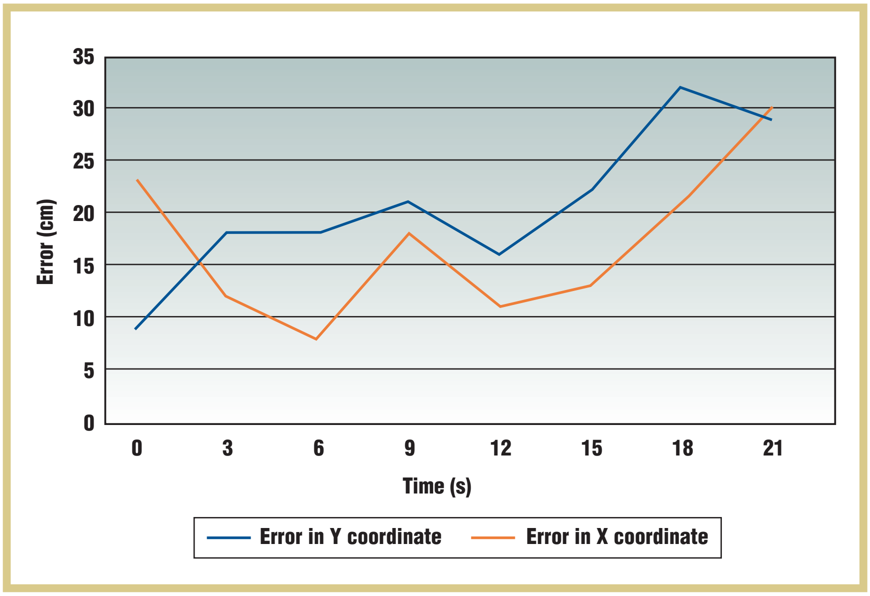

Figure 4. The absolute error of localization in the x and y directions for Experiment 1 with 24 landmark tags. The error corresponds to the difference between the estimated and real positions of the robot for the experiment shown in Figure 3.

through an improved portal made with one reader antenna on the left and the ST on the right, with a small metal shield behind the ST. The distance between the ST and the reader was 2 m, the height of the reader antenna was 1.2 m, and the height of the ST from the ground was 1.25 m.

The ST and reader detected the tag 100 percent of the time (in 10 trials). When the person with the tag went around the portal (behind the ST), the tag wasn't detected at all (0/10 times).

A real portal will have, for example, two reader antennas (one on each side) and a minimum of four STs (at least two on each side). The STs' tag detection will not only determine if the tags pass through the portal, but also estimate the direction of their movement.

The results presented here are based on our first ST prototype. To become widely used, the system's speed and the ST's orientation sensitivity, size, cost, and power consumption must be improved and the read null problem resolved. Furthermore, we plan to study novel IoT applications of the proposed system.

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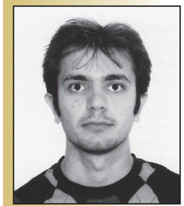

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