INTEGRATION OF PASSIVE RFID LOCATION TRACKING FOR REAL-TIME VISUALIZATION IN BUILDING INFORMATION MODELS (BIM)

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INTEGRATION OF PASSIVE RFID LOCATION TRACKING FOR REAL-TIME VISUALIZATION IN BUILDING INFORMATION MODELS (BIM)

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Dedicated to my loving wife, Lindsey,
for her patience, support,
and encouragement.

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LIST OF ABBREVIATIONS

API	Application Programming Interface
BIM	Building Information Modeling
dBm	Decibel Meters
FM	Facility Manager
GPS	Global Positioning System
IMU	Inertial Measurement Unit
LOS	Line of Sight
MHz	Megahertz
O&M	Operation and Maintenance
RF	Radio Frequency
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
RTLS	Real-Time Locating System
SLAM	Simultaneous Localization and Mapping
UHF	Ultra High Frequency
UWB	Ultra Wideband

SUMMARY

Navigation through large and unfamiliar facilities with labyrinths of corridors and rooms is difficult and often results in a person being lost. Additionally, locating a specific utility within a facility is often a tough task. The hypothesis tested in this research is that integrating real-time automated sensing technology and a Building Information Model will provide real time visualization that can assist in localization and navigation of a facility. The scope of this research is facility maintenance management during the Operation and Maintenance (O&M) phase of a facility. The thesis demonstrates how the integration of passive Radio Frequency Identification (RFID) tracking technology and Building Information Modeling (BIM) can assist in facilities maintenance management. The objectives of this research included 1) developing a framework that utilizes the integration of commercially-available RFID and a BIM model; 2) evaluating the framework for real-time resource location tracking within an indoor environment; and 3) developing an algorithm for real-time localization and visualization in a BIM model. A prototype application has been developed that simultaneously connects the RFID readers, a database, and a BIM model. The goal of this system is to have a real-time localization accuracy of 3 meters at 95% confidence. Testing was conducted in laboratory conditions, and the results show that the system error was within the 3 meters goal.

CHAPTER 1

INTRODUCTION

The operation and maintenance (O&M) phase of a building deals with management and maintenance of the building for smooth functioning. The goal of any facility is aimed at optimizing the client and end-user operation and management, and it is shown that technology and innovation improves functionality, sustainability and flexibility of facility components (Olatunji and Sher 2009). Additionally, building systems are becoming increasingly complex, causing challenges for the management and operation of the facility (Kean 2011). Maintenance is an on-going process that runs throughout the project life cycle and requires continuous navigation throughout the facility. Facility maintenance management relies heavily on the constant monitoring of numerous items located throughout the building. The process of manual inspection proves to be time consuming as it relies distinctly on a worker searching throughout a facility for problems without precise information relating to location. Manually inspecting or locating these components causes workers to spend excessive amounts of time searching for desired equipment or materials, rather than working efficiently on the tasks required for proper maintenance. It has been shown that locating equipment in facilities is the core maintenance activity that causes significant delay in maintenance (Lee and Akin, 2009). Moreover, locating building components is critical for timely repair of the component and mitigation of the damage (Taneja et al. 2012). Through the use of context-aware (e.g. location, time, three-dimensional space based) automated systems, this process can be greatly improved to increase the performance of facilities management. Real-time access to the locations of workers, materials, and equipment has been a significant advancement to the management of construction processes. Location-aware computing offers significant potential of improving such manual processes and supporting important decision making tasks in the field (Khoury and Kamat 2009). There have been a variety of technologies (e.g., Ultra Wideband, Global Positioning System, laser scanner) utilized to produce visualizations of the locations of resources on a construction site. However, there is a lack of real-time visualization of such technologies within an indoor environment to determine a person's location inside the facility, as well as an aid for navigation. The need for such technologies in an indoor setting is crucial since research has shown that 85% of the total project cost is spent in operation and maintenance from the owner's perspective (Teicholz 2004).

One solution is the integration of emerging wireless remote sensing data with Building Information Modeling (BIM) which allows for the real-time visualization of the locations of workers, materials, and equipment. Integrated building technologies allow a convergence and integration of systems to play a greater role in overall building performance (Kean 2011). Unfortunately, little research has been conducted regarding the reliability and practical benefits of the integration. "The development of a building model holds enormous potential in saving time, reducing miscommunications and enabling Internet based building/facility management integration and interoperability, but it has not evolved to a point where it incorporates the needs of facility management" (Teicholz 2004).

Purpose and Research Objectives

The purpose of this research is to demonstrate how the integration of context-aware sensing technology and a BIM model can assist in facility maintenance management in an indoor environment. The objectives of this research include 1) developing a framework that utilizes the integration of commercially-available passive radio frequency identification (RFID) technology and a BIM model; 2) evaluating the framework for real-time resource location tracking within an indoor environment; and 3) developing an algorithm for real-time localization and visualization in a BIM model. The goal is to achieve a system accuracy within 3 meters at 95% precision, as defined by the study of Taneja et al. (2012). This means that real-time visualization display must be within 3 meters of the actual location 95% of the time. An accuracy of 3 meters is small enough to guide personnel to the general location of components or equipment in a facility, which then the personnel can distinguish the desired item. This research primarily focuses on development of the system framework and does not cover an in depth error analysis of the system accuracy.

The scope of this research is the use of passive radio frequency identification (RFID) as the sensing technology and focuses on the Operation and Maintenance (O&M) phase of the lifecycle of an office building. It is assumed that objects in the facility are already tagged with RFID tags. Ideally the objects would be tagged via supply chain management, but this approach will also extend to the additional tagging of objects already in place inside a facility. This paper only deals with passive RFID location tracking based on utilities located inside a facility. An approach will be discussed on using passive RFID tags on permanently located utilities within the facility for the localization of the user within the BIM model. The position of the reader can be visualized in real-time in the BIM model, which will aid in the determination of current location within the facility, as well as facilitating navigation

Significance of Research

The contribution of this research is the integration of commercially available passive RFID technology, indoor localization techniques, and a BIM model for effective real-time indoor location tracking and visualization, without relying on existing building or wireless infrastructure. If applied to traditional labor intensive management work tasks, the integration could play a more significant role in advancing decision making in facility maintenance management. This research can also be extended to consider fire and rescue operations because it offers the potential for developing an invaluable tool for saving lives in the event of an emergency

CHAPTER 2

BACKGROUND/LITERATURE REVIEW

In an industry where time is crucial for remaining on schedule and lowering facility management costs, manual inspection remains especially inefficient and costly. Current methods of planning and executing facility management are based on personal knowledge and experience (Akcamete et al. 2010). Additionally, current manual efforts and paper-based quality inspections involve labor-intensive methods and are shown to be unreliable, ineffective, and time consuming (Wang 2008). Figure 2.1 shows a facility management using paper-based methods to locate a desired utility, which can be time consuming and add delay in maintenance. More than half of maintenance resources and activities of an average facility are reactive maintenance, which is to wait until a utility breaks before it is serviced (Sullivan et al. 2010). The most cost effective maintenance is preventative, in which actions are performed on a time based schedule with the aim of sustaining or extending a resource's useful life through controlling degradation to an acceptable level (Sullivan et al. 2010). Therefore, there is a need for real-time automated systems for preventative maintenance management. Automated systems have the potential to eliminate manual tasks (e.g., safety/inspection documents, warranties) and provide the ability for more preventative maintenance (e.g. scheduling, maintenance histories). Moreover, integrating such systems with context-aware information provides potential for improvement in working practices, particularly with respect to productivity and safety (Anumba and Aziz 2006).

Figure 2.1: Facilities Management: facilities manager locating utility on a paper map (left); and facilities manager's cart and equipment (right)

Context-Aware Information

A context-aware system is a system that automatically recognizes its location and surroundings or provides context-aware information to locate objects. Context-aware systems have promising benefits of real-time location of users and utilities for facility maintenance management. Context-aware information includes time, location, and spatial (3D) relationships. Location sensing technology can provide location and time information and a BIM model can provide the spatial relationships. However, currently available facility management systems are not fully benefiting from the 3D visualization capabilities of BIMs and the information of topological relationships between components in order to support spatial analyses of maintenance information (Akcamete et al. 2010). Circumstances may arise where poor visibility makes detection of utilities difficult for a worker, causing problems to remain unnoticed and resources to remain inoperative. In a situation where the problem is located, additional time is lost while relaying the information to the facility manager for guidance on the necessary corrective measures that must be taken. Moreover, occupants unfamiliar with a facility may have difficultly locating themselves, as well as locating a specific room within a facility. It is also of utmost importance that the facility can be navigated quickly in the event of an emergency, because a search and rescue crew has no time to waste in getting lost when human lives are at stake. A context-aware system can provide occupants, personnel, or emergency crews with location information to navigate around and find their destinations (Li et al. 2011). Therefore, the hypothesis is that integrating real-time automated sensing technology and a BIM model would provide real time visualization that would assist in localization and navigation of a facility. Additionally, the system would provide context-aware information to help increase preventative maintenance and minimize manual tasks.

Radio Frequency Identification Technology

Radio Frequency Identification (RFID) is the wireless communication via radio waves that uses three main components in this system: a computer, an interrogator, and a tag. Figure 2.2 displays the components of the system. The interrogator (also known as a reader) continuously broadcasts a RF (radio frequency) signal through the antenna. Any tag (also known as a responder) within the RF field is an activated tag that rebroadcasts a signal along with the unique data stored on the tag. The reader then captures the signal from the tag and transfers the data to the computer where it is processed through middleware and stored in a database.

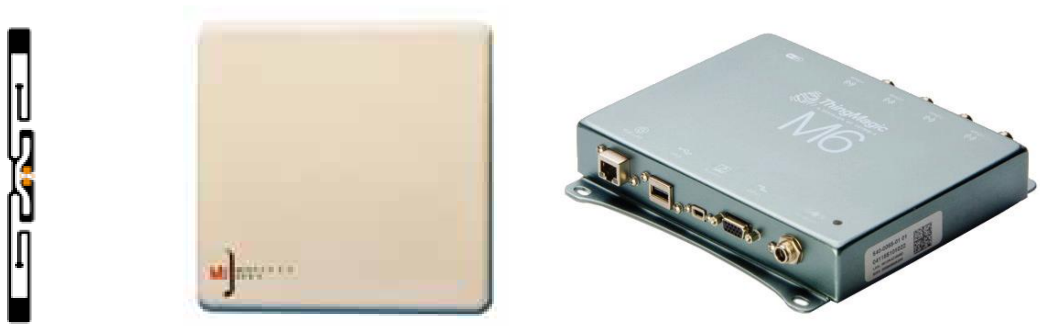


Figure 2.2: RFID System Components; Tag (left); Antenna (middle); and Reader (right)

Figure 2.3 displays a wireless RFID system, in which the interrogator has WiFi capabilities to communicate to a wireless router connected to the computer. Significantly, the tag data that the reader transfers to the computer can be utilized in many ways. A database can be used to link that data to additional data, such as information about the tagged data based on a tag's unique identification number (tag ID). Queries can be developed to make the information that has been tracked by the RFID readers easily accessible to the user, such as the facility manager. Essentially, when a tag is read all the information about that tag object can be accessed (i.e. unit name, installation date, manufacturer, safety instructions etc.).

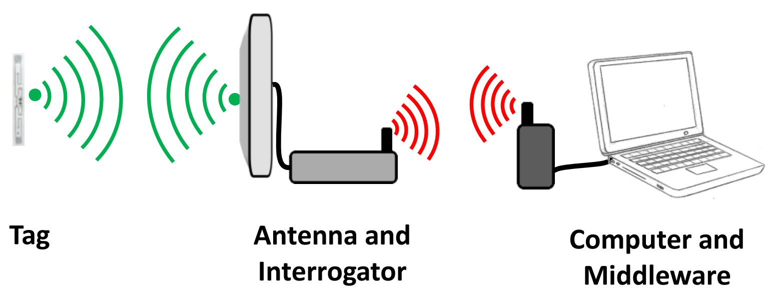


Figure 2.3: Wireless RFID system

RFID systems are classified as either active or passive. Active systems use tags that contain a battery (active tags) that enable more storage capacity and longer read ranges. Passive systems use tags without batteries (passive tags). Since passive tags do not have a battery, they harvest the RF signal from the interrogator in order to power up and send a signal. However, this limits their read range and storage capacity. RFID is similar to barcoding, but removes the human component of physically scanning each barcode. While bar code systems are limited due to line-of-sight, durability, and read-range constraints, RFID technology provides significantly greater read-ranges and works under rugged outdoor and indoor conditions, including in temperatures from -40°C to 200°C. For example, Ross et al. (2009) tested passive ultrahigh frequency tags for durability of RFID tags in various harsh conditions and found the tags were durable enough to work despite the existence of extreme moisture, pH, temperature, and pressure.

Passive RFID tags do not transmit power, but rather reflect the power back to the antenna, called incident power. In order for a passive tag to operate, the reader must supply the operating energy to the tag through the transmission of an RF wave. The output power is the energy the reader sends out. The tag then reflects the signal back (consuming some in the process). The Received Signal Strength Indicator (RSSI) is the measurement of how much power is received by the reader from the tag. The signal strength propagates and reduces when the distance between the antenna and tag is increased. The further away a tag is, the lower the RSS. The maximum RSS is the power output from the reader, and the minimum is the signal strength needed to operate the tag. Therefore, knowing the output power from the antenna and the performance characteristics of the antennas and tags, an approximation of the tag location can be made.

The Friis transmission equation (Ahson et al. 2008) is used to calculate the power received by an antenna, when transmitted from another antenna. Free-space path loss is proportional to the square of the distance between the transmitter and receiver. Additionally, path loss is also proportional to the square of the frequency of the radio signal. Tracing the power to and from the reader can provide insights into both tag detection and the RSSI. The key elements involving physical aspects of antennas are antenna gains, reflection coefficients, and polarization. However, in real world applications, other factors include the effects of impedance mismatch, misalignment of the antenna pointing, atmospheric conditions, absorption, shadowing, diffraction, and material properties. Multipath, which is the bouncing of a signal of various objects to reach the same destination, is another factor. In order to account for additional losses and multipath, the Friis transmission equation can then be derived to yield the Friis forward-link equation in Deyle et al. (2008).

$$P_{tag}^{inc} = P_{rdr} \cdot CL \cdot G_{tag} \cdot \left[\sum_{all\ paths} G_r(\theta) \cdot \left(\frac{3 \cdot 10^2}{4\pi \cdot d \cdot f} \right)^2 \right]$$

P_rdr is the power transmitted by the antenna, which can be adjusted by the user. *G_tag* is the gain of the tag, which is specified by the manufacture. *CL* is the total loss from the cables, which can be calculated by the manufacture's specification. *f* is the operation frequency and *d* is the distance measured along the RF propagation path. The gain *G_r(theta)* is a polar function of elevation angle, theta, and azimuth angle, phi, and can be determined by the two angles of the point relative to the antenna.

Building Information Modeling

Building Information Modeling (BIM) drives the traditional design approach a step ahead, adding more dimensions to the current 3D model. BIM integrates the geometric and parametric properties of the 3D model of a building with all the information and properties of that building, such as product information, site schedule sequencing, and owner histories. Paired with sensing technologies, the BIM model can provide the spatial relationships needed for context-aware information. In addition, each component of the model, their relationship with other objects in the model and logical classification of objects in the model, are stored directly within the model. By the use of BIM, an accurate virtual digital model of a project is constructed and it has been found to be one of the most promising advancement in the Architecture, Engineering and Construction (AEC) industry (Eastman et al., 2008). Integration of all the aspects on the projects like structural, architectural, mechanical and electrical plumbing (MEP), energy etc. into the same platform has enabled a new era of collaboration for better design and optimized performance. These benefits have led to a dramatic increase in the use of BIM over the years, in which 71% of construction companies, 70% of architects, and 74% of contractors are using BIM, and the use is expected to keep increasing (McGraw-Hill 2012).

Few studies have been conducted involving the integration of RFID and BIM. A study by Xie et al. (2010) focused on using GPS and RFID for tagging steel components and using the same unique tag for each component throughout the BIM model in the project. Updating the status in the BIM model would automatically keep track of the components from delivery to installation. RFID technology has also been utilized by successfully pairing with Building Information Modeling (BIM) for supply chain management (Sawyer 2008). An integration of RFID and BIM has been proposed for life cycle information management of open-buildings (Cheng and Chang, 2011), where the integration in planning and design, manufacturing, construction and maintenance, as well as recycle and reuse is discussed. A pilot study has been performed using RFID for facility management based on a BIM database (Meadati et al., 2010). However, research focusing on using a BIM model for facility maintenance management with real-time indoor localization and visualization has been lacking.

Facility Maintenance Management

Facility management requires a robust database linked to the visualization environment for identifying the items within. Currently, BIM has been used as a digital copy of the facility which is independent of the actual facility. Becerik-Gerber et al. (2012) researched the integration of BIM with facilities management. The findings conclude that BIM holds a promise for creating value for owners and facilities management organizations in various applications, including locating components, facilitating real-time data access, checking maintainability, and automatically creating digital assets. Real-time correspondence of the model with an actual facility has not been studied. Hence, BIM appears to create a promising platform if equipped with sensing technology which can facilitate real-time update of the facility.

RFID plays a major role in facilities management, such as in security, inventory, construction site delivery logistics and materials tracking, document tracking, product life cycle tracking, and building energy controls (Jaselskis and Misalami 2003, Wing 2006). Automating the tagging and tracking assets using RFID can increase the value of facility management (McAndrew et al. 2005). RFID tags are able to read multiple tags simultaneously and uniquely recognize facility items, store information regarding maintenance history of these items, and continuously update the information in real-time (Ergen 2007a). Between active and passive RFID, passive tags are shown to be the most suitable for an indoor application of tracking workers, materials, and equipment due to their small size, low cost, and low maintenance requirements (Costin et al. 2012b). Passive tags also hold potential benefits for the operation and maintenance phase of a facility. First, passive tags are inexpensive ($0.10 each) and can essentially last forever. Moreover, a facility can potentially have hundreds or thousands of tag objects, adding unnecessary costs. Although the passive tags have a significant smaller read range than an active tag, it is not necessarily beneficial to have a long read range. Having a long read range means more tags will be read at a certain time, potentially causing data overloads (Costin et al. 2012a). Missed reads (false positives) due to a high volume of tags can also result. One limitation to passive tags is the fact that they are easily obstructed by objects. In this case, active or semi-active tags could be used.

Passive tags require nonvolatile memories that retain the values stored even when the device is not powered, which is typically less than 200 bytes (Ahson et al. 2008). This means that any additional information about the tagged object (e.g. product name, maintenance history, warranty) must be stored in a separate database. There are also benefits to having data not directly stored on the tag. First, the more data the tag has, the more power it requires to send back, ultimately reducing the read range. Without the data being backed up in a database, all data would be lost in the event the tag is damaged, lost, or destroyed. Having the data stored in the database allows for the programming of an additional tag with the same unique ID in order to link it with the data. Not storing the data in the tag is also desirable for security reasons. Bhaskar (2007) explains potential security concerns with RFID and the data store on the tags, including tag cloning, tag data corruption, data theft, and illicit tracking and data mining. Fortunately, there are several security measures and techniques (e.g. encryptions, protocols) that are used to prevent security breaches. Finally, the database can hold substantially more data over the lifetime of the tagged object than on the tag itself. Moreover, if the tag were to be destroyed, the data stored on it would be lost.

Indoor Localization

Indoor localization refers to locating an object or person in an indoor environment by the use of context-aware information. While the Global Positioning System (GPS) has become synonymous with outdoor location tracking and navigation, there have been attempts with various sensing technologies for localization in an indoor environment. Sensors of different types have been tested and proven in the outdoor construction industry. GPS technology, which uses multiple satellites to triangulate position, provides context-aware information and does not require any pre-installed infrastructure for location determination (Behzadan 2008). Similarly, Ultra Wideband (UWB), a wireless radio frequency based on a real-time locating system (RTLS), also provides context-aware information that can be implemented to track and determine the location of resources in a jobsite (Cheng et al. 2011). The UWB utilizes multiple readers to identify the location of tags, but it requires careful installation of these readers at known locations. And although both GPS and UWB provide high precision locations, both of these technologies possess several drawbacks for use indoors (Khoury et al. 2009). UWB and Indoor GPS both require line-of-sight between the receiver and transmitter or reference tag, respectively, and require considerable time for deployment. Moreover, GPS cannot be used in an indoor environment (Ogaja, 2011), and neither technology is able to record the timestamps which is vital for localization. Cameras and vision technology have been used in construction for project monitoring and safety (Bohn and Teizer 2010, Memarzadeh et al. 2012), but have not been integrated with BIM based facility maintenance management. Vision based technologies are not suitable for tracking objects because they do not rely on unique identification for each utility, and therefore cannot distinguish between similar objects.

Liu et al. (2010) proposed an indoor localization and visualization environment using 2D laser scanner and inertial measurement units (IMU). A human-operated backpack system and image based rendering was used to process location. Bernoulli et al. (2010) also utilizes an IMU and an algorithm to map indoor travel to a simple computer aided design (CAD) model. However, IMU-based localization suffers from drift in the sensors (Taneja et al. 2012). Additionally, these systems require large computing time and have yet to be visualized real-time in a BIM model.

Indoor localization using RFID can be used to pin-point the current position of the reader and lead the worker with the RFID reader to the correct utility (Pradhan et al. 2009). An approach to localization using an array of passive RFID tags placed on the floor of an experimental testbed has been implemented by Park et al. (2009) for indoor mobile robot movement. Signal strength control was used for improving performance of position estimation. However, many problems resulted in high error when using RFID's received signal strength (RSSI) alone. The RSSI values do not correspond to physical positions and can change with various environmental conditions (Choi et al. 2009, Fink and Beikirch 2011, Wang 2011). Since RFID technology, alone, cannot pinpoint a location, the technology requires additional algorithms or particle filters to estimate the location. A Simultaneous Localization and Mapping (SLAM) algorithm has also been evaluated for 2D trajectory tracking using passive RFID tags (Yang et al. 2008). The work by Bekkali et al. (2007) introduced a new positioning algorithm using two mobile RFID readers and passive or active RFID tags as randomly distributed known landmarks. However, algorithms that require a large number of RSS measure samples to achieve good accuracy can be a limiting factor in processing and storage capacity. Haehnel et al. (2004) integrate indoor tag locations and laser scan data to produce accurate maps of RFID tags, which can be used for accurate localization of the robot and for moving objects without odometer information. Current techniques to determine the location of a passive RFID tag require additional labor-intensive enhancements, such as sensor histogram models or pre-mapping of tags. Therefore, to eliminate the need for these additional enhancements, Deyle et al. (2008) developed a system that utilizes a robot that houses a physical sensor model and a particle filter. The particle filter works by measuring the forward path loss from the robot. Forward path loss is the difference between the amount of RF (radio frequency) power transmitted by reader and the actual amount of power reaching the tag. The particle filter also utilizes direct-path and multi-path RF propagation models, which are integrated into the filter by low variance resampling that predicts the far-field read range. Bouet et al. (2008) surveys the current state-of-art of RFID localization techniques and concludes that the choice of technique and RFID technology significantly affects the granularity and accuracy of the location information but also the whole cost and the efficiency of the RFID system. Therefore, the best suited indoor localization technique depends on the final application.

RFID technology is shown to be effective in applications for emergency response and search and rescue (Ergen et al. 2011). Chen et al. (2012) use RFID tags for building assessment in the context of disaster occurrences and show that the tags allow an economic and effective way to store and track geographically distributed information relevant to urban search and rescue (US&R). Rüppel and Stübbe (2008) proposed an indoor navigation system that utilizes RFID, ultra-wide-band (UWB) and a wireless local area network (WLAN) for emergency response and recovery. However, testing has not been conducted to evaluate the accuracy and reliability of the system. Unfortunately, the previous systems rely heavily on the infrastructure of a facility, such as power or network connections. This presents a problem in the event of an emergency, which may result in a power outage or network failure. If the infrastructure goes down, so does the technology relying on it. Therefore, there is a need for a self-sufficient technology that does not require continuously running technological infrastructure directly from the facility. Radio Identification (RFID) technology offers a solution because it can be self-reliant. Passive tags do not require power to activate them and a mobile reader can be battery powered (Costin et al. 2012b). Additionally, prior knowledge of the layout of a facility can improve the performance of RFID localization (Taneja et al. 2012). Therefore, integrating a BIM model with RFID technology would assist in localization and navigation of a facility even in a power outage.

CHAPTER 3

METHODOLOGY

Technology and Software Framework

The framework presented in this chapter allows for the use of any commercial BIM software and RFID technology. Tekla Structures 19 was selected as the BIM platform and Trimble ThingMagic for the RFID technology. The first step was to integrate RFID and BIM by means of the application programming interface (API) of the software/hardware components. Therefore, a prototype software application was developed in Visual C# 2010 to connect the ThingMagic API, and Tekla API, with MS Access database (Figure 3.1). This application links communication between the RFID equipment, BIM model, and resource database. The software allows for the following RFID reader data to be acquired: RFID tag ID, read frequencies, timestamp of read, received signal strength and link quality indicator, and antenna number.

The application also runs the algorithms and displays the user interface and real-time visualization. In addition to storing all the geometric information (the standard 3D model), a BIM model also has the capability of storing all the attributes for each of its elements, such as part number, material type, histories, and scheduling. Although it is possible to store information about each tagged unit inside the model itself, the operation and maintenance phase of a project is very long and could be as long as 50 years. As a result, large amount of data will be needed to be stored for each element during this period (data storage and capacity is not in the scope of this paper). Hence, an additional database has been implemented instead of saving the data directly into the BIM model to avoid overwhelming the model with data. Additionally, each tagged object in the BIM model is linked to a unique RFID tag ID, which is also stored in the database. Therefore, using the database allows for efficient storage and retrieval of the maintenance data via the RFID tag reads. For instance, whenever a tag is read, the corresponding object ID in the model is retrieved from the database (along with basic information about that object) and is displayed on the user interface. If additional information about that object is desired, then clicking on the tag ID will query additional information from the database, such as user manuals, warranties, and safety specifications.

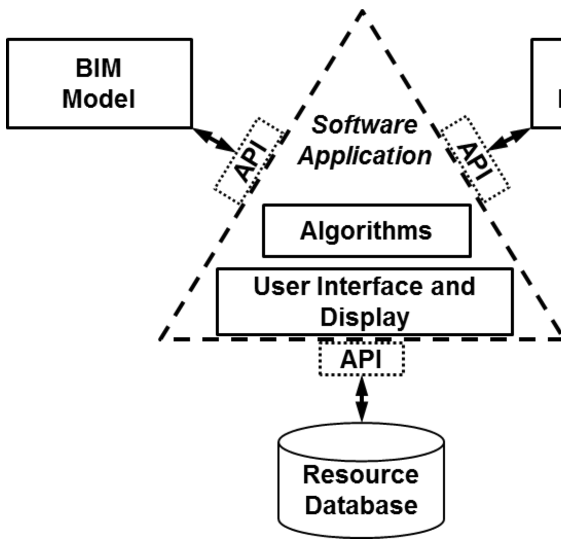


Figure 3.1: BIM and RFID Framework

Data Collection Apparatus

A prototype mobile cart (Figure 3.2) was assembled to mimic the ones used in facility management. The cart comprises of one ThingMagic M6 UHF RFID reader (Appendix A) that connects to four MTI MT-262006/TRH/A 902-928 MHz circular polarized antennas (Appendix B); top, front, and two sides. A wireless router, battery, and laptop computer are also on the cart. The design of the cart and placement of the antennas were determined based on experimental data to get the greatest view of read range. The RFID tags selected were Avery Dennison AD-223 860-969 MHz passive tags (Appendix C), which are designed for use in global supply chains. Ideally, the cart would be extremely light, compact, and has room to store the facility manager's tools. The data reads were transmitted from the reader to the laptop in real-time and stored in the database.

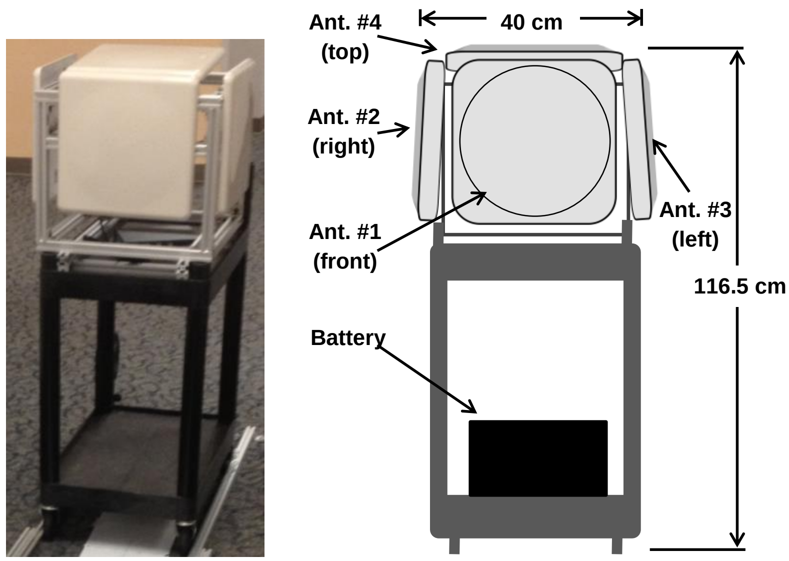


Figure 3.2: Mobile Cart (left) and Front View with Dimensions (right)

Localization and Visualization Algorithm

A major contribution of this research is the real-time display of the localization of a user (FM) in a BIM model. Figure 3.3 is a process flow diagram of the localization and visualization algorithm. The algorithm (Costin et al. 2013) works by first receiving the tag reads from the RFID readers. For each tag read at time k, the (x,y,z) location of that object is retrieved from the database. Using all the tag locations (tag ID) at time k, the algorithm computes the mean location. Supplemental information can be used for adjusting the algorithm, such as the received signal strength indicator (RSSI) and antenna of tag read. For instance, if antenna #3 reads a tag at high RSSI, the tag has high probability it will be on the left side of the cart. Additionally, if antenna #3 reads a tag with low RSSI, the tag may be further away from the cart or even result from multipath.

Finally, the adjusted calculated location is then sent to the BIM model, and the updated location is displayed on the user interface. The readers then read tags at time k+1 and the algorithm repeats.

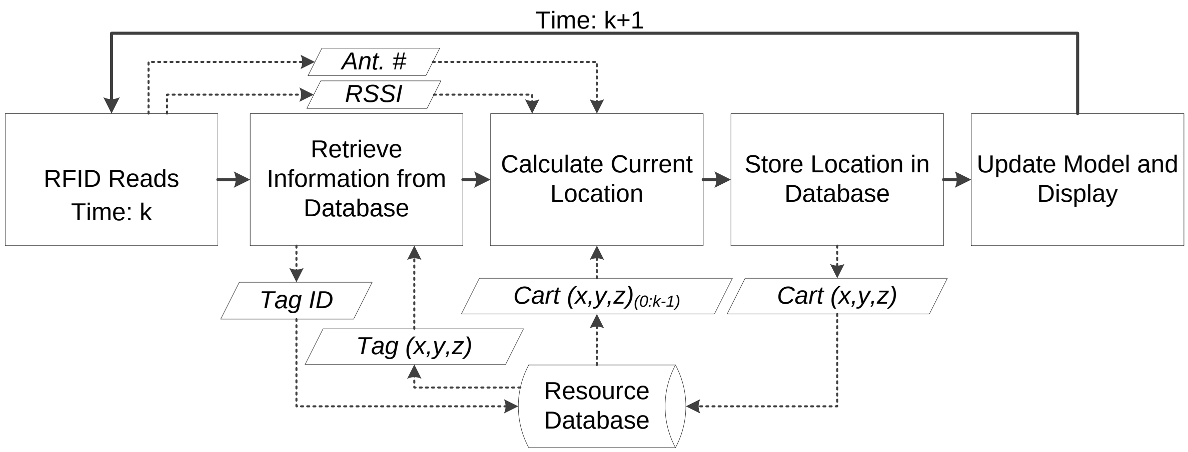


Figure 3.3: Process Flow of Localization and Visualization Algorithm

Deployment of RFID System

There are two approaches to the deployment of an RFID system. The first is when the readers are stationary (e.g., over doorways, portals) and resources that are mobile are tagged (e.g., workers, equipment, and material). This approach is generally associated with the construction phase, where all the resources (e.g., personnel, material, and equipment) are moving around the site. The second approach is when the tagged utilities are stationary (e.g., light fixtures, mechanical equipment, etc.) and the readers are mobile (e.g., cart) in order to find the current location of the readers within the building. Facility management generally deals with the second approach in order for indoor localization, and therefore is the focus of this paper. Having the location of the building's utilities and assets stored in the database sets the stage for the facilities management phase. After the completion of construction, all data and information (drawings, database, BIM model, etc.) are turned over to the owner in order to keep up with operation and maintenance of the building.

The success of this software lies with the ability to link RFID tracking technology and a BIM model for the lifecycle of a building, from pre-construction planning through the operation and maintenance (O&M) phase. The software works in two phases: (1) project management (PM) during construction and (2) facilities management after completion of construction. The PM phase uses real time visualization to track the resources (workers, tools, equipment etc.) on the job site, as well as storing the location of the building's utilities and assets (light fixtures, doors, toilets etc.) in the database. The tracking of the resources is useful in helping the project manager to optimize productivity and safety (Costin et al. 2012a). Any resource that contains an RFID tag can be read essentially anywhere on the job site (within range of the readers) and be shown in the BIM model in real-time. The facility management phase utilizes the stored tag location of the utilities in order for facilities management, including automated scheduling for maintenance, automated summary and reporting, and indoor localization.

Capabilities of the Software Application

Real-Time Feed

Knowing what resources are in facility at all times, as well as their locations, is essential for a Facility Manager (FM) to optimize safety and productivity. Resources include workers, tools, equipment, and materials used for the construction and maintenance of the building. Any tagged resources within the read range of the reader will display on the user interface. As displayed in Figure 3.4, one of these tags can then be selected for more detailed information. There is an array of additional benefits that come with knowing the approximate location of resources at all times. Real-time tracking allows an FM or observer to see which utilities are located in the vicinity of the RFID and to obtain an automated maintenance history of the utilities. It can also help in eliminating the need for manual record keeping, or at least in assisting in this labor intensive and error-prone task. Other important applications tied into automated time-clocks include site security and emergency response. Since the location of all the tags are known beforehand, by identifying misplaced or missing tags in the system, hazardous conditions can be identified and necessary measures can be taken.

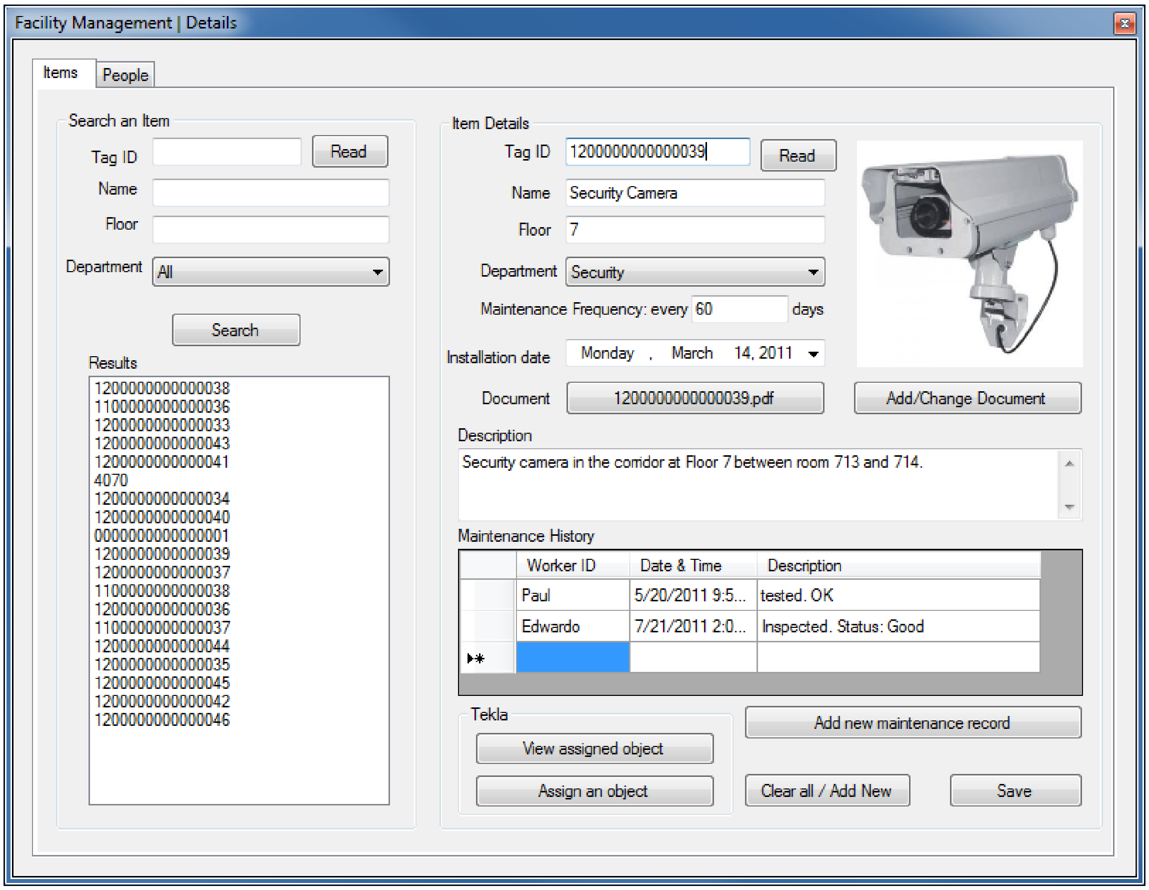


Figure 3.4: User Interface Showing Details of Selected Item

Status of Utilities

The status of the resources function allows the facility manager to automatically identify utilities that require maintenance. Every time a utility is read, its maintenance history is retrieved and if the utility has been lagging in maintenance, the FM can be notified and a maintenance request can be filed. Similarly, based on other tags in the vicinity, an oddly placed tag or missing tag can be identified and hazardous conditions can be identified.

Maintenance History and Scheduler

The maintenance history for each utility is stored in the database, along with frequency of maintenance. Whenever an item is selected, all relevant information (e.g. warranties, safety documentation, and instructions) can be accessed through the interface. Each day a report would be generated explaining what utilities need servicing along with the list of tools needed to complete the job. Then the location of the utility will be shown in the BIM model. This function automates the maintenance servicing and location, which would save time over doing it manually. Moreover, an RFID reader allows the manager to know if all the tools are there before going to the utility location. The time saved from not having a tool at the utility is also important, especially in a large facility.

Localization and Visual Display in the BIM Model

The ability to connect to a BIM model is what distinguished this approach from any ordinary RFID tagging system. Each tag is placed in a known location in the building and identified in the BIM model. Therefore, when a tag is read, an approximate location of the reader is known based on the location of the tag. This takes visualization to a new level, in which the ability to visually see where the tags are located within the BIM model creates additional capabilities. When two or more tags are read simultaneously, a triangulation method can be used to locate the location of the reader in the building. Currently the primitive approach implements a simple mean of the coordinates of the tags being read for determining the location of the reader. However, a better way would be to consider the signal strength of the RF signal and determine the location using a weighted mean based on signal strength and the coordinates of the tags.

CHAPTER 4

EXPERIMENTS & RESULTS

RFID Technology Performance

Tag Orientation

Due to the properties of radio frequency waves, the orientation of a passive tag greatly affects the amount of power absorbed and reflected back to the reader, thus affecting the read range (Ahson et al. 2008). The objective of this experiment is to determine the highest performing tag orientation. An open area with no obstacles was used to perform the test. A passive tag was attached to cardboard (to avoid interference) on a cart. The center of the tag and the center of the antenna are the same height. The cart was slowly pushed towards the reader's antenna (powered to 27 dBm) in a straight line. Once the reader indicated the tag had been read, the person pushing the cart stopped walking and marked the spot where he/she had stopped. The distance from the reader was measured and recorded. This activity was repeated six times for each of the four orientations: top (#1), right (#2), bottom (#3), and left (#4) as displayed in Figure 4.1.

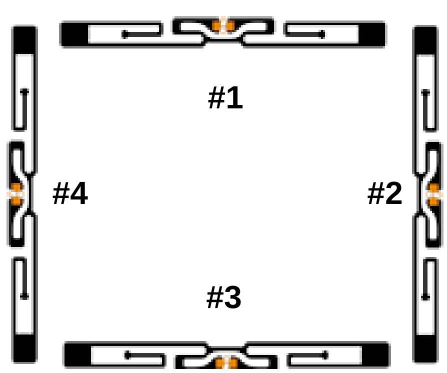


Figure 4.1: Four different RFID Tag Orientations

Table 4.1 displays the results of the experiment. Significantly, tag position #2 results in the longest average read range of 416.8 cm, and tag position #1 results in the shortest average read range of 221.0 cm. This experiment confirms that the tag orientation does affect the tag read range. The experiments and field trial for this research therefore position the tag in this manner for maximum performance.

Table 4.1: Read Range Distances (cm) with Respect to Tag Orientation

	Trial						
Tag Orientation	1	2	3	4	5	6	Average
#1	222	216	211	224	229	224	221.00
#2	406	406	418	425	430	416	416.83
#3	298	315	319	316	316	319	313.83
#4	408	372	405	408	370	402	394.17

Antenna View Angle

The objective of this experiment was to determine the antenna beamwidth, which is the angle at which the reader can no longer read a tag. This was to verify the specifications from Appendix B that states the typical beamwidth is 63 degrees. A passive tag was attached to cardboard (to avoid interference) on a cart. The center of the tag and the center of the antenna are the same height. The cart was pushed sideway and parallel to the wall (with the antenna always facing the tag). First, the reader was recording the tag and was pushed to one side. When the tag stopped reading, the distance was recorded, and the angle was calculated. Next, the reader was pushed to the other side until the tag was picked up. This was repeated for both sides numerous times. The maximum beamwidth was found to be 65 degrees, which is very close to the specifications.

Power Output and Received Signal Strength

The RSSI, alone, cannot pinpoint the location. Therefore, the accumulation of RSSI's creates a 3D probability map of tag locations. Probability maps, or radio maps, are mathematical maps of the RSSI’s for various distances and angles relative to the antenna. Therefore, an RSSI value by the reader can be matched to the maps, giving the possible locations of the tag. Moreover, each antenna has its own map, and since the view angles (beam width) overlap, the probability maps will also overlap (Figure 4.2). These maps were used with the Friis forward-link equation and the known power output resulted in the needed information to estimate the tag location.

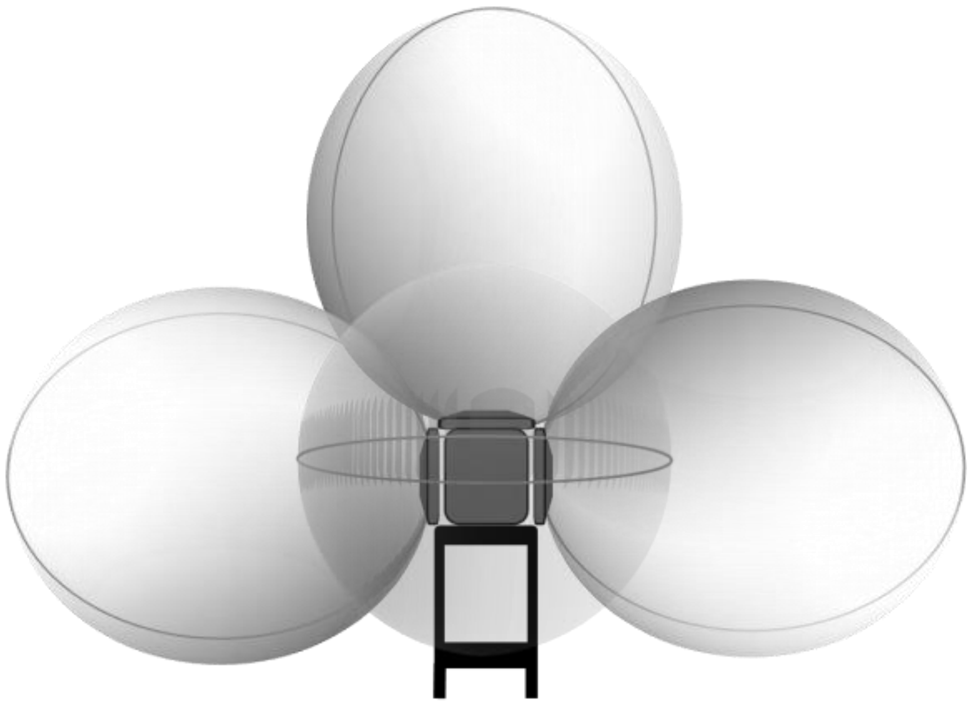


Figure 4.2: 3D RSSI Probability Map (visualization)

Most received signal strength indicator (RSSI) localization methods operate the reader at a high output power. The ThingMagic M6 UHF RFID has a maximum output power of 31.5 dBm which allows for a maximum read distance of 9 m. Additionally, the reader has a maximum tag read rate of 750 tags/second and operates at a frequency between 902-928 MHz. Using the highest allowable power results in receiving a large number of tag reads, large amounts of noise, and backscatter. For indoor applications, it may not be most efficient to have the highest power output. Reducing the power output from the transmitter limits the range of the signal, ultimately reducing the amount of backscatter and noise and improving the accuracy of the system. In this research, a power output of 27dBm was chosen, which results in a maximum read range of 430 cm.

The objective of these experiments is to compare the distance of the tag with the RSSI values to help develop RSSI probability maps. The first experiment tested the reader in a laboratory environment with the most favorable conditions (i.e. perfect pose, direct LOS, no interference). A passive tag was attached to cardboard (to avoid interference) and placed on the wall at the same height and the reader’s center. Additionally, the azimuth and elevations were kept to zero. At various marked distances, the reader took between 40 and 50 reads and recordings of the RSSI. Table 4.2 displays the maximum, minimum, and average RSSI in addition to the standard deviation. The maximum RSSI was recorded to be -36 dB m at 10 cm from the reader and the minimum was -67 at 400 cm. Figure 4.3 displays the trend line of the RSSI with respect of distance.

Table 4.2: RSSI (dBm) with Respect to Distance

Distance (cm)	Max	Min	Avg.	Stdev
10	-36	-40	-37.13	0.91
50	-45	-49	-46.66	1.42
100	-46	-50	-48.00	1.31
150	-53	-57	-54.72	1.40
200	-57	-61	-58.43	1.16
250	-57	-61	-58.17	1.30
300	-60	-66	-63.05	1.86
350	-64	-67	-65.53	1.07
400	-65	-67	-66.26	0.49

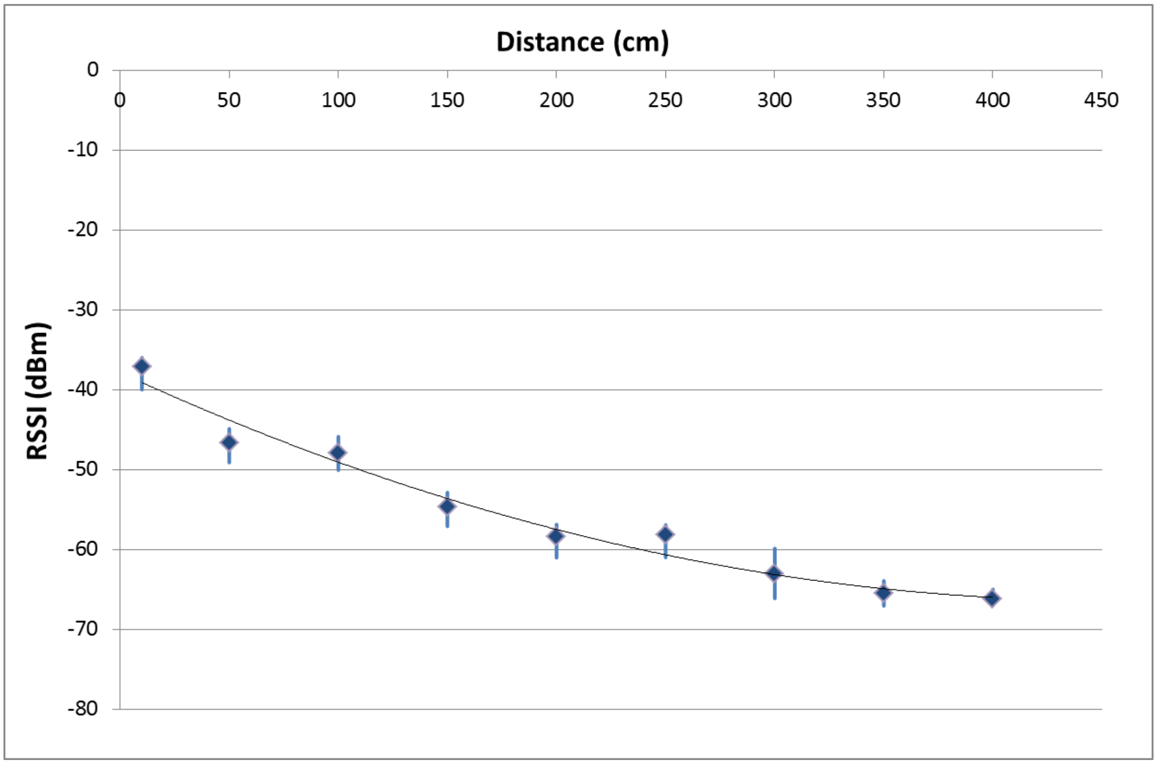


Figure 4.3: RSSI with Respect to Distance

The next experiment tested the LOS at various angles (Figure 4.4). The system was deployed in an open hallway (2.7m high by 2.4m wide). Three tags were attached (with cardboard) to two opposite side of a corridor at a height of 101 cm (keeping theta constant). The cart was pushed along a track to maintain a straight path down the center of the corridor. The cart read continuously at various marked positions. The cart was pushed in one direction, pulled back, and then repeated. The cart then reversed direction and repeated.

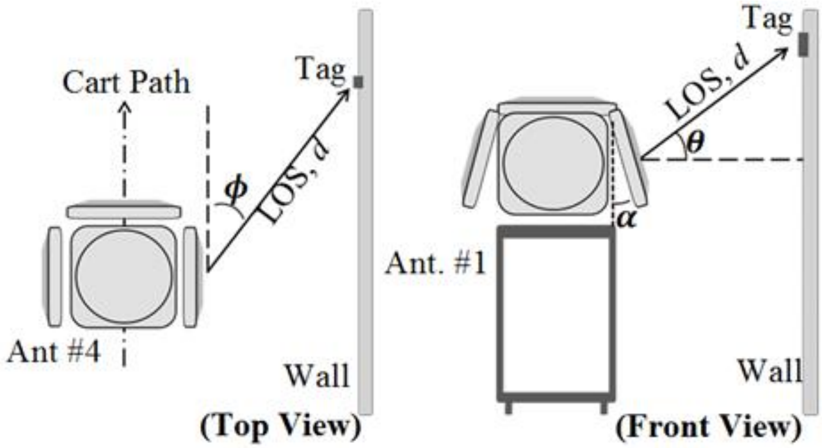


Figure 4.4: Line of Sight (LOS) of the Antennas Showing the Azimuth Angle, Phi (Left); and Elevation Angle, Theta (right)

Figure 4.5 shows how the RSSI decreases with the increase of line of sight LOS distance, d. However, having a low RSSI does not necessarily mean the tag is far away. Other factors, such as tag pose or interfere, can result in a low RSSI. For instance, an RSSI of -41 will result in a distance of around 100 cm, but an RSSI of -75 can lie within 100-200cm. Therefore, the higher the RSSI, the higher the probability that the tag is close to the reader.

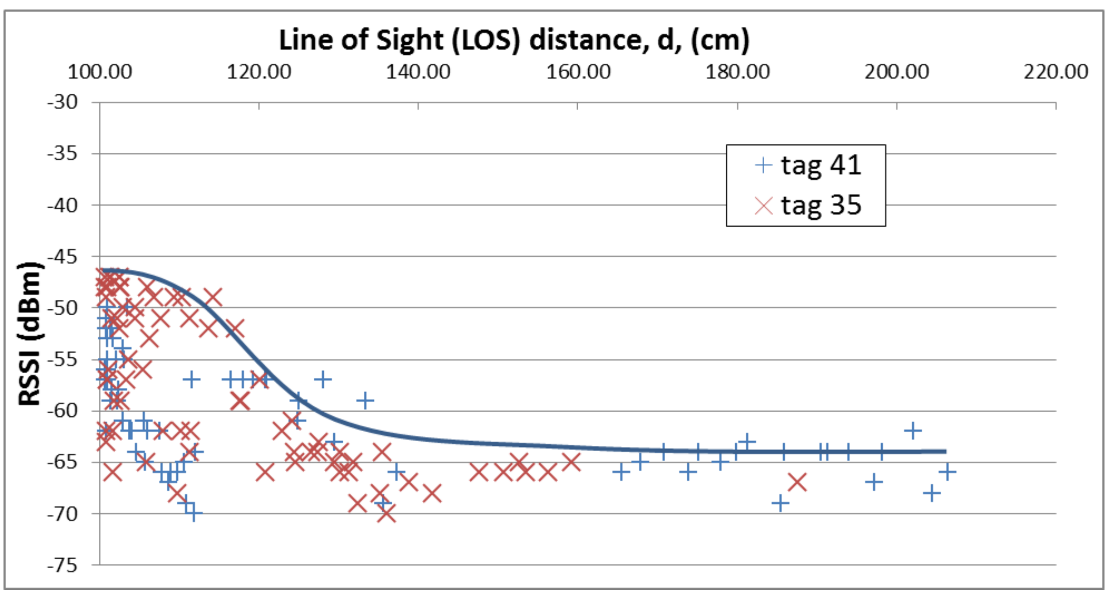


Figure 4.5: RSSI with Respect to Line of Sight Distance

Technology and Software Framework Performance

Preliminary testing was conducted to validate the accuracy and reliability of the developed RFID-BIM framework. The first part of the experiment was to show that the application can successfully link to the readers and database. Twenty unique tags were programmed to represent different utilities within a facility. Each utility is different, but similarities were made to see the application can distinguish the differences. For instance, two light bulbs are identical, except they are at different locations and have different installation dates. The first part of the experiment was to show that the application can successfully link to the readers and database. The application was deployed, and the tags were first placed one at a time to see if the correct information would be retrieved from the database and displayed properly on the screen. Once they all passed, a couple of tags at a time were placed in front to see if all their correct information would show. Finally, all tags were placed in front and all the correct information was displayed correctly.

Thereafter, the next step was to add the BIM model to the communication. In order to test the connectivity of the application with Tekla Structures, objects were assigned to each of the tags along with the (x,y,z) coordinate of the BIM object. Different trials were done storing and retrieving the objects corresponding to the tag. Again, one tag after the other was placed in front of the reader to test if the correct information was being displayed, as well as highlighting the corresponding object in the BIM model.

Visualization Display

A corridor in the Georgia Institute of Technology's Sustainable Education Building (SEB) was modeled in Tekla Structures (Figure 4.6). The cylindrical object on the left represents the position of the mobile cart in this case. It can be assumed that an FM is walking on the corridor with an RFID reader and the cylinder indicates the position of the FM at any given time. The cubes mounted on the wall represent different utilities located in the corridor (not to scale). The cubes have been made big to make it obvious for demonstration purpose. In reality, only the object ID and coordinates of the cubes will be retrieved from the Tekla model for localization purposes. For preliminary testing, the objects were generally created. However, a more elaborate model will be needed for a more accurate and reliable representation of reality. The exact locations and dimensions of the objects will be measured and supplied by the robotic total station (RTS).

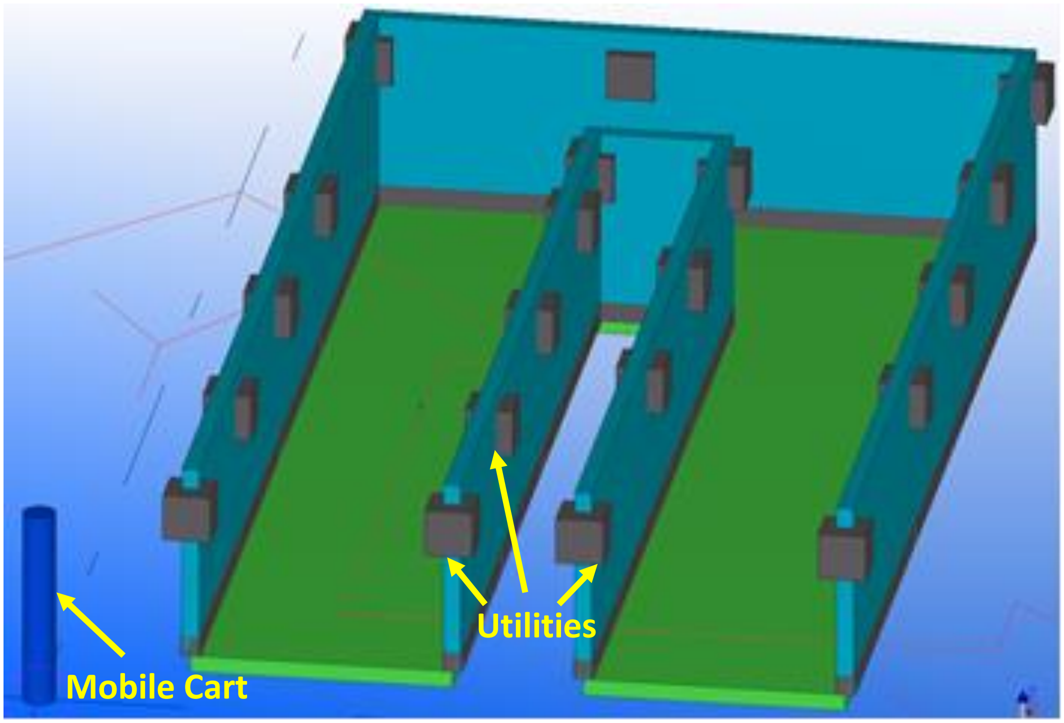
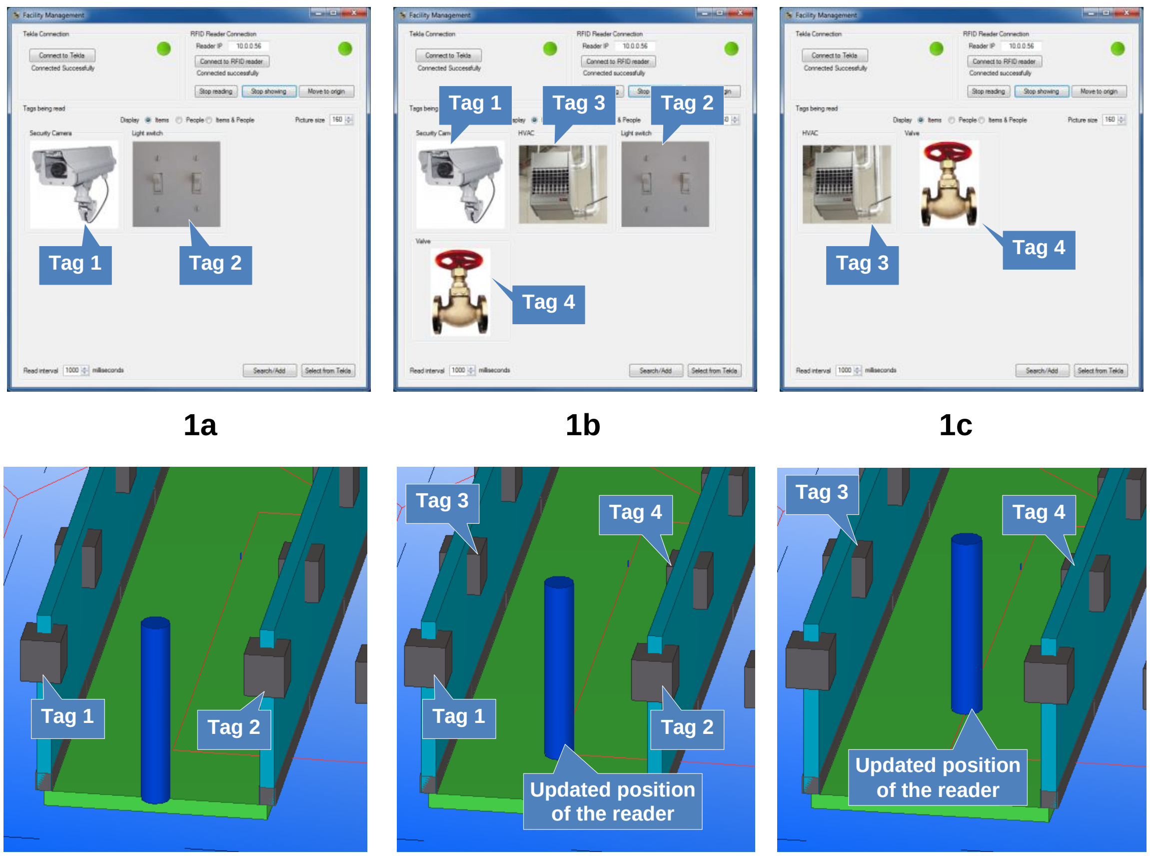


Figure 4.6: Tekla Model of Corridor and Utilities

The purpose of this testing was to validate the visualization display and localization. This preliminary testing used a triangulation algorithm to locate the mobile cart base on tag reads. In this stage of the research, the tags were not actually mounted into the utilities but, for demonstration purpose, appropriate tags were brought into the reading range of the readers and the algorithm was tested for correctness (this represents the results of the tags being localized by the algorithm).

The tags were placed in order as they would be in the corridor, simulating the path that the FM would take with the mobile cart. For instance, the cart would first approach tags 1 and 2, and then 3 and 4, and so on as it moved along the corridor. We limited the maximum cluster of tags read at once to four. Figure 4.7 provides an illustration of how the developed application can be used to determine one's location with the help of the BIM model. When tag 1 and 2 are read (Figure 4.7, 1a), both are displayed on the screen. The mean distance is calculated and placed in the correct location between the tags (Figure 4.7, 1b).



2a 2b 2c

Figure 4.7: Demonstration of Localization: (1a) Tags 1 and 2 Being Read; (2a) Localization Based on Tag Reads 1 and 2; (1b) Tags 1, 2, 3 and 4 Being Read; (2b) Localization Based on Tag Reads 1, 2, 3, and 4; (1c) Tags 3 and 4 Being Read; and (2c) Localization Based on Tag Reads 3 and 4

Field Trial

The Sustainable Education Building (SEB), located at the Georgia Institute of Technology, Atlanta, Georgia, was modeled in Tekla Structures. The purpose of the following experiment was to calculate the accuracy of the localization and visualization. Twelve unique tags were modeled at fixed (x, y, z) locations, with six tags placed on each wall (Figure 4.8). Each tag height (z) was kept at constant 1.10 m, which is the height of the center of the antennas. The height was a control variable because read angles can affect results of the RFID reads. The distance between each tag was also a control variable at 1.50 m. The corresponding tags were deployed at the identical locations in the corridor. The corridor was 2.4 m in width, and a tape measure was secured as the centerline. The rectangular box in the middle of the figure (labeled “Mobile Cart”) represents the position of the mobile cart in this case. It can be assumed that an FM is walking on the corridor with an RFID reader and the rectangular box indicates the position of the FM at any given time. The small rectangular boxes mounted on the wall represent different tagged utilities located in the corridor.

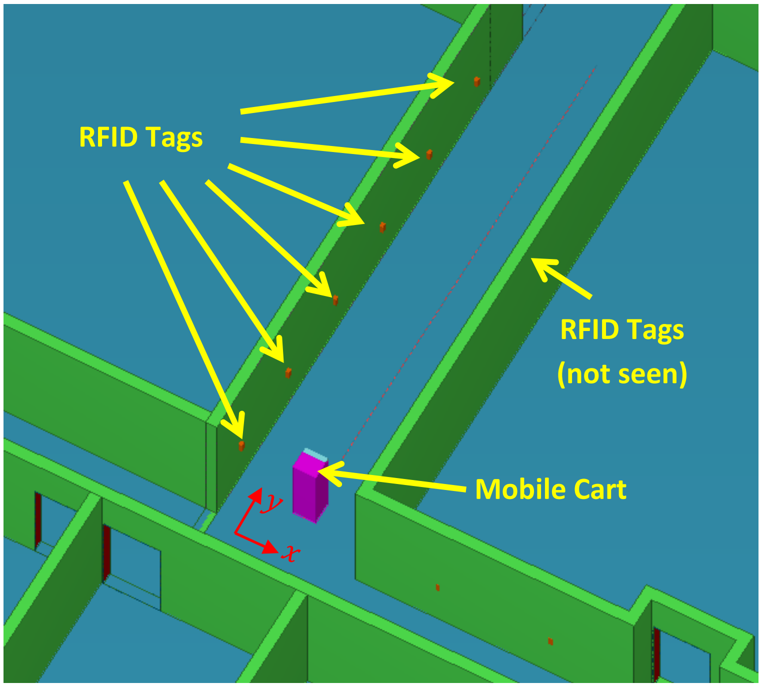


Figure 4.8: Facility Model with RFID Tags and Mobile Cart

Starting from point 0.0 meters (m), the cart took a single reading at each 0.5 m mark until the last mark at 7.5 m. The duration of the reading (read rate) was set to 1,000 milliseconds. The experiment was conducted twice with trials from 0.0 m to 7.5 m, and the cart turned around and the experiment conducted two more times, starting from 7.5 m to 0.0 m. There were a total of 64 trial recordings. The data was recorded and passed through the location algorithm. At each trial, the algorithm produces an (x,y,z) coordinate that places the cart in the BIM. The error was calculated from the coordinate produced from the algorithm and the true location at each trial. Figure 4.9 displays the visualization of localization in the BIM compared with the true position.

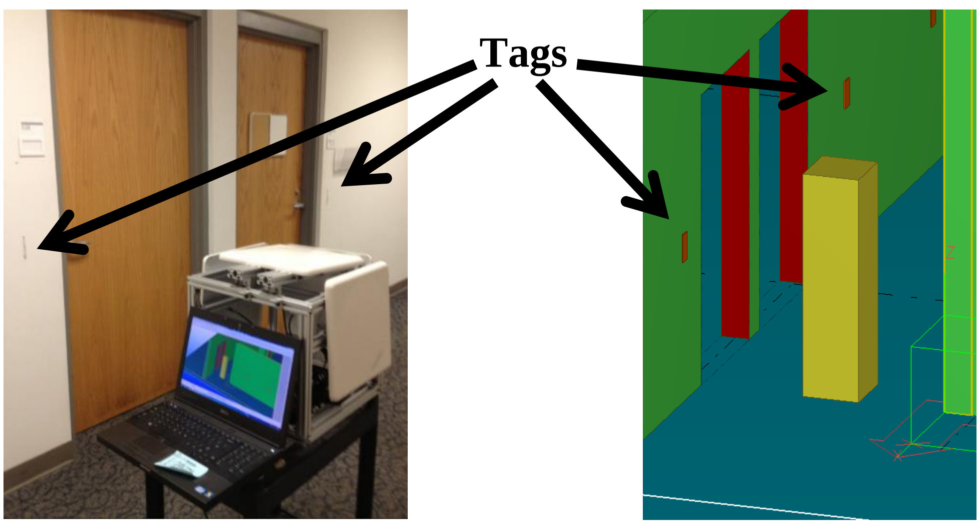


Figure 4.9: Actual location of Cart (left) and Display in BIM Model (right)

Figure 4.10 demonstrates the visualization of localization in the BIM. The walls and other objects in the model can be set to translucent to help see the cart and tags. As the user pushes the cart, the reader picks up the tags that are in the vicinity. Those tags then highlight in the model and the display is updated.

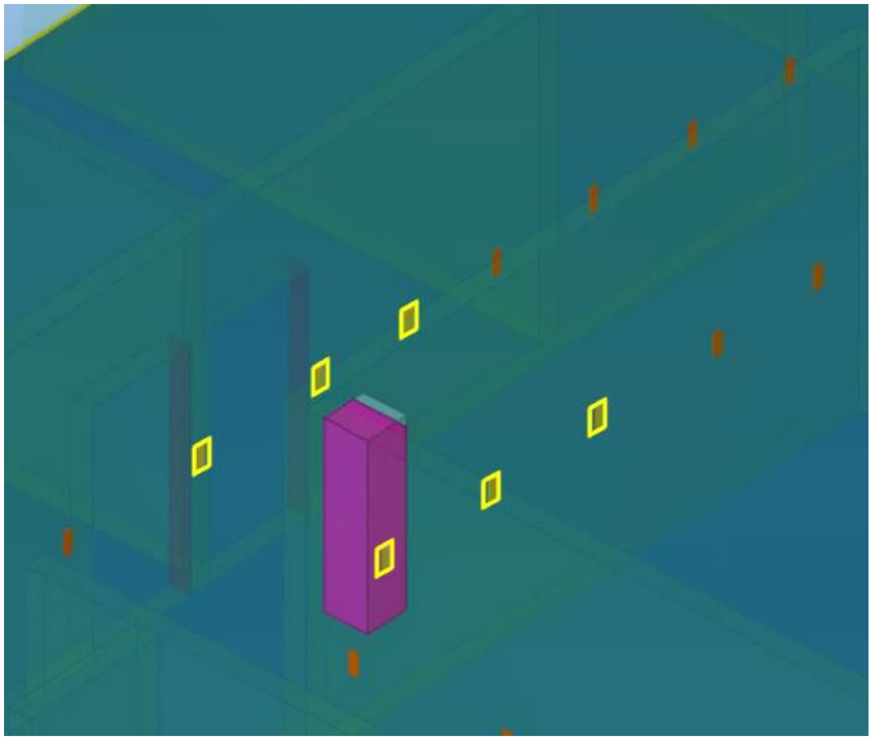


Figure 4.10: Visualization of Localization in a BIM Model with Highlighted Tags

The result of the field tests experiments are shown in Figure 4.11, a scatter plot showing the error of the estimated locations from the true locations. Error in position is calculated as a distance between the point where the cart is actually located and the location of the cart calculated by the algorithm in both the X and Y directions. The goal was to achieve an accuracy of 3 m (outer dashed circle) at 95% precision. Each “x” marks the calculated distance from the true location. The mean error for the Y direction was 0.84 m with a standard deviation of 0.72 m (solid vertical bar). The mean error for the X direction was -0.263 m with a standard deviation of 0.449 m (solid horizontal bar). Using a standard Z-test, the 95% confidence interval for the system error is 0.84 ± 1.41 m, which lies within 3 meter target.

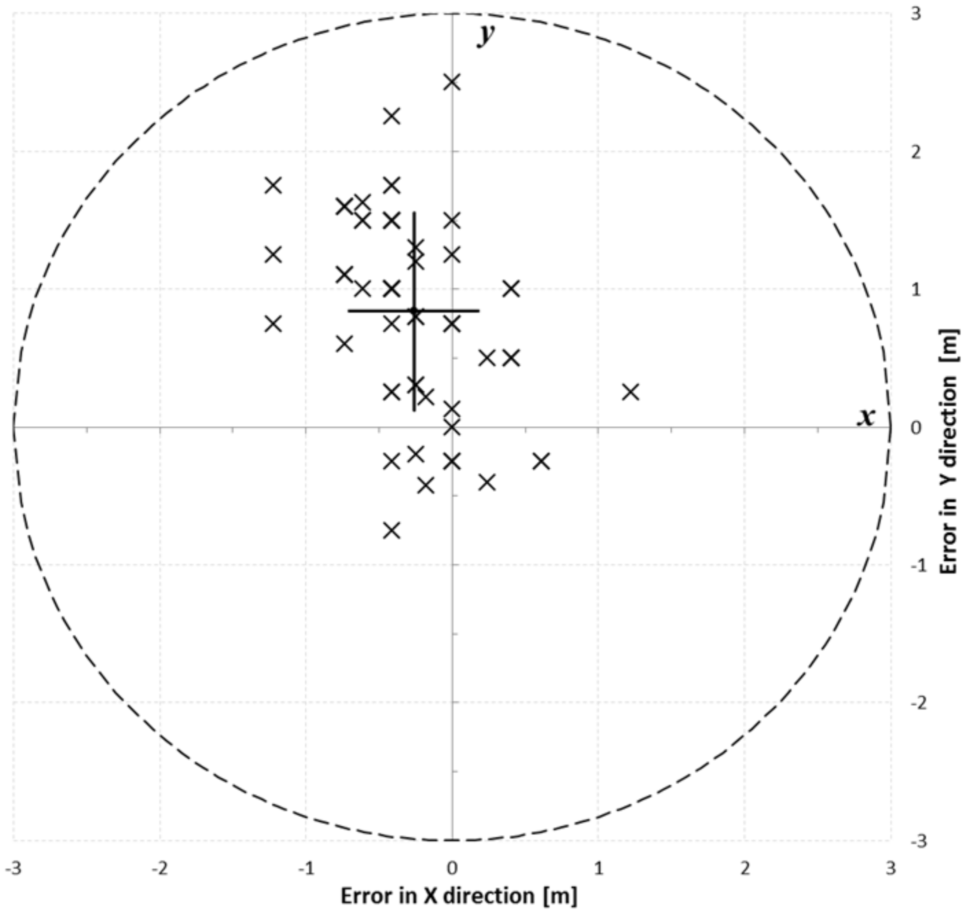


Figure 4.11: Scatter Plot of the Localization Error

The calculated path s versus the actual path s for trials one and two are displayed in Figure 4.12. The data is in the raw form, and a filter would need to be implemented to smooth the transition of points. Ideally, this filter would be implemented in the algorithm.

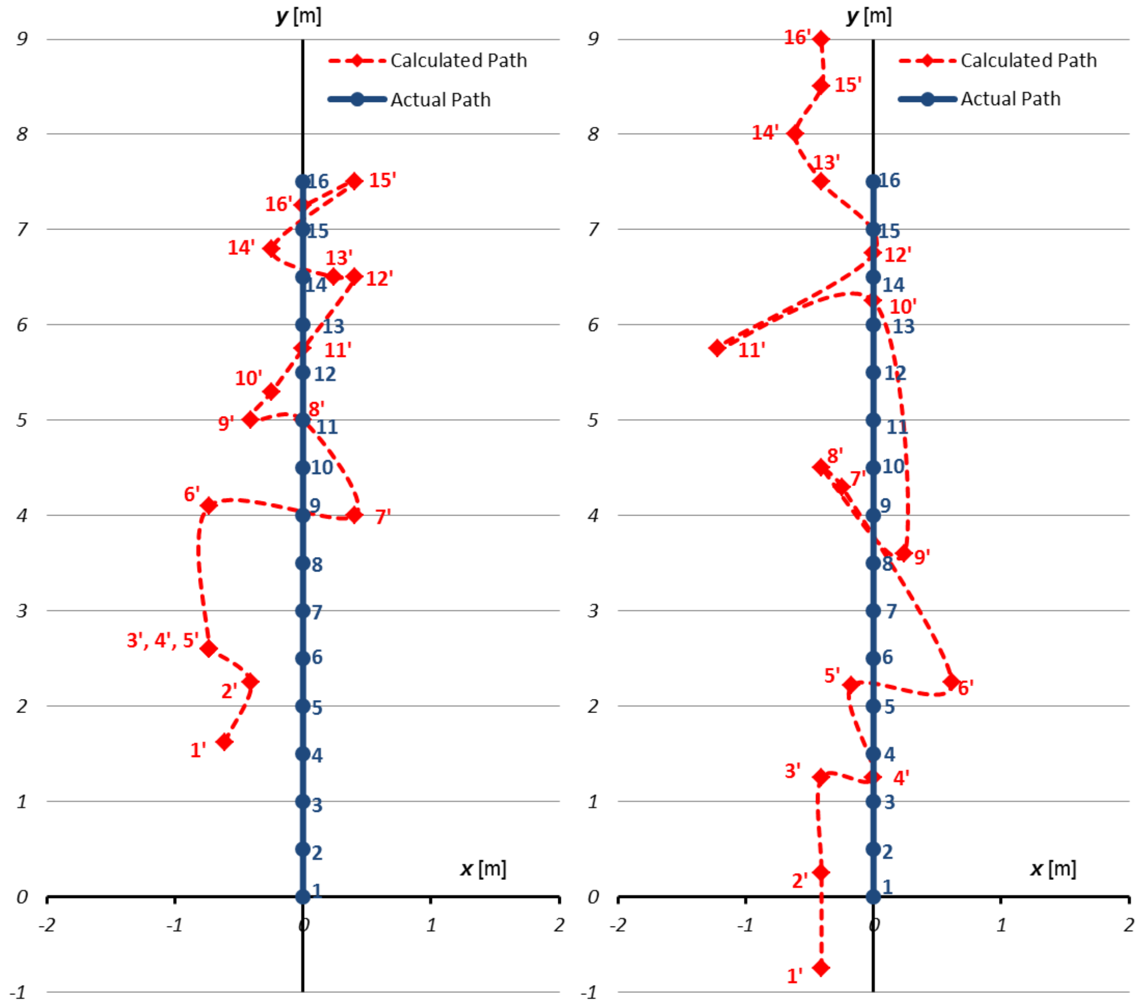


Figure 4.12: Calculated Path Versus Actual Path for Trial 1 (left) and Trial 2 (right)

CHAPTER 5

FUTURE DEVELOPEMENT

The preliminary results provided the feasibility of integrating passive RFID with the BIM for indoor settings. However, the characteristics of the passive RFID present challenges for pinpointing the true locations, such as misreads or lower RSSI than expected. Further refining is required to correct these challenges, including adjustments to the RSSI maps and the Friis forward-link equation. Adding a particle filter may help calculate the locations of the tags at a higher probability, resulting in a lower system error. More defined testing will be needed. Field implementation needs to be done with large numbers of tags, and performance of the application should be tested in real world conditions. The application still possesses huge potential to be developed and more debugging is required. The various existing indoor localization algorithms still need to be tested and compared with the current one.

A challenge to the 3 meter goal is determining what room the user is located in. The error is small enough to guide the personnel to the general area, but is also too large to guarantee the correct room. Therefore, a smaller accuracy should be achieved to address this issue. Further research is needed to take into account various environmental factors, such as corners, open rooms, or obstructions. Other considerations include the minimum number of tags required and the minimum distance between the tags.

A limitation of this research is that it assumes that there exists a BIM model of the facility. There needs to be a study to determine whether the size of the model affects the system. Future research is needed to create an algorithm that does not rely on known tag positions, for instance if the tags are not presented in the BIM model. Therefore, the algorithm can still locate the user in the building. Additionally, this would lead to research that automatically maps the tag positions into the BIM model.

With the implementation of the proposed framework presented in this paper, additional standards and best practices will need to be modified and developed to adopt the framework such as the Construction Operations Building Information Exchange (COLBie) or the National Building Information Modeling Standard (NBIMS).

CHAPTER 6

CONCLUSION

The integration of real-time location tracking data in a BIM provides many useful applications to optimize safety, security and productivity. The manual location of components can cause an FM to spend excessive amounts of time searching for desired equipment or materials, rather than working efficiently on the tasks required for proper maintenance. Additionally, navigation through an unfamiliar facility can add additional delays in finding the correct location and route to a component. Integrating passive RFID technology and a BIM model into a single application and deploying it for indoor settings could play a more significant role in advancing decision making in facility maintenance management. The integration provides valuable context-aware information that can be helpful for preventative maintenance. The data fusion between passive RFID technology and a BIM model serves to be an invaluable accomplishment that can be utilized for future research and applications.

The system will extend the use of current wireless remote sensing technologies and a BIM from being limited to design and construction phase to application throughout the project. Design and construction may take up to a few years, but operation and maintenance tasks typically span many years into the future. The system does not demand any new model but makes use of an already existing model for a much longer period of time. This will help in maintaining an up-to-date digital copy of the condition of utilities in a facility. Required data can be easily retrieved and new records can be easily inserted and maintained. Databases can be modified and the system can be made to work in the Cloud, so that the system can be monitored from any corner of the world. An automated maintenance history can be generated from the application and reporting tools can be developed and implemented so as to produce an automated maintenance schedule for all the utilities in the facility. This application can utilize the tags that were used during construction. Hence, neither a new BIM model nor new tagging system will be required. Needless to say, an automated recording and reporting system helps in avoiding the potential errors of manual entry and paper filing. Retrieving required data can require a huge effort in a paper system and moreover, manual entry can be erroneous, which is avoided with the proposed system.

This research can also be extended to consider fire and rescue operations because it offers the potential for developing an invaluable tool for saving lives in the event of an emergency. In addition to finding tagged utilities, the location of medical personnel or equipment in hospitals, police dogs trained to find explosives in a building, and evacuation routes can all be found using indoor localization. Since RFID tags do not rely on a power supply from the facility, they keep working in the event of a power outage. This may prove crucial since the rescue team can still use the tags to guide them through the facility (heat and fire resistance of tags still needs to be researched). Additionally, Passive RFID tags provide the ability to allow access to certain areas to only those with the authorized permissions, which can be determined from their tags.

APPENDIX A

M6 RFID READER SPECIFICATIONS

ThingMagic
A DIVISION OF TRIMBLE

MERCURY6

4-Port Enterprise UHF RFID Reader

The Mercury®6 (M6) is a low profile, high-performance 4-port RFID reader designed for both indoor and outdoor applications. Driven by ThingMagic's powerful Mercury6e UHF RFID reader module, the M6 Power over Ethernet (PoE) and WiFi options allow for flexible, low cost, installations. With full support for ThingMagic's enterprise-class MercuryOS software, M6 is compatible with both corporate IT infrastructures and sheltered outdoor environments.

Tag / Transponder Protocols	
RFID Protocol Support	EPCglobal Gen2 (ISO 18000-6C) with DRM ISO 18000-6B (optional)
UHF RFID Antenna Interface	
Interface	Four RP-TNC connectors
RF Power Output	Separate read and write levels, adjustable from 5 dBm to 31.5 dBm[1] (1.4W) with +/-0.5 dBm accuracy above +15 dBm
Frequency	FCC 902-928 MHz (Americas) ETSI 865.6-867.6 MHz (EU) KCC 917-920.8 MHz (Korea) TRAI 865-867 MHz (India) ACMA 920-926 MHz (Australia) IDA 920-925 MHz (Singapore)* NTC 920-925 MHz (Thailand)* NCC 922-928 MHz (Taiwan)*
Data/Control/Wireless Interfaces	
Connectors	RJ45 (10/100 Base-T Ethernet) USB Type B (console port) USB Type A (accessory port) HD15 (GPIO interface) 5.54 mm sealed connector (DC power) Reverse polarity SMA jack (optional WiFi antenna)
Wireless	Internal 802.11 b/g (optional) WEP 40-bit and 104-bit keys; WPA & WPA2 with TKIP and AES algorithms with pre-shared keys or EAP-TLS USB type A interface permits future support for external wireless technologies
Indicators, switches, and GPIOs	1 two-color LED status indicator; Reset switch; Isolated GPIOs; 4 Inputs & 4 Outputs plus +5 VDC and grounded references
Physical	
Dimensions	19 cm L x 17.8 cm W x 3.4 cm H (7.5 in L x 7.0 in W x 1.3 in H)
Weight	2 lbs (0.9 kg)
Regulatory & Safety	
Safety	IEC 60950-1 (ed.2) US-17669-UL
Other	RoHS compliant per EU directive 2002/95/EC, UL Listed (Pending)

Power	
Power Over Ethernet	Power over Ethernet 802.3af in both modes A and B (Supports 100m cable)
External DC Power	10- 30 VDC supply voltage Maximum DC power: 15 W
Environment	
Operating Temp.	-20C to +50C
Storage Temp.	-40C to +85C
Dust and water immunity	IP52
Humidity	5% to 95%, non-condensing
Architecture	
Operating System	Linux kernel version 2.6
Performance	
Max Tag Read Rate	More than 750 tags/second using high-performance settings
Max Tag Read Distance	Over 30 feet (9 m) with 6 dBi antenna (36 dBm EIRP)
Max EPC ID Length	Up to 496 bits
MercuryOS Features	
Networking	Cisco-certified DHCP & DNS-based configuration and firmware management, TCP/IP networking stack
Security	SSL/SSH-based security
Web-Based Control	Configuration and Monitoring from a web browser; HTTP/HTTPS
Application Interface	
Direct Communication	EPCglobal Low Level Reader Protocol (LLRP) v 1.1
On reader API	MercuryOS C API
Host API	Java, C, .NET

RoHS Compliant

[1] Maximum power may have to be reduced to meet regulatory limits, which specify the combined effect of the module, antenna and cable.

*Certified and available from select ThingMagic resellers.

This product includes software developed by the OpenSSL Project for use in the OpenSSL Toolkit. (http://www.openssl.org/) and cryptographic software written by Eric Young (eay@cryptsoft.com).

Specifications subject to change without notice.

ThingMagic
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Develop

Create RFID-enabled solutions
using industry-standard tools

Deploy

Enable rapid deployment and reliable
operation of RFID solutions within a wide
variety of new and existing environments

Optimize

Maximize productivity, improve ROI,
and lower operating costs

ThingMagic
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For more information, visit www.thingmagic.com

To purchase ThingMagic products, please email
sales@thingmagic.com or call 1-866-833-4069
(International callers dial +1 617-499-4090)

ThingMagic, A Division of Trimble
Four Cambridge Center
Cambridge, MA 02142

APPENDIX B

RFID ANTENNA SPECIFICATIONS

MTI WIRELESS EDGE LTD.

Antenna Data S
MT-262006/TR
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MT-262006/TRH/A

902-928 MHz, 9 dBic, Reader Antenna

Specifications

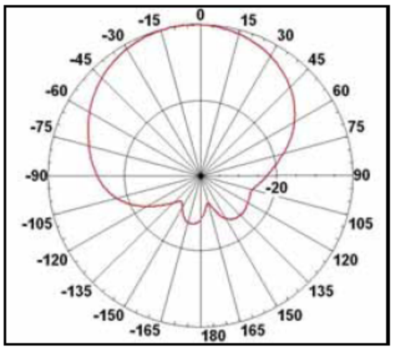
MTI PART NUMBER	MT- 262006/TRH/A
ELECTRICAL	
FREQUENCY RANGE	902-928 MHz
GAIN	9 dBic (min)
VSWR	1.3:1 (max), 1.4:1 (max) @ 10% of the range
3 dB BEAMWIDTH	63° (typ)
POLARIZATION	RHCP ** See *Other Antenna Versions* below
SIDELOBES LEVEL @ 90°	-16 dB (max)
AXIAL RATIO AT BORESIGHT	4 dB (max)
F/B RATIO	-18 dB (max) -20 dB (typ)
INPUT IMPEDANCE	50 (Ohm)
INPUT POWER	6 W (max)
LIGHTNING PROTECTION	DC Grounded
MECHANICAL	
DIMENSIONS (LxWxD)	305x305x25 mm ** See *Other Antenna Versions* below
ORIENTATION	Rectangular
WEIGHT	1.2 kg (max)
CONNECTOR	Reverse Polarity TNC ** See *Other Antenna Versions* below
RADOME	Plastic UV Resistant per ETSI 300
BASE PLATE	Aluminum with chemical conversion coating
OUTLINE DRAWING	See page 2
MOUNTING KIT	MT-120018

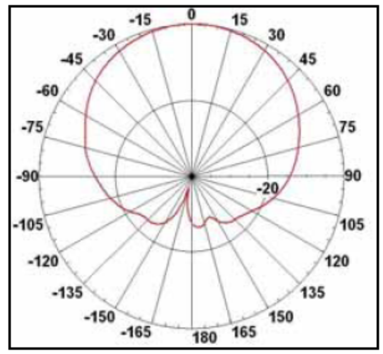
ENVIRONMENTAL

TEST	STANDARD	DURATION	TEMPERTURE	NOTES
TEMPERATURE	IEC 68-2-1/2	72 h	-55°C to +71°C	-
TEMP. CYCLING	IEC 68-2-14	1 h	-45°C to +70°C	3 Cycles
THERMAL SHOCK NON-OPER.			-30°C to +70°C	Ramp 30°C/min
HUMIDITY	ETSI EN300-2-4 T4.1E	144 h	-	95%
WATER TIGHTNESS*	IEC 529	-	-	IP54
DUST RESISTANCE*				IP54
SOLAR RADIATION	ASTM G53	1000 h	-	-
OZONE RESISTANCE	ETSI 300			
FLAMMABILITY	UL 94	-	-	Class HB
SALT SPRAY	IEC 68-2-11 Ka	500 h	-	-
ICE AND SNOW	-	-	-	25mm Radial
WIND SPEED SURVIVAL	-	-	-	220 Km/h
OPERATION	-	-	-	160 Km/h
WIND LOAD (SURV.): FRONT	-	-	-	26.8 kg
SIDE THRUST	-	-	-	2.2 kg
QUASI RANDOM VIBRATION				20g rms for 4 hours
VEHICLE VIBRATION OPERATING	1g rms, 10-500 Hz, in 3 axis	6 hours total, 2 hr in each axis. Accelerated wear - an additional 50hrs in worst case axis.		
MECHANICAL SHOCK OPERATING	10g, 11 msec, half sine pulse			

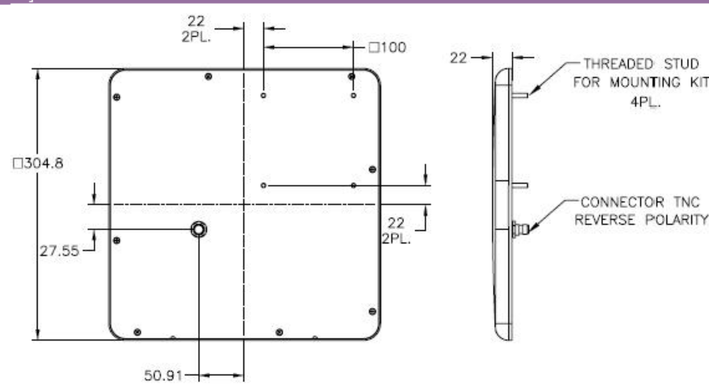
902-928 MHz, 9 dBic, Reader Antenna

Azimuth Radiation Pattern Midband Freq. 0.915 GHz	Elevation Radiation Pattern Midband Freq. 0.915 GHz





Dimensions [mm]



Existing Antenna Versions

MT-262006/NLH/A	LHCP, connector: Reverse Polarity N - type female
MT-262006/NLH	LHCP, connector: N - type female
MT-262006/NRH/A	RHCP, connector: Reverse Polarity N - type female
MT-262006/NRH	RHCP, connector: N - type female
MT-262006/TLH/A/K	LHCP, connector: Reverse Polarity TNC, IP67
MT-262006/TRH/A/K	RHCP, connector: Reverse Polarity TNC, IP67
MT-262006/NRH/B, MT-262006/NRH/D, MT-262006/NRH/F, MT-262006/NRH/G, MT-262006/TRH/D, MT-262006/TRH/G: **For more information about these models, please contact us**	
	* IP 67 AVAILABLE UPON REQUEST

MTI Wireless Edge is certified according to ISO 9001 and ISO 14001.

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APPENDIX C

PASSIVE RFID TAG SPECIFICATIONS

AD-223

AVERY DENNISON®

Print

Antenna Size:
3.741 x 0.321 in
[95 x 8.15mm]

Features:

- Best read range performance in the AD-22x family
- All-purpose transponder tuned for global supply chain application use
- Write range approaches read range
- Tight pitched high volume rolls
- Available in high yield/capacity rolls which integrate seamlessly into high-volume converting processes

Market Applications:

Electrical Characteristics	
Operating Frequency	Global (860 - 960MHz)
Integrated Circuit [IC] – Manufacturer & IC Name	Impinj Monza 3
RF Communications Protocol	ISO/IEC 18000-6C & EPCglobal Class 1 Gen 2
Memory	96 bits EPC
Environmental	
Operating Temperature	-40°F to 185°F [-40°C to 85°C]
RoHS	Designed to comply with EU Directive 2002/95/EC
Inlay Roll Format / Finishing	
Un-wind direction	Inlay-side out
Core size with adaptor insert	6 in [152 mm]
Maximum roll outer diameter [not to exceed]	12 in [305 mm]

Part Details for AD-223 (Total 3 Parts)

Part Number	**600192**
Chip	Impinj Monza 3
Antenna dimensions, [CDxMD]	3.741 in [95.03mm] x .321 [8.15mm]
Die-cut dimensions	N/A
Inlay-to-liner adhesive	N/A
Liner material	N/A
Total thickness over chip [typical]	11.5 mils [292 microns]
Standard pitch	.625 in [15.88mm]
Standard web widths	4.75 in [120.65mm]
Inlay substrate material	PET
Quality assurance	100% read tested with out-of-tolerance inlay marked
Average number of units per roll	20,000
Rev	03

Part Number	**600193**
Chip	Impinj Monza 3
Antenna dimensions, [CDxMD]	3.741 in [95.03mm] x .321 [8.15mm]
Die-cut dimensions	3.885 in [98.68] x .44 [11.18mm]
Inlay-to-liner adhesive	S-490 (Fasson®)
Liner material	40# SCK (Fasson®)
Total thickness over chip [typical]	14 mils [356 um]
Standard pitch	.625 in [15.88]
Standard web widths	4.125 in [104.78]
Inlay substrate material	
Quality assurance	100% edit and replace
Average number of units per roll	20,000
Rev	01
Part Number	**600194**
Chip	Impinj Monza 3
Antenna dimensions, [CDxMD]	3.741 in [95.03mm] x .321 [8.15mm]
Die-cut dimensions	N/A
Inlay-to-liner adhesive	N/A
Liner material	N/A
Total thickness over chip [typical]	11.5 mils [292 microns]
Standard pitch	.625 in [15.88mm]
Standard web widths	3.875 in [98.43 mm]
Inlay substrate material	PET
Quality assurance	100% read tested with out-of-tolerance inlay marked
Average number of units per roll	20,000
Rev	03

CARE AND HANDLING RFID inlays are sensitive to ESD. Observe standard practices to keep environment static charge to a minimum.

APPLICATIONS This product should be tested by the customer/user thoroughly under end use conditions to ensure the product is fit for any particular purpose or use.

WARRANTY Please refer to Avery Dennison RFID standard terms and conditions. The information contained herein is believed to be reliable but Avery Dennison makes no representation concerning the accuracy or correctness of the data.

PRODUCT CHANGES Avery Dennison RFID reserves the right to modify, change, supplement of discontinue product offerings at any time without notice.

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