RFID AND RTLS ENHANCEMENT FOR RETAINED SURGICAL INSTRUMENT IN THE BODY

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بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

In the Name of Allāh, the Most Gracious, the Most Merciful

I thank Allah Subhanahu wa ta'ala for giving me the chance to understand that He is The Incomparable, The Arrahman Arraheem. Among His uncountable creations, my knowledge is just a tiny bubble in the sea. Being obliged by Him as a human-being, however, I am in my duty to lead, do, and nurture righteous deeds for the goodness of the universe and the life hereafter (Quran Surah An-Nur: Verse 55).

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ABSTRACT

RFID AND RTLS ENHANCEMENT FOR RETAINED SURGICAL INSTRUMENT IN THE BODY

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Retained surgical items (e.g., sponges, needles, and instruments) are classified as preventable medical errors that cost the United States about $17 to $29 billion each year and the most frequently reported sentinel events in 2011 as reported by the Joint Commission. This research proposes a new approach to decrease such preventable medical errors by developing a Radio Frequency Identification-based Real Time Locating System (RTLS) for surgical operations (RfSurg). Patient safety concern, e.g. the excessive exposure of x-ray to the patient after the surgery, is a major motivation behind the need of RTLS in this research. The use of RTLS techniques in this research may eliminate the need of the x-ray procedures and improve the time needed to find the lost surgical equipment in the body. This research was performed in a non-clinical setting at the RAID Labs - RFID Laboratory, Woolf Hall Building 4th Floor of the University of Texas at Arlington. The results obtained from this research have proven that the RFID-based RTLS was able to preliminarily answer the research question of: “If the surgical equipment is detected in the patient’s body, can it be located in a timely fashion during surgery?” This research also has proven that the smaller error of localization will improve the time for the research participants to find the tag. This non-clinical study can be extended to further effort for prototyping the RTLS for surgical operations (RfSurg) with regard to its current limitations, e.g. elaborating some explanatory factors that could explain their relationship to the localization error.

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CHAPTER 1

INTRODUCTION

1.1 Problems in Healthcare Service

Medical errors have been a major source of resources waste in the healthcare service in the United States. The Institute of Medicine (IOM) estimates that medical errors cost the United States about $37.6 billion each year, about $17 to $29 billion of those costs are associated with preventable errors (MEDCEU, 2011). Medical errors rank between the fifth and eighth leading causes of American deaths, killing more Americans than breast cancer, traffic accidents or AIDS. A particular example of such medical errors is the event when there are surgical items left in the patient’s body after surgery. Specifically, preventable errors related with retained surgical items (e.g., sponges, needles, and instruments) were the most frequently reported sentinel events in a 2011 report (Joint Commission, 2012).

Retained surgical instruments during surgery may cause excessive risk to the patient’s safety, as additional surgery, unnecessary x-rays, and even death may occur while removing the retained instrument which often is the cause of expensive medical malpractice lawsuits. A study supported by the Agency for Research Healthcare and Quality (AHRQ) has estimated that as many as 1 in 1000 surgeries worldwide may result in a retained surgical instrument (Gawande, *et al.*, 2003). AHRQ is a separate subdivision of the US Department of Health and Human Services, which is also known as “sister agency” of the National Institute of Health (NIH).

This research proposes a new approach to decrease medical errors associated with retained surgical instruments in the patient’s body by developing a Radio Frequency Identification-based Real Time Locating System (RTLS) for surgical operations (RfSurg). This research is motivated by several studies intensively discussed in the AHRQ Patient Safety Network (PSNet), which show that manual surgical instruments counting is still the most practiced method in current surgical environments (Stawicki, et al., 2013; Rowlands, 2012). AHRQ Patient Safety Network (PSNet) is a national web-based resource featuring the latest news and essential resources on patient safety, funded by the Agency for Healthcare Research and Quality (AHRQ) and edited by a team at the University of California, San Francisco.

Although several research discussions supported by AHRQ PSNet have already addressed the use of automatic identification system in reducing the manual surgical counting, they are limited to only testing the presence of the surgical equipment in the body, not yet locating it to better improve the effort of reducing such medical errors (Rupp, et al, 2012; Macario, et al, 2006).

1.2 The Need of Real Time Localization System in Operating Room

Indoor Real Time Locating System (indoor RTLS) is an emerging application of Radio Frequency Identification (RFID), where techniques such as satellite-based navigation are limited or not applicable due to the restriction of the in-building coverage. In an environment such as operating room (OR), indoor RTLS techniques is suitable for object localization purpose, and therefore may be employed to contribute positively to patient safety issue related with post-surgery problems known as retained surgical items in the patient's body. This research is focusing on this potential of utilizing the RTLS techniques to locate the surgical equipments, and will initially develop indoor localization models that meet the needs for reducing these retained surgical instances in the body.

RTLS in operating room is motivated primarily by patient safety concern. According to Rivera, *et al*., one of the major patient safety concerns in the operating room is the exposure of x-ray to the patient after the surgery (Rivera, *et al.*, 2008). When surgical sponge miscount is found, an x-ray of the patient in most cases is required to find the location of the surgical item. Aside from the radiation effects to the patient safety, this x-ray procedure will further cause a significant increase in the OR time. In some hospitals, the x-ray procedure in some cases is even applied to every patient after undergoing in any open cavity surgery, which demands a radiologist to be accessible after every surgery. This also causes excessive exposure of the majority of patients to radiation. Considering this situation, the use of RTLS techniques may eliminate the need of the x-ray procedures and improve the time needed to find the lost surgical equipment in the body.

1.3 Purpose of the Research

Real time localization is a process that determines the two- (x, y) or three- (x, y, z) dimensional position of a target object with respect to a coordinate system established by some fixed infrastructure. The Real Time Locating System (RTLS) approach that becomes the primary concerns in this research is RFID-based RTLS. The rationale for this is that other non RF-based localization techniques such as ultrasonic, visual, laser and infrared localization are sensitive to environmental impacts, for instance obstacles and irregular room shapes, and are limited to the Line-of-Sight (LOS) readability (Wu, 2012).

Non RFID-based RTLS such as Ultra Wideband-based RTLS is capable to yield a decimeter level positioning resolution via Line of Sight measurement and multilateration approximation (Malik, 2009). Some UWB-based algorithms may even give higher level of resolution accuracy near to 0.04 meters (Zhao, 2007). UWB-based system also have no interference with other narrow-banded wave radio transmissions in the same frequency bands due to its pulse radio transmission style (Steggles and Gschwind), 2005. However, as cited by Wu, a concern with the UWB-based system is that various regulations on this wide spectrum are permitted in different countries (Wu, 2012). This regulation variation is due by fact that the original intention of pulse-based radio technique development was originally reserved for military usage, such as for radar and satellite systems purposes. This in turn will lead to high research and development (R&D) cost and, therefore, high price for UWB chips (Wu, 2012).

Design for Six Sigma Research (DFSS-R) methodology developed by Jones is used for the overall methodology in this research (Jones, 2005). This methodology has three main phases, which are “Plan”, “Predict”, and “Perform” (3 P’s).

The innovation of this research is that we propose to utilize Real Time Locating System to allow surgeons or OR registered nurses to know the estimated location of the lost surgical instrument in the patient’s body so that they can find the lost instrument in a real-time manner to the most possible degree of accuracy. The significance of this research is that it will enhance the speed of the decision-making process and the action for removal of the retained surgical instrument through better providing the information of the retained surgical equipment location in the body by utilizing technology, *i.e*. utilizing automatic identification systems such as radio frequency identification (RFID) systems. By better providing the information of the surgical equipment in the body, the task for finding the retained surgical items is hypothetically easier and faster.

The research question that we formulate for this research is: ““If the surgical equipment is detected in the patient’s body, can it be located in a timely fashion during surgery?” The overall goal of this research is to evaluate the performance of RFID-based RTLS technology in providing the location information of the surgical instruments. We hypothesize that Radio Frequency Identification (RFID)-based Real Time Locating System (RTLS) for Surgical Operations (RfSurg) will reduce the instances of retained surgical instruments inside the body by better informing the location of the surgical instances in the body for various types of human body habitus.

This research is performed in a non-clinical setting at the RAID Labs - RFID Laboratory of University of Texas at Arlington, Woolf Hall Building 4th Floor. The specific aims associated with our application objective consist of three aims:

1. Specific Aim 1**:** *To evaluate the performance of the RFID-based RTLS prototype in non-clinical setting (open air experiment).*
2. Specific Aim 2: *To evaluate the performance of the RFID-based RTLS prototype in non-clinical setting (simulated human fluid experiment).*
3. Specific Aim 3: *To evaluate the estimated time for research participants for finding in the tagged surgical instrument (time-study) in the body based on the performance of the RFID-based RTLS.*

1.4 Organization of Dissertation

This research follows the format given in the followings. Chapter I, Introduction, contains the information of national or international problems associated with the healthcare medical errors in general and problems associated with retained surgical equipment in the patient's body in operating room (OR). Chapter I also describes the purpose of the research.

Chapter II, Background, contains the literature research that describes related global research projects as well as theoretical insights from related journal papers and other resources.

Chapter III, Research Goals and Specific Aims, describes the overall research goal as well as its associated specific aims.

Chapter IV, Methodology, contains the description research approach, location and equipment used, research population, model development, as well as the conducted experiments and analysis of the research.

Chapter V, Results, contains data inputted by experiment (spreadsheet), statistical output (descriptive and comparative), evaluation of output, and summary of all experiments.

Chapter VI, Conclusion, contains the executive summary of the research, Description of summary of all experiments including narrative on interesting specific experiments, and recommendations for future research.

CHAPTER 2

BACKGROUND

2.1 Historical Background of the Research

This research was performed with some historical background on Real-Time Locating System studies proposed by the Director of the RAID Labs of the University of Texas at Arlington who was also a former Director of Radio Frequency and Supply Chain Logistics Labs (RfSCL), Dr. Erick Jones. This research is also motivated by several studies that were supported by the US National research agency and foundation. The researches will be briefly described in the following sections.

2.1.1. RFID and RTLS Enhancement for Inventory Management and Logistics of Space Transportation Systems

The purpose of the research is to develop an automatic data capture system that will gather inventory data automatically and provide localization for lost items for use inside of Space Transportation Systems. This research was a collaboration between the University of Nebraska-Lincoln Department of Industrial and Management System Engineering along with Teledyne Brown Engineering (TBE). The objective of the research was to reduce the loss of time for Astronauts performing inventory tracking tasks and audits to look for lost items.

The proposed research was compatible with the NASA goal of efficient mission support in that it allowed astronauts to focus on research and science tasks and minimize mission schedule impacts due to non-value added tasks. The success of developing a RFID system for use onboard ISS can lead to a cost savings and allow more time to be dedicated for conducting research and assembly operations. The same concept can be applied for use in the processing facilities for ISS, shuttle, the new Crew Exploration Vehicle (CEV), the H-II Transport Vehicle (HTV), and future NASA directives. The cost savings associated with locating lost equipment easily has not yet been realized. The research contribution is the development of a single RFID RTLS IMS system that was expected to revolutionize use of automatic data capture as a means for reducing labor associated with inventory management on board ISS.

2.1.2. RFID and RTLS Enhancement for Inventory Management and Logistics of Space Transportation Systems

This proposal was submitted to NIH to evaluate the impacts of an automated system that efficiently locates surgical sponges and instruments within the body during surgery. The author's dissertation is a part of this proposal. Specifically, the author's dissertation is intended to answer the Specific Aim #1 of the submitted proposal, which is to evaluate the performance of the Radio Frequency Locating System for Surgery (RfSurg) prototype in a non-clinical setting. The submitted research proposal proposed to support the specific purpose of the FA# PA-11-198 to address current knowledge gaps regarding the understanding of health care providers’ information needs and health care decision making processes. Of particular interest is the reliability of system in its relation with data visualization that can enhance the decision making process while adequately reflecting evidence-based health care.

The research question to investigate is, “Can utilizing automated technologies improve the performance of locating surgical instruments in the body during surgery?” Our overall research goal is to evaluate the impacts of RFID technologies in human body fluids and operational settings. We hypothesize that radio frequency identification (RFID)-based real time location system (RTLS) for surgical operations (RfSurg) will reduce the instances of retained surgical instruments inside of the body associated with Gossypiboma for various types of human body habitus.

2.2 Previous Relevant Funded Researches

Several studies that were supported by Agency for Research Healthcare and Quality (AHRQ), National Science Foundation (NSF), National Institute of Nursing Research (NINR), and Department of Veteran Affairs (Veterans Affairs Quality Scholar Program) are presented in this section. These research funding agencies / foundations are nationally (USA) and globally recognized through their high-quality research programs in the field of healthcare.

2.2.1 Studies Supported by AHRQ

A study supported by AHRQ (under the Kirschstein National Research Service Award T32-HS000020 and led by Dr. Regenbogen) developed an empirically-calibrated decision-analytic model comparing standard counting against alternative strategies: universal or selective X-ray, bar-coded sponges (BCS), and radiofrequency-tagged (RF) sponges. The goal of this study was to provide quantitative estimates from which decision-makers may evaluate the various interventions that have been proposed. Through decision-analytic modeling, the authors illustrated that in order for a sponge tracking strategy to be cost-effective it must come very close to eliminating retained surgical sponge (RSS) altogether, while keeping its incremental costs quite low. From an institutional standpoint, the costs incurred from an RSS event include the direct medical costs—the average Medicare payment for admissions with retained foreign bodies exceeded $60,000—and the costs of resulting litigation—averaging $150,000 at a large malpractice insurer in Massachusetts (W. Berry MD, personal communication), but potentially much higher elsewhere in the U.S. To be *cost-saving*, when compared with these expected losses, a strategy that completely eliminated RSS would still need to cost less than $26 per operation. In this analysis, they found that universal X-ray strategies are prohibitively costly for the prevention of RSS. Even if the sensitivity of intra-operative radiographs was perfect, and surgeons could completely eliminate RSS, this achievement would come at a cost of more than $1.3 million per RSS event prevented.

Another AHRQ-funded research (U18HS11886) concluded that more less 1,500 retained surgical instrument or sponge incidents happens each year

(Gawande, *et al.*, 3003). This study found 69 percent sponges and 31 percent surgical instruments out of a total of 61 retained surgical items inside 54 patients after surgery. There were some interesting findings in the study which indentified that the prevalence of retained surgical items would be nine times higher for patients who had to go for emergency surgery and four times higher for patients who had to have unplanned changes in their procedure. Higher body mass index patients were found to be more likely to have a foreign body left after surgery. Researchers stated that there are several techniques that are capable to reduce the incidence of retained surgical items that includes the counting methods performed on surgical instruments and sponges before and after procedures and patients x-ray for the retained instruments. This study was funded the Risk Management Foundation of the Harvard Medical Institutions., One of the researcher team, Dr. Studdert, was partly funded a grant (number KO2HS11285) from the Agency for Healthcare Research and Quality.

2.2.2 Studies Supported by NSF

Two studies supported by NSF (grant numbers 0642797 and 0907993) investigated the real-time location systems in hospital contexts (Fisher and Monahan, 2012). In the studies, it was found that hospitals have been investing in real-time location systems (RTLS) to track assets, patients, and staff. The benefits of implementing RTLS have been characterized as increasing efficiency, improving safety, and reducing operational costs. This study contributes several key insights that the technological capabilities of RTLS –

though improving – continue to underperform in hospital contexts. The specific context of each hospital must be evaluated as administrators make choices about the implementation of RTLS. Specifically, in regard to:

(a) The material environment of hospitals, which can impede the effective deployment of RTLS due to the non-standardized design of buildings and the complex flow of people and equipment;

(b) The organizational cultures of hospitals, which present their problems due to (1) the territoriality of departments limiting the scope of the deployment; and (2) poor divisions of labor, surrounding the use of RTLS and the mistrust of personnel.

With important caveats detailed in the paper, their sample of hospitals indicated that asset tracking is currently the “best-use” for RTLS, and the worst results of RTLS were linked to hospital implementations that tracked patients and staff.

2.2.3 Study Supported by NINR

This research (under the contract NINR NIH HHS 1R43 NR07915-01A2) performed clinical study by detecting retained surgical sponges using a handheld RFID device (Macario, *et al.*, 2006). The research has the objective of testing the hypothesis that the wand device has a 100% read rate, a 100% specificity, and a 100% sensitivity. The design of the research was prospective, blinded, experimental clinical trial. The outcome of the research was a 100% detection of the RFID surgical sponges and which was performed within 1 minute. They also performed a questionnaire of usability to the surgeon and nurse involved in the experiment. The results obtained from the study stated that for all of the sponges, the RFID wand was able to detect the presence of the RFID tags in less than 3 seconds. There was no false-positive or false-negative indicated in this study. They concluded te RFID wand device was found to be a 100% accurate.

2.2.4 Study Supported by Department of Veteran Affairs

This study was performed under the Veterans Affairs Quality Scholar Program grant. It studied detection sensitivity of surgical sponges. The study performed a design of prospective, crossover, and observer blinded investigation. They performed the study with the subject supine, placing 4 surgical sponges sequentially behind the subject’s torso in locations that was estimated to approximate the abdominal quadrants. Among the two hundred ten of study participants, almost half (n = 101) were morbidly obese. The total readings were eight hundred forty. There was no false-positive or false-negative indicated in the study. The study found that the sensitivity and specificity of the RF sponges detection through the torsos of subjects of varying body habitus were 100%.

2.3 Previous Relevant Publications

This section presents the literature research based on the publications described in the grants previously discussed. Most of these publications are peer-reviewed journals, and the rest are publications from relevant conference papers, articles from web, magazines, comments, and white papers presented in the funded researches.

2.3.1 Current Situation Related With Retained Surgical Instances in Operating Room

Numerous technical terms have been applied to different types of retained surgical objects. For retained sponges and towels, frequently used terms include S*oft Tissue Textiloma* (Mouhsine, et al., 2005), G*ossypiboma* (Tajyildiz and Aldemir, 2004), and M*uslinoma*.(Ribalta, et al., 2004) There are no specialized medical terms for retained surgical instruments and needles.

“Retained surgical instances” or “retained surgical items” is defined by Gibbs in an AHRQ publication as any item inadvertently left behind in a patient’s body in the course of surgery (Gibbs, 2009). AORN classification of surgical items and placed them into four groups; soft goods/sponges, needles, instruments and miscellaneous small items (NoThing Left Behind, 2013). Example of a retained surgical instance known as surgical sponge, Textiloma or Gossypiboma is presented in the following Figure 2.1.

Presentation of Gossypiboma is either acute or delayed, with acute symptoms resulting in abscess or granuloma and delayed symptoms resulting typically in adhesion formation and encapsulation, resulting in a subacute intestinal obstruction months or even years after the initial operation (Zbar, et al., 1998). In some extreme cases, complications have been observed including perforation of the bowel, sepsis, and, in very rare instances, death (Gawandee, et al., 2003).

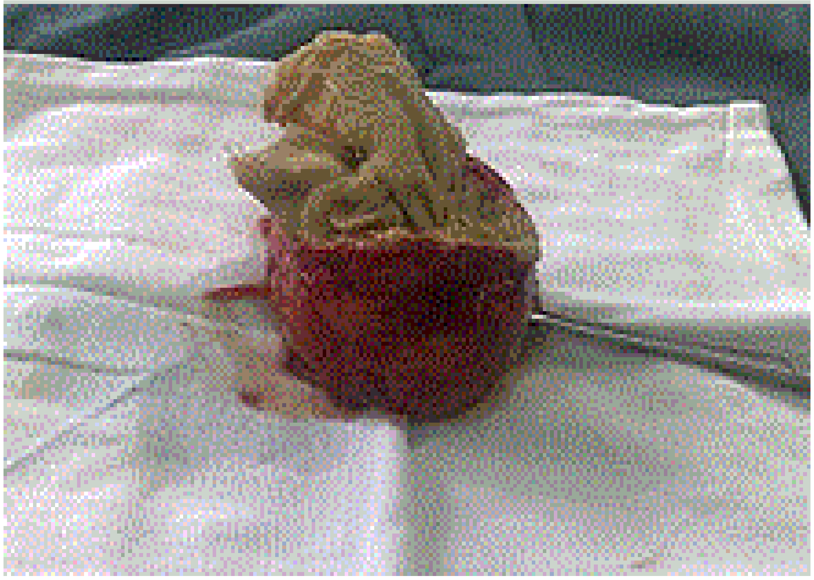

Figure 2.1 Surgical Sponge (Gossypiboma) (Source of Image: Wikipedia)

Several studies that intensively discussed in the AHRQ Patient Safety Network (PSNet) describes that manual surgical instrument counting is still the most practiced method in current surgical environments (Stawicki, et al., 2013; Rowlands, 2012). Although this method is still widely adopted, the majority of hospitals that utilize this counting method for retained surgical items in the body have no standard regarding the method.

Steelman and Cullen, two researchers that were supported by the Veterans Affairs Quality Scholar Program in their research project stated in a journal article that current standards rely on manual counting show that the accuracy of counting may be not accountable, as yet little is known about why counting fails to prevent retained sponges (Cullen and Steelman, 2011). In many cases, the count procedure is defined by the individual hospital and is frequently omitted in cases of emergency or transvaginal surgery or for vaginal deliveries (Christian, et.al., 2006). Any number of factors can contribute to this possibility, including but not limited to surgical packs used during fascial closure, hurried counts at the end of long operations (Zbar, et.al., 1998), emergency surgeries, or surgeries where complications arise over the course of the proceedings (Kaiser, et.al., 1996).

Rivera, et al. stated that: “Human error is not the only drawback of manual counting. During sponge counting, nurses are unable to provide support for the surgeon as they are focused on accurately counting sponges” (Rivera, et al., 2008). Further, they stated that each sponge count takes a couple of minutes, with at least three counts per surgical procedure. They argued that under these manual counting procedures, the nurse is inevitably distracted from her primary role for a significant part of the time. When a miscount is found, an x-ray of the patient in most cases is required. This x-ray procedure will further cause a significant increase in the OR time. In some hospitals, the x-ray procedure in some cases is even applied to every patient after undergoing in any open cavity surgery, which demands a radiologist to be accessible after every surgery. This also causes excessive exposure of the majority of patients to radiation.

The argument above is coupled by the findings from the research by Stawicki, et al., which found that longer duration of surgery, safety variances, and incorrect counts during the procedure result in elevated Retained Surgical Items (RSI) risk (Stawicki, et al., 2013). Their findings highlight the need for zero tolerance for safety omissions, continued study and development of novel approaches to RSI reduction, and establishing anonymous RSI reporting systems to better track both the incidence and risks associated with RSI, which has yet to be solved.

Steelman and Cullen also suggested that most of the failures in manual counting are not likely to be affected by an educational intervention (Steelman and Cullen, 2011). According to them, the most frequently identified causes of failures included distraction, multitasking, not following procedure, and time pressure. Therefore, they agreed with the arguments from the researchers mentioned above by stating that additional technological controls should be considered in efforts to improve safety.

2.3.2 Automated Identification Technologies (AIT) in Healthcare

Automated Identification Technologies (AIT) have become common place in access control and security applications, in industries requiring the tracking of products through the supply chain or manufacturing process, and in industries requiring the identification of products at the point of sale or point of service (Agarwal, 2001). Two prominent AITs are discussed in the following.

Barcode scanning is the oldest machine-readable identification system and has been widely used in industrial manufacturing, shipping, and inventory control (Rappoport. A,1984). Barcode is an array of parallel, narrow, rectangular bars and spaces that represent a group of characters in a particular pattern. A reader scans the barcode, decodes it, and transfers data to a host computer. The use of bar-code medication administration (BCMA) systems to improve patient safety has been recommended by many organizations, including the Institute of Medicine, the National Patient Safety Foundation, the American Society of Health-System Pharmacists, and the National Alliance for Health Information Technology (Patterson, 2004). FDA’s barcode rule is the first step in facilitating the implementation of bar coding systems to automate hospital pharmacies and improve hospital supply chain efficiency. The applications of AIT are briefly described in Table 1.

Table 2.1 Applications of AIT in various departments of the hospital (Supply Insight Inc, 2006)

Application	Benefits	Workflow
Medical equipment /instruments 1. Real time location 2. Boundary checking	a. Reduced time to find assets 1. Responsiveness 2. Idle time - staff waiting b. Increased utilization - Lower asset investment required 1. Reduced shrinkage/lost 2. Efficiency /process synchronization	a. Automatic routing for request for equipment b. Automatic notification / alerts / Interface with actuators (i.e Locks) c. Process triggers activation/expedition) by logic of asset moves
Pharmaceuticals Inventory 1. Pedigree	a. Safety b. Faster response to critical events	Automatic acquisition/verification of product origin/history
Blood Product management	a. Safety b. Faster response to critical events	Automatic acquisition/ verification of product origin/history

Radio Frequency Identification (RFID) is defined as the process of identifying an object by means of radio frequency transmission (Jones and Silveray, 2008). Items can be tracked, identified, sorted, and detected in a wide variety of applications. RFID systems consist of two main components, the radio frequency (RF) tags (transponders), and the RF readers (transceivers). The RFID tag reader interrogates the tag for its information which is stored on a digital memory chip which contains information like location, price, color, date, and age by broadcasting a specific RF signal. The RF tags will respond to this signal by transmitting back a unique serial number or electronic product code. Figure 2.2 describes how RFID System works.

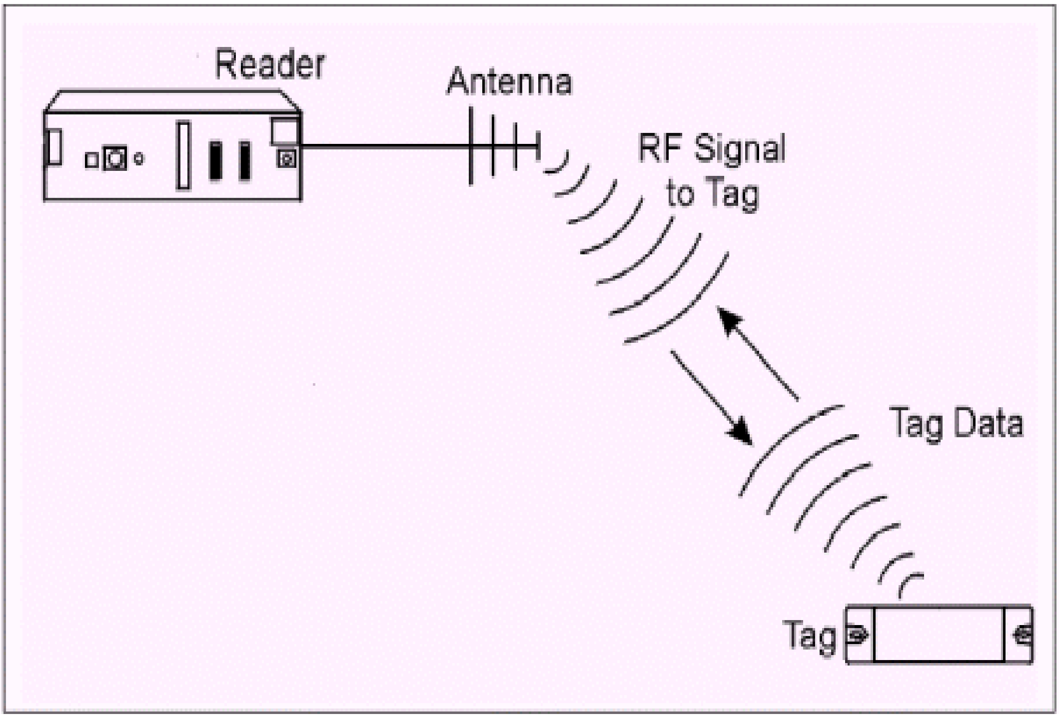

Figure 2.2 How Radio Frequency System Works

This research is also motivated by previous research conducted by the Rogers et al., which investigated the ability of inventory tagged with RFID to be detected reliably at levels greater than or equal to 99% when wet, submerged within water for up to an hour, and within the body of a pig carcass. It was shown that these levels can be met under certain conditions (Rogers, et al., 2007).

Further, this research is also motivated by the work of Cima, et al., as discussed by Steelman, which stated that the sensitivity and specificity of RFID sponge detection technology were found to be far superior to the reported accuracy of intraoperative radiography. The latter failed to identify 33% of retained surgical items that were later identified during postoperative survey imaging (Steelman, 2010). The study found that the sensitivity to detect sponges in the morbidly obese and all subjects of experiment were 100% for each of subject classifications.

This research builds upon modern automation technologies to reduce human errors in the operating room. The technologies envisioned in the system are based on radio theory which has limitations when working in hospital environments. Identifying the frequencies and power requirements that work in this environment for the performance required for reliable location of inventory inside the problem will provide scientific merit for future researchers and developers of these types of technologies. This research also provides a method that allows for “automated” and “real-time location” of inventory in time sensitive surgeries. This allows for safer outcomes for patients, reduced healthcare labor cost (excess counting nurses), and reduced healthcare claims. The students involved in the project will include engineering, nursing and medical students as a team supporting multi-disciplinary efforts.

In term of its applicability, RFID in operating room might also be potentially able to be generalized to the broad range body habitus of patients undergoing surgical procedures (Steelman, 2010). Steelman confirmed in her AHRQ-supported study that the use of RFID confirmed a result of 100% sensitivity when the RFID system is used to detect the presence of tagged sponges in the patients' body. This would be a precursor for considering RFID as a basis of RTLS in this research.

2.3.3 Radio Frequency Identification (RFID)

As has been briefly discussed in the previous section, RFID is defined as the process of identifying an object by means of radio frequency transmission. Items can be tracked, identified, sorted, and detected in a wide variety of applications only limited by a person's imagination (Jones, 2005). Although the applications of RFID include an endless amount of possibilities, there are three distinct application groups of RFID: item tagging and tracking, transfer of further data, and localization (Jones and Silveray, 2008).

RFID works via electromagnetic communication between a reader (interrogator) and a tag (transponder). A tag is attached to an object with some internal memory storage which contains information about the object, such as a serial number, manufacture date, or other information that might be important to the object. A reader emits an electromagnetic field and when a tag enters the field, it transmits back the information stored on the tag. In general, when the reader emits a radio frequency signal, any corresponding tag within range of the reader will detect the signal. Once a tag has verified the signal, it replies back to the reader indicating its presence. A second major application of RFID technology involves not only retrieving an identity from a tag, but also reading and writing data. Some products may provide instructions for operation or handling; for instance, food tags could instruct an oven the optimal cooking time or temperature. The third application, localization, is a mechanism for discovering spatial relationships between objects. Localization is accomplished by ranging, which is the process of determining the distance between objects.

Some unique advantages of RFID technologies include the following:

1. They can manage collected data through databases, some of which are portable because they are imbedded into the tag
2. They can communicate instructions to other devices. These instructions can be automatically routed and used to control other equipment.
3. They can perform reliably in harsh environments. In certain applications, RFID tags outperform other automatic data capture (auto-id) technologies such as barcodes. For instance an operation where vision is blocked because the surface has become dirty. RFID performs better than barcodes due to the fact that RFID tags do not need to be ‘seen’ to

be scanned by a reader. Also, physical contact is not required for RFID tags, which provides an advantage over magnetic strips and touch buttons.

RFID systems can be generally categorized into two types of systems; active systems and passive systems. In an active system, tags are powered by batteries and are generally more expensive. Because of the energy provided by the battery, active tags generally have more functionality than the non-battery powered tags called passive tags. Passive tags do not have batteries but make use of magnetic induction to power their transmission back to the initiating reader. Basically, the tag takes the power created by an initiating reader's energy field and reflects a signal back to the reader. This allows the tag to be manufactured at a lower cost because it does not require additional circuitry or batteries to perform effectively. Moreover, the type of tag dictates the memory capacity of the tag, which varies from 64 bytes to 32,768 bytes of memory (Jones, et al., 2010).

RFID type technologies have been in existence a significant period of time, first originating with the development of radar in the 1920s. Although this technology is not new, it has emerged into different areas of the supply chain as a process for efficient asset tracking (Jones, et al., 2010).

2.3.3.1 Types of Tags

RFID is radio-frequency identification. RFID uses tags to identify objects. An RFID tag is made up of, at the minimum, two parts. The first part of the tag if the integrated circuit. The integrated circuit, also known as IC, allows information storage and processing. The IC is also used to carry out certain functions and commands. An RFID tag also has an antenna used to transmit and receive radio-frequency signals.

There are three main types of RFID tags. The first type, the passive tag is cheap and small, but lacks extensive range. It uses the energy from radio frequency waves to power itself. The second type of tag, the semi-passive tag has a battery. The battery powers the internal functions of the tag. Like the passive tag, the semi-passive tag transmits signals using the power of radio frequency waves. The active tag typically has the greatest range. It is a self-powered device that transmits signals intermittently.

RFID tags are popular in real time locating systems. A real time locating system (RLTS) is used to track or locate people in real time. In these systems, active tags, because they have greater range than passive and semi-passive tags, are most popular – even though the other two tag types may be more secure. Plus active tags are self-powered, so they are reliable compared to the other tag varieties.

2.3.3.2 Passive Tags

While RFID tags may come with many internal components, a passive RFID tag is limited in its features. Batteries and sensors don’t come equipped on passive RFID tags. These RFID tags are called passive because they are not constantly interacting. They are passive until a signal from a reader activates them. Passive tags can only interact with one reader at a time. This is because of its unique information transmission process.

A passive tag uses a passive reader. Because of this, the passive tag can only receive incoming transmissions from active tags. In near field communication, tags communicate in very close range to each other because devices are in contact with one another. Near field communication is also known as NFC. In NFC there is always a device that initiates communication and one that is the target of communication. The device that initiates the transmission can generate enough energy from a radio frequency field to power a passive tag target.

The fact that a passive tag comes without a battery is not necessarily a disadvantage. A RFID passive tag can function for decades even without battery operations. Plus, a battery may add bulk and weight to a tag – the passive tag does not have this. But, the biggest disadvantage to the passive tag is the fact that it can only be read from a relatively short range. This means transmission must occur within the small range of the passive tag. But, with application in NFC a passive tag is certainly sufficient and may be a good option.

2.3.3.3 Semi-passive Tags

The semi-passive tag functions similarly to the passive tag. The semi-passive tag often comes with a battery and sensor. This means that the semi-passive tag has a longer range and reading distance compared to the passive tag. As the semi-passive tag has more functionality it is a more expensive option. Still, it is not a tag that transmits power. The battery functions to power the extra functions of the semi-passive tag. The semi-passive tag still functions like a passive tag in that it communicates with other devices passively. But, because it saves power it can use all the energy from the radio-frequency waves to transmit information to other readers.

2.3.3.4 Active Tags

The active tag is the most functional of all of the tags. While the semi-passive tag also has a battery, the active tag uses the battery for power. An active tag can actively transmit data. This means that according to intervals, an active tag will send out data to readers. Because of this function, an active tag is not limited in the same way a passive tag is. While a passive tag can only communicate with one reader at a time, an active tag can transmit data to many at the same time.

Active tags have the most functions of the three types of tags (passive, semi-passive, and active), plus they have the greatest range. These tags can transmit signals at wider ranges because they have access to a battery. The battery provides extra power for the active-tag, and thus the device can devote more power to transmitting data. The active tag relies on the battery to send data to a reader. It does not rely on radio-frequency waves for power.

An active tag is extremely useful in situations where signal strength is not the greatest. These tags have the capability to function in low signal strength areas. Plus, under ideal conditions, an active tag can transmit data to range of one hundred meters or more. It makes sense that an active tag, because of its distinct advantages in power and transmission, would cost more than a passive tag. Whereas a passive tag is not going to cost more than a few dollars, an active tag can be up to $100 or more.

Active tags are very versatile. Some tags can be about as cheap as passive tags, and can be about the same size as well. Other tags can be much larger. The uses of active tags vary too. It is possible to use these types of tags to communicate over WiFi networks.

Tags that are not battery operated have very long operation lives. But, the battery operated active tag relies on a battery for power and therefore, when the battery runs out, the tag will not function anymore. An active tag can run for a few years before the battery runs out.

2.3.3.5 Readers

Tags communicate with readers. Readers are necessary devices for RFID. Readers are able to transmit data between tags using antennas to receive and send the data. It is rare to find a reader that can function with both active and passive tags. Most readers function exclusively with one type of tag or another, though there are some readers that function dually.

2.3.4 Real-Time Localization System (RTLS)

Localization for RFID is an important aspect in this proposed research. Radio enabled localization has been used for medical supply tracking, finding lost golf balls, and determining the location of hospital patients. Triangulation methods are generally implemented where distances from static reference readers are measured. The continuous monitoring of movable items using the localization techniques is referred to as a Real Time Location System (RTLS). RTLS systems are typically active systems (using battery operated tags) to detect presence and location within a 2D coordinate system (XY position only, not height) (Brchan, 2008, Brchan and Perez, 2008).

Recent RTLS systems rely on the signal strength as an indicator for distance approximation. The system works by using received signal strength indications between multiple access points throughout the tracking area. This provides accuracy indoors of 3 to 9 feet (0.91m to 2.74m). The system does not cause any interference to the existing network traffic because the tag communicates only about 60 bytes of data per location update. The tags generally require a 4-6V power source. The tags have built in accelerometers and can be configured to identify and report tag location every time it is moved. Active RFID RTLS and infrared (IR) systems generally have a read range of up to 10 meters. Some passive RFID RTLS systems have reported accuracies within 0.6 m of the actual location using advanced statistical models from data collected from multi-reader configurations.

Passive systems by definition do not need battery-powered tags and thus have lower installation, infrastructure and maintenance costs. The use of RSS ranging simplifies the RFID reader and allows a well-known organization such as NASA to leverage existing RFID reader technologies. Recent work has demonstrated the feasibility of this approach (Brchan, 2008; Brchan and Perez, 2008).

Jones and Silveray’s research conducted at NASA, described RFID based RTLS systems is a passive based system utilizing received signal strength (RSS) ranging (Jones and Silveray, 2008). This also integrates well based on the recommendations from previous NASA studies using passive Gen 2 (915MHz) RFID technologies tested previously by Dr. Jones’ research team. These studies recommended using passive RFID technologies for consumables and NASA operations have moved in this direction. The use of this same passive RFID technology for “locating” inventory was the next logical research steps in pursuing “crew-free inventories” for astronauts. This step builds upon previous research in which RFID equipment such as tags, antennas, and readers have been approved by NASA at the 915MHz frequencies.

The research in this proposed dissertation is an evaluation of these ideas, but we will be using these ideas in the medical realm. We specifically interested in using the RFID-based RTLS in the effort for automating the elimination of the retained *Gossypiboma* in the patient’s body.

2.3.5 Wireless Local Area Network (WLAN) and Wireless Sensor Network (WSN)

A WSN is a wireless sensor network, much like WSN is active RFID. The main differences between the two are that: active RFID typically runs at a lower frequency, plus RFID cannot communicate on a tag-to-tag level. WSN and active RFID rely on similar movements. So WSN and active RFID can be deployed in the nearly same way.

There is an exception to the rule that active RFID runs at a lower frequency, which emerges when the RFID is on a Wi-Fi network. When active RFID runs on Wi-Fi it is called Wi-Fi based RFID. Wi-Fi based RFID systems are capable of communicating with Wi-Fi networks. Either that or they are built into Wi-Fi systems. Plus these types of RFID systems run on a 2.4 GHz frequency. A Wi-Fi based RFID is easy to position and manage. The one problem with RFID systems on Wi-Fi is that there may be some unwanted, intersecting traffic transmitting between Wi-Fi and RFID signals. This can be fixed with better configuration.

2.3.6 Ultra Wide Band (UWB)

Ultra Wide Band, more simply known as UWB, can handle high volumes of data. UWB can manage up to one gigabit of data per second. UWB uses very short, rapid pulses, which allow this radio technique to handle a great amount of data. UWB sends out one to two giga-pulses each second and transmits these pulses over a wide spectrum of frequencies. It can handle anything from 3.1 to 10.6 GHz. Depending on the positioning and applied algorithm, localization based on a UWB system can offer great resolution, accurate at up to 4/100 of a meter.

Another advantage to UWB is the fact that communicating with pulses ensures transmission of signals that do not interfere with other radio communications in the same frequencies. There is no insurance that there will be no interference. As with some areas where there is a high volume of GPS systems there may be some interference in communication.

2.3.7 Non RF-based

There are techniques for communication besides those based on radio frequencies. These non RF-based techniques include infrared, ultrasonic, and laser localization. These techniques have long been in use, but are more vulnerable to environmental irregularities. Plus these non RF-based techniques are costlier than other techniques.

2.4 RFID-based RTLS

There are several different algorithms related to the scheme of RFID-based RTLS positioning logistics. In a typical RFID system structure, you could identify many varieties of RIFD tags. While RFID tags are a key part of the fundamentals involved in system structure, the large variety available necessitates a plethora of schemes, as well.

2.4.1 RFID-based RTLS Schemes

RFID-based localization is a cost effective solution. Sometimes classified as fixed-tag localization or fixed reader / antenna localization, the deployment is in accordance with the use of varying readers / antennas as well as the different roles of tags (Sanpechuda and Kovavisaruch, 2008). To follow a fixed-tag scheme, tags are typically deployed either on the floor or ceiling and programmed with a prescribed set of rules, whereas readers / antennas would typically be attached to mobile objects. This process works best and achieves cost effectiveness when the objects are relatively large. Tracking a smaller number of objects that typically move on a similar route makes RFID-based localization that much more cost efficient.

We will find this process used frequently with robotics or a guided vehicle (Yeh, et al., 2009; Seo, et al., 2005). Another variable is the fixed reader / antenna scheme. Here, readers / antennas and tags are placed opposite to the fixed-tag scheme deployment methodology. The tags would be attached to the items needing to be tracked while the readers / antennas are in fixed positions. This type of implementation is excellent when there are many items needing to be tracked and located. Tags are smaller, and less costly, than readers / antennas.

2.4.2 RFID-based RTLS Algorithms

The effectiveness of RF waves can be impacted by many different issues such as interference, reflection, fading, or absorbing. These issues can cause disruptions that affect the direction, strength, or distribution of RF waves. To resolve this inconsistency, multitude of positioning algorithms have been developed. Some of the more popular algorithm types are summarized here. A determination is first required as to whether or not the RF signal needs to reach a specified, or estimated, distance.

There are two steps to determining and implementing a range-based localization algorithm. The first step is to determine the elementary range results. Some methods used to determine this are Time of Arrival (TOA), Adaptive Power Multilateration (APM), Received Signal Strength Indication (RSSI), or Time Difference of Arrival (TDOA). The second step is to estimate the final position. A variety of methods are used to determine geographical calculation such as multilateration, triangulation, or trilateration.

Other methods of determining the algorithm and altogether avoiding the distance estimate step are the proximity approach or the k Nearest-Neighbor (kNN) approach. The kNN approach uses the centroid of certain neighbors, and the proximity approach uses the intersections of multiple coverage areas. These two methods rely rather significantly on the density of reader/antenna distribution or of the reference tags to improve accuracy when determine positioning in range-based localization approaches.

2.4.3 Localization Techniques Based on Range

2.4.3.1 Time of Arrival (TOA)

Time of Arrival (TOA) is a theoretical propagation model for an RF signal. The travel time between two points is measured, and thus the distance between them can be determined. The location of a tag can be ascertained by using measurements as they come in from the various antennas. To improve results and minimize errors, cycle intersections and nonlinear least-squares approaches may also be implemented. One important fact is that the velocity of the EM wave travels in a matter of mere nanoseconds within a particular room. Therefore, it is crucial that all readers and tags be synchronized precisely. Additionally, all signals must be time-stamped. Accuracy is extremely high in a TOA deployment, and with properly configured synchronization equipment the location resolution is oftentimes within 1 to 2 meters (CSL, 2011).

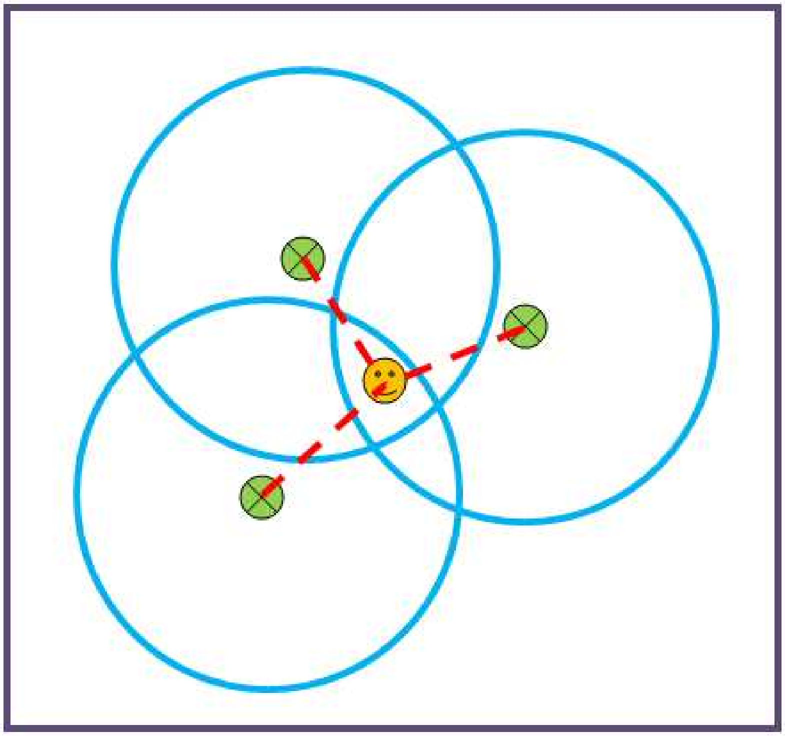

Figure 2.3 TOA Approach

2.4.3.2 Adaptive Power Multilateration (APM)

Adaptive Power Multilateration (APM) measures an estimated distance from reader to tag. This is achieved by adjusting the reader transmission power either higher or lower until the tag disappears or appears. A pre-calibrated chart is then used to translate the corresponding power level into distance. A multilateration reading of distances on all readers is then pulled to determine the exact position of the tag.

APM's accuracy is heavily dependent on two factors. The first factor is the amount of tolerance of the power circle. If the edge tolerance is not clear, there will be distortion in the readings. The second factor is environmental. Certain environmental disruptions may reduce the validity of the pre-calibrated chart and thus the results. One could try reader rotation to achieve improved results (Allipi, et al., 2006 and Almaaitah, et al., 2010).

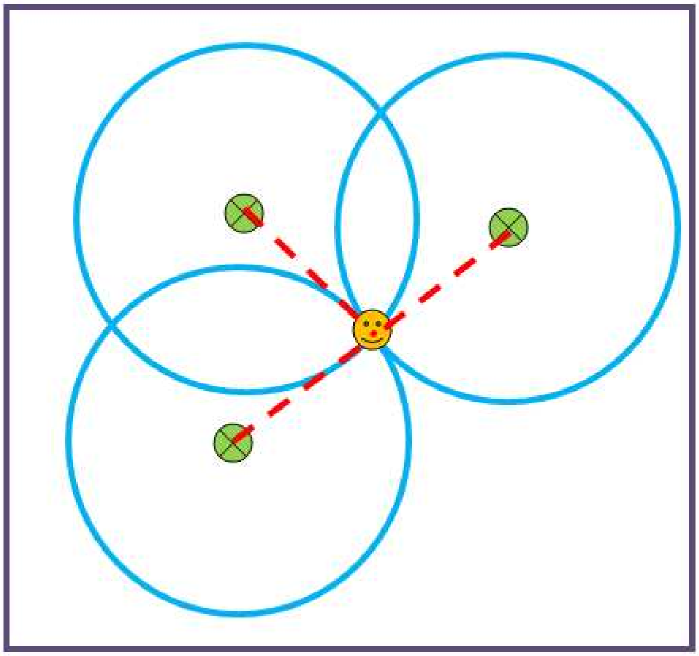

Figure 2.4 APM Approach

2.4.3.3 Ranging Based on Received Signal Strength Indicator (RSSI)

Received Signal Strength Indicator (RSSI) is often the simplest approach since most system collect RSSI data, thereby adding almost no additional cost

(Bouet and dos Santos, 2008). RSSI is quite simply the measurement of received radio signal power. Measurement is in terms of the ratio of measured power decibels (dB) to one milliwatt (mW). Unfortunately, it is one of the least accurate methods due to challenges with the propagation of the RF signals caused by a plethora of environmental impacts. (Hightower, et. al., 2000). There is just not one model that can be applied across the board as an overall effective and universal solution.

Some tips to improve functionality in an RSSI deployment are outlined here. First, the RSSI map needs to be calibrated for each antenna for best results. The RSSI map is used to translate signal strength to determine the distance. It is positively not a practical solution to measure the RSSI values at each point periodically to keep the map updated.

Therefore, fingerprinting, or profiling, was created. The process creates anchors at certain positions to be used as reference tags. A dynamic RSSI map can then be built by collecting the signal strength from each of these tags, which have recorded locations so as to minimize, or at least track, any environmental impact. The RSSI map is then used to translate the RSSI value for each tag by calculating the estimated distance between the antenna and the tag. This information is then used to locate tags that previously were reporting unknown coordinates. Classical lateration can also be helpful by collecting data from several antennas to determine the approximate position of the unknown tag. The potential for improved RSSI results through fingerprinting relies primarily on the density of anchor nodes.

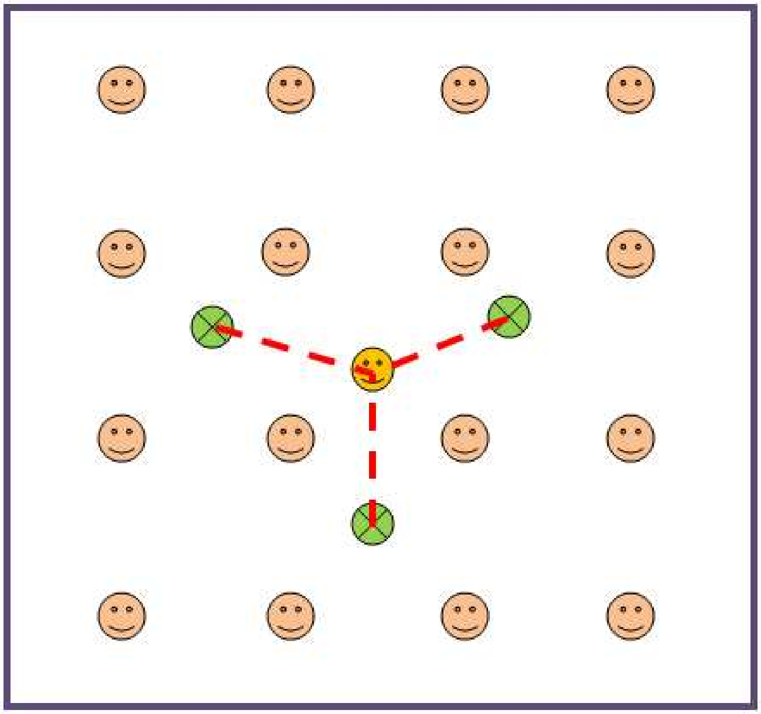

Figure 2.5 Received Signal Strength Indicator (RSSI) Approach

2.4.3.4 Angle of Arrival (AOA)

Angle of Arrival (AOA) can best be described by thinking of a triangle. If you know the coordinates of any two of the points then the third location can easily be calculated. However, this only works if the angles from each of the known points to the unknown point are available.

This method is also referred to as triangulation. Both 3D and 2D spaces are perfect environments for AOA deployments. However, to utilize AOA in a 3D space, customized RF signal modulating / demodulating units are required, adding cost to the project. Be advised that precise calibration of the units is also necessary. Accuracy is ensured up to 1.7° for smaller spaces, but it decreases dramatically when there are longer distances between the antennas and tags, or for larger angles (Zhou, *et al*, 2011).

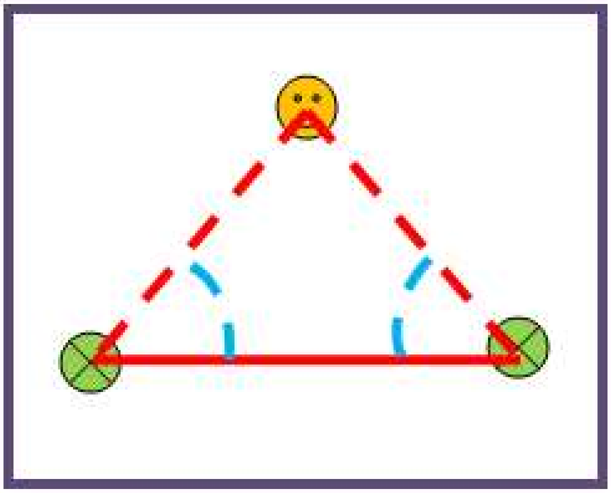

Figure 2.6 Angle of Arrival (AOA) Approach

AOA methodologies are sub-meter level for a normal room, but much depends on the density of the deployment of the readers / antennas.

2.4.3.5 Time Difference of Arrival (TDOA)

The Time Difference of Arrival (TDOA) algorithm methodology is very similar to a TOA approach. Both rely heavily on the precise synchronization of tags and readers. TDOA goes about determining the location of the actual unknown point a little bit differently than TOA. For an effective TDOA deployment, all feasible locations of the unknown tag must fall into a half section of a 2D space hyperbola or a 3D space hyperboloid. The methodology requires that the actual time difference of RF signals between the antennas to the tag in question be known. As such, the intersection of hyperbolas or hyperboloids that is then generated by all pairs of antennas will indicate the location of the unknown tag. The TDOA and the TOA methods share the same limitations and drawbacks.

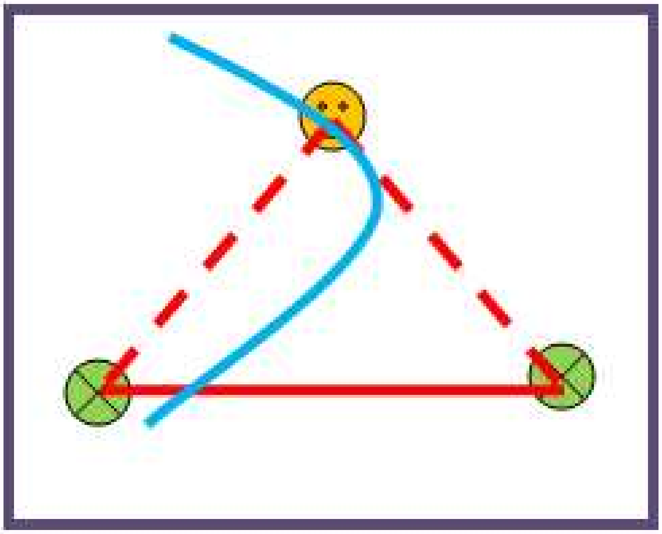

Figure 2.7 Time Difference of Arrival (TDOA) Approach

2.4.4 Range-free Localization

2.4.4.1 k Nearest-Neighbor (kNN)

kNN uses a variation of the fingerprinting technique seen in an RSSI deployment. However, it does so without ranging. First the reference anchors are deployed in cells so that the Euclidian distances between the RSSI values from the unknown tag and all anchors can then be calculated. Next, the k anchors that have the lowest distance to this tag are selected as its k nearest neighbors. By using the centroid of all anchors, the coordinates of the tag can easily be estimated. You can improve accuracy in a particular deployment by utilizing a weighted kNN. This method simply applies the Euclidian distances from the unknown tag to its kNN as weights (Shetty, 2010).

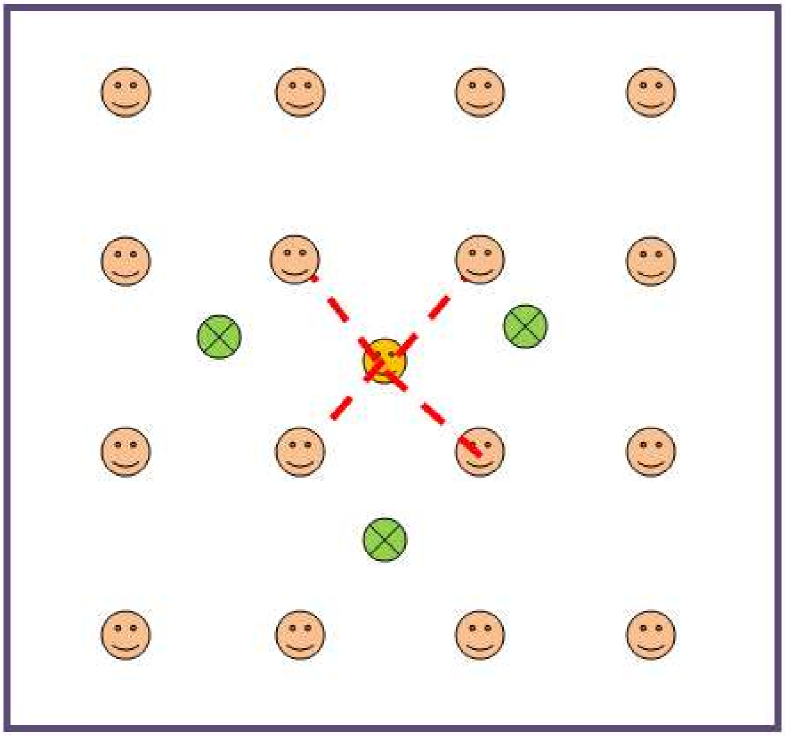

Figure 2.8 k-Nearest Neighbor (kKN) Approach

2.4.4.2 Proximity

The proximity approach can be impacted by fading at the edge and thus is not necessarily practical in indoor environments. However, to explain the functionality, each antenna has what is called a predefined coverage area. This coverage area could be a calibrated result or simply an approximation. Then, if the unknown tag is detected by more than one antenna, the location of this tag is estimated by the intersection of the coverage areas of these antennas. To see improved results, an implementation could increase the density of antenna deployment. Figure 2.9 explains the proximity approach in a simple graphical description.

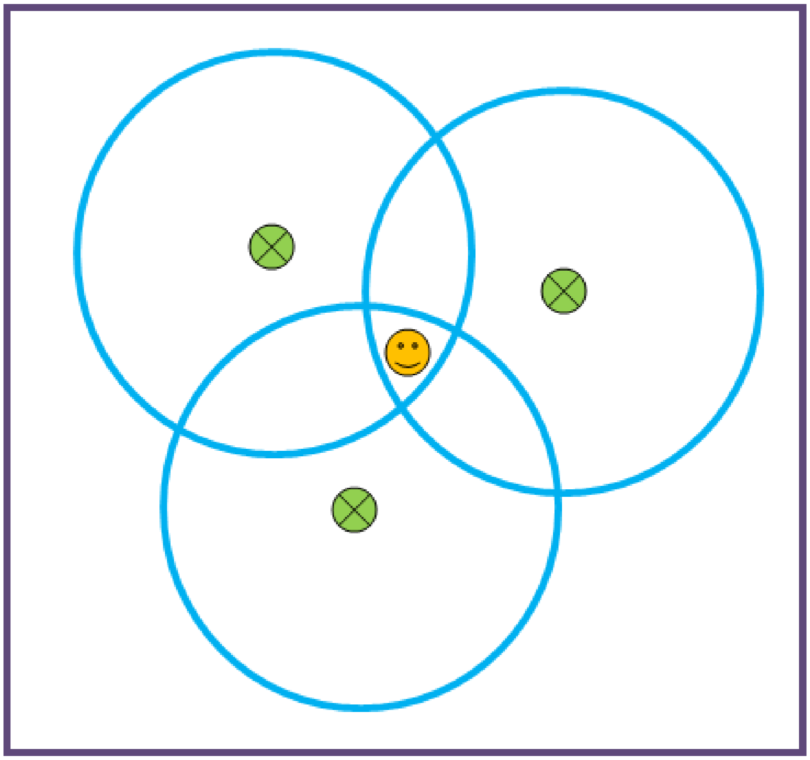

Figure 2.9 Proximity

2.4.5 Trilateration

Trilateration computes the intersection of three circles. Trilateration is used to estimate the location of the unknown node. As shown in Figure 2.10, A, B and C are three beacon nodes with known location $(x_A, y_A),(x_B, y_B)$, and (x_C, y_C) respectively, and D is an unknown node with assumed location (x, y). Let d_A, d_B, d_C be distances between D and A, B, C respectively and they can be expressed as the following equations (Qin-Qin, *et al*., 2006).

$$\begin{cases} \sqrt{(x-x_A)^2+(y-y_A)^2}=d_A \\ \sqrt{(x-x_B)^2+(y-y_B)^2}=d_B \\ \sqrt{(x-x_C)^2+(y-y_C)^2}=d_C \end{cases} \tag{1}$$

The location of D is deduced from equation system (1) and written in matrix format as the following.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_A-x_C) & 2(y_A-y_C) \\ 2(x_B-x_C) & 2(y_B-y_C) \end{bmatrix}^{-1} \begin{bmatrix} x_A^2-x_C^2+y_A^2-y_C^2+d_C^2-d_A^2 \\ x_B^2-x_C^2+y_A^2-y_C^2+d_C^2-d_A^2 \end{bmatrix} \tag{2}$$

The following Figure 2.10 describes the schematic diagram of Trilateration approach.

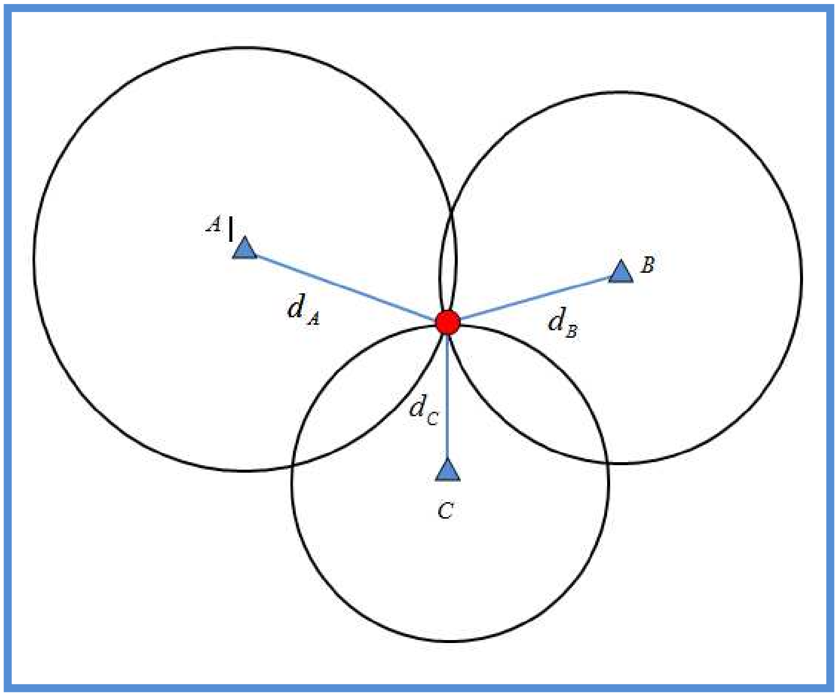

Figure 2.10 Schematic Diagram of Trilateration

CHAPTER 3

RESEARCH GOAL AND SPECIFIC AIMS

Real time localization is a process that determines the two- (x, y) or three- (x, y, z) dimensional position of a target object with respect to a coordinate system established by some fixed infrastructure. The Real Time Locating System (RTLS) approach that becomes the primary concerns in this research is RFID-based RTLS. The rationale for this is that other non RF-based localization techniques such as ultrasonic, visual, laser and infrared localization are sensitive to environmental impacts, for instance obstacles and irregular room shapes, and are limited to the Line-of-Sight (LOS) readability (Wu, 2012).

Non RFID-based RTLS such as Ultra Wideband-based RTLS is capable to yield a decimeter level positioning resolution via Line of Sight measurement and multilateration approximation (Malik, 2009). Some UWB-based algorithms may even give higher level of resolution accuracy near to 0.04 meters (Zhao, 2007). UWB-based system also have no interference with other narrow-banded wave radio transmissions in the same frequency bands due to its pulse radio transmission style (Steggles and Gschwind), 2005. However, as cited by Wu, a concern with the UWB-based system is that various regulations on this wide spectrum are permitted in different countries (Wu, 2012). This regulation variation is due by fact that the original intention of pulse-based radio technique development was originally reserved for military usage, such as for radar and satellite systems purposes. This in turn will lead to high research and development (R&D) cost and, therefore, high price for UWB chips (Wu, 2012).

Design for Six Sigma Research (DFSS-R) methodology developed by Jones is used for the overall methodology in this research (Jones, 2007). This methodology has three main phases, which are “Plan”, “Predict”, and “Perform” (3 P’s).

The innovation of this research is that we propose to utilize Real Time Locating System to allow surgeons or OR registered nurses to know the estimated location of the lost surgical instrument in the patient’s body so that they can find the lost instrument in a real-time manner to the most possible degree of accuracy. The significance of this research is that it will enhance the speed of the decision-making process and the action for removal of the retained surgical instrument through better providing the information of the retained surgical equipment location in the body by utilizing technology, *i.e*. utilizing automatic identification systems such as radio frequency identification (RFID) systems. By better providing the information of the surgical equipment in the body, the task for finding the retained surgical items is hypothetically easier and faster.

The research question that we formulate for this research is: “If the surgical equipment is detected in the patient’s body, can it be located in a timely fashion during surgery?” The overall goal of this research is to evaluate the performance of RFID-based RTLS technology in providing the location information of the surgical instruments. We hypothesize that Radio Frequency Identification (RFID)-based Real Time Locating System (RTLS) for Surgical Operations (RfSurg) will reduce the instances of retained surgical instruments inside the body by better informing the location of the surgical instances in the body for various types of human body habitus.

This research is performed in a non-clinical setting at the RAID Labs - RFID Laboratory of University of Texas at Arlington, Woolf Hall Building 4th Floor. The specific aims associated with our application objective consist of three aims:

1. Specific Aim 1: To evaluate the performance of the RFID-based RTLS prototype in non-clinical setting (open air experiment).
2. Specific Aim 2: To evaluate the performance of the RFID-based RTLS prototype in non-clinical setting (simulated human fluid experiment).
3. Specific Aim 3: To evaluate the estimated time for research participants for finding in the tagged surgical instrument (time-study) in the body based on the performance of the RFID-based RTLS.

CHAPTER 4

METHODOLOGY

The overall methodology that is employed in this research is the Design of Six Sigma-Research (DFSS-R) strategy. Briefly stated, the methodology uses DFSS-R approach to assess the needs of the candidate environment and develop the RTLS for surgery prototype. The prototype is tested in unique environments by using design of experiment methods in the development process to get the “best results with minimal effort”. The methodology, DFSS-R method, has been successful in developing operational prototypes for research and development purposes.

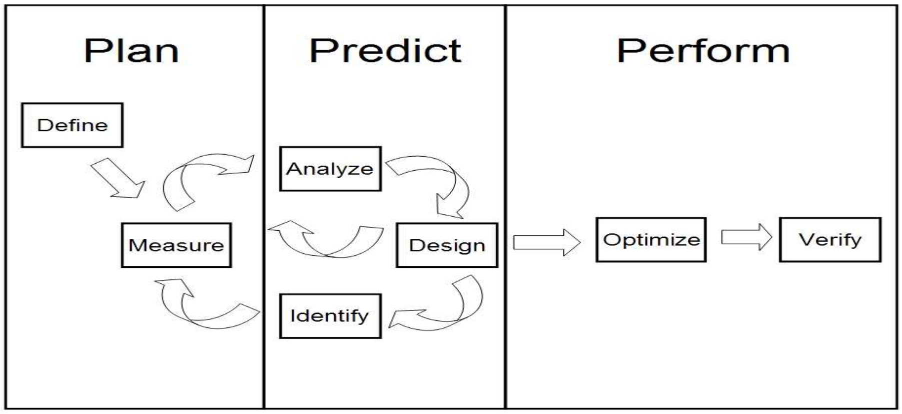

Figure 4.1 Design for Six Sigma Research (DFSS-R) Methodology (Jones and Chung, 2005)

The DFSS-R method in Figure 4.1 is divide into three phases, which are Plan, Predict, and Perform (3P) that consist of seven steps namely “Define”, “Measure”, “Analyze”, “Identify”, “Design”, “Optimize”, and “Verify” (DMAIDOV). This DFSS-R methodology is employed in this research to perform the testing and achieve the formulated research objectives.

In the “Plan” phase, we are interested in examining the existing problem and then formulate it in the “Define” step. In the next step, it would be necessary to identify the design the “roadmap” for each of the experiments and formulate it in the “Measure” step. The “Plan” phase covers two major steps:

- Step 1 - Define: In this “Define” step we will identify the research question upon the big picture of the problem statement. We will also define the selection background of the research topic. In short, this step focuses on answering the “whys” of the problem.
- Step 2 - Measure: In this second step of “Plan” phase, we will perform an important activity, which is defining the metrics that is needed in the research. The metrics are intended as the means to measure the existing process. By utilizing metrics of the problems of interest, we will be able to extract data from the focused existing system. This data would be needed as the basis to model the improved state of the current state of the art. This data will also be necessary in the planning process to achieve the objective of the research.

The next phase of DFSSR methodology is “Predict”. In this phase, we would examine the expected outcomes that will be obtained from the experiment. An attempt to identify the relevant technologies that will be utilized in designing the RFID-based RTLS is performed in this phase. Major stages in this phase are “Analyze”, “Identify”, and “Design”, which are described in the followings:

- Step 3 - Analyze: In this step we carefully study the causes of variation and errors. We also identify the root cause of the existing problems in the process (Southard, et al., 2012).
- Step 4 - Identify: The next step of the predict phase is identify. In this step, we would make sure that the organization is able to identify the critical criteria for success (Antony, 2002).
- Step 5 - Design: This is the final step of the predict phase. Here, the identified parameters of design must be translated into actual and effective design (Antony, 2002).

“Perform” phase is the third phase in the DFSS-R methodology. The big picture of this phase is the attempt to prove the designed prototype is feasible by utilizing the design of experiment approach. Two major steps below are necessary in this phase:

- Step 6 - Optimize: An important feature in this step is effective “makeability”, which involves deeper consideration of design in order that we can make sure that the product can be produced within the defined specification and within the financial agreement that has been set (Antony, 2002).

- Step 7 - Verify: This is the second step of perform phase, where we are interested in verifying the design of the proposed approach to prove the improvements as stated by the hypothesis statement (Sokovic, et al., 2010).

4.1 Research Approach

This research was performed in a non-clinical setting. The primary tool used for measurement and analysis is Design of Experiments (DOE). A specific DOE is designed for each of the specific aims.

The proposed localization approach in this research is based on a two-dimensional RSSI-based localization (x, y). The justification for the selection of this two-dimensional localization approach is that the height of the object (the height of the tagged surgical instrument in the body cavity) was fixed at a certain height. From the interview with an OR nurse in the University of Texas at Southwestern, we found out that an operating table is about (700-1000) ± 50mm high from the ground. Therefore, we assumed that the z position of the object (the height of the tagged surgical instrument in the body cavity) was at a fixed height (1 meter) from the ground. The graphical description of the object of interest in this research can be seen in the following Figure 4.2.

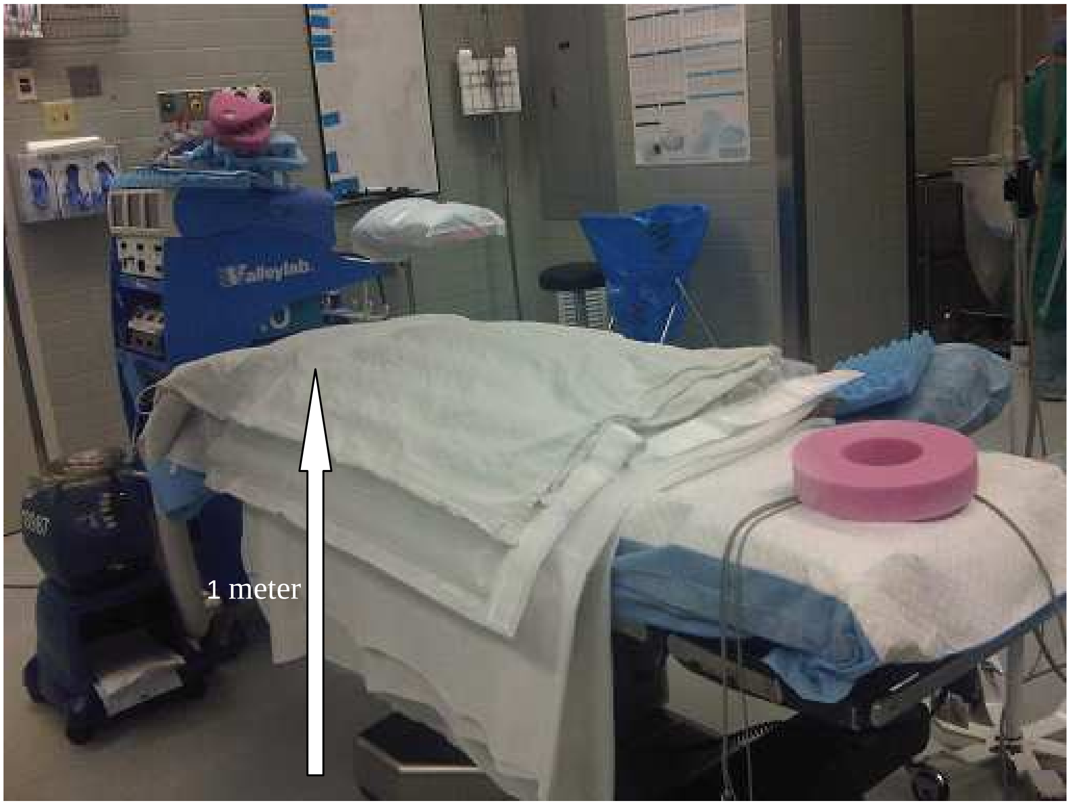

Figure 4.2 Height of the Retained Surgical Instrument (Fixed at 1 Meter)

4.2 Location of Experiment and Equipment Used

The experiments were performed in the the Radio Frequency and Auto Identificaiton (RAID) Labs, Woolf Hall Building 4th Floor of UTA to collect. A population of UTA students were employed to collect the experimental data.

The equipment that was used to perform the experiments above is the active system RF-Code 433.92 MHz. The main components for this active RFID system are RF-Code M250 reader and RF-Code M171 durable tag.

RF-Code M250 readers are dual-channel radio receivers tuned to 433.92 MHz. The readers are programmed, calibrated and dedicated to interpreting and reporting the radio frequency messages emitted by RF Code tags. The processing of tag transmissions is real-time. This allows quickly locating and identification of tagged objects or human in specified areas. M250 readers are compatible with wired and wireless networks for rapid integration into an organization’s IT infrastructure (RF Code, 2013). Figure 4.3 shows a fixed 433.92 M250 RF-Code reader.

Figure 4.3 RF-Code 433.92 MHz M250 Fixed Reader (Source: RF Code, 2013)

The 433 MHz M171 Durable Tag is a battery-powered RF transmitter designed with a sealed, water-resistant, crush-proof enclosure for general-purpose asset tracking. The unique ID and the status message of each tag are broadcasted at a periodic rate, which is programmed at the factory. These tags provide an economical solution for a variety of asset tracking environments. Figure 4.4 shows an RF-Code M171 durable tag.

Figure 4.4 RF-Code M171 Durable Tag (Source: RF Code, 2013)

4.3 Ranging and Localization Protocols

The ranging and localization were performed to evaluate the performance of the system in the open air setting and simulated body fluids setting. This step of research is used to answer the Specific Aim 1 and Specific Aim 2.

4.3.1 Setting-up the System

A four meter times four meter area close to the mannequins in the SMART Hospital area of a high complexity laboratory room in the RAID Labs, Woolf Hall Building 4th Floor, at the University of Texas at Arlington. The rationale for designing the size of experiment area to be four meter times four meter is that according to previous research by Brchan as mentioned in the research by Wu, the RSSI values are approximately linear within a range of 4 meters in the anechoic chamber and to a range of 10 meters in the clear hallway (Wu, 2012).

The chosen area was divided into one half meter times one half meter grids and marked using tape (refer to Figure 4.5). There were thirty two grids. The first experiment was performed for the open air in the chosen area.

Figure 4.5 One-Half Meter Times One-Half Meter Grids Marked with Tape

A total of twenty four active tags were randomly chosen out of twenty five tags available in the RAID Labs. Twelve tags were used as reference (anchor) tags, and twelve other were used as unknown (random) tags. Based on some initial experiments, the tags were assumed to have similar characteristics. Each of these twenty four tags was attached on a two-meter long PVC pipe stand so that the tag was fixed at a one meter height above the ground. Each stand was randomly put at the marked spots in the grids. Figure 4.6 shows a tag attached to the PVC stand.

Figure 4.6 A Tag Attached to the PVC Stand

There are four orientations of the tag attached to the PVC stand, which are:

- Tag facing the y direction;.
- Tag facing the x direction;
- Tag facing the z direction (tag label up);
- Tag facing the z direction (tag label down).

There are several experiments that were performed in this step of research, which are listed below:

A. Open-Air Experiments
  - Experiment in open air for tag facing the y direction.
  - Experiment in open air for tag facing the x direction.
  - Experiment in open air for tag facing the z direction (tag label up).
  - Experiment in open air for tag facing the z direction (tag label down)

B. Simulated Human Body Fluid Experiment
  - Experiment in water.
  - Experiment in oil.
  - Experiment mixed medium (water and oil).
  - Experiment for tag facing the z direction (tag label down) in oil.

The localization algorithm in this research is based on the Trilateration approach as described previously in section 2.1.1 (equation (1) and equation (2)), and as presented again below.

Trilateration computes the intersection of three circles. Suppose A, B and C are three beacon nodes with known location $(x_A, y_A), (x_B, y_B)$, and (x_C, y_C) respectively, and D is an unknown node with assumed location (x, y). Let d_A, d_B, d_C be distances between D and A, B, C respectively and they can be expressed as the following equations (Qin-Qin, *et al*., 2006).

$$\begin{cases} \sqrt{(x-x_A)^2+(y-y_A)^2}=d_A \\ \sqrt{(x-x_B)^2+(y-y_B)^2}=d_B \\ \sqrt{(x-x_C)^2+(y-y_C)^2}=d_C \end{cases} \tag{1}$$

The location of D is deduced from equation system (1) and written in matrix format as the following.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_A-x_C) & 2(y_A-y_C) \\ 2(x_B-x_C) & 2(y_B-y_C) \end{bmatrix}^{-1} \begin{bmatrix} x_A^2-x_C^2+y_A^2-y_C^2+d_C^2-d_A^2 \\ x_B^2-x_C^2+y_A^2-y_C^2+d_C^2-d_A^2 \end{bmatrix} \tag{2}$$

Figure 4.7 shows the schematic layout of the area of experiment. Because we have only one fixed RF-Code reader and one mobile RF-Code reader in the RAID Labs, and we have no middleware facility to read the RSSI values simultaneously, there is only reader that was used in this experiment, which was the fixed 433.92 MHz RF-Code reader.

The coordinate of reader position 1, reader position 2, reader position 3, and reader position 4 is presented in Table 4.1.

Table 4.1 Coordinate of Reader Position 1, 2, 3, and Reader Position 4

#	Reader Position	Coordinate	#	Reader Position	Coordinate
1	Reader Position #1	[6.0, 0.0, 2.33]	2	Reader Position #2	[6.0, 4.0, 2.33]
3	Reader Position #3	[4.0, 2.0, 2.33]	4	Reader Position #4	[8.0, 2.0, 2.33]

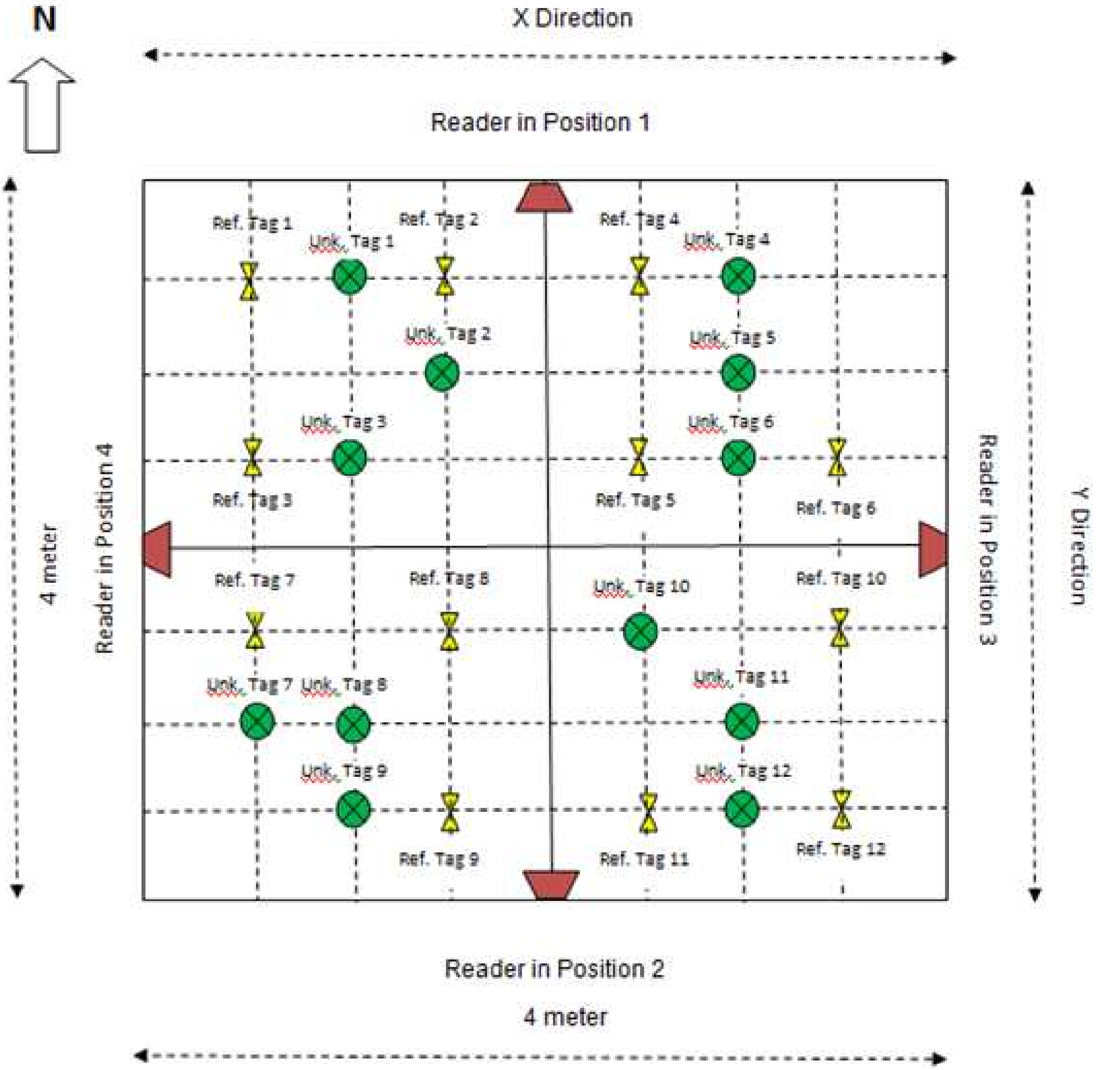

Figure 4.7 Schematic Layout of the Experiment

The coordinates for the twelve reference tags and the twelve unknown tags are presented in the following Table 4.2.

Table 4.2 Coordinate of Reference (Anchor) Tags and Unkown (Random) Tags

#	Tag	Coordinate	#	Tag	Coordinate
1	Reference Tag #1	[4.5, 0.5, 1]	2	Reference Tag #2	[5.5, 0.5, 1]
3	Reference Tag #3	[4.5, 1.5, 1]	4	Reference Tag #4	[6.5, 0.5, 1]
5	Reference Tag #5	[6.5, 1.5, 1]	6	Reference Tag #6	[7.5, 1.5, 1]
7	Reference Tag #7	[4.5, 2.5, 1]	8	Reference Tag #8	[5.5, 2.5, 1]
9	Reference Tag #9	[5.5, 3.5, 1]	10	Reference Tag #10	[7.5, 2.5, 1]
11	Reference Tag #11	[6.5, 3.5, 1]	12	Reference Tag #12	[7.5, 3.5, 1]
13	Unknown Tag #1	[5.5, 1.0, 1]	14	Unknown Tag #2	[5.0, 1.0, 1]
15	Unknown Tag #3	[5.0, 1.5, 1]	16	Unknown Tag #4	[7.0, 0.5, 1]
17	Unknown Tag #5	[7.0, 1.0, 1]	18	Unknown Tag #6	[7.0, 1.5, 1]
19	Unknown Tag #7	[4.5, 3.0, 1]	20	Unknown Tag #8	[5.0, 3.0, 1]
21	Unknown Tag #9	[5.0, 3.5, 1]	22	Unknown Tag #10	[6.5, 2.5, 1]
23	Unknown Tag #11	[7.0, 3.0, 1]	24	Unknown Tag #12	[7.0, 3.5, 1]

The 433.92 RF-Code reader was fixed at a height of 2.33 meter from ground and placed in position 1, position 2, position 3, and position 4 one after another experiment. For each position of reader, data was collected with a total number of 120 RSSI readings (12 reference tags * 10 repetition) for each experiment (experiment with tag orientation X, tag orientation Y, tag orientation, Z label up, tag orientation Z label down). Therefore, the total number of the

RSSI readings in the open air experiment is (12 tags * 10 repetition * 4 readers) = 480 RSSI readings. The values of RSSI from the reference tags were used in the next stages called ranging and localization processes.

Figure 4.8 Data Collection in the Smart Hospital of RAID Labs.

4.3.2 Ranging and Localization Algorithm

The 2D ranging and localization algorithm in this research can be broken down into three steps.

- Side detection / Sub area determination;
- RSSI ranging / Propagation Modeling;
- Final position estimation.

4.3.2.1 Step 1: Sub Area Determination

The purpose of the sub area determination step is to identify the most likely sub area of the quadrant within which the unknown tag is located. Once the RSSI value is collected from an unknown tag, the quadrant is determined which is most likely to contain the coordinates for the unknown tag position by comparing the RSSI values among the four different positions of the fixed reader. Figure 4.9 shows the schematic representation of quadrant determination.

The quadrant shown in Figure 4.9 is the area where the ranges and coordinates for the unknown tag are expected to be. We estimated that range for an unknown tag are most accurate within the determined quadrant. For the unknown tag, the strongest RSSI values from three reporting reader positions were identified. For example, if we found that a certain unknown tag has the strongest RSSI according to reader position 1, and then second strongest is reader position 2, and reader position 3 gives the third strongest, then we can determine that the unknown tag is most likely in Quadrant II. Likewise, if we found that a certain unknown tag has the strongest RSSI according to reader position 1, and then second strongest is reader position 2, and reader position 4 gives the third strongest, then we can determine that the unknown tag is most likely in Quadrant I.

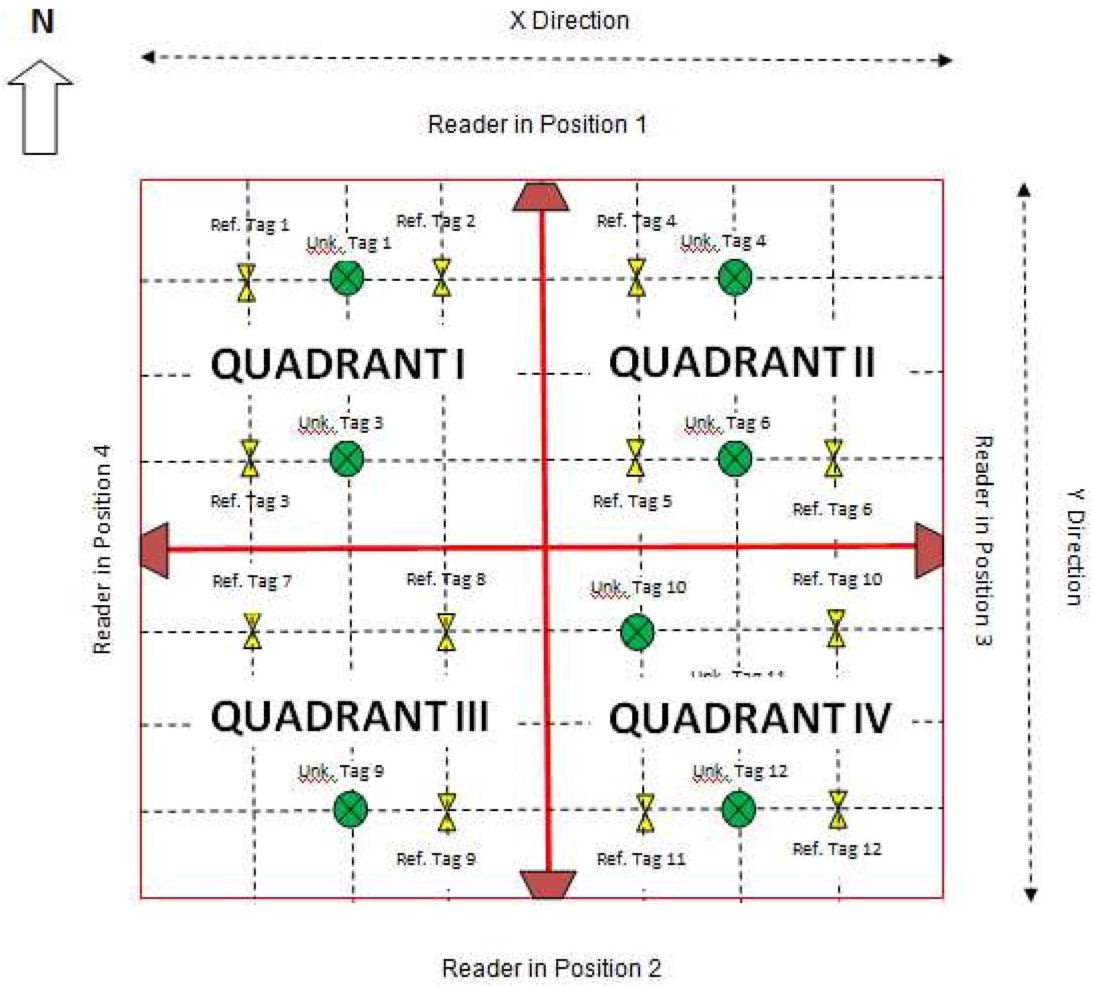

Figure 4.9 Schematic Representation of Quadrant Determination

4.3.2.2 Step 2: RSSI Ranging / Propagation Modeling

For each reader position, we created linear propagation models by using the RSSI values and distances that correspond to the reader position. In this case, we have linear propagation models for each experiment. Based on the quadrant that was selected as the candidate of the unknown tag position previously, we selected three linear propagation models which correspond to the three strongest RSSI values. For example, if we found that a certain unknown tag has the strongest RSSI according to reader position 1, and then second strongest is reader position 2, and reader position 3 gives the third strongest, then we selected the propagation models from these three readers to be used in the localization process using the Trilateration approach.

4.3.2.3 Step 3: Final Estimation

The Trilateration approach as described previously in section 2.1.1 (equation (1) and equation (2)) gives the estimation for the two dimensional unknown tags coordinates (x, y). Based on this estimated coordinate of the unknown tag, we can compute the error (which is the distance between the actual coordinate and the estimated coordinate using the Least Square model.

4.4 Specific Aims

The Specific Aims associated with our application objective consist of three aims that are presented in the following sections.

4.4.1 Specific Aim 1: To Evaluate the Performance of the RFID-based RTLS Prototype in Non-clinical Setting (Open Air Experiment)

This Specific Aim 1 is intended to answer the following questions:

1. How is the performance of the system in the open air experiment?
2. What is the effect of tag orientation to the localization error?
3. What is the effect of the number of reference tags (used for the propagation modeling purpose) to the error?

To address this specific aim, the ranging and localization process that was previously described will answer the Question 1 and Question 2. For

Question 3, the following experiments were designed to answer these questions.

A scenario of experiment with an unknown tag was created using two factors of experiment. Those factors are the number of reference tags used for propagation modeling (6 reference tags and 12 reference tags), and the tag orientation (X, Y, Z-UP (tag label facing the ceiling), Z-DOWN (tag label facing the floor). This scenario is presented in Table 4.3.

Table 4.3 Design of Experiment for Specific Aim 1 – Question 3

Factor	Σ Reference Tags		Reference Tag Orientation			
	6	12	Y	X	Z-UP	Z-DOWN
Expected Error (meter)						

4.4.2 Specific Aim 2: To Evaluate the Performance of the RFID-based RTLS Prototype in Non-clinical Setting (Simulated Human Fluid Experiment)

This Specific Aim 2 is intended to answer the following questions:

1. How is the performance of the system in the simulated human body fluid experiment?
2. What is the effect of different type of body fluids to the localization error?
3. What is the effect of the number of tags to the localization error?

To address this specific aim, the ranging and localization process that was previously described will answer the Question 1 and Question 2. For Question 3, the following experiments in Table 4.4 were designed.

Table 4.4 Design of Experiment for Specific Aim 2 – Question 3

Factor	Σ Reference Tags		Medium		
	6	12	Water	Oil	Mixed (water and Oil)
Expected Error (meter)					

4.4.3 Specific Aim 3: To Evaluate the Estimated Time for Research Participants for Finding in the Tagged Surgical Instrument (Time-Study) in the Body Based on the Performance of the RFID-based RTLS.

This Specific Aim is intended to evaluate how long it takes for a study participant to find a tag in a specified area associated with the localization error. To serve this Specific Aim, an experiment was designed.

4.5 Data Analysis Tools

We will use various data analysis tools for each of the Specific Aims. The explanations for each tool are described in the following sections.

4.5.1 Analysis of Variance (ANOVA)

This tool is applied to applications where the effects of one or several predictor variables on the response variable are of interest. For both experimental and observational research, analysis of variance models are useful for analyzing the effect of the explanatory variable(s) under study on the response variable. Table 4.5 shows ANOVA elements adapted from Neter, et al. (Neter, et al., 1996).

Table 4.5 ANOVA Table Elements (Neter, et al., 1996)

Source of Variation	$\boldsymbol{SS}$	$\boldsymbol{df}$	$\boldsymbol{MS}$	$\boldsymbol{E\{MS\}}$
Between treatments	$SSTR = \Sigma n_i \, (\bar{Y}_{i.} - \bar{Y}..)^2$	$r - 1$	$MSTR = \frac{STTR}{r-1}$	$\sigma^2 + \frac{\Sigma \, n_i \, (\mu_i - \mu_.)^2}{r-1}$
Error (Within Treatments)	$SSE = \Sigma\Sigma \left(Y_{ij} - \bar{Y}_{i.} \right)^2$	$n_T - r$	$MSE = \frac{SSE}{n_T - 1}$	σ^2
Total	$SSTO = \Sigma\Sigma \left(Y_{ij} - \bar{Y}_{..} \right)^2$	$n_T - 1$		

4.5.2 F-Test

Generally, the analysis of a single factor study is performed by determining whether or not the factor level means (μ_i) are equal. We can state these as:

H_0: $\mu_1 = \mu_2 = \ldots = \mu_r$

H_a: not all μ_i are equal

F^* is distributed as $F\,(r - 1, n_T - 1)$ when H_0 holds. It is also known that high values of F^* lead to the conclusion of H_a. Thus, the appropriate decision rule to control the level of significance at α is: If $F^* \leq F\ (1-\alpha; r-1, n_T - r)$ conclude H$_0$ and If $F^* > F\ (1-\alpha; r-1, n_T - r)$ conclude H$_a$ (Neter, et al., 1996).

4.5.3 Normal Probability Plot

Normal probability plot represents each residual against its expected value under normality. A nearly linear plot shows conformity with normality, while a plot that is off significantly from linearity indicates that the error distribution is not normal.

4.5.4 Box Plot

Box plot is a statistical technique that is employed for the purpose of exploratory data analysis. Box plot is generally utilized to identify hidden patterns in a group of numbers. In this case, box plot will visually summarize and compare groups of data. It uses the median, the approximate quartiles, and the lowest and highest data points to suggest the distribution of data values' level, spread, and symmetry. Box plot can be refined to spot outlier data. Moreover, it can be constructed by hand.

4.5.5 Tukey's Multiple Comparison Procedure

Tukey's range test performs the comparison for all possible pairs of means. Tukey's test is based on studentized range distribution, while this distributions is similar to the t-test. In Tukey's test, the set of the pairwise comparisons of factor level means will be the family of interest. We can state that the family consists of approximates of all pairs $D = \mu_i - \mu_{i'}$ or of all tests of the form: $H_0: \mu_i - \mu_{i'} = 0, H_0: \mu_i - \mu_{i'} \neq 0.$, The family confidence coefficient for the Tukey's method is exactly $1 - \alpha$ and the family significance level is exactly α in the case that all sample sizes are equal. In the case that the sample sizes are not equal, we will say that the family confidence coefficient is greater than $1 - \alpha$ and the family significance level is less than α. Thus, according to Netter, in the case that the sample sizes are not equal, the Tukey's test is conventional (Neter, 1996).

4.5.6 Residual Plot

There are four residual plots that are of use for analysis of variance models. These include: (1) plot against the fitted values (2) time plots / other sequence plots, (3) dot plots, and (4) normal probability plots. Residual plots is often utilized to analyze these deviations from ANOVA model: non-constancy of error variance, non-independence of error terms, outliers, exception of important explanatory variables and non-normality of error terms, variables and non-normality of error terms (Netter, 1996).

CHAPTER 5

RESULTS

5.1 Ranging and Localization

As described before, ranging processes were performed as the means for developing the linear propagation models that were used in the localization processes. The results of the localization process were the estimated coordinates of the unknown tags in two dimensional platform (x, y) and their corresponding distance errors in meters.

5.1.1 The Linear Propagation Models and Localization Process

The linear propagation models obtained from the ranging process described previously are listed in the following sections.

5.1.1 1 Open Air Experiment

In this phase of research, the linear propagation models take the following linear regression model:

$$E(\hat{y}_d) = \beta_0 + \beta_1 x_{RSSI} + \beta_2 d_x + \beta_3 d_y + \beta_4 d_{Z-up} + \beta_5 d_{Z-down} + \varepsilon \qquad (3)$$

where:

$E(\hat{y}_d)$ = the estimated distance of the unknown tag from a certain reader position.

β_0 = the intercept of the linear model

β_1 = the slope of the Received Signal Strength Index (RSSI)

x_{RSSI} = the RSSI value of the unknown tag.

β_2 = the slope of the dummy variable that represent the orientation of the unknown tag facing the x orientation.

d_x = dummy variable that represent the orientation x of the reference tag.

β_3 = the slope of the dummy variable that represent the orientation of the unknown tag facing the y orientation.

d_y = dummy variable that represent the orientation y of the reference tag.

β_4 = the slope of the dummy variable that represent the orientation of the unknown tag facing the z orientation with the tag label facing the ceiling.

d_{Z-up} = dummy variable that represent the orientation z with the tag label facing the ceiling.

β_5 = the slope of the dummy variable that represent the orientation of the unknown tag facing the z orientation z with the tag label facing the floor.

d_{Z-down} = dummy variable that represent the orientation z with the tag label facing the floor.

ε = random error.

For example of $E(\hat{y}_d)$ modeling and computation, we refer to the following analysis for the Open Air experiment. This example of analysis calculation is for the open air experiment when the reader was positioned at the first position with the 2 dimensional coordinate of [6.0, 0.0].

The first thing that we would like to see is the “goodness of fit” of the model. The Regression analysis in Table 5.1.(a) below shows the R-Square statistic that represents the percent of the total variation in the dependent variable that is explained by the independent variables, *i.e*., the model's overall “goodness of fit.” But whether a model is really a "good" fit or not depends on context.

Table 5.1.(a) Regression Statistics

Regression Statistics	
Multiple R	0.618221
R Square	0.382197
Adjusted R Square	0.301471
Standard Error	0.692216
Observations	48

The context in this research indicates that the linear propagation models developed for each of the reader positions (reader position #1, reader position #2, reader postion #3, and reader position #4) now are aimed to be used in later localization process, where the localization process itself, *i.e.* the Trilateration localization approach, is a product of three linear propagation models, which equations are described previously in section 2.1.1 (equation (1) and equation

(2)). Thus, even though the R-Square statistics for this case is only 0.382197, which is not close to 1, we would like to see how "good" this linear propagation will yield the expected error in later analysis. Within this context, we have to remember that our real objective is to test our hypothesis, *not* to maximize R-square by including irrelevant variables in our model and then making up some "hypothesis" after the fact to "explain" the results we got.

The next thing that we should check is the statistical significance of the model coefficients whether the model coefficients are statistically significant. The appropriate hypothesis testing in this situation is presented below:

$$H_0 : \beta_i = 0$$

$$H_a : \beta_i \neq 0$$

Where *i* = 1, 2, 3, 4, and 5 which represent the slopes for x_{RSSI}, d_x, d_y, d_{Z-up}, d_{Z-down}. We reject $H_0 : \beta_i = 0$, if the $p-value$ is less than 0.05, then we conclude $H_a : \beta_i \neq 0$.

Table 5.1.(b) below provides the analysis of variance for the Open Air Experiment when the reader was positioned at the coordinate of [6.0, 0.0].

Table 5.1.(b) Analysis of Variance for the Open Air Experiment – Reader Position #1

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	12.74643	2.549287	6.650364277	0.000121175
Residual	43	20.60401	0.479163		
Total	48	33.35044			

Table 5.1.(c) Parameter Estimation, Open Air Experiment – Reader Position #1

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-12.39467031	2.943544451	-4.2108	0.0001274
RSSI Open Air Experiment	-0.27289324	0.052910281	-5.15766	6.031E-06
Y	0.799170152	0.322287817	2.479678	0.017146
X	0	0	65535	1.24E-173
Z-UP	0.209450673	0.285498921	0.73363	0.4671554
Z-DOWN	0.234711162	0.286236625	0.81999	0.4167441

From Table 5.1.(b) above, the analysis of variance shows that the overall model is statistically significant with a *p*-value of 0.000121175. From Table 5.1 (c) we can see that the independent variables are all have *p*-values that are higher than 0.05, except for the RSSI and the tag orientation X and Y. This means that statistically, the reference tag with orientation Z-up and Z-down are those of the explanatory variables that don't really "explain" the linear propagation model $E(\hat{y}_d)$. The RSSI coefficient indicates that it is statistically significant, which means it is an explanatory variable for the expected distance of an unknown tag $E(\hat{y}_d)$. On the other hand, the coefficient of the tag with X orientation, although it has a *p*-value of 1.24E-173, which is very low, it is definitely not an explanatory variable in the linear propagation model $E(\hat{y}_d)$ as its coefficient value is zero. Thus, we can intuitively infer from this that the tag orientation Y, X, Z-up, and Z-down statistically don't have any effect on the estimated distance of the tag to a certain position of a reader. In this case, theoretically, the expected distance $E(\hat{y}_d)$ is a function of the RSSI. However, for the purpose of obtaining as much information as we can in this research, we will still compute the next necessary calculations with regard to these tag orientation Y, X, Z-up, and Z-down.

The obtained propagation models for all of the reader position #1, reader position #2, reader position #3, and reader position #4 for each of tag orientation are then used to compute the $E(\hat{y}_d)$ values of the twelve unkown tags. The corresponding average RSSI for each of the unknown tags will be the input for the along $E(\hat{y}_d)$ computation. The RSSI values along with their computed $E(\hat{y}_d)$ values are presented in the following Table 5.2 and Table 5.3.

The results of $E(\hat{y}_d)$ are then used to estimate the coordinate (x, y) of an unknown tag based on the Trilateration equations described previously. Three sets of expected distance of an unknown tag $E(\hat{y}_d)$ are chosen among four sets of $E(\hat{y}_d)$ based on the strongest RSSI value associated with a particular unknown tag to be localized.

Table 5.2 RSSI Value for the Unknown Tags for the Y Tag Orientation

Tag	RSSI Value for the Unknow Tags (dB)			
	Reader Position #1	*Reader Position #2*	*Reader Position #3*	*Reader Position #4*
Unkn. Tag #1	-48.139	-51.33882252	-52.45154135	-54.13980755
Unkn. Tag #2	-48.590	-51.78999716	-49.38999716	-52.68575472
Unkn. Tag #3	-52.452	-52.45154135	-48.93882252	-52.43985897
Unkn. Tag #4	-51.339	-51.33882252	-53.7787717	-50.75154135
Unkn. Tag #5	-51.390	-51.38999716	-54.78575472	-51.48999716
Unkn. Tag #6	-53.952	-52.35154135	-54.83985897	-51.33882252
Unkn. Tag #7	-56.879	-56.5787717	-50.03882252	-54.77022015
Unkn. Tag #8	-57.786	-56.18575472	-52.88999716	-56.18575472
Unkn. Tag #9	-57.570	-55.17022015	-51.55154135	-54.5787717
Unkn. Tag #10	-54.657	-52.95746537	-52.95746537	-51.16611463
Unkn. Tag #11	-56.186	-55.78575472	-55.78575472	-52.48999716
Unkn. Tag #12	-58.970	-56.77022015	-56.1787717	-53.15154135

Table 5.3 Expected Distance Values $E(\hat{y}_d)$ for the Unknown Tags for the Y Orientation

Tag	Expected Distance Value (meter)			
	Reader Position #1	*Reader Position #2*	*Reader Position #3*	*Reader Position #4*
Unkn. Tag #1	1.541259097	3.357328482	2.613658768	3.249843692
Unkn. Tag #2	1.664381606	3.18967801	1.790807536	2.632511022
Unkn. Tag #3	2.718170911	2.943857021	1.669545329	2.528113526
Unkn. Tag #4	2.414517465	3.357328482	2.97037847	1.811321394
Unkn. Tag #5	2.428482678	3.33831267	3.241025295	2.124840193
Unkn. Tag #6	3.127510771	2.981015686	3.255566897	2.060657489
Unkn. Tag #7	3.926332147	1.41023332	1.965192329	3.517491668
Unkn. Tag #8	4.17384168	1.556273184	2.731502536	4.118471022
Unkn. Tag #9	4.115023755	1.93363227	2.371765768	3.436210313
Unkn. Tag #10	3.320152665	2.755862408	2.749635967	1.987332629
Unkn. Tag #11	3.737212496	1.704907844	3.509795295	2.549400193
Unkn. Tag #12	4.497074291	1.33909363	3.61542647	2.830265394

For example, if for the unknown tag #1 the corresponding strongest RSSI values are from reader position #1 (-48.139 dB), reader position #2 (51.33882252 dB), and reader position #3 (-52.45154135 dB), then the associated expected distance for these RSSI are 1.541259097 (meter), 3.357328482 (meter), and 2.613658768 (meter) respectively. This selection of the three strongest RSSI makes sense, because the higher the RSSI value, the greater the expected range of the reader is. We want to know if this RSSI values really do have any effect on the expected error calculated later in the Trilateration process. Thus, the associated expected distances that correspond with these three strongest RSSI values for a particular unknown tag will be the input for the Trilateration step described below.

As described previously, Trilateration computes the intersection of three circles. Suppose A, B and C are three beacon nodes with known locations $(x_A, y_A),(x_B, y_B)$, and (x_C, y_C) respectively, and D is an unknown tags with assumed location (x, y). Let (d_A, d_B, d_C)be distances between D and A, B, C respectively and they can be expressed as the following equations (Qin-Qin, *et al*., 2006).

$$\begin{cases} \sqrt{(x-x_A)^2+(y-y_A)^2}=d_A \\ \sqrt{(x-x_B)^2+(y-y_B)^2}=d_B \\ \sqrt{(x-x_C)^2+(y-y_C)^2}=d_C \end{cases} \tag{1}$$

The location of D is deduced from equation system (1) and written in matrix format as the following.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_A - x_C) & 2(y_A - y_C) \\ 2(x_B - x_C) & 2(y_B - y_C) \end{bmatrix}^{-1} \begin{bmatrix} x_A^2 - x_C^2 + y_A^2 - y_C^2 + d_C^2 - d_A^2 \\ x_B^2 - x_C^2 + y_A^2 - y_C^2 + d_C^2 - d_A^2 \end{bmatrix} \qquad (2)$$

Within this context, we assume that , and are the actual coordinates of the three reader positions that correspond to the selected three RSSI and expected distances $E(\hat{y}_d)$ described in the previous paragraph. Thus, these three actual pair of coordinates are [6.0, 0.0] (reader position #1), [6.0, 4.0] (reader position #2), and [4.0, 2.0] (reader position #3) respectively. The notations d_A, d_B, d_C are the three selected expected distances values that we have discussed above, which are 1.541259097 (meter), 3.357328482 (meter), and 2.613658768 (meter) respectively. The next step is plugging in these selected coordinate values and the associates estimated distances into the Trilateration equations.

The final results of these Trilateration process are the estimated coordinates of each unknown tags (x, y). By plugging in these estimated coordinate values and the actual coordinate values for a particular unknown tag, we will obtain the expected error of that unknown tag in term of its relative two dimensional position to its actual position. The results of its Trilateration process are presented in section 5.1.2.

5.1.1 2 Simulated Body Fluids Experiments

The simulated body fluids were represented by tap water, vegetable oil, and mixed of tap water and vegetable oil. The following Figure In this phase of research, the linear propagation models take the following linear regression model.

$$E(\hat{y}_d) = \beta_0 + \beta_1 x_{RSSI} + \beta_2 d_W + \beta_3 d_O + \beta_4 d_M + \varepsilon \qquad (4)$$

where:

$E(\hat{y}_d)$ = the estimated distance of the unknown tag from a certain reader position.

β_0 = the intercept of the linear model

β_1 = the slope of the Received Signal Strength Index (RSSI)

x_{RSSI} = the RSSI value of the unknown tag.

β_2 = the slope of the dummy variable that represent the orientation of the unknown tag.

d_W = dummy variable that represent the water medium.

β_3 = the slope of the dummy variable that represent the water medium.

d_O = dummy variable that represent the oil medium.

β_4 = the slope of the dummy variable that represent the evenly mixed water and oil medium.

d_M = dummy variable that represent the evenly mixed water and oil.

The final results of the Trilateration process, which are the estimated coordinates of each unknown tags (x, y), and their actual positions are presented in section 5.1.3.

5.1.2 The Localization Results

The localization results as mentioned above are the estimated coordinates of the unknown tags and their associated distance errors. The results are presented in the following sections.

The similar algorithm as presented previously in the Open Air experiment is employed for the parameter estimation and computation for this Simulated Human Body Fluid setting.

5.1.2.1 Results for the Open Air Experiments

Results for from this experiments are presented in the following Table 5.4, Table 5.5, Table 5.6 (a) and Table 5.6 (b). Table 5.4 describes the localization results which show the errors associated with the orientation of the unknown tags. Table 5.5 describes the estimated coordinates of the unknown tags ((x, y) pred) and the true location coordinates of the unknown tags. Table 5.6 (a) and Table 5.6 (b) describe the classification of errors and their associated percentages of frequencies.

Table 5.4 Localization Results for Open Air Experiments

Tag	*Orientation*	*Error (m)*	*Tag*	*Orientation*	*Error (m)*
Unkn. Tag #1	Y	1.342238	Unkn. Tag #1	Z-UP	1.413118703
Unkn. Tag #2	Y	0.601822	Unkn. Tag #2	Z-UP	3.212737125
Unkn. Tag #3	Y	1.449509	Unkn. Tag #3	Z-UP	0.767271853
Unkn. Tag #4	Y	1.241164	Unkn. Tag #4	Z-UP	1.014241239
Unkn. Tag #5	Y	0.266906	Unkn. Tag #5	Z-UP	0.58324197
Unkn. Tag #6	Y	1.332568	Unkn. Tag #6	Z-UP	0.947929092
Unkn. Tag #7	Y	1.077929	Unkn. Tag #7	Z-UP	0.608765286
Unkn. Tag #8	Y	1.158933	Unkn. Tag #8	Z-UP	0.573374554
Unkn. Tag #9	Y	0.649553	Unkn. Tag #9	Z-UP	0.841307494
Unkn. Tag #10	Y	0.939867	Unkn. Tag #10	Z-UP	0.025255659
Unkn. Tag #11	Y	0.383643	Unkn. Tag #11	Z-UP	0.405297723
Unkn. Tag #12	Y	0.938425	Unkn. Tag #12	Z-UP	0.589347179
Unkn. Tag #1	X	1.890908	Unkn. Tag #1	Z-DOWN	1.927767853
Unkn. Tag #2	X	1.438821	Unkn. Tag #2	Z-DOWN	1.95018619
Unkn. Tag #3	X	0.644663	Unkn. Tag #3	Z-DOWN	2.422789362
Unkn. Tag #4	X	1.44739	Unkn. Tag #4	Z-DOWN	1.086266145
Unkn. Tag #5	X	1.830207	Unkn. Tag #5	Z-DOWN	1.755046321
Unkn. Tag #6	X	2.457743	Unkn. Tag #6	Z-DOWN	2.005439726
Unkn. Tag #7	X	0.679686	Unkn. Tag #7	Z-DOWN	1.6468261
Unkn. Tag #8	X	0.487511	Unkn. Tag #8	Z-DOWN	1.030554591
Unkn. Tag #9	X	0.358838	Unkn. Tag #9	Z-DOWN	1.286296811
Unkn. Tag #10	X	0.988906	Unkn. Tag #10	Z-DOWN	0.194393741
Unkn. Tag #11	X	1.198126	Unkn. Tag #11	Z-DOWN	0.572492463
Unkn. Tag #12	X	1.261421	Unkn. Tag #12	Z-DOWN	1.27374894

Table 5.5 Estimated Coordinates for the Unknown Tags in Open Air Experiments

Unknown Tag	Y- Orientation		X-Orientation	
Tag	(x, y) pred	(x, y) true	(x, y) pred	(x, y) true
Unkn. Tag #1	(5.533, 1.356)	(4.5, 0.5)	(5.841, 1.833)	(4.5, 0.5)
Unkn. Tag #2	(5.534, 0.723)	(5.0,1.0)	(5.109, 2.435)	(5.0,1.0)
Unkn. Tag #3	(6.409, 1.840)	(5.0, 1.5)	(5.404, 2.003)	(5.0, 1.5)
Unkn. Tag #4	(6.968, 1.319)	(7.0, 0.5)	(6.478, 0.149)	(7.0, 0.5)
Unkn. Tag #5	(20.606, 53.989)	(6.5, 1.5)	(5.609, 3.096)	(6.5, 1.5)
Unkn. Tag #6	(6.316, 2.112)	(7.5, 1.5)	(5.444, 2.847)	(7.5, 1.5)
Unkn. Tag #7	(4.702, 4.059)	(4.5, 3.0)	(5.075, 3.363)	(4.5, 3.0)
Unkn. Tag #8	(4.239, 3.875)	(5.0, 3.0)	(5.433, 2.776)	(5.0, 3.0)
Unkn. Tag #9	(5.623, 3.649)	(5.0, 3.5)	(5.359, 3.491)	(5.0, 3.5)
Unkn. Tag #10	(5.563, 2.428)	(6.5, 2.5)	(5.626, 2.963)	(6.5, 2.5)
Unkn. Tag #11	(6.970, 3.383)	(7.0, 3.0)	(5.8225, 3.221)	(7.0, 3.0)
Unkn. Tag #12	(6.516, 7, 3.5)	(7.0, 3.5)	(5.788, 3.149)	(7.0, 3.5)
Unknown Tag	Z-UP Orientation		Z-DOWN Orientation	
Tag	(x, y) pred	(x, y) true	(x, y) pred	(x, y) true
Unkn. Tag #1	(5.742, 1.174)	(4.5, 0.5)	(5.753, 1.315)	(4.5, 0.5)
Unkn. Tag #2	(4.932, 4.212)	(5.0,1.0)	(3.652, 2.409)	(5.0,1.0)
Unkn. Tag #3	(4.629, 2.172)	(5.0, 1.5)	(5.437, 2.735)	(5.0, 1.5)
Unkn. Tag #4	(6.528, -0.398)	(7.0, 0.5)	(7.734, 1.301)	(7.0, 0.5)
Unkn. Tag #5	(6.010, 1.183)	(6.5, 1.5)	(4.745, 1.525)	(6.5, 1.5)
Unkn. Tag #6	(6.831, 2.172)	(7.5, 1.5)	(5.672, 2.324)	(7.5, 1.5)
Unkn. Tag #7	(3.896, 3.077)	(4.5, 3.0)	(5.553, 4.266)	(4.5, 3.0)
Unkn. Tag #8	(4.427, 2.969)	(5.0, 3.0)	(5.937, 2.572)	(5.0, 3.0)
Unkn. Tag #9	(4.189, 3.278)	(5.0, 3.5)	(5.772, 4.529)	(5.0, 3.5)
Unkn. Tag #10	(6.476, 2.491)	(6.5, 2.5)	(6.363, 2.363)	(6.5, 2.5)
Unkn. Tag #11	(6.704, 2.723)	(7.0, 3.0)	(6.594, 2.597)	(7.0, 3.0)
Unkn. Tag #12	(6.757, 2.963)	(7.0, 3.5)	(6.493, 2.332)	(7.0, 3.5)

Table 5.6 (a) Percentage of Errors for the Unknown Tags in Y and X Orientation

Y Orientation			X Orientation		
Category (meter)	Number of Error	%	Category (meter)	Number of Error	%
0.0 - < 0.5	2	16.67	0.0 - < 0.5	2	16.67
0.5 - < 1.00	4	33.33	0.5 - < 1.00	8	66.67
1.00 - < 1.5	6	50	1.00 - < 1.5	1	8.33
1.5 - < 2.0	0	0	1.5 - < 2.0	0	0
>= 2.0	0	0	>= 2.0	1	8.33
Total	12		Total	12	

Table 5.6 (b) Percentage of Errors for the Unknown Tags in Z-up and Z-down Orientation

Z-Up Orientation			Z-Down Orientation		
Category (meter)	Number of Error	%	Category (meter)	Number of Error	%
0.0 - < 0.5	2	16.67	0.0 - < 0.5	1	8.33
0.5 - < 1.00	3	25	0.5 - < 1.00	1	8.33
1.00 - < 1.5	4	33.33	1.00 - < 1.5	8	66.67
1.5 - < 2.0	2	16.67	1.5 - < 2.0	0	0
>= 2.0	1	8.33	>= 2.0	2	16.67
Total	12		Total	12	

5.1.2.2 Results for the Simulated Body Fluids Experiments

Results for from the simulated body fluids experiments are presented in the following Table 5.7, Table 5.8, and Table 5.9 (a) and Table 5.9.

Table 5.7 Localization Results for Water Experiments (1000 ml)

Tag	*Medium*	*Error (m)*
Unkn. Tag #1	Water	1.968524
Unkn. Tag #2	Water	0.882103
Unkn. Tag #3	Water	0.549172
Unkn. Tag #4	Water	0.647001
Unkn. Tag #5	Water	0.520386
Unkn. Tag #6	Water	0.957997
Unkn. Tag #7	Water	0.964186
Unkn. Tag #8	Water	0.587991
Unkn. Tag #9	Water	0.792772
Unkn. Tag #10	Water	0.810772
Unkn. Tag #11	Water	0.609035
Unkn. Tag #12	Water	1.086247

Table 5.8 Localization Results for Oil Experiments (1000 ml)

Tag	*Medium*	*Error (m)*
Unkn. Tag #1	Oil	2.358034
Unkn. Tag #2	Oil	0.829961
Unkn. Tag #3	Oil	2.04821
Unkn. Tag #4	Oil	2.588258
Unkn. Tag #5	Oil	0.884733
Unkn. Tag #6	Oil	0.711385
Unkn. Tag #7	Oil	1.744356
Unkn. Tag #8	Oil	1.153072
Unkn. Tag #9	Oil	0.843208
Unkn. Tag #10	Oil	0.255741
Unkn. Tag #11	Oil	0.744913
Unkn. Tag #12	Oil	0.967993

Table 5.9 Localization Results for Mixed Water and Oil Experiments (1000 ml)

Tag	*Medium*	*Error (m)*
Unkn. Tag #1	Mixed	2.294679
Unkn. Tag #2	Mixed	0.530516
Unkn. Tag #3	Mixed	0.467392
Unkn. Tag #4	Mixed	1.887806
Unkn. Tag #5	Mixed	0.258094
Unkn. Tag #6	Mixed	0.183273
Unkn. Tag #7	Mixed	0.876286
Unkn. Tag #8	Mixed	0.567905
Unkn. Tag #9	Mixed	0.251369
Unkn. Tag #10	Mixed	0.164623
Unkn. Tag #11	Mixed	0.481122
Unkn. Tag #12	Mixed	0.44548

Table 5.7, Table 5.8, and Table 5.9 describe the localization results which shows the errors associated with the medium used (water, oil, mixed water and oil, of which 1000 ml each).

Table 5.10 Estimated Coordinates for the Unknown Tags in Water 1000 ml

Tag	(x, y) pred	(x, y) true
Unkn. Tag #1	(5.643, 2.103)	(4.5, 0.5)
Unkn. Tag #2	(5.050, 1.881)	(5.0,1.0)
Unkn. Tag #3	(5.323, 1.944)	(5.0, 1.5)
Unkn. Tag #4	(6.762, 1.219)	(7.0, 0.5)
Unkn. Tag #5	(7.011, 4.965)	(6.5, 1.5)
Unkn. Tag #6	(6.842, 2.078)	(7.5, 1.5)
Unkn. Tag #7	(5.291, 2.459)	(4.5, 3.0)
Unkn. Tag #8	(5.412, 2.580)	(5.0, 3.0)
Unkn. Tag #9	(5.334, 2.781)	(5.0, 3.5)
Unkn. Tag #10	(6.004, 1.858)	(6.5, 2.5)
Unkn. Tag #11	(5.902, 2.447)	(7.0, 3.0)
Unkn. Tag #12	(6.524, 2.534)	(7.0, 3.5)

Table 5.11 Estimated Coordinates for the Unknown Tags in Oil 1000 ml

Tag	(x, y) pred	(x, y) true
Unkn. Tag #1	(5.894, 2.402)	(4.5, 0.5)
Unkn. Tag #2	(5.512, 1.654)	(5.0,1.0)
Unkn. Tag #3	(6.817, 2.445)	(5.0, 1.5)
Unkn. Tag #4	(6.681, 2.432)	(7.0, 0.5)
Unkn. Tag #5	(6.571, 2.382)	(6.5, 1.5)
Unkn. Tag #6	(6.829, 1.737)	(7.5, 1.5)
Unkn. Tag #7	(6.243, 2.926)	(4.5, 3.0)
Unkn. Tag #8	(6.153, 3.015)	(5.0, 3.0)
Unkn. Tag #9	(5.843, 3.507)	(5.0, 3.5)
Unkn. Tag #10	(6.250, 2.445)	(6.5, 2.5)
Unkn. Tag #11	(6.312, 2.714)	(7.0, 3.0)
Unkn. Tag #12	(6.6324, 2.807)	(7.0, 3.5)

Table 5.12 Estimated Coordinates for the Unknown Tags in Mixed Water and Oil 1000 ml

Tag	(x, y) pred	(x, y) true
Unkn. Tag #1	(6.348, 1.862)	(4.5, 0.5)
Unkn. Tag #2	(5.087, 1.523)	(5.0,1.0)
Unkn. Tag #3	(5.361, 1.797)	(5.0, 1.5)
Unkn. Tag #4	(7.575, 2.298)	(7.0, 0.5)
Unkn. Tag #5	(6.616, 1.629)	(6.5, 1.5)
Unkn. Tag #6	(7.546, 1.677)	(7.5, 1.5)
Unkn. Tag #7	(5.346, 2.772)	(4.5, 3.0)
Unkn. Tag #8	(5.495, 12.722)	(5.0, 3.0)
Unkn. Tag #9	(5.103, 3.703)	(5.0, 3.5)
Unkn. Tag #10	(6.357, 2.581)	(6.5, 2.5)
Unkn. Tag #11	(6.521, 2.961)	(7.0, 3.0)
Unkn. Tag #12	(7.032, 3.944)	(7.0, 3.5)

Table 5.10, Table 5.11, and Table 5.12 describe the estimated coordinates of the unknown tags ((x, y) pred) and the true location coordinates of the unknown tags.

Table 5.13, Table 5.14, and Table 5.15 describes the classification of errors and their associated percentages of frequencies in water experiment, oil experiment, and mixed water and oil experiment.

Table 5.13 Percentage of Errors for the Unknown Tags in Water 1000 ml Experiment

Water 1000 ml		
Category (meter)	Number of Error	%
0.0 - < 0.5	0	0.00%
0.5 - < 1.00	10	83.33%
1.00 - < 1.5	1	8.33%
1.5 - < 2.0	1	8.33%
>= 2.0	0	0.00%
Total	12	

Table 5.14 Percentage of Errors for the Unknown Tags in Oil 1000 ml Experiment

Oil 1000 ml		
Category	Number of Error	%
0.0 - < 0.5	1	8.33%
0.5 - < 1.00	6	50.00%
1.00 - < 1.5	1	8.33%
1.5 - < 2.0	1	8.33%
>= 2.0	3	25.00%
Total	12	

Table 5.15 Percentage of Errors for the Unknown Tags in Mixed Water and Oil 1000 ml Experiment

Mixed Water and Oil 1000 ml		
Category (meter)	Number of Error	%
0.0 - < 0.5	7	58.33%
0.5 - < 1.00	3	25.00%
1.00 - < 1.5	0	0.00%
1.5 - < 2.0	1	8.33%
>= 2.0	1	8.33%
Total	12	

5.2 Design of Experiments for Specific Aim 1 and Specific Aim 2

Although it has been found in the linear propagation modeling hypothesis testing in previous section that the tag orientation X, tag orientation Y, tag orientation Z-up, tag orientation Z-down, water, oil, and mixed water and oil do not have any statistical significance, we will test once again using some design of experiment by involving the factor of the number of tags that is used for the linear propagation modeling purpose. This experiment will serve the answer for question 3 in Specific Aim 1 and also question 3 in Specific Aim 2.

5.2.1 Design of Experiment for Specific Aim 1 Question Number 3

As previously described, to address this specific aim, the ranging and localization process that was previously described will answer the Question 1 and 2. For Question 3, the following experiments were designed to answer this question.

A scenario of experiment with an unknown tag was created using two factors of experiment. Those factors are the number of reference tags used for propagation modeling (6 reference tags and 12 reference tags), and the tag orientation (X, Y, Z-UP (tag label facing the ceiling), Z-DOWN (tag label facing the floor). This scenario is presented in Table 5.16.

Table 5.16 Design of Experiment for Specific Aim 1 – Question 3

Factor	Σ Reference Tags		Reference Tag Orientation			
	6	12	Y	X	Z-UP	Z-DOWN
Expected Error (meter)						

The experiment was run, and error (meter) data were calculated as the input for Table 5.16. A number of 60 data points were served for this experiment as presented in Table 5.17 (a) and Table 5.17 (b).

Table 5.17 (a) Data for DOE Specific Aim 1– Question 3 – 6 Tags

		Orientation			
		Y	X	Z-UP	Z-DOWN
Number of Tags	6	1.742238	1.590908	1.813119	2.227768
		1.001822	1.138821	3.612737	2.250186
		1.849509	0.344663	1.067272	2.722789
		1.641164	1.14739	1.314241	1.386266
		0.666906	1.530207	0.883242	2.055046
		1.032568	2.857743	1.347929	2.30544
		1.477929	1.079686	1.008765	1.946826
		1.558933	0.887511	0.973375	1.330555
		1.049553	0.758838	1.241307	2.086297
		1.339867	0.688906	0.825256	0.994394

Table 5.17 (b) Data for Design of Experiment for Specific Aim 1 – Question 3 – 12 Tags

		Orientation			
		Y	X	Z-UP	Z-DOWN
Number of Tags	12	1.342238	1.890908	1.413119	1.927768
		0.601822	1.438821	3.212737	1.950186
		1.449509	0.644663	0.767272	2.422789
		1.241164	1.44739	1.014241	1.086266
		0.266906	1.830207	0.583242	1.755046
		1.332568	2.457743	0.947929	2.00544
		1.077929	0.679686	0.608765	1.646826
		1.158933	0.487511	0.573375	1.030555
		0.649553	0.358838	0.841307	1.286297
		0.939867	0.988906	0.025256	0.194394

5.2.1.1 Results for Specific Aim 1 – Question 3

The objective for this design of experiment is to provide the answer for Specific Aim 1 Question 3: "What is the effect of the number of reference tags (used for the propagation modeling purpose) to the error?"

The ANOVA analysis results in Table 5.18 (a) shows that the *p*-value of the model is greater than 0.05, which means that this time, the dependent variable "error" has very weak evidence that it has the explanatory factors that represented by the number of tags and the tags orientation. The parameter estimate results in Table 5.18 (b) confirmed this analysis conclusion and also strengthen the previous analysis in section 5.1.1.1 that the orientation of the tags cannot be an explanatory variable in this research.

Table 5.18 (a) ANOVA Table of Error vs. Number of Tags and Orientation

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.87468	0.43734	1.01	0.3705
Error	57	24.67488	0.43289		
Corrected Total	59	25.54956			

Table 5.18 (b) Parameter Estimation of Number of Tags and Tags Orientation

Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	1.52307	0.33976	4.48	<.0001
Number of Tags	1	-0.24000	0.16988	-1.41	0.1632
Tags Orientation	1	0.01634	0.10403	0.16	0.8758

The plot of the data for both the relationship between the number of tags versus the error (meter) and between the tags orientation and the error (meter) are presented in Figure 5.1 and Figure 5.2. These figures show that they suggest some type of distribution other than linear pattern. We hypothesize that this probably the reason why the orientation of tags and the number of reference tags cannot explain the error model.

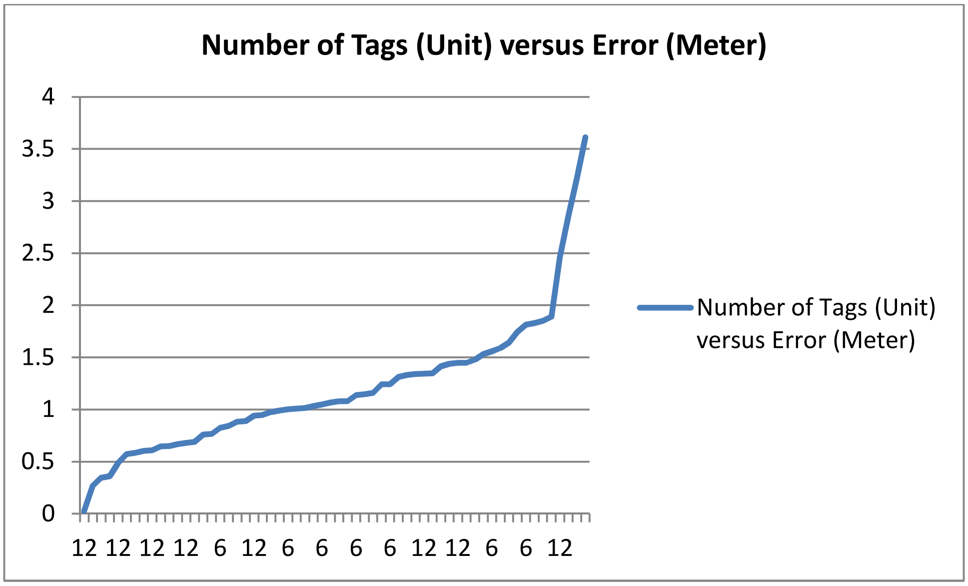

Figure 5.1 Number of Tags (6 and 12 Units) versus Error of Localization (Meter)

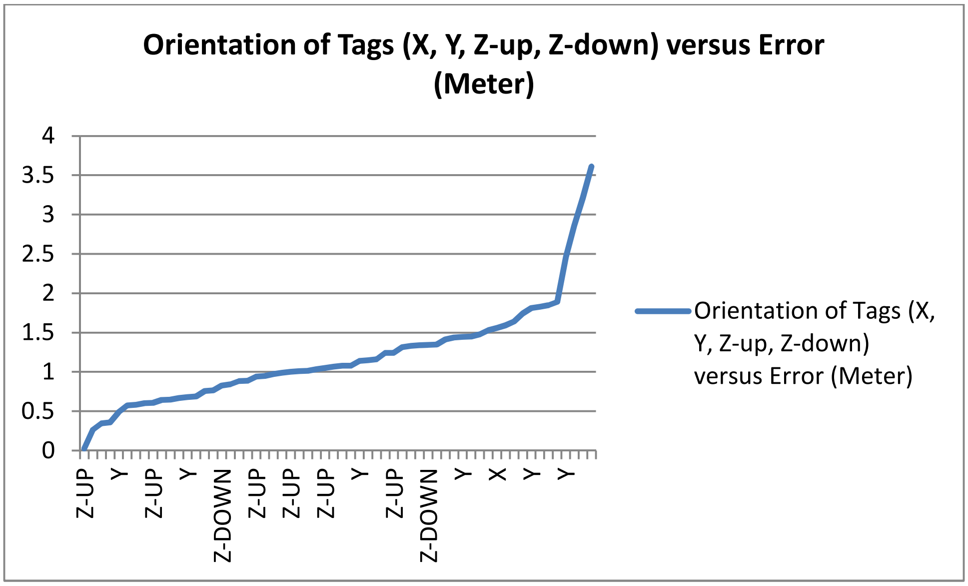

Figure 5.2 Orientation of Tags (X, Y, Z-up, Z-down) versus Error of Localization (Meter)

Although the patterns in the figures above suggest some other type of distribution other than linear model, this research uses the linear Trilateration approach for the justification of initial prototyping, to see if the localization using RFID-based RTLS will actually yield an initial improvement from the state of “only detecting the presence of a tag” into “localizing a tag”. Thus, we assume that the linear Trilateration Approach still works to meet the overall goal of this research.

5.2.2 Design Experiment for Specific Aim 2 Question Number 3

As previously described, to address this specific aim, the ranging and localization process that was previously described will answer the Question 1 and 2. For Question 3, the following experiments were designed to answer this question.

A scenario of experiment with an unknown tag was created using two factors of experiment. Those factors are the number of reference tags used for propagation modeling (6 reference tags and 12 reference tags), and the 1000 ml of medium (water, oil, and mixed water and oil). This scenario is presented in Table 5.19.

To serve this purpose for answering the Specific Aim 2 Question 3, the following experiments in Table 5.19 were designed.

Table 5.19 Design of Experiment for Specific Aim 2 – Question 3

Factor	Σ Reference Tags		Medium		
	6	12	Water	Oil	Mixed (water and Oil)
Expected Error (meter)					

The experiment was run, and error data were calculated as the input for Table 5.19. A number of 30 data points of error (meter) were served for this experiment analysis as presented in Table 5.20 and Table 5.21.

Table 5.20 Data for Design of Experiment for Specific Aim 2 – Question 3 – 6 Tags

		Medium (1000 ml)		
		Water	Oil	Mixed Water and Oil
Number of Tags	6	1.74	1.59	1.81
		1.00	1.14	1.00
		1.85	0.34	1.00
		1.64	1.15	1.00
		0.87	1.53	1.88

Table 5.21 Data for Design of Experiment for Specific Aim 2 – Question 3 – 12 Tags

		Medium (1000 ml)		
		Water	Oil	Mixed Water and Oil
Number of Tags	12	1.34	1.01	1.41
		0.55	0.95	3.15
		1.45	0.64	0.77
		1.24	1.45	1.03
		0.27	0.83	1.58

5.2.2.1 Results for Specific Aim 2 – Question 3

The objective for this design of experiment is to provide the answer for Specific Aim 2 Question 3: “What is the effect of the number of reference tags (used for the propagation modeling purpose) to the error in the simulated body fluid setting?”

The ANOVA analysis results in Table 5.22 (a) shows that the *p*-value of the model is greater than 0.05, which means that this time, the dependent variable “error” has very weak evidence that it has the explanatory factors that represented by the number of tags and the type of medium (water, oil, mixed water and oil). The parameter estimate results in Table 5.22 (b) confirmed this analysis conclusion and also strengthen the previous analysis in section 5.1.1.1 that the type of the medium cannot be an explanatory variable in this research.

Table 5.22 (a) Analysis of Variance Table of Error versus Number of Tags and Medium (Water, Oil, Mixed Water and Oil)

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2	0.45596	0.22798	0.70
Error	57	27	8.82320	0.32679	
Corrected Total	59	29	9.27916		

Table 5.22 (b) Parameter Estimation of Number of Tags and Medium

Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	1.24988	0.41748	2.99	0.0058
Number of Tags	1	-0.15401	0.20874	-0.74	0.4670
Medium	1	0.11791	0.12783	0.92	0.3645

The plot of the data for both the relationship between the number of tags versus the error (meter) and between the tags orientation and the error (meter) are presented in Figure 5.3 and Figure 5.4. These figures show that they suggest some type of distribution other than linear pattern. We hypothesize that this probably the reason why the orientation of tags and the number of reference tags cannot explain the error model.

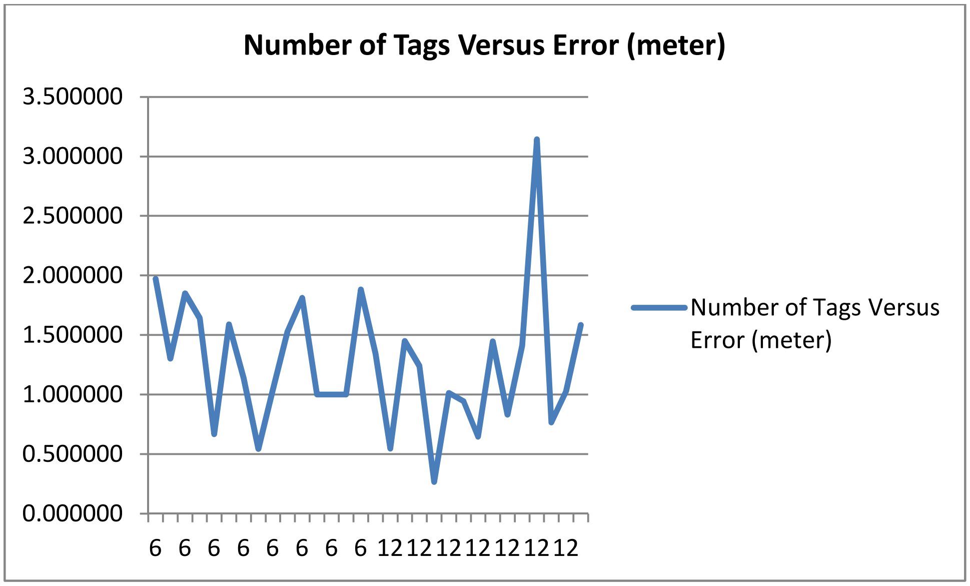

Figure 5.3 Number of Tags (6 and 12 Units) versus Error of Localization (Meter)

Although the patterns in the figures above suggest some other type of distribution other than linear model, this research uses the linear Trilateration approach for the justification of initial prototyping, to see if the localization using RFID-based RTLS will actually yield an initial improvement from the state of “only detecting the presence of a tag” into “localizing a tag”. Thus, in the simulated human body fluid setting we also assume that the linear Trilateration Approach still works to meet the overall goal of this research.

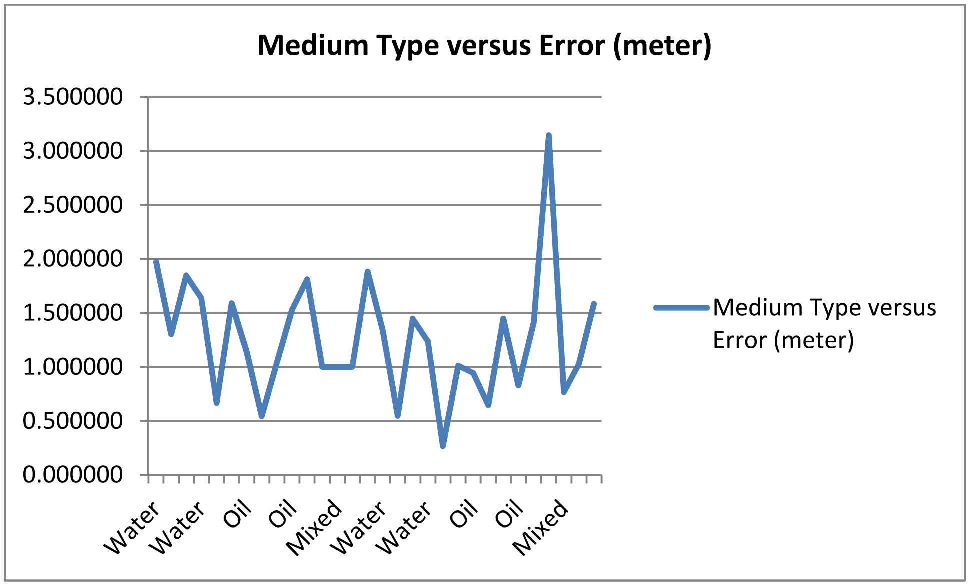

Figure 5.4 Medium Type (Water, Oil, Mixed Water and Oil) versus Error of Localization (meter)

5.3 Design Experiments for Specific Aim 3

Specific Aim 3: *To evaluate the estimated time for research participants for finding in the tagged surgical instrument (time-study) in the body based on the performance of the RFID-based RTLS.*

As previously described, this Specific Aim is intended to evaluate how long it takes for a study participant to find a tag in a specified area associated with the localization error. To serve this Specific Aim, an experiment was designed using five participants as study population, which were randomly chosen from the research assistant undergraduate and graduate student population in the RAID Labs of UTA. These participants have a certain degree of knowledge on RFID and its application.

Before the experiment began, these participants were shown how to run the experiment by giving them an example. Each time the experiment was run, there were three people involved. One person performed the experiment of finding the tag, one person operated, monitored, and recorded the experiment results in the RF-Code system, and the last person performed as an instructor before the experiment started as well as performed as the time counter. The time was measured using a stopwatch.

There were two factors involved in the design of this experiment. The first factor is the length of area that corresponds to the classification of errors that were obtained in the effort of answering Specific Aim 1 and Specific Aim 2. This classification of errors is presented in the following Table 5.23. There were four classifications of errors. The maximum error length that was considered in this experiment was 2.0 meter, which is the estimated maximum height of a person who goes under a surgery.

Table 5.23 Example of Errors Classification

Experiment X		
Category (meter)	Number of Error	%
0.0 - < 0.5		
0.5 - < 1.00		
1.00 - < 1.5		
1.5 - < 2.0		
>= 2.0		
Total	12	

Based on these classifications, a number of cardboard boxes were constructed so that the length of the box followed the length of errors. Thus, there were four lengths of the cardboard boxes, which are 0.50 meter, 1.00 meter, 1.50 meter, and 2.0 meter.

The second factor in this experiment is the type of the medium that was used to fill in the cardboard boxes. The types of medium consist of two type of material, which the first one is shredded fabrics and the second one is the blocks of 10 cm x 10 cm Styrofoam. The shredded fabrics represent the soft tissue in the human body such as flesh and skin, and the Styrofoam represents the hard tissue in the human body such as bones.

Let $\mu_{0.5}, \mu_{1.0}, \mu_{1.5}, \mu_{2.0}$ be the mean of the time needed to find the tag at the specified cardboard boxes with different length. The hypothesis testing that is appropriate for this Specific Aim is presented below.

$H_0 : \mu_{0.5} = \mu_{1.0} = \mu_{1.5} = \mu_{2.0}$

H_a : Not all the mean time for finding the tag in the specified box with a certain length is the same

The experiment was run, and the completion time data were recorded. A number of 40 data points of were collected for this experiment analysis as presented in Table 5.24.

Table 5.24 Completion Time for Specific Aim 3 Experiment

Length of Cardboard Box	**Observed Completion Time (Seconds)**									
	Fabric	Styro	Fab	Styro	Fabric	Styro	Fab	Styro	Fab	Styro
0.0 - < 0.5	27	15	24	16	23	19	22	20	18	21
0.5 - < 1.00	75	49	71	56	68	62	53	64	63	65
1.00 - < 1.5	192	136	183	159	167	159	163	167	144	176
1.5 - < 2.0	324	248	346	258	361	287	265	313	274	332

The ANOVA analysis results in Table 5.25 (a) shows that the *p*-value of the model is much lower than 0.05, which tells us that the completion time for finding the tags do statistically have significant differences based on the length of the cardboard box. This shows a successful rejection of the null hypothesis of means being the same. This is shown by the p value being <0.0001 which is smaller than the alpha level and the F value of 219.87 being larger than the theoretical value. This means that there is at least one significant factor. At least one of the means of the factors being test is different than the others. This means that there is one significant variable. We can find here from Table 5.25 (b) that the length of the cardboard box is the only significant variable with the F value that is greater than the theoretical F value.

Table 5.25 (a) Analysis of Variance Table of Completion Time

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	2	443281	221641	219.87
Error	57	37	37297	1008.03635	
Corrected Total	59	39	480578		

Table 5.25 (b) Parameter Estimation of Medium Type and Length of Box

Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-116.92500	19.44257	-6.01	<.0001
Medium Type	1	12.55000	10.04010	1.25	0.2192
Length of Box	1	187.98000	8.98014	20.93	<.0001

The box plot of the mean times of completion for the different length of boxes is presented in Figure 5.5. It can be visually inferred from this box plot that there is a significant difference between the mean times of completion between the four categories of error.

It can be also inferred that the mean times for finding the tag is significantly increasing with the increase of the length of the cardboard box. Tukey test will further analyze this difference in the completion time.

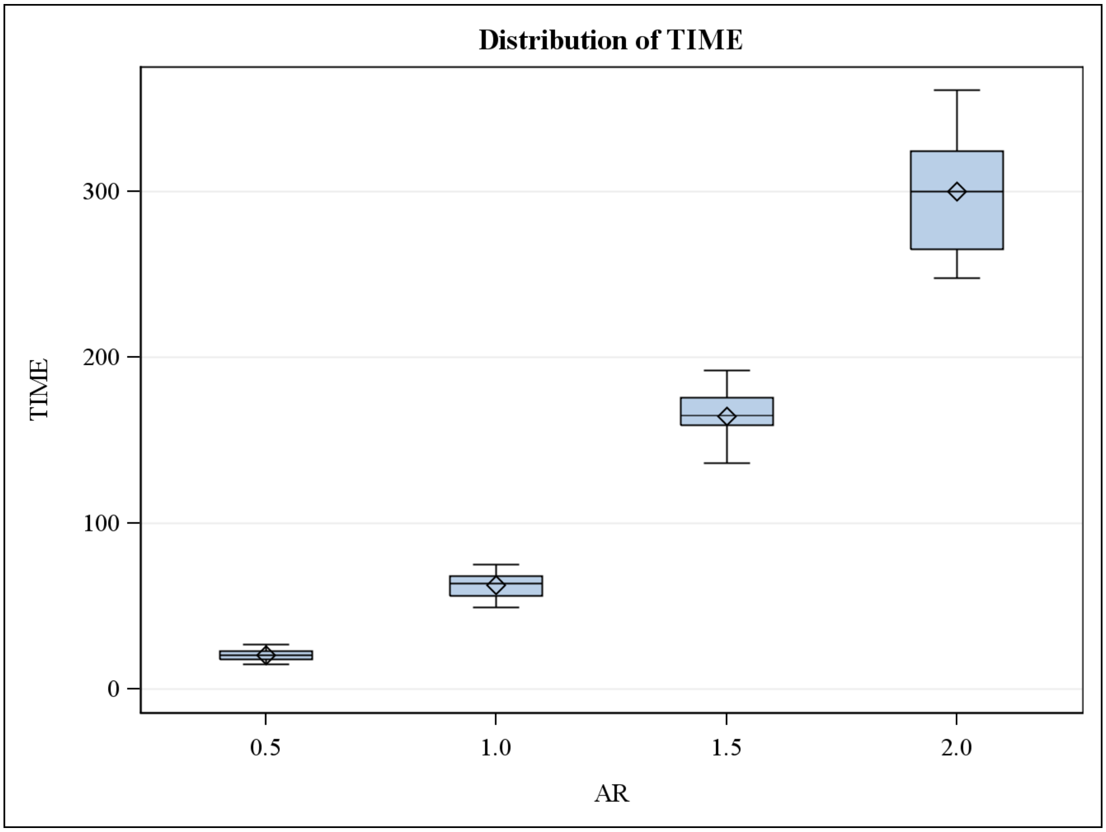

Figure 5.5 Box Plot of the Means Time of Completion between Four Categories of Cardboard Box Length

The results of Tukey’s test are shown in table 5.26. As it mentioned before, Tukey’s is a comparison test to recognize if there is any difference between the means of each category for specified significant level. Table 5.27 shows only categories that have a significance difference between their means.

Table 5.26 Tukey Test for the Mean Difference

Alpha	0.05
Error Degrees of Freedom	32
Error Mean Square	449.7375
Critical Value of Studentized Range	3.83162
Minimum Significant Difference	25.696

Table 5.27 Tukey Grouping With The Mean of Each Group

Tukey Grouping	Mean	N	Length of Box
A	299.800	10	2.0
B	164.600	10	1.5
C	62.600	10	1.0
D	20.500	10	0.5

From Table 5.26, we can see that the mean difference between the Length of Box categories are all greater that the minimum significant difference at 0.05, which is 25.696. This again proves that there is a significant difference between the mean times of completion between the four categories of error.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion and Recommendation

This research has proven that the RFID-based RTLS were able to answer the research question of: “If the surgical instrument is detected in the patient’s body, can it be located in a timely fashion during surgery?” The results from the localization experiment gave this proof. This research also has proven that the smaller error of localization will improve the time for the research participants to find the tag.

However, there are several limitations of this research:

1. This research was done under a laboratory-setting environment (non-clinical).
2. Some analysis showed that we failed to further elaborate some explanatory factors that could explain their relationship to error (for example: the tag orientation, number of reference tags, and the medium type).

The possible explanation for the limitation #2 is that the error model suggest suggests some type of distribution other than linear pattern, as shown in the Figure below.

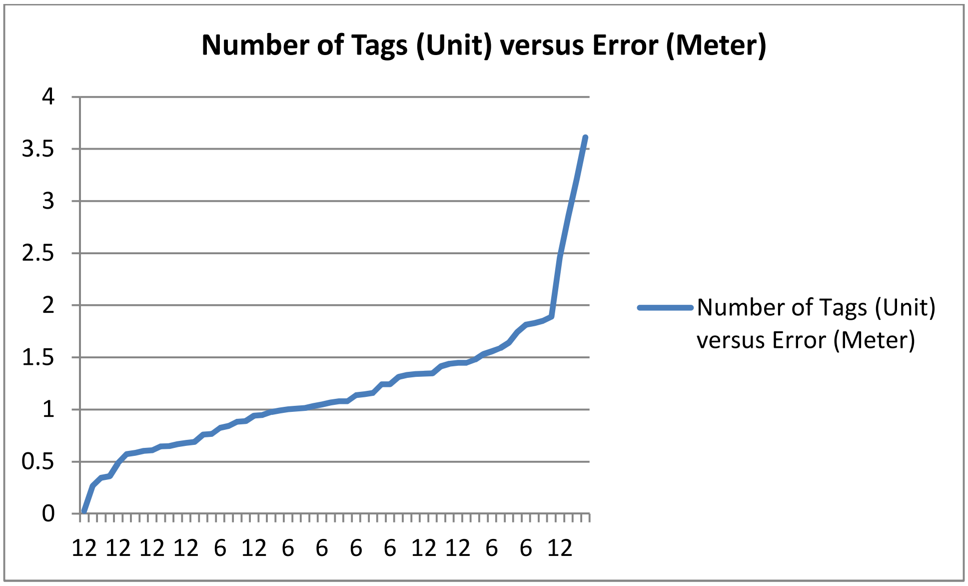

Figure 6.1 Error Model May Follow Some Type of Distribution Other Than Linear Pattern

Further research may address this issue both theoretically and experimentally through technological and algorithm advancement.

APPENDIX A

RESEARCH DATA

A1. Data Collected in the Open Air Experiment for Reader Position#1 [6, 0, 2.33]

Reader Postion#1 [6, 0, 2.33]					
		RSSI			
Obs #	Distance	Avg Y	Avg X	Avg Z-Up	Avg Z-Down
Ref. Tag #1	2.0661	-51.966	-54.065	-53.927	-53.827
Ref. Tag #2	1.5063	-49.627	-53.623	-51.214	-52.773
Ref. Tag #3	2.5038	-50.435	-52.623	-52.848	-51.614
Ref. Tag #4	1.5063	-48.827	-56.776	-51.604	-54.664
Ref. Tag #5	2.0661	-50.066	-56.782	-54.289	-55.868
Ref. Tag #6	2.5038	-51.835	-57.637	-55.298	-57.237
Ref. Tag #7	3.2045	-54.585	-54.223	-56.976	-53.823
Ref. Tag #8	2.8756	-53.257	-55.365	-56.582	-54.765
Ref. Tag #9	3.7774	-55.253	-54.923	-56.837	-54.523
Ref. Tag #10	3.2045	-53.985	-56.837	-54.768	-55.851
Ref. Tag #11	3.7774	-54.653	-55.976	-55.277	-53.964
Ref. Tag #12	4.0335	-56.420	-57.222	-57.222	-56.822
Unk. Tag#1	1.7375	-48.139	-54.027	-53.271	-53.627
Unk. Tag#2	1.9414	-48.590	-56.077	-56.077	-55.577
Unk. Tag#3	2.2403	-52.452	-54.371	-55.127	-54.071
Unk. Tag#4	1.7375	-51.339	-56.483	-51.727	-54.999
Unk. Tag#5	1.9414	-51.390	-57.516	-52.952	-55.019
Unk. Tag#6	2.2403	-53.952	-56.749	-55.127	-56.249
Unk. Tag#7	3.6082	-56.879	-54.471	-57.283	-53.971
Unk. Tag#8	3.4306	-57.786	-54.477	-57.016	-52.977
Unk. Tag#9	3.8754	-57.570	-55.227	-57.785	-54.927
Unk. Tag#10	2.8756	-54.657	-56.182	-55.868	-55.468
Unk. Tag#11	3.4306	-56.186	-56.716	-56.419	-56.019
Unk. Tag#12	3.8754	-58.970	-56.383	-57.001	-55.183

A2. Data Collected in the Open Air Experiment for Reader Position#2 [6, 4, 2.33]

Reader Postion#2 [6, 4, 2.33]					
		RSSI			
Obs #	Distance	Avg Y	Avg X	Avg Z-Up	Avg Z-Down
Ref. Tag #1	4.0335	-51.566115	-54.065	-53.927	-53.827
Ref. Tag #2	3.7774	-50.727133	-52.123	-51.214	-51.214
Ref. Tag #3	3.2045	-52.134659	-54.123	-52.848	-53.173
Ref. Tag #4	3.7774	-49.927133	-54.223	-51.604	-51.959
Ref. Tag #5	2.8756	-50.666115	-55.565	-54.289	-54.627
Ref. Tag #6	3.2045	-51.834659	-55.723	-55.298	-55.323
Ref. Tag #7	2.5038	-54.585442	-56.776	-56.976	-56.376
Ref. Tag #8	2.0661	-53.257465	-56.582	-56.582	-55.982
Ref. Tag #9	1.5063	-55.253332	-56.837	-56.837	-56.437
Ref. Tag #10	2.5038	-53.985442	-55.976	-54.768	-54.972
Ref. Tag #11	1.5063	-55.253332	-56.837	-55.277	-54.877
Ref. Tag #12	2.0661	-56.419997	-57.222	-57.222	-56.822
Unk. Tag#1	3.3195	-51.338823	-53.271	-53.271	-52.871
Unk. Tag#2	3.4306	-51.789997	-56.077	-56.077	-55.577
Unk. Tag#3	3.0031	-52.451541	-55.127	-55.127	-54.827
Unk. Tag#4	3.8754	-51.338823	-53.671	-51.727	-52.075
Unk. Tag#5	3.4306	-51.389997	-55.277	-52.952	-52.736
Unk. Tag#6	3.0031	-52.351541	-55.127	-55.127	-54.627
Unk. Tag#7	2.2403	-56.578772	-57.283	-57.283	-56.783
Unk. Tag#8	1.9414	-56.185755	-56.716	-57.016	-55.216
Unk. Tag#9	1.7375	-55.170220	-57.685	-57.785	-57.385
Unk. Tag#10	2.0661	-52.957465	-56.182	-55.868	-55.468
Unk. Tag#11	1.9414	-55.785755	-56.716	-56.419	-56.019
Unk. Tag#12	1.7375	-56.770220	-56.785	-57.001	-55.585

A3. Data Collected in the Open Air Experiment for Reader Position#3 [4, 2, 2.33]

Reader Postion#3 [4, 2, 2.33]					
		RSSI			
Obs #	Distance	Avg Y	Avg X	Avg Z-Up	Avg Z-Down
Ref. Tag #1	2.0661	-51.566	-54.065	-53.927	-53.827
Ref. Tag #2	2.5038	-52.935	-52.123	-52.773	-51.214
Ref. Tag #3	1.5063	-49.927	-54.123	-51.259	-53.173
Ref. Tag #4	3.2045	-53.685	-54.223	-54.361	-51.959
Ref. Tag #5	2.8756	-52.457	-55.565	-55.554	-54.627
Ref. Tag #6	3.7774	-54.653	-55.723	-57.251	-55.323
Ref. Tag #7	1.5063	-50.827	-56.776	-54.423	-56.376
Ref. Tag #8	2.0661	-51.466	-56.582	-55.365	-55.982
Ref. Tag #9	2.5038	-52.435	-56.837	-54.923	-56.437
Ref. Tag #10	3.7774	-55.253	-55.976	-55.664	-54.972
Ref. Tag #11	3.2045	-53.985	-56.837	-54.364	-54.877
Ref. Tag #12	4.0335	-56.420	-57.222	-57.222	-56.822
Unk. Tag#1	2.2403	-52.452	-54.027	-54.027	-52.871
Unk. Tag#2	1.9414	-49.390	-56.077	-56.077	-55.577
Unk. Tag#3	1.7375	-48.939	-54.371	-54.371	-54.827
Unk. Tag#4	3.6082	-53.779	-56.483	-54.708	-52.075
Unk. Tag#5	3.4306	-54.786	-57.516	-55.325	-52.736
Unk. Tag#6	3.3195	-54.840	-56.749	-56.749	-54.627
Unk. Tag#7	1.7375	-50.039	-54.471	-54.471	-56.783
Unk. Tag#8	1.9414	-52.890	-54.477	-54.777	-55.216
Unk. Tag#9	2.2403	-51.552	-55.227	-55.327	-57.385
Unk. Tag#10	2.8756	-52.957	-56.182	-55.868	-55.468
Unk. Tag#11	3.4306	-55.786	-56.716	-56.419	-56.019
Unk. Tag#12	3.6082	-56.179	-56.383	-56.591	-55.585

A4. Data Collected in the Open Air Experiment for Reader Position#4 [8, 2, 2.33]

Reader Postion#4 [8, 2, 2.33]					
		RSSI			
Obs #	Distance	Avg Y	Avg X	Avg Z-Up	Avg Z-Down
Ref. Tag #1	4.0335	-55.920	-57.022	-56.943	-56.843
Ref. Tag #2	3.2045	-54.485	-54.676	-53.868	-53.868
Ref. Tag #3	3.7774	-54.953	-56.037	-54.877	-55.164
Ref. Tag #4	2.5038	-52.135	-55.723	-53.223	-53.548
Ref. Tag #5	2.0661	-50.666	-55.565	-54.289	-54.627
Ref. Tag #6	1.5063	-49.627	-54.223	-53.769	-53.823
Ref. Tag #7	3.7774	-55.853	-57.637	-57.837	-57.237
Ref. Tag #8	2.8756	-53.257	-56.582	-56.582	-55.982
Ref. Tag #9	3.2045	-53.985	-55.976	-55.976	-55.576
Ref. Tag #10	1.5063	-50.227	-53.423	-52.114	-52.369
Ref. Tag #11	2.5038	-52.435	-54.923	-53.248	-52.848
Ref. Tag #12	2.0661	-52.066	-54.265	-54.265	-53.865
Unk. Tag#1	3.0031	-54.140	-55.173	-55.173	-54.773
Unk. Tag#2	3.4306	-52.686	-58.316	-58.316	-57.816
Unk. Tag#3	3.3195	-52.440	-56.749	-56.749	-56.449
Unk. Tag#4	2.2403	-50.752	-54.427	-52.528	-52.861
Unk. Tag#5	1.9414	-51.490	-55.277	-52.952	-52.736
Unk. Tag#6	1.7375	-51.339	-54.371	-54.371	-53.871
Unk. Tag#7	3.8754	-54.770	-57.685	-57.685	-57.185
Unk. Tag#8	3.4306	-56.186	-56.716	-57.016	-55.216
Unk. Tag#9	3.6082	-54.579	-57.283	-57.383	-56.983
Unk. Tag#10	2.0661	-51.166	-54.965	-54.627	-54.227
Unk. Tag#11	1.9414	-52.490	-54.477	-54.136	-53.736
Unk. Tag#12	2.2403	-53.152	-54.327	-54.494	-53.127

A5. Data Collected in the Water 1000 ml Experiment for Reader Position#1 [6, 0, 2.33]

Reader Position#1 [6, 0, 2.33]		
		RSSI
Obs #	**Distance**	**Avg Y**
Ref. Tag #1	2.0661	-60.256
Ref. Tag #2	1.5063	-56.461
Ref. Tag #3	2.5038	-64.895
Ref. Tag #4	1.5063	-58.062
Ref. Tag #5	2.0661	-56.814
Ref. Tag #6	2.5038	-59.312
Ref. Tag #7	3.2045	-67.581
Ref. Tag #8	2.8756	-61.382
Ref. Tag #9	3.7774	-62.252
Ref. Tag #10	3.2045	-61.246
Ref. Tag #11	3.7774	-60.487
Ref. Tag #12	4.0335	-70.576
Unk. Tag#1	1.7375	-62.298
Unk. Tag#2	1.9414	-62.298
Unk. Tag#3	2.2403	-66.320
Unk. Tag#4	1.7375	-57.042
Unk. Tag#5	1.9414	-58.025
Unk. Tag#6	2.2403	-59.992
Unk. Tag#7	3.6082	-61.959
Unk. Tag#8	3.4306	-61.959
Unk. Tag#9	3.8754	-62.943
Unk. Tag#10	2.8756	-56.404
Unk. Tag#11	3.4306	-63.582
Unk. Tag#12	3.8754	-63.582

A6. Data Collected in the Water 1000 ml Experiment for Reader Position#2 [6, 4, 2.33]

Reader Postion#2 [6, 4, 2.33]		
		RSSI
Obs #	**Distance**	**Avg Y**
Ref. Tag #1	4.0335	-67
Ref. Tag #2	3.7774	-66
Ref. Tag #3	3.2045	-67
Ref. Tag #4	3.7774	-64
Ref. Tag #5	2.8756	-56
Ref. Tag #6	3.2045	-59
Ref. Tag #7	2.5038	-58
Ref. Tag #8	2.0661	-61
Ref. Tag #9	1.5063	-53
Ref. Tag #10	2.5038	-57
Ref. Tag #11	1.5063	-55
Ref. Tag #12	2.0661	-61
Unk. Tag#1	3.3195	-65
Unk. Tag#2	3.4306	-68
Unk. Tag#3	3.0031	-63
Unk. Tag#4	3.8754	-66
Unk. Tag#5	3.4306	-62
Unk. Tag#6	3.0031	-59
Unk. Tag#7	2.2403	-57
Unk. Tag#8	1.9414	-55
Unk. Tag#9	1.7375	-53
Unk. Tag#10	2.0661	-58
Unk. Tag#11	1.9414	-59
Unk. Tag#12	1.7375	-58

A7. Data Collected in the Water 1000 ml Experiment for Reader Position#3 [4, 2, 2.33]

Reader Postion#3 [4, 2, 2.33]		
		RSSI
Obs #	**Distance**	**Avg Y**
Ref. Tag #1	2.0661	-56.978
Ref. Tag #2	2.5038	-56.461
Ref. Tag #3	1.5063	-58.841
Ref. Tag #4	3.2045	-60.463
Ref. Tag #5	2.8756	-56.814
Ref. Tag #6	3.7774	-59.112
Ref. Tag #7	1.5063	-57.260
Ref. Tag #8	2.0661	-60.682
Ref. Tag #9	2.5038	-54.310
Ref. Tag #10	3.7774	-63.893
Ref. Tag #11	3.2045	-57.840
Ref. Tag #12	4.0335	-70.576
Unk. Tag#1	2.2403	-61.360
Unk. Tag#2	1.9414	-58.545
Unk. Tag#3	1.7375	-59.766
Unk. Tag#4	3.6082	-62.343
Unk. Tag#5	3.4306	-62.443
Unk. Tag#6	3.3195	-59.992
Unk. Tag#7	1.7375	-54.891
Unk. Tag#8	1.9414	-54.891
Unk. Tag#9	2.2403	-54.108
Unk. Tag#10	2.8756	-59.180
Unk. Tag#11	3.4306	-66.359
Unk. Tag#12	3.6082	-67.285

A8. Data Collected in the Water 1000 ml Experiment for Reader Position#4 [8, 2, 2.33]

Reader Postion#4 [8, 2, 2.33]		
		RSSI
Obs #	**Distance**	**Avg Y**
Ref. Tag #1	4.0335	-66.813
Ref. Tag #2	3.2045	-63.665
Ref. Tag #3	3.7774	-69.219
Ref. Tag #4	2.5038	-57.261
Ref. Tag #5	2.0661	-55.237
Ref. Tag #6	1.5063	-58.512
Ref. Tag #7	3.7774	-68.520
Ref. Tag #8	2.8756	-60.682
Ref. Tag #9	3.2045	-57.840
Ref. Tag #10	1.5063	-53.304
Ref. Tag #11	2.5038	-55.193
Ref. Tag #12	2.0661	-57.440
Unk. Tag#1	3.0031	-62.298
Unk. Tag#2	3.4306	-66.990
Unk. Tag#3	3.3195	-65.383
Unk. Tag#4	2.2403	-55.275
Unk. Tag#5	1.9414	-53.608
Unk. Tag#6	1.7375	-53.808
Unk. Tag#7	3.8754	-65.493
Unk. Tag#8	3.4306	-61.959
Unk. Tag#9	3.6082	-65.593
Unk. Tag#10	2.0661	-57.329
Unk. Tag#11	1.9414	-57.104
Unk. Tag#12	2.2403	-58.029

A9. Data Collected in the Oil 1000 ml Experiment for Reader Position#1 [6, 0, 2.33]

Reader Postion#1 [6, 0, 2.33]		
		RSSI
Obs #	Distance	Avg Y
Ref. Tag #1	2.0661	-56.978
Ref. Tag #2	1.5063	-53.259
Ref. Tag #3	2.5038	-57.977
Ref. Tag #4	1.5063	-53.259
Ref. Tag #5	2.0661	-53.660
Ref. Tag #6	2.5038	-58.512
Ref. Tag #7	3.2045	-58.198
Ref. Tag #8	2.8756	-60.582
Ref. Tag #9	3.7774	-60.487
Ref. Tag #10	3.2045	-59.481
Ref. Tag #11	3.7774	-60.487
Ref. Tag #12	4.0335	-66.823
Unk. Tag#1	1.7375	-61.360
Unk. Tag#2	1.9414	-61.360
Unk. Tag#3	2.2403	-62.575
Unk. Tag#4	1.7375	-56.158
Unk. Tag#5	1.9414	-56.258
Unk. Tag#6	2.2403	-59.109
Unk. Tag#7	3.6082	-60.192
Unk. Tag#8	3.4306	-60.192
Unk. Tag#9	3.8754	-62.059
Unk. Tag#10	2.8756	-61.031
Unk. Tag#11	3.4306	-62.657
Unk. Tag#12	3.8754	-63.582

A10. Data Collected in the Oil 1000 ml Experiment for Reader Position#2 [6, 4, 2.33]

Reader Position#2 [6, 4, 2.33]		
		RSSI
Obs #	Distance	Avg Y
Ref. Tag #1	4.0335	-64
Ref. Tag #2	3.7774	-61
Ref. Tag #3	3.2045	-64
Ref. Tag #4	3.7774	-62
Ref. Tag #5	2.8756	-57
Ref. Tag #6	3.2045	-59
Ref. Tag #7	2.5038	-60
Ref. Tag #8	2.0661	-60
Ref. Tag #9	1.5063	-53
Ref. Tag #10	2.5038	-56
Ref. Tag #11	1.5063	-53
Ref. Tag #12	2.0661	-59
Unk. Tag#1	3.3195	-63
Unk. Tag#2	3.4306	-64
Unk. Tag#3	3.0031	-63
Unk. Tag#4	3.8754	-63
Unk. Tag#5	3.4306	-62
Unk. Tag#6	3.0031	-61
Unk. Tag#7	2.2403	-57
Unk. Tag#8	1.9414	-56
Unk. Tag#9	1.7375	-53
Unk. Tag#10	2.0661	-56
Unk. Tag#11	1.9414	-55
Unk. Tag#12	1.7375	-55

A11. Data Collected in the Oil 1000 ml Experiment for Reader Position#3 [4, 2, 2.33]

Reader Position#3 [4, 2, 2.33]		
		RSSI
Obs #	Distance	Avg Y
Ref. Tag #1	2.0661	-55.339
Ref. Tag #2	2.5038	-55.660
Ref. Tag #3	1.5063	-57.112
Ref. Tag #4	3.2045	-58.062
Ref. Tag #5	2.8756	-56.814
Ref. Tag #6	3.7774	-59.412
Ref. Tag #7	1.5063	-55.383
Ref. Tag #8	2.0661	-60.682
Ref. Tag #9	2.5038	-55.193
Ref. Tag #10	3.7774	-62.128
Ref. Tag #11	3.2045	-60.487
Ref. Tag #12	4.0335	-67.761
Unk. Tag#1	2.2403	-58.545
Unk. Tag#2	1.9414	-55.730
Unk. Tag#3	1.7375	-56.021
Unk. Tag#4	3.6082	-62.343
Unk. Tag#5	3.4306	-61.559
Unk. Tag#6	3.3195	-61.759
Unk. Tag#7	1.7375	-54.008
Unk. Tag#8	1.9414	-54.008
Unk. Tag#9	2.2403	-54.991
Unk. Tag#10	2.8756	-59.180
Unk. Tag#11	3.4306	-61.731
Unk. Tag#12	3.6082	-66.359

A12. Data Collected in the Oil 1000 ml Experiment for Reader Position#4 [8, 2, 2.33]

Reader Position#4 [8, 2, 2.33]		
		RSSI
Obs #	Distance	Avg Y
Ref. Tag #1	4.0335	-64.354
Ref. Tag #2	3.2045	-59.663
Ref. Tag #3	3.7774	-64.895
Ref. Tag #4	2.5038	-55.660
Ref. Tag #5	2.0661	-54.449
Ref. Tag #6	1.5063	-58.312
Ref. Tag #7	3.7774	-62.890
Ref. Tag #8	2.8756	-61.082
Ref. Tag #9	3.2045	-59.605
Ref. Tag #10	1.5063	-52.421
Ref. Tag #11	2.5038	-53.428
Ref. Tag #12	2.0661	-55.563
Unk. Tag#1	3.0031	-60.422
Unk. Tag#2	3.4306	-62.298
Unk. Tag#3	3.3195	-62.575
Unk. Tag#4	2.2403	-53.508
Unk. Tag#5	1.9414	-53.608
Unk. Tag#6	1.7375	-52.924
Unk. Tag#7	3.8754	-63.726
Unk. Tag#8	3.4306	-62.843
Unk. Tag#9	3.6082	-62.059
Unk. Tag#10	2.0661	-55.478
Unk. Tag#11	1.9414	-55.253
Unk. Tag#12	2.2403	-56.178

A13. Data Collected in the Mixed 500 ml Water and 500 ml Oil (1000 ml Total) Experiment for Reader Position#1 [6, 0, 2.33]

Reader Position#1 [6, 0, 2.33]		
		RSSI
Obs #	**Distance**	**Avg Y**
Ref. Tag #1	2.0661	-59.437
Ref. Tag #2	1.5063	-55.660
Ref. Tag #3	2.5038	-64.895
Ref. Tag #4	1.5063	-55.660
Ref. Tag #5	2.0661	-56.814
Ref. Tag #6	2.5038	-58.912
Ref. Tag #7	3.2045	-65.705
Ref. Tag #8	2.8756	-61.382
Ref. Tag #9	3.7774	-65.782
Ref. Tag #10	3.2045	-62.128
Ref. Tag #11	3.7774	-66.664
Ref. Tag #12	4.0335	-73.391
Unk. Tag#1	1.7375	-59.483
Unk. Tag#2	1.9414	-61.360
Unk. Tag#3	2.2403	-61.638
Unk. Tag#4	1.7375	-57.042
Unk. Tag#5	1.9414	-58.025
Unk. Tag#6	2.2403	-55.575
Unk. Tag#7	3.6082	-64.610
Unk. Tag#8	3.4306	-63.726
Unk. Tag#9	3.8754	-68.244
Unk. Tag#10	2.8756	-63.808
Unk. Tag#11	3.4306	-66.359
Unk. Tag#12	3.8754	-70.987

A14. Data Collected in the Mixed 500 ml Water and 500 ml Oil (1000 ml Total) Experiment for Reader Position#2 [6, 4, 2.33]

Reader Position#2 [6, 4, 2.33]		
		RSSI
Obs #	**Distance**	**Avg Y**
Ref. Tag #1	2.0661	-59.437
Ref. Tag #2	1.5063	-55.660
Ref. Tag #3	2.5038	-64.895
Ref. Tag #4	1.5063	-55.660
Ref. Tag #5	2.0661	-56.814
Ref. Tag #6	2.5038	-58.912
Ref. Tag #7	3.2045	-65.705
Ref. Tag #8	2.8756	-61.382
Ref. Tag #9	3.7774	-65.782
Ref. Tag #10	3.2045	-62.128
Ref. Tag #11	3.7774	-66.664
Ref. Tag #12	4.0335	-73.391
Unk. Tag#1	1.7375	-59.483
Unk. Tag#2	1.9414	-61.360
Unk. Tag#3	2.2403	-61.638
Unk. Tag#4	1.7375	-57.042
Unk. Tag#5	1.9414	-58.025
Unk. Tag#6	2.2403	-55.575
Unk. Tag#7	3.6082	-64.610
Unk. Tag#8	3.4306	-63.726
Unk. Tag#9	3.8754	-68.244
Unk. Tag#10	2.8756	-63.808
Unk. Tag#11	3.4306	-66.359
Unk. Tag#12	3.8754	-70.987

A15. Data Collected in the Mixed 500 ml Water and 500 ml Oil (1000 ml Total) Experiment for Reader Position#3 [4, 2, 2.33]

Reader Postion#3 [4, 2, 2.33]		
		RSSI
Obs #	**Distance**	**Avg Y**
Ref. Tag #1	2.0661	-55.339
Ref. Tag #2	2.5038	-55.660
Ref. Tag #3	1.5063	-57.112
Ref. Tag #4	3.2045	-58.062
Ref. Tag #5	2.8756	-56.814
Ref. Tag #6	3.7774	-59.412
Ref. Tag #7	1.5063	-55.383
Ref. Tag #8	2.0661	-60.682
Ref. Tag #9	2.5038	-55.193
Ref. Tag #10	3.7774	-62.128
Ref. Tag #11	3.2045	-60.487
Ref. Tag #12	4.0335	-67.761
Unk. Tag#1	2.2403	-58.545
Unk. Tag#2	1.9414	-55.730
Unk. Tag#3	1.7375	-56.021
Unk. Tag#4	3.6082	-62.343
Unk. Tag#5	3.4306	-61.559
Unk. Tag#6	3.3195	-61.759
Unk. Tag#7	1.7375	-54.008
Unk. Tag#8	1.9414	-54.008
Unk. Tag#9	2.2403	-54.991
Unk. Tag#10	2.8756	-59.180
Unk. Tag#11	3.4306	-61.731
Unk. Tag#12	3.6082	-66.359

A16. Data Collected in the Mixed 500 ml Water and 500 ml Oil (1000 ml Total) Experiment for Reader Position#4 [8, 2, 2.33]

Reader Postion#4 [8, 2, 2.33]		
		RSSI
Obs #	Distance	Avg Y
Ref. Tag #1	4.0335	-71.730
Ref. Tag #2	3.2045	-65.266
Ref. Tag #3	3.7774	-73.543
Ref. Tag #4	2.5038	-66.066
Ref. Tag #5	2.0661	-62.334
Ref. Tag #6	1.5063	-58.912
Ref. Tag #7	3.7774	-74.150
Ref. Tag #8	2.8756	-61.782
Ref. Tag #9	3.2045	-67.547
Ref. Tag #10	1.5063	-57.716
Ref. Tag #11	2.5038	-66.664
Ref. Tag #12	2.0661	-66.823
Unk. Tag#1	3.0031	-68.867
Unk. Tag#2	3.4306	-69.805
Unk. Tag#3	3.3195	-71.937
Unk. Tag#4	2.2403	-64.110
Unk. Tag#5	1.9414	-62.443
Unk. Tag#6	1.7375	-62.643
Unk. Tag#7	3.8754	-70.794
Unk. Tag#8	3.4306	-68.144
Unk. Tag#9	3.6082	-70.894
Unk. Tag#10	2.0661	-64.733
Unk. Tag#11	1.9414	-64.508
Unk. Tag#12	2.2403	-66.359

APPENDIX B

SAS CODE FOR TIME STUDY EXPERIMENT 2

```
Data FLUID;
Input PT MD$ AR$ TIME;

Cards;
1    1    0.5   19
1    1    1.0   62
1    1    1.5   167
1    1    2.0   313
1    2    0.5   24
1    2    1.0   68
1    2    1.5   183
1    2    2.0   346
2    1    0.5   16
2    1    1.0   56
2    1    1.5   159
2    1    2.0   258
2    2    0.5   22
2    2    1.0   63
2    2    1.5   167
2    2    2.0   324
3    1    0.5   21
3    1    1.0   65
3    1    1.5   176
3    1    2.0   322
3    2    0.5   27
3    2    1.0   75
3    2    1.5   192
3    2    2.0   361
4    1    0.5   15
4    1    1.0   49
4    1    1.5   136
4    1    2.0   248
4    2    0.5   18
4    2    1.0   53
4    2    1.5   144
4    2    2.0   265
5    1    0.5   20
5    1    1.0   64
5    1    1.5   159
5    1    2.0   287
5    2    0.5   23
5    2    1.0   71
```

```
5       2       1.5     163
5       2       2.0     274
;
ODS RTF;ODS LISTING CLOSE;

Proc ANOVA;
Class MD AR;
Model TIME = AR;
Means AR/ Tukey ;
Run;

Proc ANOVA;
Class MD AR;
Model TIME = MD;
Means MD/ Tukey ;
Run;

Proc ANOVA;
Class MD AR;
Model TIME = MD*AR;
Means MD*AR/ Tukey hovtest=levene ;
Run;

Proc ANOVA;
Class MD AR;
Model TIME = MD AR MD*AR;
Means MD AR MD*AR/ Tukey hovtest=levene ;
Run;

QUIT;

ODS RTF close;

ODS LISTING;
```

REFERENCES

Agarwal, V. 2001. *Assessing the benefits of Auto-ID Technology in the Consumer Goods Industry*. Cambridge, University of Cambridge.

Alippi, C., Cogliati, D., and Vanini, G. 2006. "A Statistical Approach to Localize Passive RFIDs," *Proceedings of IEEE International Symposium on Circuits and Systems*, Island of Kos, Greece, May 21-24, T. Stouraitis, ed. 769-772.

Almaaitah, A., Ali, K., Hassanein, H. S. 2010. "3D Passive Tag Localization Schemes for Indoor RFID Applications," *IEEE International Conference on Communications (ICC)*, Cape Town, South Africa, May 23-27, F. Takawira and W. Leuschner, eds. 1-5.

Antony, J. 2002. "Design for Six Sigma: A Breakthrough Business Improvement Strategy for Achieving Competitive Advantage," *Work Study*, 51(1): 6-8.

Bouet, M. and dos Santos, A. L. 2008. "RFID Tags: Positioning Principles and Pocalization Techniques," *1st IFIP Wireless Days*, Dubai, United Arab Emirates, November 24-27, 1-5.

Brchan, J. 2008. *Realization of A Real-time Localization System Using A Passive Radio Frequency Identification Infrastructure*. Master’s Thesis, Department of Electrical Engineering, University of Nebraska-Lincoln, Brchan, J., Pérez, L. C. and Jones, E., 2008. “Performance of a Real-Time Localization System using a Passive RFID Infrastructure and Stochastic Received Signal Strength Ranging,” *To be submitted to the 2009 IEEE RFID Conference.*

Christian, et. al. 2006. “A Prospective Study of Patient Safety in the Operating Room,” *Surgery*, 139(2): 159-73.

CSL. 2013. *Active RTLS RFID Products*. Retrieved on 13 March 2013 from http://convergence.Com.hk/products_cat.Php?id=1.

Dean, A, and Voss, D.1999. *Design and Analysis of Experiments*. Springer Science + Business Media, Inc. NY, USA.

Fisher, J. A. and Monaha, T. 2012. “Evaluation of Real-Time Location Systems in Their Hospital Context”, *International Journal of Medical Informatics,* 81: 705-712.

Gawande A. A., et al. 2003. “Risk Factors for Retained Instruments and Sponges After Surgery,” *N Engl J Med*., 348: 229–235

Mouhsine E., et al. 2005. “Soft-tissue Textiloma: A Potential Diagnostic Pitfall,” *Can J Surg*., 48:495-496.

Gibbs, V. C. 2009. *Chapter 22. The Retained Surgical Sponge*. AHRQ. U.S. Department of Health and Human Services, n.d. Web.

Hightower, J., Want, R., and Borriello, G. 2000. *SpotON: An Indoor 3D Location Sensing Technology Based on RF Signal Strength*. UW CSE Technical Report #2000-02-02, University of Washington, Department of Computer Science and Engineering, Seattle, WA.

Joint Commission. 2011. *Sentinel Event Data: General Information: 1995–Third Quarter 2011*. Retreived on 27 November 2012 from http://www.jointcommission.org/assets/1/18/General_Information_1995-3Q2011.pdf.

Jones, E. C. 2005, "RFID Technology for tracking Inventory in the Space Shuttle," *Proceedings of the Annual Meeting of the Nebraska Academy of Sciences, Aeronautics & Space Science*, Lincoln, NE.

Jones, E.C., et al. 2010. *Investigating RFID for Roadside Identification Involving Freight Commercial Vehicle Operators (CVO)*. Final Report. Mid-America Transportation Center (MATC)

Jones, E. C. and Siveray, J. 2008. "Testing of Gen 2 RFID Tags for Tracking Inventory in The Space Shuttle," *Journal of Air Transportation*, v.12.

Kaiser C.W., et al. 1996. "The Retained Surgical Sponge," *Annals of Surgery*, 224(1):79-84

Malik, A. 2009, *RTLS for Dummies*. John Wiley, Hoboken, N.J.; Chichester.

Macario A., Morris D., and Morris S. 2006. “Initial Clinical Evaluation of A Handheld Device for Detecting Retained Surgical Gauze Sponges Using Radiofrequency identification Technology,” *Arch Surg*.; 141:659-662

MEDCEU, 2011. *Medical Error Prevention and Patient Safety*.. Retrieved on 30 January 2013 from http://www.medceu.com/index/index.php?page=get_course&courseID=3016&nocheck

No Thing Left Behind. *Retained Surgical Items*. Retrieved on March 15, 2013 from http://www.nothingleftbehind.org/.

Patterson, E. S., Rogers, M. L., and Render, M. L. 2004. “Fifteen Best Practice Recommendations For Bar-code Medication Administration in The Veterans Health Administration,” *Joint Commission Journal on Quality and Safety.* 355-365.

Qin-Qin, S., et al. 2006. “Using Linear Intersection for Node Location Computation in Wireless,” *Acta Automatica SInica*, 32: 6.

Rao, B. M., Shukla, ,Saint-Cyr and Teotia, S. M..2012. “Take Two And Text Me in The Morning: Optimizing Clinical Time With A Short Messaging System,” *American Society of Plastic Surgeons,* 130:1.

Rappoport, A. 1984. “A Hospital Patient And Laboratory Machine-readable Identification System (MRIS) Revisited,” *J Med Syst*, 8:133–156.

RF Code. 2013. *M250 Fixed Reader*. Retrieved 15 March 2013 from http://www.rfcode.com/Readers-RTLS-Devices/m250-fixed-reader.html.

Ribalta T., et al. 2004. “Textiloma (Gossypiboma) Mimicking Recurrent Intracranial Tumor,” *Arch Pathol Lab Med*; 128:749-758.

Rivera, *et. al.* 2008. “ASSIST – Automated System for Surgical Instrument And Sponge Tracking,” *IEEE International Conference on RFID*. Nevada.

Rogers A. 2007, Jones, E. C., and Oleynikov D. “Radiofrequency Identification (RFID) Applied to Surgical Sponges*,” J Surg Endosc,* 21(7):1235–7.

Rowlands, A. 2012. “Risk Factors Associated With Incorrect Surgical Counts,” *AORN J*. 96: 272 284.

Rupp C.C., Kagarise M.J., Nelson S.M., et al. *J Am Coll Surg. 2012*;215:524-533.

Sanpechuda, T., and Kovavisaruch, L. 2008. "A Review of RFID Localization: Applications and Techniques," *IEEE 5th International Conference on Electrical Engineering / Electronics, Computer, Telecommunications and Information Technology, (ECTI-CON)*, Krabi, Thailand, May 14-17, 2: 769-772.

Seo, D., Won, D., and Yang, G. 2005. "A Probabilistic Approach for Mobile Robot Localization under RFID Tag Infrastructures," *International*

Conference on Control, Automation, and Systems (ICCAS), Gyeonggi-do, Korea, June 2-5, 1797-1801.

Sokovic, M., Pavletic, D. and Kern Pipan, K. 2010. “Quality Improvement Methodologies – PDCA Cycle, Radar Matrix, DMAIC and DFSS,” *Journal of Achievements in Materials and Manufacturing Engineering*, 43(1): 476-483

Southard, P. B., Charu, C. and Kumar, S. 2012. "RFID in Healthcare: A Six Sigma DMAIC and Simulation Case Study," *International Journal of Healthcare Quality Assurance*, 25:4.

Stawicki, et al. 2013. “Retained Surgical Items: A Problem Yet to Be Solved,” *Journal of the American College of Surgeon*, 216(1): 15-22.

Steelman, V.M. 2010. “Sensitivity of Detection of Radiofrequency Surgical Sponges: A Prospective, Cross-over Study,” *The American Journal of Surger*, 201: 233-237.

Steelman, V. M. and Alasagheirin, M. H. 2012. “Assesment of Radiofrequency Device Sensitivity for The Detection of Retained Surgical Sponges in Patient With Morbid Obesity,” *Archive Surgery*;147: 955-960

Steelman V. M. and Cullen J.J. 2011. “Designing A Safer Process To Prevent Retained Surgical Sponges: A Healthcare Failure Mode And Effect Analysis,” *AORN Journal,* 94: 132-141.

Steggles, P. and Gschwind, S., 2005. “The Ubisense Smart Space Platform,” *Adjunct Proceedings of The Third International Conference on Pervasive Computing*,191:73–76.

Tacyildiz I. and Aldemir M. 2004. “The Mistakes of Surgeons: “Gossypiboma”,” *Acta Chir. Belg*., 104:71-75.

Wu, J. 2012. “Three-Dimensional Indoor RFID Localization System,” Dissertation, University of Nebraska-Lincoln, Lincoln, NE.

Yeh, L., Hsu, M., and Lee, Y. 2009. "Indoor Localization: Automatically Constructing Today's Radio Map by iRobot and RFIDs," *IEEE Sensors*, Christchurch, New Zealand, October 25-28, S. C. Mukhopadhyay, ed. 1463-1466.

Zbar, A. P., et al. 1998. “Gossypiboma Revisited: A Case Report And Review of The Literature,” *Journal of the Royal College of Surgeons of Edinburgh*, 43(6): 417– 418.

Zhao, L., 2007. *Design and Performance of Ultra Wide Band Localization Systems*. M.S. Thesis, University of Nebraska-Lincoln, Lincoln, NE.

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