REAL TIME LOCATION TOOL FOR PRECISION TRACKING OF PASSIVE UHF RFID TAGS IN TWO DIMENSIONS

by

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ABSTRACT

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TRACKING OF PASSIVE UHF RFID

TAGS IN TWO DIMENSIONS

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This thesis considers a precise RTLS (Real Time Location System) implemented with a Passive UHF RFID system. Software is created to interact with an RFID reader to collect the tag's backscatter power in terms of the RSSI (Received Signal Strength Indicator), as well as read the tag's ID. The software also reads from a web camera, and locates the tags within the camera's point of view by using only the RSSI of the tag. It is capable of computing the locations of tags by locking on each tag's unique EPC, and marking their location and corresponding tag ID on the screen. By comparing the tag on the screen, with the marker of the calculated location, the accuracy of this system is established.

The calculations involve a simplified path loss model which computes the tag's distance from the reader antennas, followed by a multilateration calculation which locates the tag on a two dimensional plane in front of the web camera. To compensate for environmental factors, the software first performs a calibration to map the environment using numerous calibration tags with known locations. The result of this work is a tool which can be used to identify, locate and track tags in real time, and also to analyze the environment and perform RFID localization in general.

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CHAPTER 1

INTRODUCTION

RTLS (Real Time Location System), as the name implies, is a system that enables the localization of people and objects in real time. These systems utilize increasingly sophisticated electronic devices called tags that are attached to objects. Location sensors can then find, track, and manage these objects by associating them with the tags that are attached to them. Technologies such as GPS, camera vision, infrared, sound, Wi-Fi, radio frequency identification (RFID), cellular, and many more can be used for both indoor and outdoor locating of people and objects. Each technology comes with its own advantages and disadvantages based on the requirements for line-of-sight, cost, range, and environmental performance. In this thesis the application of RFID for RTLS was investigated. The passive UHF (Ultra High Frequency) RFID system includes a reader with antennas connected to it, passive tags, and custom software developed for analysis. This is a relatively inexpensive system.

Various RTLS models exist for a variety of applications. For example you may want to detect objects at a choke point, or to sense whether an object is present in a room or near a specific area [1]. However, a much more interesting problem which is delved into in this thesis is posed by attempting a more precise localization. In this model the tag is “read” by the reader and is then localized externally by the custom software which marks its location in the frames which are captured from the point of view of the webcam.

Section 1 gives a brief introduction to the components of the passive UHF RFID system, its communication technique and its interactions with the environment. This section also describes the nomenclature used in describing the system. Section 2 discusses the background and application of RFID systems, and emphasizes the importance of RTLS in various supply chain applications. Finally, Section 3 outlines the remainder of this thesis.

1.1 RFID System

RFID systems are an automated identification, and data collection technology with a wide array of applications. The requirements from one application to another vary extensively. Generally greater operating frequency and power will result in greater transmission range between the tag and the reader. Some applications require short range, i.e. 1-cm at the low operating frequency of 13.56MHz, while other applications, particularly those with extended range requirements, will necessitate the use of UHF (Ultra High Frequency).

1.1.1 RFID Tag

RFID systems are composed of three vital subsystems; tag, reader, and the information system. The tag identifies the unit it is attached to, and may contain other useful data as well. A typical passive RFID tag will include an antenna, and a rectifier for deriving power from an electrical field, and a control unit [2]. An application subsystem within the tag would require additional processing capacity, and may include capabilities such as temperature, shock, or pressure sensing.

Low cost passive tags usually don't include an application subsystem; however some like the Gen-2 tag may contain user writable memory. Tags are defined by a certain protocol, which is typically programmed into the tag. For the purposes of this thesis the EPC Class 1 Gen 2 protocol will be the protocol of interest. This is the current protocol most often used with passive UHF tags. Technological development has been hampered by the lack of standardization, and this is no less true for UHF RFID systems. EPC is a standardization effort in order to provide the framework for the development of the RFID technology [3]. The protocol for EPCGlobal Class 1 Generation 2 is available in [4].Tags operate as coprocessors, or slaves to the reader. Most tags (passive tags especially) do not have a backend interface, since they only communicate with the reader.

1.1.2 RFID Reader

The reader is a gateway to the information contained on the tag. It is comprised of RF interface, a communication control system, some sort of an application subsystem, and a network. The control system contains the protocol for interacting with and identifying the tag. This protocol is defined by the same protocol as the one on the tag, i.e. the EPC Class 1 Gen 2 protocol.

Aside from its basic operation, an application dependant subsystem may exist on the reader, depending on the application requirement. The reader network decodes the data and sends it to the information subsystem. Figure 1.1 illustrates the general setup of an RFID network. The reader has a backend interface linking it with the information subsystem. The reader and the information subsystem are linked to each other via some sort of a cable or wireless communication interface. The readers themselves contain one or more antennas that are used to communicate with the tags.

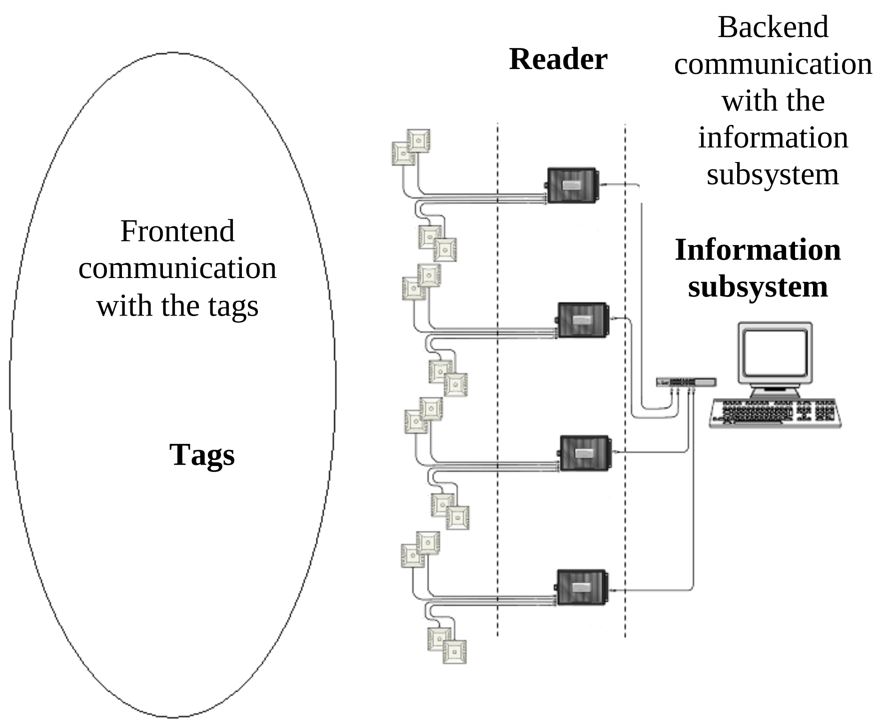


Figure 1.1 RFID Network

A reader cannot communicate using more than one antenna at a time, so for readers that implement more than one antenna, the antennas are cycled from one to another. Cycling of multiple antennas would decrease the ranges of the individual antennas. For the purposes of this thesis, only two antennas are connected to the Sirit reader. The antenna pair works in two modes. In the first mode each antenna is utilized to read the tags in the interrogation zone separately, and then all the tags within both antennas' interrogation zones are identified and combined into a single list. In the second mode each antenna is utilized to read the tags within its respective interrogation zone separately, and the resulting data is archived and analyzed separately.

1.1.3 RFID Information System

The information subsystem is where the real processing of a RFID system takes place. This is where the data collected from the tags is archived. The user is provided with various important data, and alerted if there are any discrepancies or relevant events arise.

This thesis relates to all three components of the RFID system; the tag, reader, and the information subsystem. Much of the work involves the reader, and developing a program within its information subsystem. The development of the information subsystem incorporates the ability for capturing the desired data from the reader and storing it in the computer. The data is then analyzed using the developed software tool to provide insight into the reader's environment when the software is in calibration mode, and the tag location when the software is in localization mode.

1.1.4 RFID Passive Communication

The RFID system is classified based primarily on the classification of the tags [5]. The tags are classified on the basis of their communication scheme and whether they contain an on tag power source. Tags that do not feature an on tag power source are classified as passive tags. A passive system uses various passive communication techniques such as load modulation, backscatter communication, and derive their power from the reader's interrogation signal [6]. Passive systems rectify the RF signal and boost it to a suitable DC level using a charge pump or voltage multiplier [7]. Remote powering of the tag is considered the most challenging problem in passive UHF RFID systems. This is especially true for UHF tags due to their longer transmission range, and the limited power they extract from the reader's signal.

In passive RFID systems there are two primary ways of communication, i.e., in the near field, and in the far field. Near field is generally applied for HF and LF tags but more recently near field UHF systems are becoming more and more of interest [8]. Generally most passive UHF is currently geared for far field, but the same analysis that can be done for far field tags can be done for near field tags [9]. Note that near field and far field regions are determined by the physical characteristics of the antennas and the ranges involved.

For the near field case, the Reader antennas also should be optimized for inductive coupling to the tag. The time-varying magnetic field then induces current through the coils on the tag, thus charging the capacitor. The tags within this field will then power up. These tags communicate by altering the impedance of the load connected to their antenna. This causes the antenna of the tags to be tuned in and out, causing variations in the tag's coupled power. These variations are assigned a coding scheme and impedance modulated. Because of the closely coupled antennas the reader detects the variations on the coupled power.

The Reader antennas that are utilized here do not generate a significant reactive near field; rather the reader and tag communication, for the purposes of this thesis, takes place in the far field region. Here the reader generates a sinusoidaly modulated electromagnetic "carrier" wave. Tags detect the electromagnetic radiation and begin harvesting power from it [6]. In this case the reader cannot detect how much power is being coupled, but rather it detects the reflected signal [10]. The program developed in this thesis will utilize the measured strength of this signal, which is also called the backscatter signal. The RF signal from the reader induces a voltage at the input terminals of the tag, thus charging the capacitor and powering the tag.

1.1.5 RFID Nomenclature

In the RFID nomenclature the UHF frequency range is between 860 and 960 MHz. 2.45GHz and 433MHz are technically UHF but in the RFID nomenclature they are called microwave and 433 respectively [11]. The 902-928 MHz band is devoted to UHF RFID communication under FCC regulations [12]. In this thesis the focus is on the passive UHF frequency range which is centered at 915MHz. UHF systems have large interrogation zones that are influenced heavily by the environment.

1.1.6 RFID Environment

The power in the signal attenuates exponentially as a result of spreading loss through the air. Water, humidity and other obstructions make the attenuation even more severe. The environment in which the RFID system is operating is one of the most important factors in making decisions about how to use an RFID system. Thus, in order to characterize RFID system operation the environmental impact must be taken in to account.

Passive systems are generally reader-talk-first systems. The reader sends a moderate power, signal into the interrogation zone. The tags then go through a power up sequence, and wait for the command using envelope detection. UHF tags are broad band receivers. If a reader sends a command to a tag, and another reader is talking to another tag somewhere else, the tag will receive both of these signals superimposed, and then interpret what it has received [13]. Passive UHF tags do not filter or differentiate channels. This is where if multiple readers are on at the same time reader collision issues come into play, and errors can take place, especially for sensitive tags. This is also one of the reasons why readers implementing more than one antenna must operate only one antenna at a time by cycling through them.

In this thesis it is necessary to implement only two antennas, however up to four antennas can be connected to the reader at any one time, since we are utilizing the Sirit Infinity 510 reader. The localization solution presented in this thesis implements only one reader, thus avoiding the complexity of reader collisions. Aside from alleviating the problem of reader collisions, implementing multiple readers becomes a fairly expensive solution to the tag localization problem.

1.2 Background

RFID is a technology intended for identification of objects within the reader's interrogation zone. Unlike bar codes, RFID tags do not have to be within the line of sight of the reader. RFID tags can also perform under harsh environmental conditions while barcodes may not [11]. Barcodes also cannot store a great deal of data and cannot be altered, while RFID tags contain on-tag memory containing relevant data about the objects they are attached to. RFID tags also allow the user to write additional information on to the tag's memory, as well as uniquely identify the object they are attached to, while bar codes do not. RFID tags are more efficient in that multiple tags can be read at the same time while barcodes cannot.

1.2.1 Application

Adaptation of RFID technology is a move towards automation, where human interaction with the product is minimized. By using RFID, retailers like Wal-Mart can better track and control the merchandise, and thus make various decisions regarding the stock quantities [15]. This technology will potentially lead to more efficient stocking and smaller quantities of merchandise stored in warehouses. RFID is an excellent tool in the prevention of theft, and finding lost or misplaced merchandise.

In light of these benefits it is not hard to see why Wal-Mart is the biggest backer of RFID technology in the retail supply chain. RFID is becoming more and more common throughout the retail industry. Wal-Mart now mandates its top suppliers to tag pallets of merchandise. These mandates specifically require the use of EPC Class0 and Class 1, 96-bit Gen1 tags [11]. As for the future requirements, Wal-Mart is moving towards the adoption of passive UHF tags currently on the market that implement the Gen2 EPC protocol. The RFID tag will have the Electronic Product Code (EPC) which is a unique item identification code contained within the tag [16].

Other large organizations like Procter and Gamble, and the United States Department of Defense are also deploying RFID as a useful tool for making the oversight of their supply chains more automated. Four intervals in the distribution cycle have generally been identified [11]: Initially the RFID tags are placed on their respective items at the manufacturer's facility. This is when the tracking of the item begins. The next interval is at the distribution center where the items are not only tracked as they enter and move around the facility but also as they are finally leaving the facility. The item is then shipped to the retailer and stored at the warehouse in that center. The items are tracked as they are transported throughout the facility and as they are finally moved from the store room to the sales floor. The final interval is when the customer purchases that item.

Companies that supply Wal-Mart with a diverse variety of products, ranging from foods and household cleaning products to clothing and athletics equipment, will need to allocate resources to the understanding and implementation of the RFID technology. To implement RFID on these products these suppliers have to take into account the various requirements for their application. The requirements will depend upon the shape, orientation and material properties of these products, as well as what environment these products will located in. They will also need to assess different tags available on the market today, and choose the one which is most suitable for their application requirements.

The tool developed in this thesis helps compare performance for different environments, over the ranges the tags will need to operate in. This is an important research topic for various RFID applications. This tool after characterizing the environment can then be applied to solve another major issue in the RFID world which is tag localization which goes hand in hand with tag tracking. As mentioned above tracking of tags is a major application of an RFID system.

Another aim of the tool created in this thesis is to map real-world situations to the virtual world. Tags located within the point of view of a web camera are localized and identified by the RFID tool and their locations are specified on the computer screen. This could potentially allow us to create a real time model of the real world in the virtual world. This model can account for the dynamics of the real world, by associating tags to objects that can be tracked even if no line of sight is available.

1.3 Thesis Organization

The remainder of this thesis gives detailed descriptions of tools, processes, and algorithms implemented in this thesis. The thesis also provides details regarding the software tool that was developed and finally the results. Chapter 2 details the selection of the hardware used in the system development. Chapter 3 details the localization techniques, and the algorithms which are implemented in the software tool. Chapter 4 provides information about the software tool's capabilities, and architecture. Finally Chapter 5 provides the analysis of the performance carried out by the software tool, as well as conclusions and future work.

CHAPTER 2

HARDWARE SELECTION

Equipment such as a high performance RFID reader, two reader antennas, a web camera, and RFID tags were utilized for the completion of this thesis for evaluating RFID tags, in order to become familiar with their characteristics, and to ensure that the requirements for the achievement of the goals are met. Both commercial and custom built software were used, the latter being the primary realization of this thesis. The environmental harmony was a major factor in the operation of RTLS. The amount of metal, human traffic and other interferences such as florescent lighting was controlled in the physical layouts of the experiments.

Section 2.1 gives details about the Sirit reader and how this particular reader's capabilities satisfy the requirements of the RTLS developed in this thesis. Section 2.2 explains the selection of the reader antennas, what specifications and constraints were considered and what regulations were considered. Section 2.3 explains in detail the experiments carried out in order to select the most suitable tag, and how the Voyantic system, which is a tool for analyzing tags, was useful in this endeavor. Section 2.3 gives a brief summary of the capabilities of the selected tag type, and why this particular tag type was selected. Finally, section 2.4 describes additional aspects important to this thesis, including other off the shelf devices, the environment selected and custom-built components.

2.1 Reader Selection

The passive UHF RFID system INfinity 510 from Sirit Inc. was configured as the location sensor for RTLS. Figure 2.1 shows the Sirit reader. This reader is designed to be stationary, and it will have a fixed position during the experimentation. The Sirit reader can be connected to a computer through either Serial or Ethernet ports. For this thesis the connection from the Ethernet port was utilized. The reader is interfaced with the custom software through a socket communication, containing its own IP address and port number as if communicating with a computer.

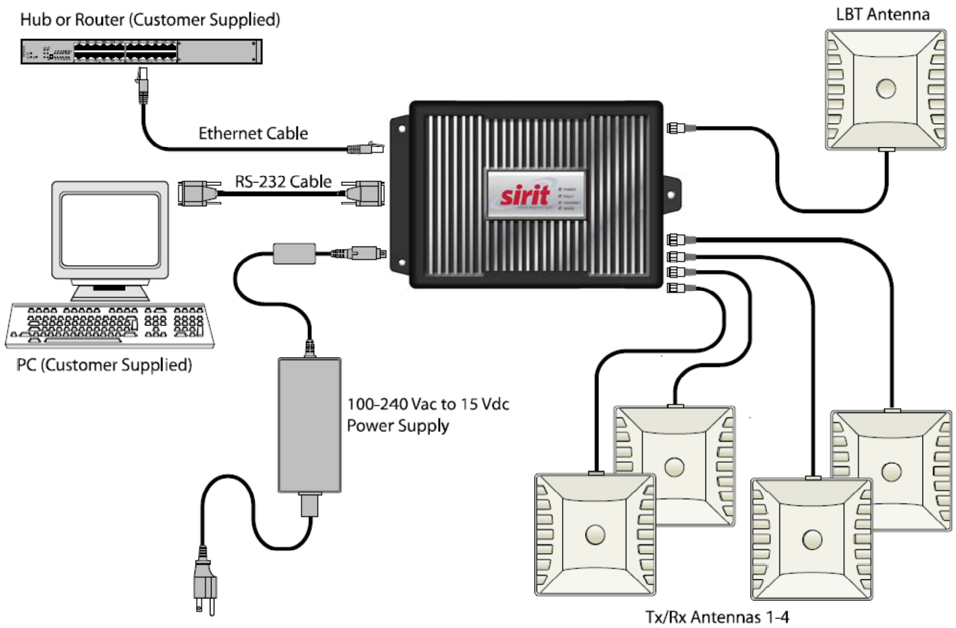


Figure 2.1 Configuration of Sirit INfinity 510 Reader [17]

One major advantage in using this particular reader, as opposed to other available high performance readers such as the Alien ALR-9800, is that for the Sirit system the RSSI (Reflected Signal Strength Indicator) for the backscatter signal of the tag is internally measured and readily accessible via commands sent by the software. Without this feature the RSSI must be calculated via analysis of the backscatter signal of the tag at varying transmission power levels.

Although RSSI is used often in various modern communication systems, there are no set standards and as the name RSSI "reflected signal strength indicator" implies it is merely a quantified indicator, not the actual power measurement [18]. The calibration mapping and the localization analysis carried out in this thesis are based on the RSSI values recorded by the Sirit reader.

The INfinity 510 reader is equipped with four Tx/Rx antenna ports and one listen before talk (Rx) antenna port. Using a single antenna for both transmitting and receiving signals will result in a loss of communication range. This system offers the choice to devote some antennas in the system exclusively for transmitting operations, and others for receiving. However this would increase the number of antennas required to communicate with a single tag. The procedure opted for in the analysis presented here each of the antennas be utilized for both sending and receiving, with one antenna operating at any one time.

While this technique would reduce the number of antennas needed it comes at the expense of significant loss of range. In the case where multiple antennas are connected to the reader, in addition to circulating a single antenna between receiving and transmitting, the individual antennas connected to the system may be cycled through. The Sirit Reader offers great flexibility in configuring which antenna ports to use and in what sequence and frequency to use them [19].

2.2 Reader Antenna Selection

In order to minimize the likelihood of polarization mismatch the two antennas used were chosen to be circularly polarized, and capable of reading in any orientation. The radiation pattern shows that this antenna radiates more power directly in front of it. The easy to mount PATCH-A0025 antenna shown in Figure 2.2 was used.

Figure 2.2 PATCH-A0025 Antenna [20]

The antennas are designed for operation over 860 – 960 MHz, with maximum gain and minimum VSWR at 915 MHz which is the center frequency. The antenna is designed to operate at a maximum of 1watt, which is the maximum power that the sirit reader offers in line with FCC regulations. To meet these regulations the antennas with higher gain must have decreased power to compensate for their increased gain.

The antenna features VSWR of less than 1.2:1 [21]. VSWR **(**voltage standing wave ratio) is the ratio of the amplitude of the standing wave at its maximum to the amplitude at an adjacent minimum. The phenomenon of standing wave in this case is caused by some of the transmitted power through the coaxial cable being reflected back to the transmitter due to the mismatch of the antenna impedance. The interaction of these reflected waves with the transmitted waves causes the standing waves. This will result in distortion and loss of energy in the transmission and, if significant, it will damage the reader. According to the antenna datasheet the return loss expected from this phenomenon is 20dB.

2.3 Tag Selection

In our experiments it was important to keep the tag performance consistent, which meant that only one model tag was to be used at a time. Hence one of the objectives was to select the most appropriate tag for our experiments. The ideal tag for this thesis is a versatile tag that can operate in a wide range of environments. To help make this selection, a RFID analysis tool called Voyantic system was utilized. This system was used to analyze a wide range of passive UHF tags on different products.

The Voyantic system emulates a reader, and collects a range of useful data about the tag's performance. In a series of experiments 10 tags were tested on 4 typical materials that may be of interest in a real world scenario. Since the majority of tags perform differently on different materials, the Voyantic system facilitates comparisons of different tags. The results of this analysis showed which one of the tags would operate best under each scenario.

2.3.1 Voyantic Tagformance System

The Voyantic [22] system was used to test the performance of RFID tags in a variety of scenarios. The Voyantic system measures the various properties of the tag during the communication process. Thus the Voyantic system controls the generated RF carrier and the modulated carrier.

The Voyantic system comes along with a specially designed circulator which is intended to limit the power in order to protect the RF input. This is important because the dynamic range at the receiver input is -120 to 0 dBm while the RF output reaches 30dBm, thus the isolation provided by the circulator should be better than 30dBm.

The software controls frequency and power sweep operations. Tag sensitivity is determined by doing a power sweep where the power level required for turning on and communicating with the tag is plotted. The backscatter signal level is also recorded.

2.3.2 Experimental Setup

It was strongly recommended by the Tagformance Manual that the transmitting and receiving antennas be positioned at least 20 centimeters apart from each other. Also the support structure for the antennas should be made out of wood or plastic, and large metallic objects and sheets should be kept at least one meter away from the antennas. It is also recommended that the antennas be placed at a height of one meter from the ground [22].

The tags were tested in a two meter-wide hallway and at a one meter distance from the transmitting antenna. In these experiments the tag was placed 1 meter from the antenna. The environment for which the testing took place was far from ideal, because of the interactions with the walls, the door and other objects.

Table 2.1. Material Used for Posting the Tags

Material:	Electric Permittivitvity	Dimensions:	Description:
Card Board	2 [23]	3 mm thickness, 30 cm length, and 15 cm width	a chunk of card board from a box with
Water	80 [23]	28 cm high and 5 cm radius	20 oz, plastic bottle of water
Olive Oil	3.0981 [24]	30 cm x 7 cm x 7 cm	a liter, Oil in rectangular glass
Butter	6.226 [25]	3cm x 3cm x 12cm	a stick of butter

The series of experiments were carried out, as each of the ten tags were successively tested on cardboard, water, stick of butter, and glass bottle of olive oil. The list and descriptions of the objects used in this experiment are shown in Table 2.1.

Table 2.2. List of Tags Used in the Experimentation

	Tag name:
1	Corporate express T1-UHF Gen2
2	MPI systems alien squiggle Gen2 MPI-ALN-9640
3	MPI systems Ti Dalins Gen2 MPI-RX-UHF-0001-03
4	UHF tag labels for T87 George Dyche by Avery Denisson
5	MPI Systems Avery Gen2 MPI-AD220
6	Smart mark, by William Frick and Company
7	WF-SM-IN02 blue colored tubes embedded in foam 360 degree Fahrenheit proof by William Frick and Company
8	Corporate express UPM Rafsel PD70-18-6-MI
9	ADASA
10	Bow tie tag by Avery Dennison

The tags were chosen to be UHF tags implementing the EPC Class1 Gen2 Protocol. HF tags and those using any protocol other than the EPC Gen2 were not used in these experiments since the Voyantic Tagformance is only meant to accommodate UHF Gen2 tags [22]. The ten tags analyzed in this project are listed in Table 2.2.

2.3.3 Tag Performance Measurements

The Voyantic system offers two measurements; the Electromagnetic field thresholds, and the Backscatter analyzer. In the Electromagnetic field thresholds mode the frequency can be swept from 800MHz to 1000MHz with a certain specified frequency and power step, and the transmitted power is plotted in dBm versus frequency. In the Backscatter analyzer mode the transmitted power is swept from 0-27dBm with a certain specified power step and set frequency, and the received power is plotted in dBm versus transmitted power in dBm.

The electromagnetic field threshold experiments were carried out by setting the frequency sweep start frequency to 860MHz, and the sweep stop frequency to 960MHz. The frequency step specifies the frequency change with each measurement point, and in the experiments carried out here the value was left to the default 5MHz. The power step value was set to the default value which is 0.5dB.

In the Backscatter analysis mode the transmitted power was swept from 0 dBm to 27dBm, while the frequency was set at a constant 915MHz. The power step was set at the default

.5dB. The software can generate the plot of frequency and power for UHF ranges, starting from the minimum power required to turn the tag on (which is a good indicator of the tag sensitivity). The software also allows for the measure of the tag's backscatter signal strength.

2.3.4 Tag Performance Evaluation

Each experiment included the ten tags being placed, one by one at a distance of one meter from the transmitting antenna. The backscatter analyzer measurements were taken first. This is because it was necessary to first determine whether the tag is responding in the first place. Each time around, four measurements were taken to insure consistency, and accuracy of the tag reading operation. If the measurements were too different, e.g..due to interference or change in the environment, steps were taken to correct this inconsistency. During the experiments the tags were oriented so as to optimize its polarization characteristics. The summary of the backscatter analysis is shown in Tables 2.3 and 2.4.

Table 2.3. Summary of Tag Performance Specifications, Results of the Frequency Sweep Analysis, Tag's Backscatter Power at 915MHz

Tag #	Transmitted Power at 915MHz for cardboard	Transmitted Power at 915MHz for Water	Transmitted Power at 915MHz for Olive Oil	Transmitted Power at 915MHz for Butter
1	14.5dBm	26.5dBm	21dBm	16dBm
2	15dBm	23dBm	21.5dBm	13dBm
3	14.5dBm	0dBm	26dBm	19dBm
4	16dBm	0dBm	22dBm	17.5dBm
5	14dBm	24.7dBm	20dBm	16dBm
6	14dBm	23.5dBm	19dBm	15.5dBm
7	16dBm	24dBm	19dBm	15.5dBm
8	13.5dBm	27.5dBm	21dBm	17dBm
9	13.5dBm	22.5dBm	18dBm	14.5dBm
10	12.5dBm	28dBm	20.5dBm	16dBm

Table 2.4. Summary of Tag Performance Specifications, Results of the Backscatter Analysis

Tag #	Maximum Backscatter Power in Cardboard	Maximum Backscatter Power in Water	Maximum Backscatter Power in Olive Oil	Maximum Backscatter Power in Butter
1	-46 dBm	-45.9 dBm	-38.5 dBm	-36.1 dBm
2	- 41 dBm	-47.9 dBm	-47.9 dBm	-40.5 dBm
3	- 38 dBm	0 dBm	- 47.9 dBm	-43.6 dBm
4	- 45 dBm	0 dBm	-46.4 dBm	-38.4 dBm
5	-46 dBm	-47 dBm	- 39 dBm	-36.8 dBm
6	- 40 dBm	- 48.3 dBm	- 42.4 dBm	-36.5 dBm
7	-35 dBm	-35 dBm	- 37.7 dBm	-34 dBm
8	- 46 dBm	-63.2 dBm	-38.5 dBm	-36 dBm
9	- 47 dBm	-45.2 dBm	-39.1 dBm	-37.8 dBm
10	- 37 dBm	- 66 dBm	- 38.2 dBm	-35 dBm

The electromagnetic fields threshold measurements were taken next, as the frequency was swept from 860 MHz to 960 MHz. The power step was selected by default to be 0.5 dB. During the Electromagnetic Field Thresholds analysis the transmitted power is increased or decreased by the originally set power step just enough to keep the tag operational at each of the frequency points during the sweep. Because of the regulations set by FCC for UHF RFID systems, in the United States the UHF tag must operate in 902 - 928 MHz range. In a none-ideal laboratory environment like the one in this Thesis, various imperfections like objects in the vicinity of the testing zone have the effect of changing the tag's operating frequency. Despite this, in the quest to find the optimal tags for the various scenarios (ie. Cardboard, water, olive oil, and butter) tested for, the tag operation near 915 MHz was given special attention. The summary of the frequency sweep analysis is shown in Table 2.3.

2.3.5 Tag Performance Conclusion

Tag2, the Alien squiggle tag has the least transmitted power requirements of all the tags when placed on butter, which is 13 dBm at 915 MHz, thus performing most favorably. The Alien squiggle tag had a consistent overall performance on a variety of objects. For example Tag3 showed better performance on cardboard than Tag2, but failed completely when used on a water bottle. Hence the Alien Squiggle tag was the tag of choice for the localization experiments.

The results of this analysis were accurate: The data gathered from the backscatter analysis followed the same trend as the data gathered from the threshold analysis.

The testing of tags in different scenarios allowed for deeper understanding of some of the fundamental concepts of Electromagnetism, and electric properties of material. It was shown that material with low electric permittivity like cardboard, or olive oil do not influence the operation frequency of the tag as much as material with high electric permittivity.

During the frequency sweep experiment, as the frequency was increased the general trend was that the tags required higher transmitted power to communicate. This is currently one of the major issues with implementation of UHF versus HF tags. Tables 2.3 and 2.4 summarize two of the most important parameters used in this thesis to analyze the Tag performances.

2.3.5 ALN-9640 Squiggle tag

In an RFID system, designing an appropriate tag antenna is an issue of major concern. Maximizing the received energy is the key to increasing the range and robustness of an RFID system. The existing two-dimensional UHF RFID tag antennas have natural orientation limitations and material sensitivities. The ALN-9640 Squiggle tag is an EPC Gen2 compliant passive UHF RFID tag [26]. It supports all mandatory and optional commands of the Gen2 protocol. This versatile tag is designed for wide ranging applications as confirmed by the experiments carried out. Figure 2.3 shows the tag selected for use in the localization experiments.

Figure 2.3 ALN-9640 Squiggle Tag [26]

It was shown by a series of experiments that although the interrogating RF waves are circularly polarized, the most nearly optimal orientation for the tags is a vertical placement. And this is corroborated by the tag datasheet. During subsequent experimentations from one environment to another the orientation of the tag should remain consistent. Polarization of the tag antenna must be matched with the reader antenna for maximizing the range. The matching is characterized by the polarization matching coefficient. For example using a circularly polarized reader antenna with a linearly polarized tag antenna will incur a 3 dB loss [27].

Although not needed for the localization process the tag offers writable memory, various levels of password protection, and implements some commands which will not be used, such as the kill command. The software developed in this thesis gives the user the ability to manually type in these commands.

2.4 Additional Infrastructure

The Programming, simulations, and analysis were carried out by a computer [28], which was linked to the reader by an Ethernet connection. A web camera was linked to the computer via USB. This camera was used to capture the tag localization environment, the calculated tag locations, and the positions of the unknown and calibration tags. Both the camera and the reader were interfaced to the software tool. The custom software is the major development of this thesis and will be detailed in Chapter 4.

Several web cameras were purchased and evaluated. Inexpensive web cameras were used at the early phase of development. In this phase, the features of web cameras and the accessibility of their functionality from the localization tool were explored. After some evaluation and exploration it was decided that a higher end web camera with a wider screen resolution, and a minimum capability of 640x480 was desirable. This choice would allow more tags to be visible in the camera's point of view. Microsoft's LifeCam Cinema web camera was found to be suitable.

Coaxial cables were used to connect the reader and the antennas [19]. Stands were built on which the antennas were mounted. Care was taken so that the infrastructure was as metal free as possible. Figure 2.4 shows the front and back views of the antenna, tag, and the web camera arrangement. The figure shows the web camera mounted at the intersection of the poles on which the antennas are mounted. Also shown in the figure are the tags arranged on the wall. The antennas are positioned one meter from the wall. The computer and the reader connected to this infrastructure are behind the antennas and not visible in Figure 2.4.

Figure 2.4 Antennas, Web Camera and Tag Mounting on Infrastructure, Front and Back View

CHAPTER 3

LOCALIZATION

In this chapter, the RTLS procedure utilizing the components of the passive UHF RFID system will be discussed. Tags characterized as passive can only be read when located within the RF field of the reader. This limitation in itself presents a built in RTLS. This is because if the tag is successfully read, then it can be inferred that the tag is somewhere within the reader's interrogation range. However a much more precise RTLS can be achieved by analyzing the tag's RSSI, and accounting for the environmental attenuation. This is done by using a path loss model, which is applied to determine the empirical effects of the attenuation within an environment [30].

The complexities posed by passive RFID communication in a variety of environments have been previously described in Chapter 1. Although it is difficult to find a path loss model that can be applied to any specific environment, when used along with the numerical analysis and procedures described in this chapter, the characteristics of path loss across a range of environments can be partially accounted for. Location estimation techniques are essentially composed of two processes; a ranging process and a position estimation process. This chapter details these processes, and the location sensing algorithm that was implemented in the localization software tool developed in this thesis.

Section 1 gives a brief description of some of the systems and architectures that have been developed over the years regarding the problem of tag location sensing. Each system is designed to fulfill a different goal and presents a different solution. Section 2 discusses various ranging techniques, and whether they are suitable for the purposes of this thesis. Section 3 specifies the radio propagation model that will be implemented in this thesis for ranging of the RFID tags. Section 3 will also show the solving of some of the environmental parameters. Section 4 details regression analysis method carried out in this thesis. Section 5 describes the positioning techniques available, and selects the one that is most appropriate for this thesis. Finally, Section

6 describes the numerical analysis conducted for the multilateration technique. The least squares method was used to analyze the data and accomplish the localization of tags in this thesis.

3.1 Related Work

Indoor location sensing algorithms for RFID tags, using one or more RFID readers, and implementing landmarks which may be passive or active tags with known locations is a widely studied subject. This section discusses some of the solutions that have been proposed over the years. The solutions differ in the methods and hardware they use, and they also vary in their specific goals and applications.

3.1.1 Active Badge

This solution presents a design of an active badge which emits a unique code every tenth of a second using a PWM (Pulse Width Modulated) IR (Infra Red) signals. Networks of sensors detect these signals; the sensors are then polled by a master station. The master station processes the data and provides the user with the location information [31]. Indoor localization is accomplished with the use of diffuse infra-red technology. The Active Badge system is limited by a short signal transmission range, requirement for line of sight, and since it implements IR technology it suffers from interferences such as direct sunlight.

3.1.2 LANDMARC

LANDMARC is an indoor localization system that is based on RFID technology. On average, this system was able to localize tags within one meter of their actual location. This system implements the closest neighbor technique with the use of active RFID tags as reference tags. The use of reference or landmark tags reduces the number of expensive readers and reader antennas while at the same time increasing the accuracy of localization. This system relies on first gathering the RSSIs of the landmark tags. The system then estimates the location of an unknown tag based on the reference tag's measured RSSI, and how closely it matches the unknown tag's RSSI value [32]. The four nearest neighbor tags are then used in the pinpointing of the unknown tag since the landmark tags are arranged in a grid format.

The landmark tags whose signal strength most closely matches the signal strength of the unknown tag are assigned a higher weighing value, and the unknown tag's calculated location will be more influence by these landmark tags. The LANDMARC system requires a minimum of three readers, and active tags that are distributed one per square meter. The accuracy of the localization increases with an increase in the density of landmark tags. However increasing the number of landmark tags results in an increase in the complexity of the system and the overhead costs.

3.1.2 RADAR

RADAR is an RF based indoor tracking and localization system. RSSI values are gathered from tags by multiple receivers at several locations, and the distance of the tag from each receiver is calculated. The system applies triangulation technique to localize and track the tags [33]. This system applies both an empirical data gathering method and a theoretical model to determine the RSSI information. This system is similar to the LANDMARC system in that RSSI measurements are gathered from landmark tags by several readers first, then during the tag localization phase the RSSI measurement from the unknown tag is recorded by the same readers. The system uses the closest neighbor technique and triangulation for localizing the tag.

The RADAR system uses two different methods to estimate the location of the tags, an empirical method and a radio propagation method. In the empirical method data is gathered at several locations off-line, and then time stamped and tabulated [33]. This method then applies a nearest neighbor signal strength search, to find the landmark tags with the closest RSSI match with the unknown tag.

The radio propagation method, applies a model while the system is on-line. This method does not require a RSSI map generated from the archiving landmark tag RSSIs. As a result this system is more versatile and quick to deploy. The radio propagation method is however less accurate with a median resolution of 4.3 meters, while the empirical method had a resolution of 2.94 meters. The low accuracy is because the radio propagation method does not account for some of the environmental effects.

3.1.2 SpotON

SpotON is an object tagging technology focusing on the hardware to achieve three dimensional location sensing. This system uses aggregation algorithm to minimize signal strength error relative to empirical data, and is used to compute the tag locations [34]. The system works by taking measurements of the RSSI of the signals. These signals would be arriving from the tags, and the measurements would be obtained by the multiple base stations that are positioned at different locations. The base stations then measure the path length of the signals traveling from the tag to the base station in order to approximate the range of the tag from the base station. The base stations are connected to a central server which puts together the values gathered from each base station. The principal of triangulation is then applied to calculate the three dimensional location of the tag.

3.2 Ranging Techniques

As previously mentioned location estimation techniques are essentially composed of two processes. Firstly, the ranging process, where the tags distance relative to the reader antenna is estimated; and secondly, position estimation process where the tags relative position in an environment is calculated. This section details some of the available ranging techniques that implement some of the physical parameters in order to estimate the tag's distance to the reader's antenna. Ranging is done with the use of some physical parameter, such as time of flight of a signal from the location sensor to the tag, or the RSSI measurement of the tag's backscatter signal.

3.2.1 Proximity Detection

In general there is no single ranging parameter that can be utilized for accurate ranging under all circumstances. Each parameter carries certain advantages and disadvantages in terms of ranging accuracy. Proximity detection techniques may rely on a variety of available physical ranging parameters, and may not be limited to any one of them [1]. This technique essentially estimates the nearness of a tag to a certain landmark with a known position.

3.2.2 Time of Arrival (TOA)

A TOA would utilize the propagation delay. This is the time it takes for a signal to propagate from a base station, in this case a reader antenna to a tag and vice versa. The distance from the tag to the reader antenna is then determined by multiplying this propagation delay by the propagation speed, which is the speed at which the signal travels or disperses in space. There are several techniques that utilize TOA. These techniques require high resolution synchronized clocks imbedded on the tag and/or the reader [1]. In one such technique, the system finds the difference in the propagation delays recorded by several readers, and uses this difference to estimate the distance between the tag and the location sensors. It is required that the measurements from all the readers be precisely synchronized in time in order for this technique to work.

In another technique, the signal transmitted by the readers would contain the data regarding the exact time of departure of the signal. The tag would then know the flight time of the signal and calculate its distance from the reader based on the estimated propagation speed. Some techniques eliminate the requirements for a high resolution clock embedded on the tag. This is achieved by using the total time it takes for the signal to be transmitted from the reader, and for the reply to be sent back by the tag.

TOA techniques are difficult to apply since electromagnetic propagation speeds are at the speed of light, making the measuring of the propagation delay very difficult especially at close ranges. TOA techniques cannot be applied to passive UHF RFID systems implementing the Gen2 protocol. This is because the Gen2 protocol implements an anti-collision algorithm which utilizes randomized time slot procedure. So the time it would take for a particular tag to respond to a reader quarry, will vary depending on the time slot allotted for that particular tag. Passive RFID systems minimize the infrastructure on the tag due to limitations in cost, size, and the availability of power for the tag.

3.2.3 Angle of Arrival (AOA)

AOA technique utilizes directionally sensitive antennas for the reader in order to determine the angle of arrival of the signal from the tag. This angle would be calculated with respect to the tag’s backscatter signal’s propagation angle and some reference angle. The propagation paths from the tag to each of the reader’s antennas would be constructed by using the reader antenna’s known position and the propagation angle each one of them detects. The tag can then be localized by finding the intersection of the propagation paths as calculated from different antennas.

This method is ideal for short range localization, and its accuracy diminishes as the range increases. Two antennas can be implemented for locating a tag on a two dimensional plane, and three antennas can be implemented for locating a tag on a three dimensional plane [1]. However this technique requires an antenna array to be implemented for each reader antenna. This adds significant cost to the reader setup, and greatly increases the complexity of the system. Also this technique is not robust for use in RFID tag localization since it requires a direct line of sight. Also a small discrepancy in the angle measurement will result in a much larger error in the calculated distance.

3.2.4 Received Signal Strength Indicator (RSSI)

This technique utilizes the tag's backscatter RSSI as recorded by either multiple readers at different locations or a single reader implementing multiple antennas at different locations [35]. Alternatively this technique could utilize the tag to make RSSI measurements of the reader signal, but as mentioned previously the infrastructure on a passive tag is minimized, and such capability does not exist on passive UHF RFID tags. The following are some basic techniques that are used for ranging by implementing RSSI measurements.

3.2.4.1 Nearest Neighbor

This technique implements multiple location sensors at different locations and assumes that the location sensor that records the higher RSSI value for the tag is closer to the tag [36]. Then a weighing procedure is applied based on the measured RSSI values. The weighing procedure would weigh the location sensor that records the higher RSSI more heavily.

In a practical environment the RSSI value measured for a tag positioned more closely to the location sensor will not always be higher. This is due to the effects of multipath, where the signal may take paths which bounce off various objects in the environment. The reader may also contain holes in its interrogation zone in which tags located closely may not communicate or communicate with a weaker signal than tags located further away.

3.2.4.2 Scene Analysis

In the scene analysis technique, a database of RSSI measurements at various distances from various location sensors is created before the unknown tags are localized. Then during localization phase the unknown tag's RSSI value is matched with the closest RSSI values that were previously recorded. The range of the unknown tag is assumed to be closest to the point of the closest RSSI match [37]. This method assumes that the RF environment in which the database was created will behave the same at different times, although that is usually not the case. The RF environment is dynamic and constantly changing, so the implementation of this method would require that the database be constantly updated.

3.2.4.3 Propagation Model

By accounting for the attenuation factor as the signal departs from the tag, the path loss during the propagation can be calculated. By utilizing these models the distance between the tag and the reader antenna can be estimated [35]. Obstacles in the propagation path such as people and objects, as well as factors such as temperature and humidity should have an effect on the parameters calculated in the model.

According to the available path loss models, the drop in power with respect to the distance is estimated to be logarithmic in nature. Due to the exponential nature of RSSI with respect to distance changes, denser employment of location sensors will increase the ranging and localization accuracy, although this will come at an added cost. The next section details the path loss model implemented in this thesis.

3.3 Empirical Path Loss Models

In the application presented in this thesis a ranging technique that uses RSSI as its parameter is found to be most suitable. Although this technique is heavily dependent on environmental factors, utilizing this technique is relatively simple and inexpensive. A number of path loss models have been developed over the years for a variety of different scenarios. Path loss models are based on empirical measurements over a given distance in a given frequency range [30]. Finding a single model that accurately characterizes the path loss across a range of different environments is a difficult task due to the complexity of the signal propagation.

Calibration procedures are added to account for some of the environmental factors. Another advantage of his method is that, as pointed out in Chapter 1, the RSSI measurement of the tag's backscatter signal is made readily available by the Sirit INfinity 510 reader. The RSSI measurements can be accessed by commands that are sent by the software presented in this thesis. Chapter 4 details the software's architecture, and capabilities.

During the calibration process a series of 12 calibration tags will be organized in a grid structure as shown in Figure 2.3. The tag RSSI parameters are then recorded, and regression analysis is applied to account for the propagation parameters. The archiving, organizing, and the analysis of the data are carried out automatically by the localization tool developed in this thesis. The regression analysis is applied to each of the reader antennas separately, resulting in the curve fitting of the numerical data from the observations for each antenna.

3.3.1 Simplified Path Loss Model

Figure 3.1 illustrates reflection, scattering, diffraction, and refraction which are features of signal interaction with obstacles. Each copy of the signal may have its own time delay since after scattering or diffraction they may have taken different paths and traveled different distances.

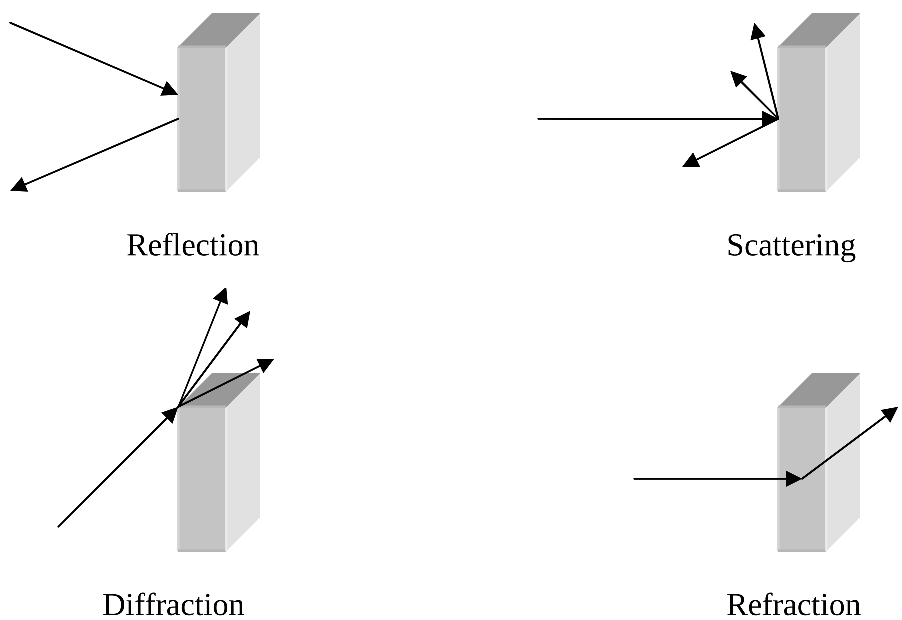


Figure 3.1 Signal Interactions with Obstacles

Multipath fading occurs when multiple copies of signals are superimposed due to the effects shown in Figure 3.1. In addition to multipath fading, the time delay may cause phase and polarization variations as well. These variations will distort the data encoded in the signal as well as alter the strength of the signal. The log-normal shadow fading model represents the variations in the signal power introduced by the interaction of the signal with the obstacles. Section 3.3.2 will discuss the log-normal shadow fading model, and Section 3.3.3 will combine it with the simplified path loss model [30].

Some propagation models attempt to model large scale fading. This is when RF wave behavior is averaged over large distances. Other propagation models model small scale fading which is for smaller distances [35]. This section describes the selection of the simplified path loss model that will accommodate some of the environmental factors. The environmental factors should be accounted for in order to achieve a somewhat reliable estimation of distance between the tags and the reader antenna. The simplified path loss model was chosen because it is a simple model to implement, and it captures the fundamental nature of the signal propagation. Thus implementing this model would avoid resorting to more complex and complicated analytical models, which are at the end, only approximations [30].

Equation (3.1) presents the function for the simplified model. It represents the path loss as an exponential decay in received power function with distance.

$$P_r = P_t K \left[\frac{d}{d_o}\right]^n \quad (3.1)$$

P_t is the transmitted signal power

P_r is the received signal power

K is a unitless constant

d_o is the far field reference distance

d is the transmission distance from the tag to the reader antenna

n is the path loss exponent

The reference distance d_o is selected to be 1 meters, and equation (3.1) is valid only for $d > d_o$. K, which is a unitless constant, depends mainly on the antenna characteristics and the average channel attenuation. The antenna selected for the reader is circularly polarized, and the value for K will be analytically approximated. This analytical approximation will be an optimization problem using the mean square error (MSE) minimization. This procedure is detailed in section 3.4.

The value n depends on the propagation environment, and is shown in Table 3.1 for some common environments at frequencies of 900MHz and 1.9GHz. n is different for different environments, and it will be obtained together with K via MSE minimization during the calibration process.

Table 3.1 Path Loss Exponent at Some Typical Environments [30]

Environment	*n range*
Urban macro-cells	3.7-6.5
Urban micro-cells	2.7-3.5
Office Building (same Floor)	1.6-3.5
Office Building (multiple Floors)	2-6
Store	1.8-2.2
Factory	1.6-3.3
Home	3

dBm is a more appropriate representation of signal power referenced to 1mW, because of the small power levels that passive UHF RFID systems operate with. Attenuation is put in dBm format to get equation (3.2)

$$P_r dBm = P_t dBm + K\ dBm - 10\ n\ log_{10}\left[\frac{d}{d_o}\right] \quad (3.2)$$

3.3.2 Shadow Fading

The attenuation begins just as the signal leaves its source. The extent to which the signal attenuates depends in part on its interaction with the various obstacles in its path. The log-normal shadow fading model represents the variations in the signal power introduced by the interaction of the signal with the obstacles. In this model the variations in the transmitted to received power ratio is

$$\psi = P_t/P_r \quad (3.3)$$

Where

$$\psi_{dB} = 10log_{10}[\psi] \quad (3.4)$$

ψ is assumed to be distributed randomly with log-normal distribution [30]. The value of ψ is always greater than one. ψ_{dB} would then be a Gaussian distributed random variable.

3.3.3 Combined Path Loss and Shadow Fading

Shadow fading can be super imposed on the simplified path loss model, by simply adding in the variations in the transmitter to receiver power ratio [30]. As a result, the variations are created about the path loss model. The combined model would then become

$$P_r dBm = P_t dBm + K\ dBm - 10\ n\ log_{10}\left[\frac{d}{d_o}\right] - \psi_{dB} \qquad (3.5)$$

3.4 Regression Analysis

Regression analysis is also known as the method of least squares or minimum mean square method or simply as curve fitting. The goal of this analysis is to attempt to find the optimal curve for an irregular and discontinuous set of data points. This is a numerical analysis technique in which the empirical data is assumed to be a linear function of independent variables. Finally this technique will be applied to the simplified path loss model. This is done so that by resolving the path loss at a reference distance, and the path loss exponent, the changes in the environment could be accounted for. This process is called RSS calibration [39].

3.4.1 Weighted Linear Regression Analysis Formulation

As the name *mean square error* implies, the square of the errors between the empirical measurements, and the data based on the model, are minimized [40]. The square of the error between the measured and calculated values is called the residual. The mean square equation is as follows

$$S = \sum_{j=1}^{M}(y_j - f(x))^2 \qquad (3.6)$$

Where the modeling function is

$$f(x) = \sum_{i=1}^{N} C_i\, x_{i,j} \qquad (3.7)$$

y_j is the j_{th} measured value

$x_{i,j}$ is the j_{th} measured independent variable for the for the i_{th} variable

M represents the number of data points

N represents the number of linear terms

C_i is the coefficient to be solved for

All the errors in equation (3.6) do not have the same significance, and thus it would be sensible to weigh some heavier than others. Including weighing factors in the minimum least squares algorithm would provide the added advantage of transforming the dependant variable y, in order to get a better linear representation. The weighing factor would be multiplied to the residual values and it would only require the following simple alteration

$$S = \sum_{j=1}^{M} w_j (y_j - f(x))^2 \qquad (3.8)$$

3.4.2 Solution to the Weighted Linear Regression

The objective is to solve for C_i coefficients which are the least squares estimates of the weighted linear regression [40]. The resulting analysis will require a solution for a set of simultaneous equations, using linear algebra. First the gradient of the least squares sum equation (3.8) must be taken with respect to C_i, and then set equal to zero as follows

$$\frac{\delta S}{\delta C_i} = -2 \sum_{j=1}^{M} x_j \, w_{k,j} \left[y_j - \left(C_i x_{k,j} \right) \right] = 0 \qquad (3.9)$$

Solving for C_i gives

$$C_i = \frac{\sum_{j=1}^{M} x_{k,j} y_j - \frac{1}{M} \sum_{j=1}^{M} x_{k,j} \sum_{j=1}^{M} y_j}{\sum_{j=1}^{M} x_{k,j}^2 - \frac{1}{M} (\sum_{j=1}^{M} x_{k,j})^2} \qquad (3.10)$$

For $k = 1,2, \dots N$

This results in a set of simultaneous equations with the coefficients C_i as unknowns. The coefficients are then to be solved for with linear algebra. The weights are included in each of the sums as follows

$$\sum_{j=1}^{M} w_j x_{k,j} y_j = \sum_{i=1}^{N} C_i \sum_{j=1}^{M} w_j x_{i,j} x_{k,j} \qquad (3.11)$$

For $k = 1,2, \dots N$

The Gaussian elimination method is then implemented for solving the system of linear equations. This method greatly simplifies the problem by eliminating the need to deal with the system in terms of equations, but rather the problem is determined by forming an augmented matrix, where

$$Cx = B \tag{3.12}$$

is in inward appearance

$$\begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_N \end{bmatrix} \begin{bmatrix} \sum_{j=1}^{M} w_j x_{1,j} x_{1,j} & \sum_{j=1}^{M} w_j x_{1,j} x_{2,j} & \cdots & \sum_{j=1}^{M} w_j x_{1,j} x_{N,j} \\ \sum_{j=1}^{M} w_j x_{2,j} x_{1,j} & \sum_{j=1}^{M} w_j x_{2,j} x_{2,j} & & \sum_{j=1}^{M} w_j x_{2,j} x_{N,j} \\ \vdots & & \ddots & \vdots \\ \sum_{j=1}^{M} w_j x_{N,j} x_{1,j} & \sum_{j=1}^{M} w_j x_{N,j} x_{2,j} & \cdots & \sum_{j=1}^{M} w_j x_{N,j} x_{N,j} \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{M} x_{1,j} y_j \\ \sum_{j=1}^{M} x_{2,j} y_j \\ \vdots \\ \sum_{j=1}^{M} x_{N,j} y_j \end{bmatrix}$$

(3.13)

The coefficients C_i are then determined by inverting the x matrix and multiplying it to both sides of the equation. Note that the x matrix must be a square symmetric matrix.

$$x^{-1}Cx = x^{-1}B \xrightarrow{yields} C = x^{-1}B \tag{3.14}$$

3.4.3 RSS Calibration by Weighted Linear Regression

The goal of applying regression analysis is to account for the unique environmental conditions; which is done by running a calibration process before the actual localization. The algorithms presented in this section are applied to the software developed in this thesis, giving the user the ability to run such calibration processes in a range of environments. Using the software these processes are run almost effortlessly and without having to deal with the subtleties of linear algebra. The calibration process resolves the propagation parameters for each of the reader antennas separately [35]. As hinted before, in the calibration process, a series of 12 tags with known locations and in a grid structure are implemented. The calibration tags are visible in Figure 2.3. They are used to obtain empirical data concerning the environment.

The simplified path loss model described in section 3.4.2 happens to be a logarithmic function of distance. In order to apply linear regression analysis to the model represented by equation (3.5), the model has to be converted into a linear form. The model is then simplified further to

$$P_l dBm = \frac{P_r}{P_t} dBm = K\ dBm - 10\ n\ log_{10}\left[\frac{d}{d_o}\right] - \psi_{dB} \qquad (3.15)$$

Where the ratio $P_l dBm = \frac{P_r}{P_t} dBm$ is the total path loss at distance d.

The equation is then further simplified by omitting the random variable ψ_{dB}. The random variations could be alternatively accounted for by averaging of multiple RSS samples taken from each of the 12 calibration tags [35]. The averaged RSSI detected from each tag is P_l, and is plotted on the y axis, and the corresponding distances from the reader antennas are on the x axis. The results of these plots are in Chapter 5. The equation (3.15) then becomes

$$P_l dBm = K\ dBm - 10\ n\ log_{10}\left[\frac{d}{d_o}\right] \qquad (3.16)$$

The desire of the regression analysis is to solve for the propagation parameters. These propagation parameters are the path loss exponent n, which is represented by the slope, and the path loss at reference distance $d_O = 1 meters$, which is represented here by the y interecept K. The next step is to convert equation (3.16) into the linear form y= c + $m\ x$ as follows

$$P_l dBm = K\ dBm + n\ D \qquad (3.17)$$

Where

$$D = -10\ \ log_{10}\left[\frac{d}{d_o}\right] \qquad (3.18)$$

Since equation (3.17) is a linear equation, the matrix formulation (3.13) greatly simplifies. The matrix of coefficients then becomes merely a column matrix containing two elements.

With the known location of the calibration tags which corresponds to D_i , and the average RSSI of each tag which corresponds to P_{li}, the solution yields the y intercept K and the slope n. These values correspond to the referenced path loss at one meters, and the path loss exponent, respectively. After these values are obtained, they can then be inserted back into the simplified path loss equation (3.17). The distances for any tag can then be calculated just by taking RSSI measurements. Remember that after finding *D*, the distances are found by equation (3.18).

3.5 Positioning Estimation Techniques

Just as done for the ranging process and for the same reasons, the localization process for the tags will be by means of the RSSI measurements. As mentioned before the precise localization of tags is composed of two stages, first the ranging stage, which has been discussed thus far, and finally the positioning stage, where the tag will be localized in a two dimensional plane. The plane itself is a constant one meter distance apart from the antennas. The experimental setup is illustrated in Figure 3.2.

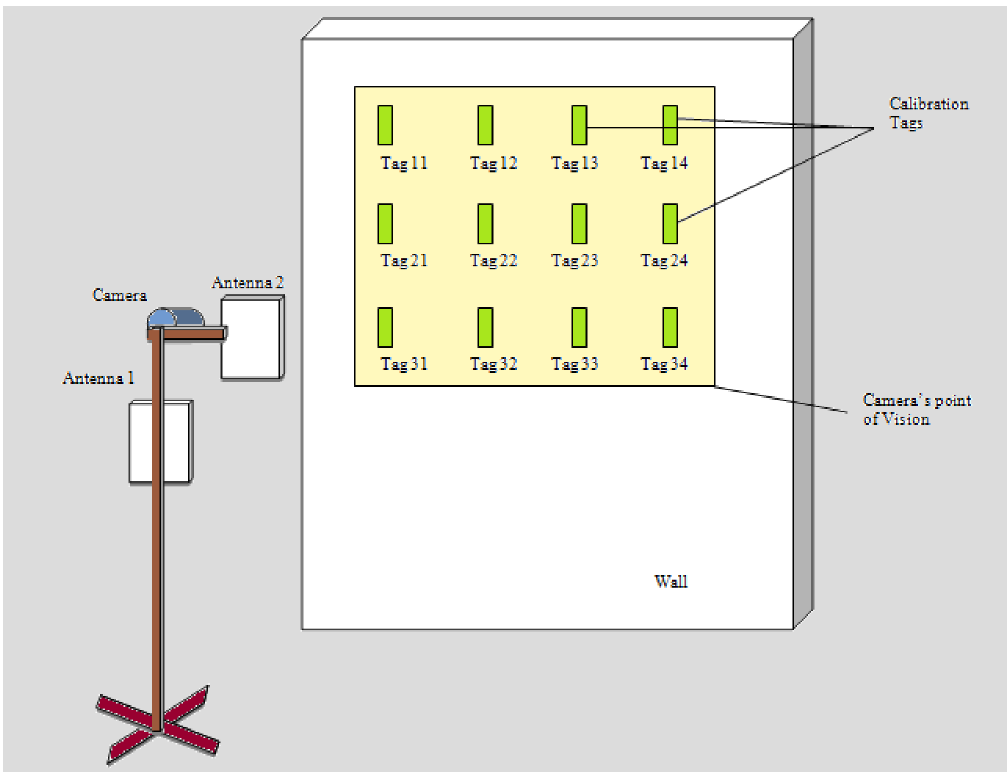


Figure 3.2 Illustration of the Reader Antenna, Web Camera, and Calibration Tag Setup

After estimating the tag's distance from the reader antennas, and having prior knowledge of the location of the reader antennas, the aim of the positioning process is to find the tag's position in terms of coordinates on the plane in which the tag is located. In this case the plane is located on a wall, and the coordinates are the pixel coordinates of the tag on the frame captured by the camera. So the coordinates of the tag are first calculated in terms of real distances in meters from some reference point, and then a conversion takes place from meters to pixels. All this is done by the software developed in this thesis.

For any one the ranging techniques described in Section 3.2 there is an assortment of positioning techniques, any combination of which could be a viable solution. A variation of some of the ranging techniques described could also be used for the purposes of positioning. In this thesis, two dimensional positioning will be focused on. This section describes some of the techniques available, and which one was most suitable for this thesis.

3.5.1 Triangulation and Angulation

Triangulation as the name implies requires knowledge of the line angle between three different points with respect to a common reference line in order to estimate the position. One simple explanation for this technique is illustrated on the left of Figure 3.3. Here the position sensors are assumed to be on top of the cones, and the angle of the cone is the angle from which the position sensor detects an object. The reference angle is in this case is assumed to be vertical. When three position sensors detect the angle, then the intersection of the cones is the estimated position of the object.

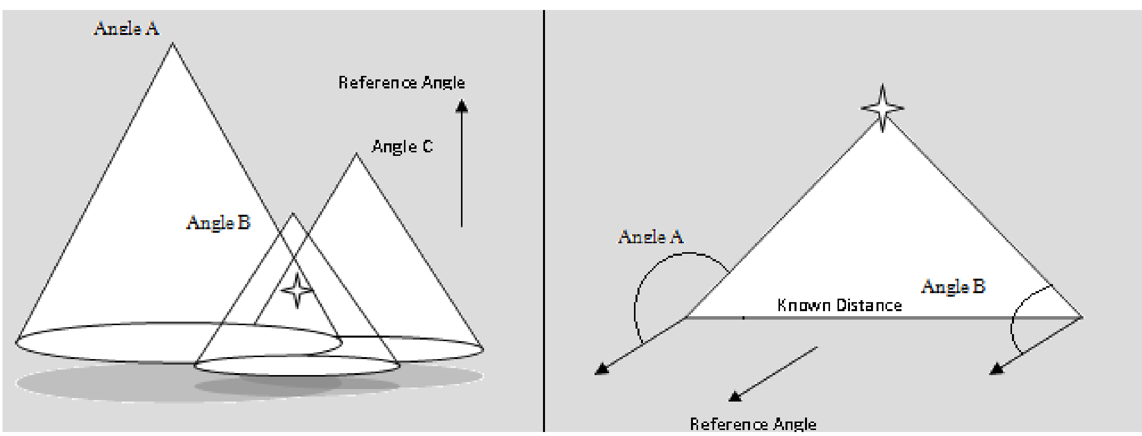


Figure 3.3 Triangulation and Angulation, the Star Marks the Position of the Unknown Tag

Alternatively a minimum of two position sensors, plus the distance between the two position sensors are necessary for positioning. This method is called angulation, shown on the right hand in Figure 3.3. In this thesis the capability of detecting the angle of the tag's backscatter signal does not exist, so triangulation and angulation could not be implemented.

3.5.2 Scene Analysis

The scene analysis technique for positioning is similar in concept to the scene analysis technique used for ranging described in Section 3.2.4.2. This technique relies on mapping of the localization space, or some sort of use of landmarks [37]. This technique requires prior knowledge of the environment. This method is viable for implementation in this thesis. Here the RSSI from the calibration tags are also used as landmarks, and are recorded in a database. An unknown tag's position is then assumed to be near that of the calibration tags with the most similar RSSI measurements from each of the reader antennas. Because of the dynamic RF environment the database containing the RSSIs of the calibration tags must be constantly updated. This solution was explored, and the results were encouraging, however this solution is not included in this thesis.

3.5.3 Nearest Neighbor

The nearest neighbor technique for positioning is conceptually similar to the nearest neighbor technique implemented for the ranging process as described in Section 3.2.4.1. Multiple location sensors at different locations sense the backscatter power of the tag. The closer the tag to the reader antenna, the stronger the recorded RSSI for that tag will be. Hence the position of the tag is assumed to be closer to that reader antenna. An algorithm must be developed that can associate the RSSI recordings from each of the antennas to the position of the tags [36]. Denser reader antenna population will result in greater accuracy. Because the passive RFID communication is subject to severe environmental effects, tags located more closely to the reader antenna will not always have higher RSSI recordings than those located further away.

3.5.4 Trilateration

Trilateration and multilateration is similar to Triangulation and angulation, except that here the distances between the location sensors and tags are used for positioning, rather than the angles. In the trilateration technique, the distance of a tag to three known points is required, in order for the tag to be pinpointed. When the distance of the tag to one known location is at hand then the tag is within the radius of that location. As shown in Figure 3.4 when three such distances are at hand, then the tag lies at the intersection of the circles with those radii.

When more than three locations are implemented it becomes multilateration. In this thesis the multilateration technique is implemented, where the unknown tag's distances from each of the twelve calibration tags are used for positioning. The coordinates and the distances from the reader antennas for each of the twelve calibration tags are known, as well as the distance between the reader antennas. The next section details the application of the multilateration process.

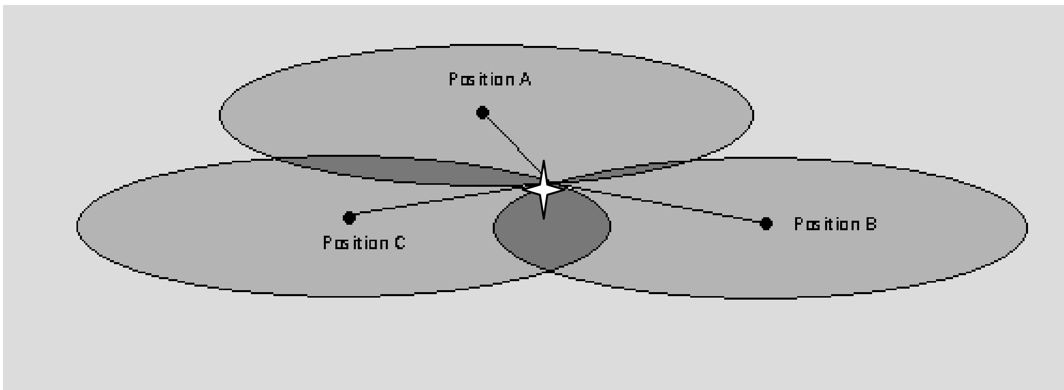


Figure 3.4 Trilateration, the Star Marks the Position of the Unknown Tag

3.5.5 Multiateration

As mentioned before, the position of the landmark tags which will be implemented as anchor nodes, as well as the position of the two reader antennas is assumed to be known for this algorithm to work [35]. Figure 3.5 illustrates two different perspectives of the multilateration scenario. In the figure the calibration tags are green and the unknown tag is the red star.

The top part of Figure 3.5 is the three dimensional view of the antennas and all the calibration tags. The bottom part shows the two dimensional view of the situation with only one of the calibration tags visible. This two dimensional view breaks down the situation, and illustrates the geometric parameters involved in calculating the distance of the unknown to each of the landmark tags.

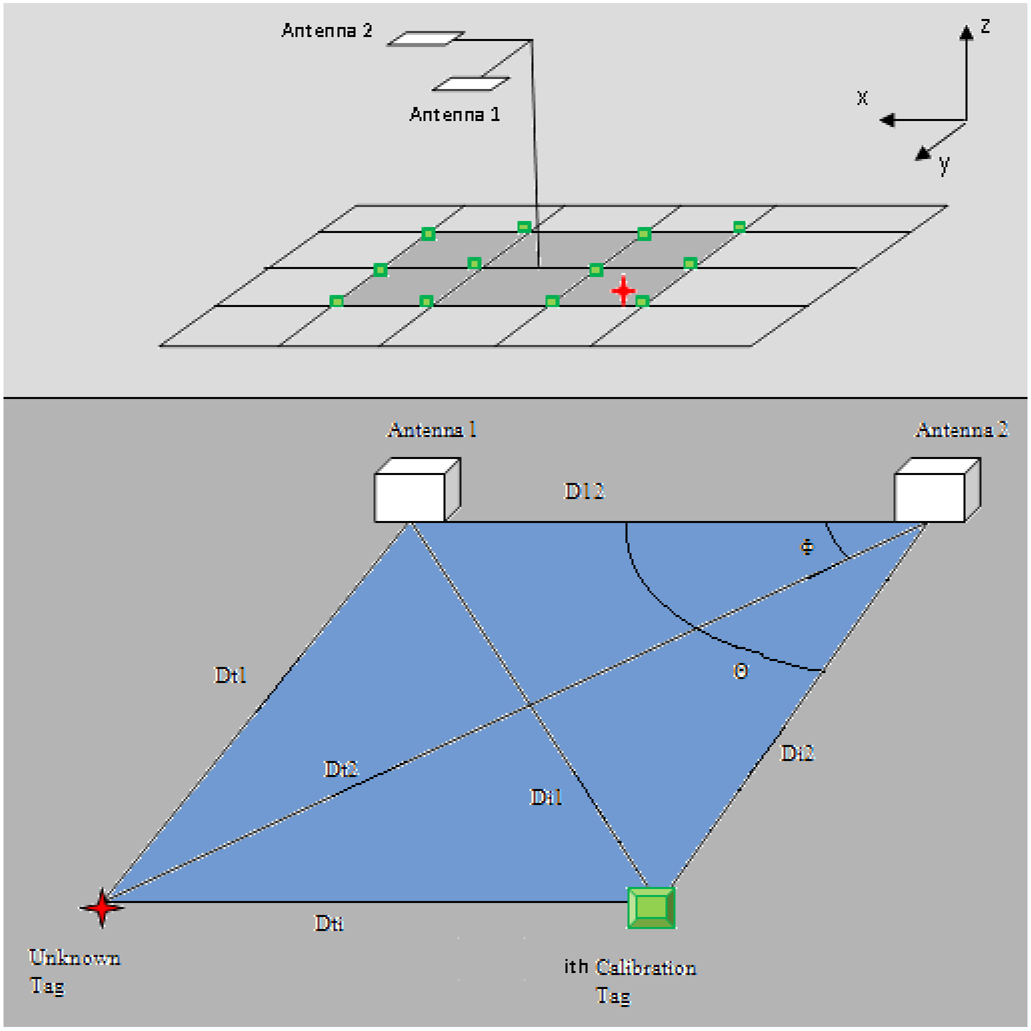


Figure 3.5 (on top) Three Dimensional Setup, (on bottom) Simplified Two Dimensional Breakdown

Figure 3.5 shows the distance between the *i*th calibration tag and the unknown tag as Dti, where $i = 1, \dots N$, and $\mathrm{N} = 12$. D12 is the distance between the two reader antennas. *Dt1* and *Dt2* are the distances from the unknown tag to reader Antenna 1 and 2 respectively. *Di1* and *Di2* where $i = 1, \dots N$, and $N = 12$ are the distances of the *i*th calibration tag and reader Antenna 1 and 2 respectively.

3.6 Localization Algorithm

The localization algorithm in this thesis applies a multilateration technique for positioning. This technique is appropriate because of the availability of twelve calibration tags which are used as anchors in the multilateration calculations. Although theoretically a minimum of only three anchor points are necessary to carry out precise localization, the real world application of this technique is not as accurate. Thus more anchor points will improve the accuracy. The localization procedure described here applies the simplified path loss model for resolving the range of the unknown tag from each of the antennas. The resulting analysis is then a set of simultaneous equations which are resolved by least square technique described previously.

3.6.1 Localization Calculations

In the technique implemented here, the reader antennas do not participate as anchor nodes. They only gather the RSSI parameters necessary to determine their range from the calibration tags and the unknown tags. The reader antennas have a known distance separating them. All the calibration tags and unknown tags are positioned on the same plane one meter in front of the reader antennas.

Because the exact positions of the calibration tags are already known, it is advisable to use these previously known distances from each of the reader antennas rather than using the distances derived from the ranging technique previously explained. Thus the ranging technique is only implemented on the unknown tags.

As previously explained, multilateration works by finding the unknown tag's distances from anchor points, in this case calibration tags situated at different locations. Hence the unknown tags distance from each of the calibration tags has to be determined as follows

$$Dti = \sqrt{(Di2)^2 + (Dt2)^2 - 2(Di2)(Dt2)\cos(\Theta i - \phi)} \qquad (3.19)$$

Where,

$$\phi = \cos^{-1}\left(\frac{(D12)^2 + (Dt2)^2 - (Dt1)^2}{2(D12)(Dt2)}\right) \qquad (3.20)$$

and

$$\Theta i = \cos^{-1}\left(\frac{(D12)^2 + (Di2)^2 - (Di1)^2}{2(D12)(Di2)}\right) \qquad (3.21)$$

After the distances of the unknown tag to each of the calibration tags are determined, the next step is to calculate its precise coordinates. The coordinates system developed in this thesis assumes that the top left hand corner of the camera's point of vision shown in Figure 3.2

as (0,0). Using the distances calculated in equation (3.21), the coordinates can be calculated as follows

$$(Dti)^2 = (xi - x)^2 + (yi - y)^2 \quad \text{for i = } 1,\ldots\text{N, and where N = 12} \qquad (3.22)$$

Here the coordinates for the landmark tags are denoted as (*xi, yi*), and the coordinates for the unknown tag as (*x, y*). A series of simultaneous equations are formed when this formulation is applied between each of the calibration tags and the unknown tag.

Both sides of the Nth equation is subtracted from both sides of all the other equations. This of course eliminates the Nth equation, and so eleven equations are left. This is done in order for the *x* and *y* coordinates of the unknown tag be separated, so that linear algebraic techniques can then be applied.

$$(xi - x)^2 - (xN - x)^2 + (yi - y)^2 - (yN - y)^2 = (Dti)^2 - (DtN)^2 \qquad (3.23)$$

Further simplification yields

$$2(xN - xi)x + 2(yN - yi)y = ((Dti)^2 - (DtN)^2) - ((xi)^2 - (xN)^2) - ((yi)^2 - (yN)^2) \qquad (3.24)$$

The previously described MMSE technique is employed to solve this system of eleven equations of form *Cx* = *b*.

$$2\begin{bmatrix} (xN - x1) & (yN - y1) \\ (xN - x2) & (yN - y2) \\ \vdots & \\ (xN - (xN - 1)) & (yN - (yN - 1)) \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} =$$

$$\begin{bmatrix} ((Dt1)^2 - (DtN)^2) - ((x1)^2 - (xN)^2) - ((y1)^2 - (yN)^2) \\ ((Dt2)^2 - (DtN)^2) - ((x2)^2 - (xN)^2) - ((y2)^2 - (yN)^2) \\ \vdots \\ ((DtN - 1)^2 - (DtN)^2) - ((xN - 1)^2 - (xN)^2) - ((yN - 1)^2 - (yN)^2) \end{bmatrix} \qquad (3.25)$$

x and *y* must be isolated in the left hand side of the equation as shown in equation (3.14). However, first the 2x11 matrix had to be converted into a square form with size 2x2. This was accomplished as follows.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \left(\begin{bmatrix} 2(xN - x1) & 2(yN - y1) \\ 2(xN - x2) & 2(yN - y2) \\ \vdots & \vdots \\ 2(xN - (xN - 1)) & 2(yN - (yN - 1)) \end{bmatrix}^T \begin{bmatrix} 2(xN - x1) & 2(yN - y1) \\ 2(xN - x2) & 2(yN - y2) \\ \vdots & \vdots \\ 2(xN - (xN - 1)) & 2(yN - (yN - 1)) \end{bmatrix} \right)^{-1}$$

$$\begin{bmatrix} 2(xN - x1) & 2(yN - y1) \\ 2(xN - x2) & 2(yN - y2) \\ \vdots & \vdots \\ 2(xN - (xN - 1)) & 2(yN - (yN - 1)) \end{bmatrix}^T \begin{bmatrix} ((Dt1)^2 - (DtN)^2) - ((x1)^2 - (xN)^2) - ((y1)^2 - (yN)^2) \\ ((Dt2)^2 - (DtN)^2) - ((x2)^2 - (xN)^2) - ((y2)^2 - (yN)^2) \\ \vdots \\ ((DtN-1)^2 - (DtN)^2) - ((xN-1)^2 - (xN)^2) - ((yN-1)^2 - (yN)^2) \end{bmatrix}$$

(3.26)

The *x* and *y* have units of meters and they are the coordinates of the unknown tag within the camera's point of vision. The software tool identifies and then localizes the unknown tag on the frames captured by a web camera. To do this the units of the unknown tag's coordinates are converted to pixel scale, and the calculated pixel coordinates are then marked on the captured frame.

CHAPTER 4

TAG LOCALIZATION SOFTWARE TOOL

Up to this point, this thesis has described the various methods and algorithms, utilized for localization. These methods and algorithms are all implemented in user friendly software in which all the localization is automated. This chapter details the localization software tool developed in this thesis, as well as instructions on how to use the software. All the operations and analysis are processed internally in the software, and no other software program has been leveraged in any of the procedures.

The idea behind this localization tool was to provide the user with an easy to conceptualize tag localization. The question is, why integrate RFID localization tool with a web camera? The camera does nothing other than capture video of the environment, and all the localization of the tags are achieved by the RFID reader. The answer is that humans depend heavily on their visual cortex in analyzing situations. This tool brings the virtual and the real world together, as the location of the tags in the real world is translated to coordinates on the computer screen. If the view of the camera was blocked, the localization process would proceed as normal and the tags would then be localized behind that obstacle. Thus this tool can also allow the user to determine the location of tags behind obstacles in the camera's point of view. Of course this only works if obstacle does not interfere too much with the RF environment.

Section 1 discusses the various APIs (Application Programming Interface) and other resources used in the creation of the localization tool, as well as the software architecture. Section 2 describes the software's connection to the reader and the web camera and the user interface. Section 3 describes the software in calibration mode of operation. This is where the software accounts for some of the environmental parameters by reading and analyzing the RSSIs of calibration tags. Finally Section 4 describes the software operation in localization mode, where the unknown tag's location in the real world and its position within the frames captured by the camera are estimated.

4.1 Software Resources

The software utilizes the RAPID application programming interface (API). This API is provided by the Sirit producers for developers to extend the functionality of the Sirit INfinity510 reader. Another major resource for development of our software is the sample source code provided by Sirit. This source code provided the essentials of connecting to the reader, sending commands to it, and receiving feedback from it by utilizing the RAPID API. Figure 4.1 illustrates the layers of the RAPID architecture. Note that in this thesis only the TCP/IP connection was used.

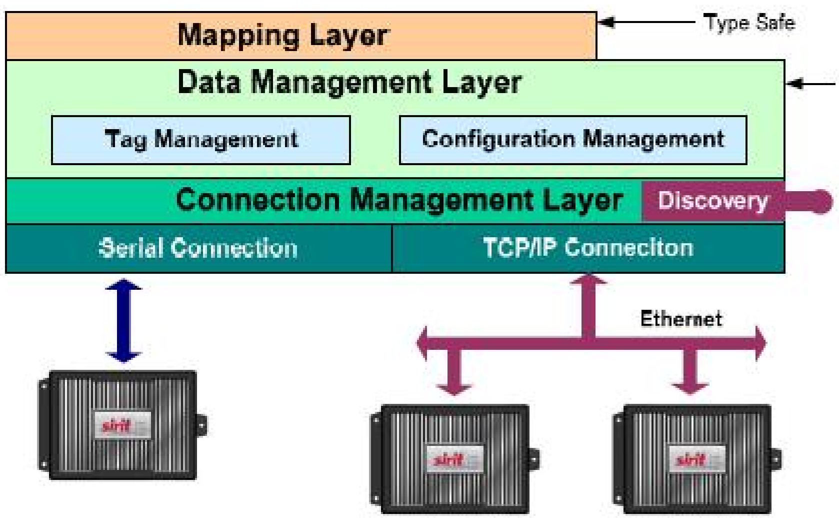


Figure 4.1 Layers of RAPID Architecture [29]

See [29] for details of each of the layers, and see [41] for the detail on the command structure of the Sirit reader. Similarly avicap32.dll, which is already available in most computers, is used to access some of the web camera's functionality from our software. Matrix operation libraries and numerical analysis algorithms with open source codes were available in online resources, and are cited in the reference section of this thesis. The programming was done with C#, which is an object oriented programming language with simple to use GUI (Graphic User Interface).

4.2 Starting the Tag Localization Software Tool

The objective of the software developed in this thesis was to exploit the functionalities of the Sirit reader by interfacing it to the computer. The aim was to develop a system to localize UHF passive RFID tags within a wide range of environments. The tags are to be tested in typical environment, and various distances from the reader antenna. The reader was programmed to collect a range of useful data about the tags in its field. This section will introduce the user interface of the software tool. Next this section shows how to begin using the software by connecting to the reader, initializing the reader and connecting to the web camera.

4.2.1 Connecting to the Hardware

Once the software has been installed on the user's computer, the application can then be run. The first thing that the user sees when the tag localization software tool is started is shown in Figure 4.2. The menu bar contains various settings and commands dealing with the reader's operation and the localization process. The first step would be to establish a connection between the reader and the computer by clicking on the **Connection →Connect to Reader** option from the drop down list. Remember that the Reader must be connected to the computer through an Ethernet connection by either a crossover cable or a router. The reader should be powered and connected to antennas through a coaxial cable in an arrangement as previously described.

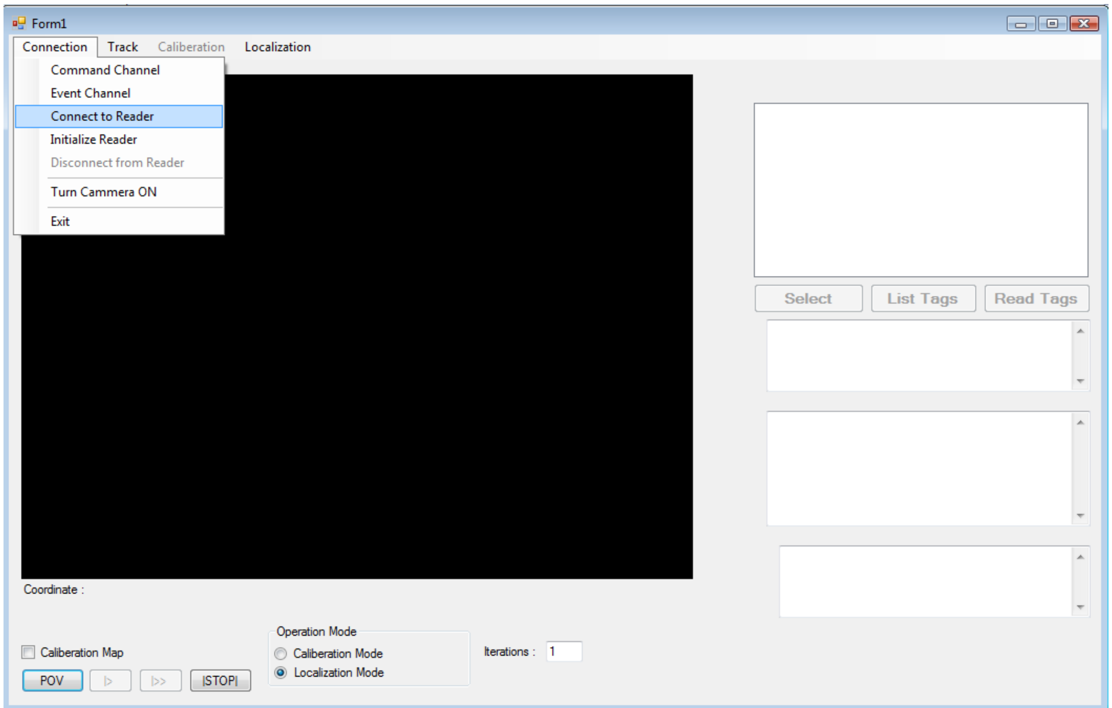


Figure 4.2 Tag Localization Tool

Also visible in the drop down list in Figure 4.2 is **Command Channel** and **Event Channel** options. Once the **Connect to Reader** option is selected the software connects to the command channel and event channel. It is through these two channels that the software sends commands to the reader, receives acknowledgements from the reader, and any relevant event data. The command channel is bidirectional in that commands are sent, and acknowledgements and reader responses are sent back through the same channel. The event channel is however unidirectional, and it reports asynchronous events such as errors, tag arrivals, and digital output triggers.

The connections to these two channels are made separately and internally within the program. This is done using socket programming, where the IP address and the port number of the devices being connected to are required to make the connection. In this case the IP address is the IP address of the reader and the Port numbers 50007 and 50008 are for the command channel and event channel respectively. Figure 4.3 illustrates the establishment of a connection between the computer and the reader through the Command/Response Channel and the Event Channel.

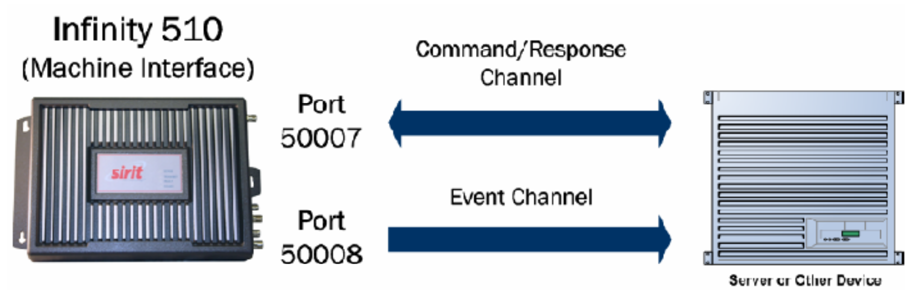


Figure 4.3 Reader Connection [41]

By clicking **Connection→ Command Channel**, the command channel window will pop up as seen in Figure 4.4. This window was part of a sample user application program that was available, and is included here only to demonstrate the operation of the software. It is not part of the tag localization. The localization process does not require any manual commands, the user does not ever have to open this window to localize tags. This window creates a log of the reader's responses, to various commands, as well as the connectivity status of the command channel. For the interface protocol and the format of the commands, as well as sample code see [29], and also to see various commands that could be implemented observe [41].

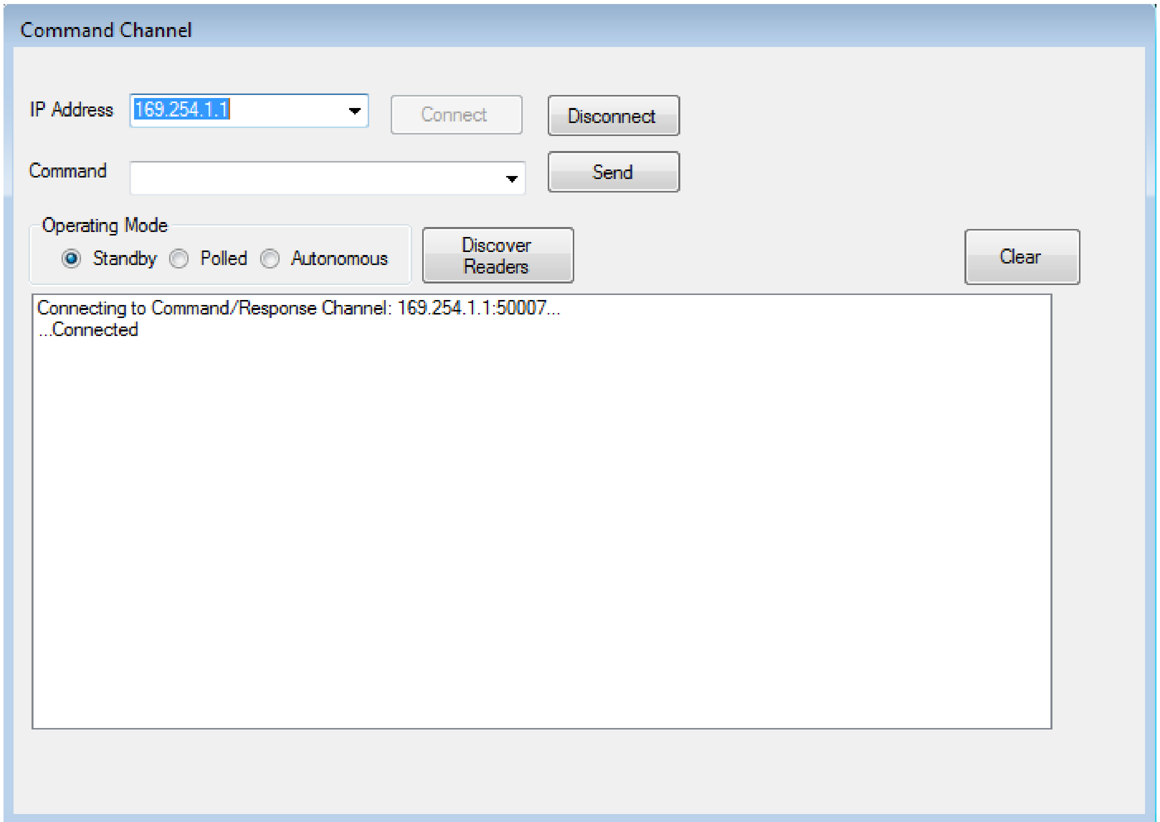


Figure 4.4 View of the Command Channel Window

This window also enables changing the reader's operation mode between **Standby**, **Polled**, and **Autonomous**. This can also be done by sending manual commands. Through this window alone most of the functionalities of the reader could be accessed by sending manual commands. Through this interface the user can connect to the command channel however not to the event channel.

By clicking **Connection→ Event Channel**, the Event channel window will pop up as seen in Figure 4.5. This window was also part of a sample user application program that was available, and is included here only to demonstrate the operation of the software. The users don't ever have to open this window to localize tags. This window creates a log of the events sent by the reader. The software needs to first register for these events in order for the events to be received. Event registration is done by sending the appropriate command through the command channel. All the necessary registration to the events is done by commands sent internally by the software. The connectivity status of the event channel is also presented in this window. Any events that arise during the reader operation that has been registered for will appear in this window as well.

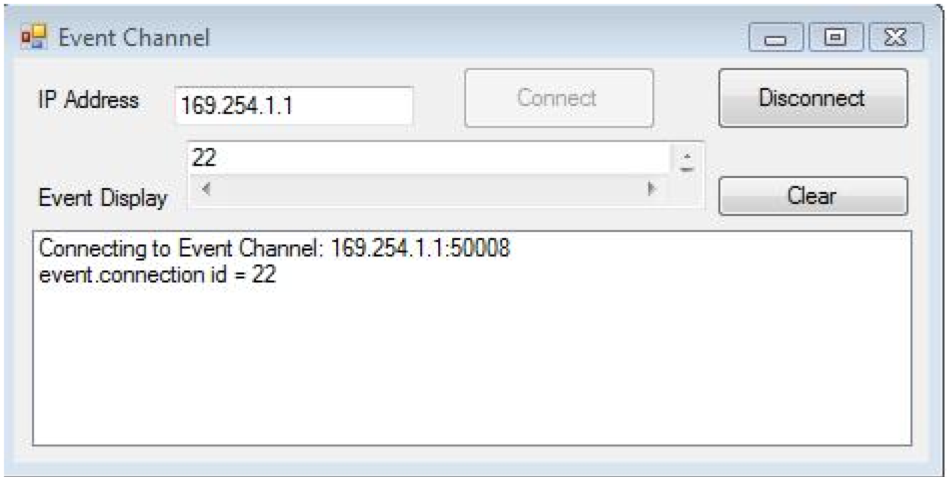


Figure 4.5 View of the Event Channel Window

For the events available in the reader as well as the commands which access them see [41]. This window enables the user to connect to the event channel, at which case the reader will respond with an event id. The event id is used to specify the events being registered for. Again all this is done internally in the software, and the user need not worry about this window for the localization process.

Once **Connection →Connect to Reader** option has been selected, and the software connects to the reader the reader has to be initialized. The reader comes with a default setting. Before the localization procedure begins, it has to be established that the reader is in correct mode of operation. This is done by selecting **Connection →Initialize Reader.** The results of this initialization process can be viewed from the command channel window, as shown in Figure 4.6.

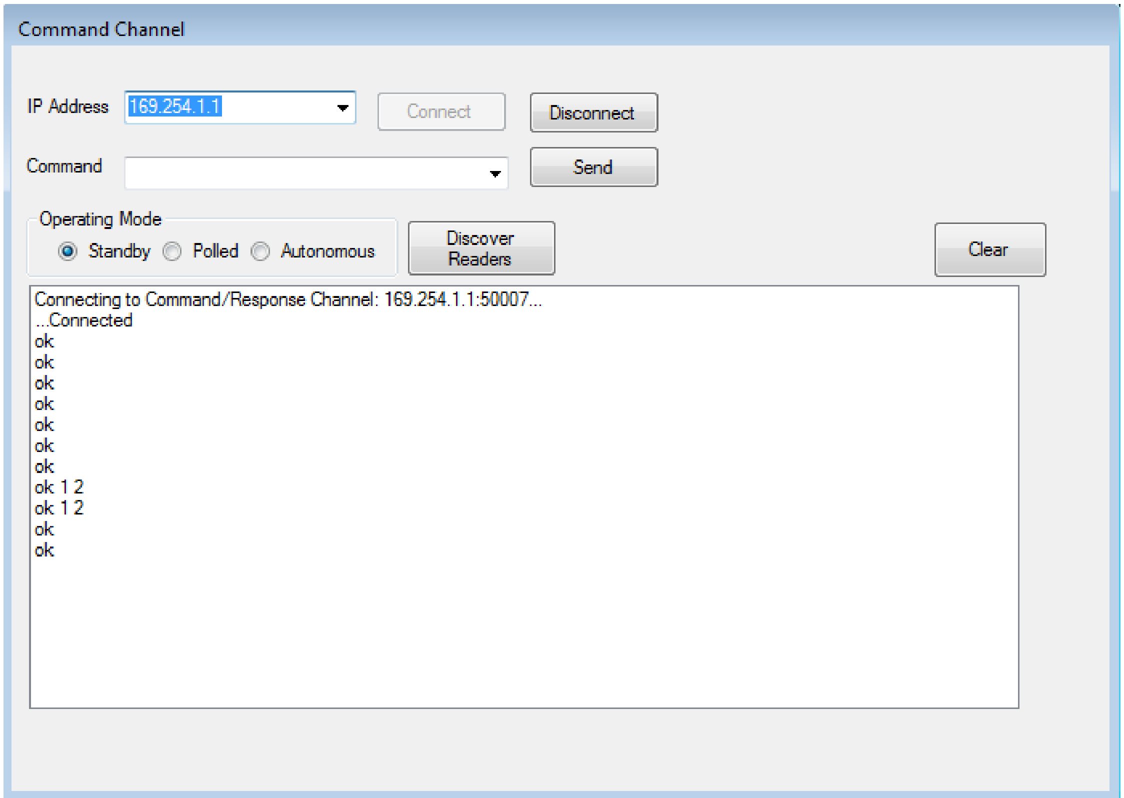


Figure 4.6 View of the Command Channel Window, Initialization Response

The initialization process goes through the following procedure:

1. Log in: (prefer to log in as admin, support access is not necessary)

2. Ensure the reader is in standby mode

3. Connect to event channel, reader discovery is not necessary since we already know the IP Address of the reader

4. Set carrier wave during idle time to false

5. Register to the tag.report event

6. Set tag.report event fields, here we want the tag's id and RSSI reported

7. Set taglist fields

8. Set up the antennas 1 and 2

9. Check to make sure that the antennas 1 and 2 are operational

10. Determine tag density

11. Purge the database

The reader responses to these commands are visible from Figure 4.6. There are more settings that have to be initialized, however these are already set when the reader powers up. The initialization process insures that the proper events have been registered for, the reader is operating in the correct mode, and the antenna connections are working properly.

The initialization process executes many times in the software's operation automatically, and it is not necessary for the user to initialize the reader. This feature is added in the unforeseen case that somehow the readers' operation settings have been changed before the software automatically reinitializes them. The software would not be working properly if the reader is not initialized. By running the initialization procedure you can see in the command channel window if you are getting "ok" responses, which means the reader is operating as expected or not. For example if both of the antennas are connected and initialization procedure is running then on the command channel window you should see "ok12". If not there is something wrong with the antenna connection.

Next the user should insure that a web camera is connected to the computer and situated as instructed in the previous chapters. The next step is to select **Connection →Turn Camera ON.** If a web camera is connected to the computer via USB, then the software will connect to it. However if multiple web cameras are connected, then the user will be prompted to select one of them as shown in Figure 4.7. After that the user should click on the POV button at the bottom of the window shown in Figure 4.2 to begin importing the video captured by the camera into to the big black box. Now the software is ready to proceed to calibration and localization processes.

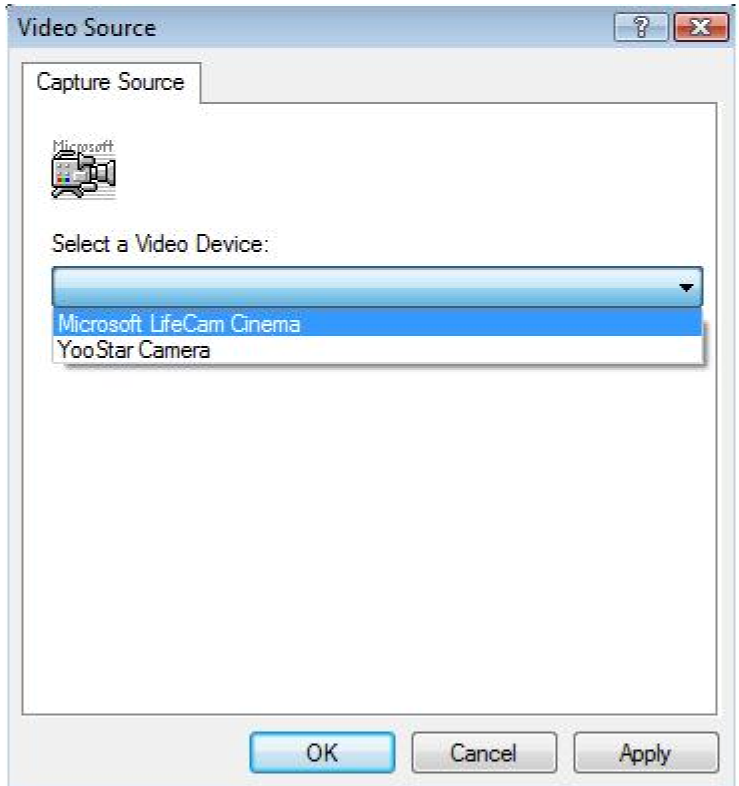


Figure 4.7 Video Source Selection Window

4.3 Calibration Mode

As explained before, the passive UHF RFID communication takes place in a dynamic environment and the system must first be calibrated by accounting for some of the environmental parameters. This is done by using twelve calibration tags with known positions and distances from each of the RFID antennas. The algorithms applied in the process of calibration were previously detailed. The two calibration parameters to be resolved are the path loss exponent, and the reference path loss at one meter. This section presents the software operation in calibration mode.

4.3.1 Localization Software Tool Calibration Operation

After the completing the instructions of the previous section, the calibration process can begin. First it must be insured that the software operation is in calibration mode as in Figure 4.8. Notice that many of the buttons are disabled, that is because first the calibration tags must be specified. All the calibration tags are visible on the screen in 4x3 arrangements; also an unknown tag is visible on the screen. The red dot is placed in the center of the calibration tags to mark the center of the camera's point of view.

Figure 4.8 Tag Localization Tool in Calibration Mode

To begin selecting the calibration tags, first all the tags in the reader's interrogation zone will be read clicking the **Read Tags** button. The software will then read all the tags, including calibration tags and unknown tags in the reader's antennas range. Then the **Cal Tags** button should be clicked in order to select which tags out of all the tags in the reader's read range the user wants to utilize as calibration tags. After the button has been clicked, another window will pop up as seen in Figure 4.9. This is where the calibration tags are selected.

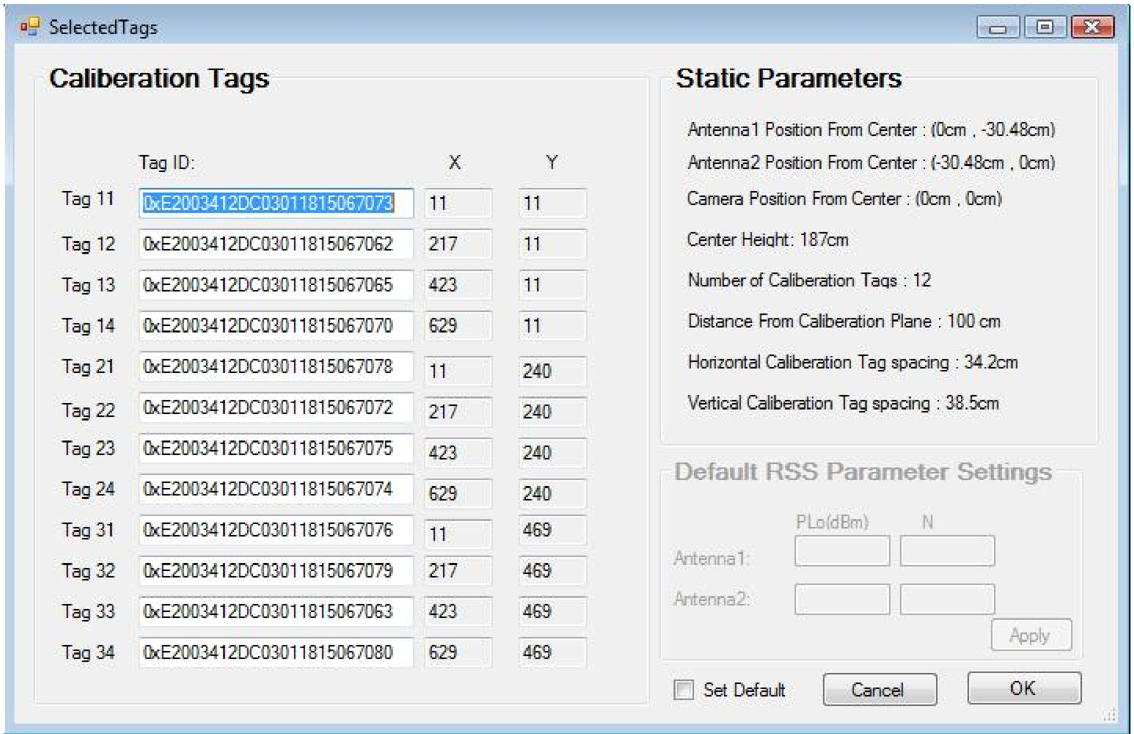


Figure 4.9 Tag Localization Tool in Calibration Mode

In this thesis an attempt was made to give the user as much flexibility as possible. However, at this point in the development coordinates selected for the calibration tags, as well as other parameters shown in the *Static Parameters* box cannot be altered. These settings are essentially the specifications of the experimental setup in this thesis. This window also offers the user the option of selecting default RSS parameters. These are the parameters that the calibration process is trying to resolve. The user is given the ability to set these parameters without continuing with the calibration process. After the selection of calibration tags is made the user should then click OK.

At this point note that many of the buttons are now enabled and the calibration tags are listed in the first box in the top right hand of the page as shown in Figure 4.10. Now after selecting the calibration tags by clicking the **Select** button, the box under the **Select** button is populated in the proper order in which the calibration tags need to be read.

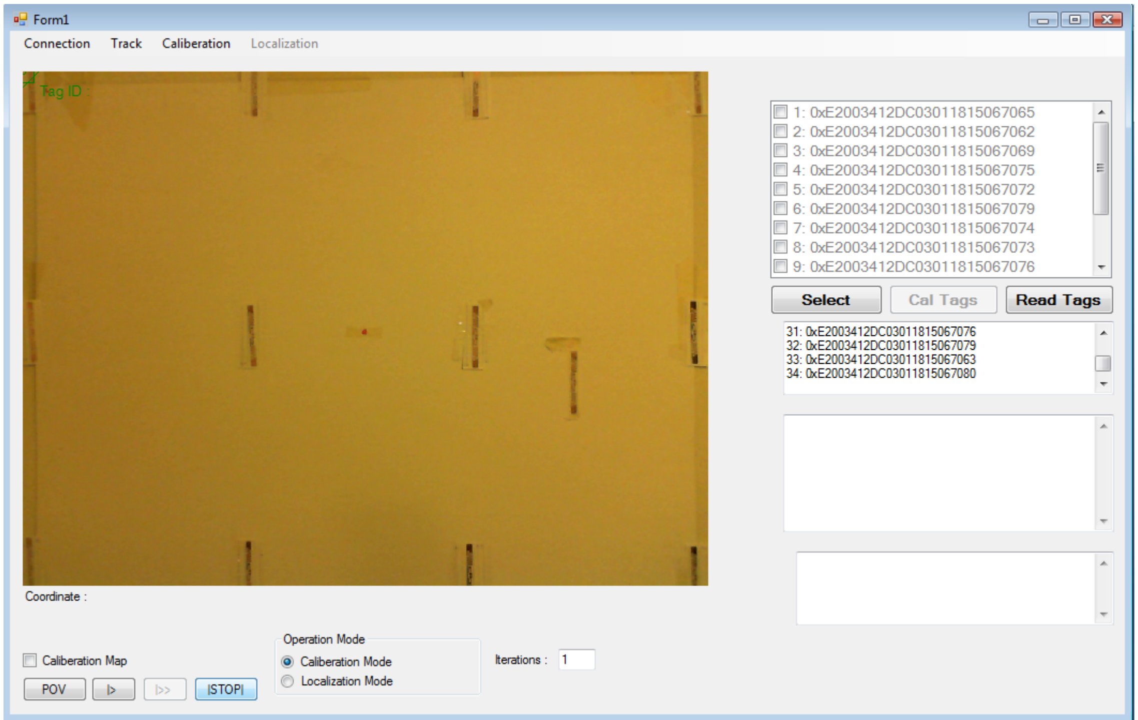


Figure 4.10 Tag Localization Tool in Calibration Mode With Calibration Tags Selected

To make it easy to see the selected calibration tags on the screen and not confuse calibration tags and the unknown tags the user can check the Calibration Map Checkbox. Upon doing so, all the calibration tags, as well as the center and corners of the calibration plane will be marked as shown in Figure 4.11. This feature is especially helpful in the set up of the experiment when the camera and reader antennas are being lined up with the center of the calibration plane.

Another added feature is that the coordinates of the mouse cursor are written under the picture box, as shown in Figure 4.11. This is a very helpful feature, since this allows the user to evaluate the accuracy of the localization system by using the mouse cursor to see the unknown tag’s actual coordinates, and comparing it with the coordinates estimated by the localization tool. Also since there is a direct correlation between the pixel coordinates on the computer screen and the actual coordinates of the tag in the real world, one could determine the coordinates in the real world based on the coordinates provided in pixels on the computer screen.

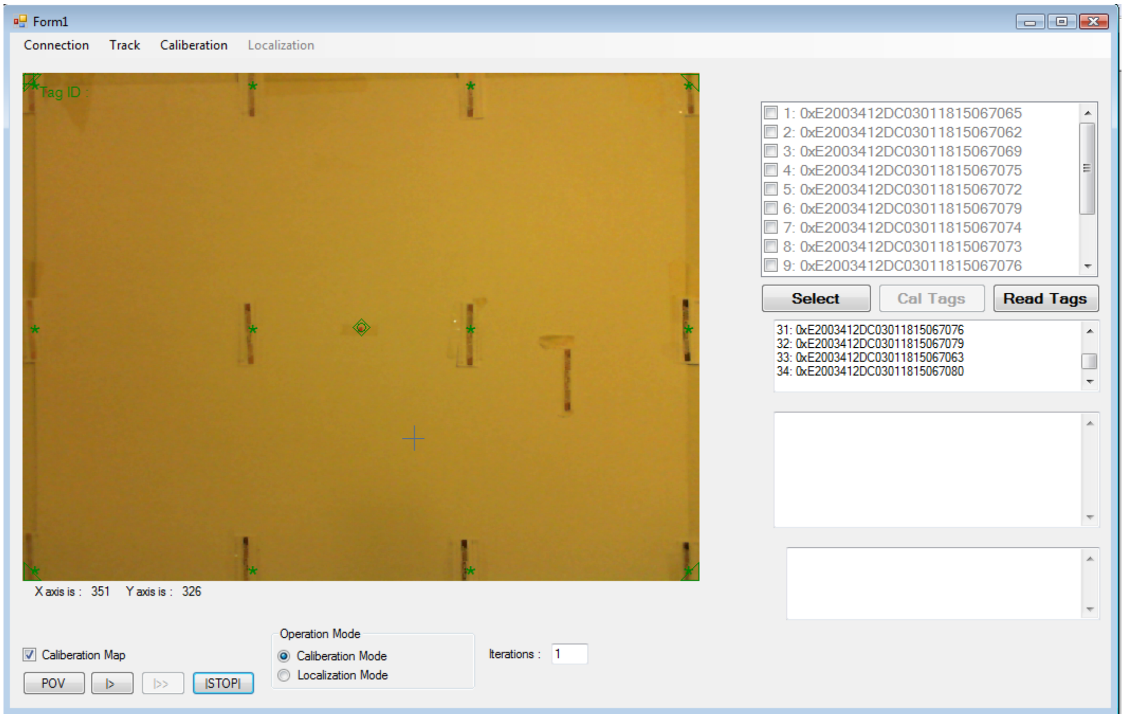


Figure 4.11 Tag Localization Tool in Calibration Mode With Calibration Map Box Checked

The iteration text box denotes how many times the user wants each tag to be read in order for its average RSSI value to be calculated. There are two ways the software reads the tags, one is the single cycle denoted by **>** button, the other is continuous cycle denoted by **>>** button. In the single cycle, each of the selected tags are read as many times as indicated by the number the user types in the iteration box. Then after the cycle ends the RSSI value of each of the tags are averaged out over the specified number of iterations. If the tag is in localization mode, then the tag's location will be estimated. Figure 4.12 shows the result of single cycle operation while the software is in calibration mode.

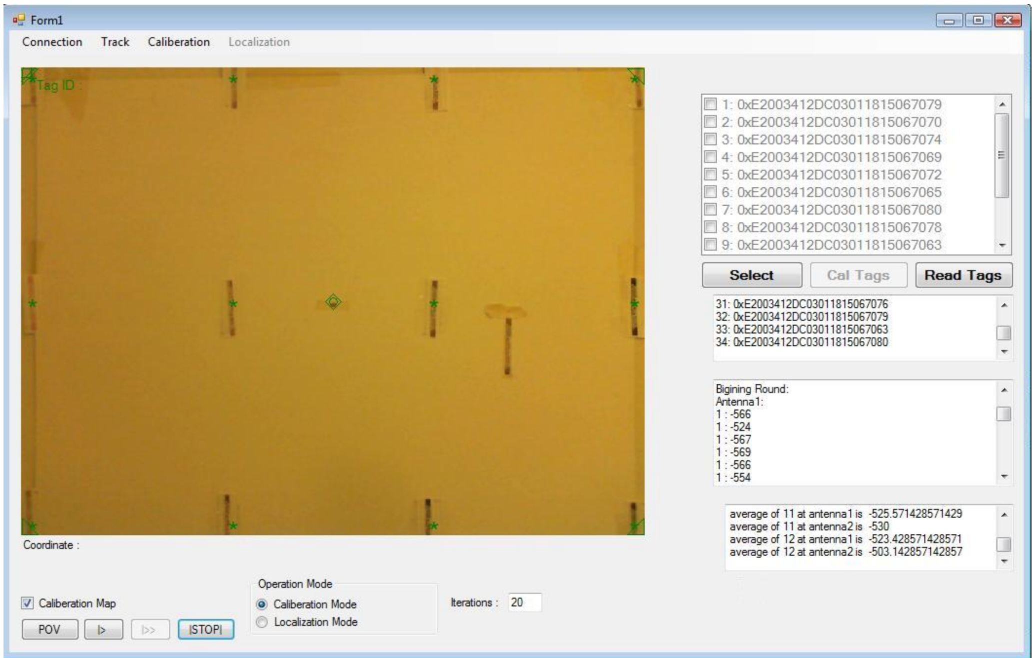


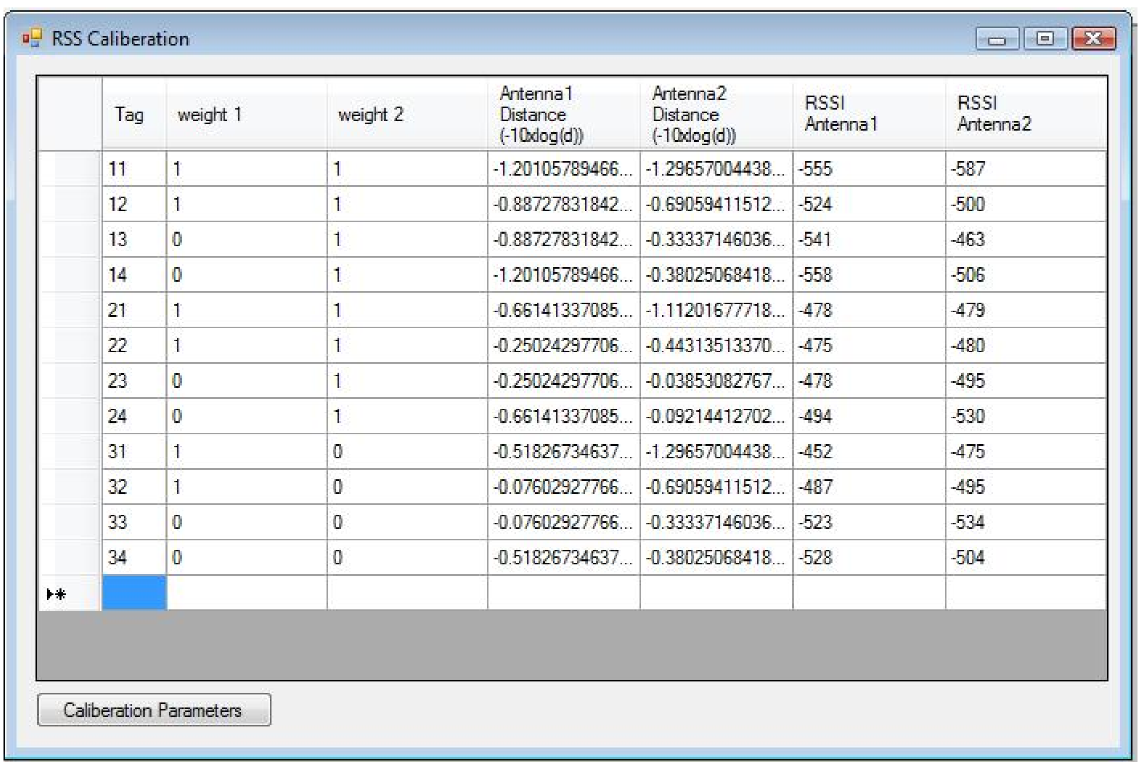
Figure 4.12 Tag Localization Tool in Calibration Mode after Finding the Average RSSIs for each of the Calibration tags

The third box from the top in the right hand side of the window shows the RSSI values of the tags as they are being read. In this case each tag is to be read 20 times. After each tag in the list has been read 20 times, the average values for each antenna are displayed in the box in the bottom right hand corner of the window. These values are saved in the system. These displays are only for informing the user with various operational data. It is important for the calibration tags to be within the RFID antennas read range. If the calibration tag cannot be read, then the software will send an error and prompt the user to restart calibration process.

If the user clicks the continuous cycle button, then each of the selected tags will be read as many times as specified by the user in the iteration text box. Then the average RSSI value for the tag will be calculated for each antenna over the specified number of iterations, and the tag location will be updated. In the continuous mode, the cycle then repeats and the tag location updates until the user selects the **Stop** button. As seen in the previous figures, the continuous cycle button is disabled when the software is in calibration mode. This is because there is no need to continually track the tag's RSSI in calibration mode.

After the software is finished calculating the average RSSI for each tag, the user may then access the calibration results by clicking on **Calibration →Results.** The window shown in Figure 4.13 will then open. This window lists the various parameters such as the average RSSI values from each antenna. Also the $-10 \log d$, and the weights assigned to each of the calibration tags are included in this window. The calculation of the calibration parameters will be based on these values.

Notice that some of the weights assigned are zero; this is because some of the tags are equidistant to the antennas. So in order to reduce the error in the analysis some tags were eliminated in order to eliminate the repetitiveness. By assigning a weight of a zero for a tag, the tag then does not influence the calculations carried out. However note that two weights exist, *Weight1* and *Weight2*. *Weight1* is the weight assigned to the tags influencing the calibration parameters for Antenna1, and *Weight2* is the weight assigned to the tags influencing the calibration parameters for Antenna2. So for example a tag's influence on Antenna2 may be eliminated while its influence on Antenna1 may remain unchanged.



Tag	weight 1	weight 2	Antenna1 Distance (-10xlog(d))	Antenna2 Distance (-10xlog(d))	RSSI Antenna1	RSSI Antenna2
11	1	1	-1.20105789466...	-1.29657004438...	-555	-587
12	1	1	-0.88727831842...	-0.69059411512...	-524	-500
13	0	1	-0.88727831842...	-0.33337146036...	-541	-463
14	0	1	-1.20105789466...	-0.38025068418...	-558	-506
21	1	1	-0.66141337085...	-1.11201677718...	-478	-479
22	1	1	-0.25024297706...	-0.44313513370...	-475	-480
23	0	1	-0.25024297706...	-0.03853082767...	-478	-495
24	0	1	-0.66141337085...	-0.09214412702...	-494	-530
31	1	0	-0.51826734637...	-1.29657004438...	-452	-475
32	1	0	-0.07602927766...	-0.69059411512...	-487	-495
33	0	0	-0.07602927766...	-0.33337146036...	-523	-534
34	0	0	-0.51826734637...	-0.38025068418...	-528	-504

Figure 4.13 RSS Calibration Adjustment Window

After clicking **Calibration Parameters** button, the values calculated for the calibration parameters for each of the antennas can be seen in another window that opens as seen in Figure 4.14. At this point the calibration process is over, all the relevant parameters have been saved in the software, and the software is ready to conduct the localization. The windows can then be closed while proceeding to the localization procedure.

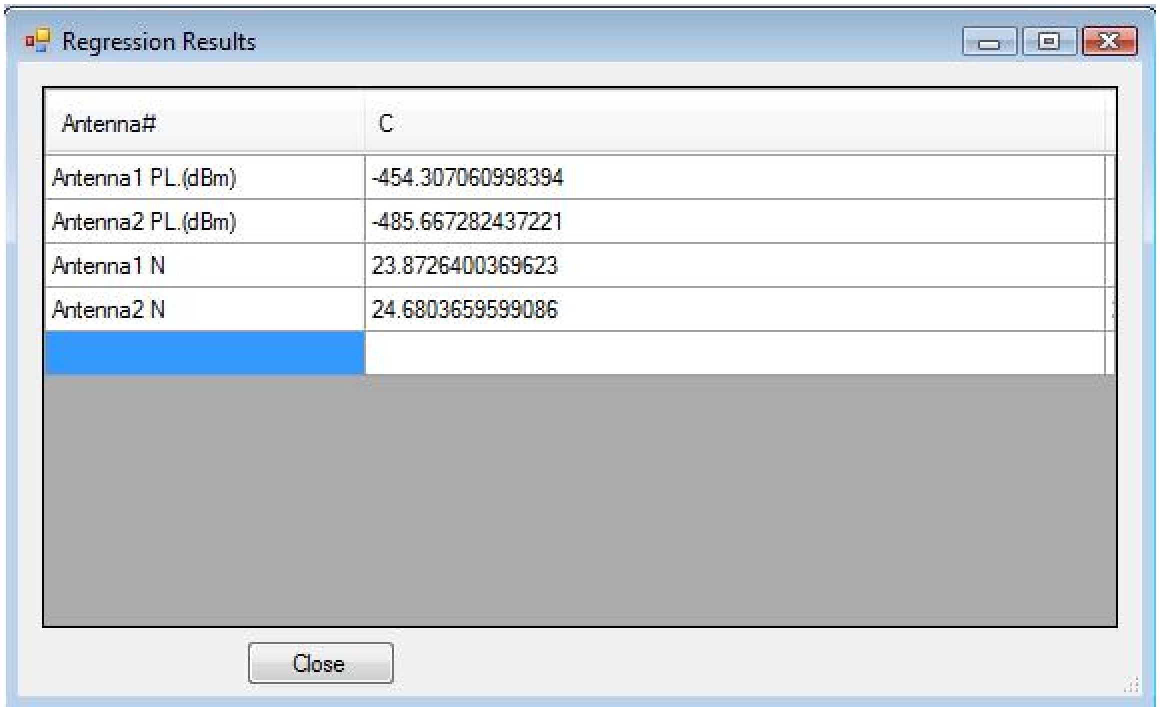


Figure 4.14 Calibration Parameters for Antenna1 and Antenna2

4.4 Localization Mode

Once the calibration parameters are at had localization procedure can proceed. At this stage in the development of this localization tool, only one unknown tag is localized at any one time. Again as before the user can set the number of iterations, which will tell the tool to average out the unknown tag's RSSI over that many iterations. These values are then used to calculate the location of the tag. By pressing **>** button the unknown tag can be located once, and by pressing **>>** button the unknown tag is continuously localized and the results are updated, this is called tracking.

4.4.1 Localization Software Tool Localization Operation

As previously done in the case of the operation in the calibration mode, the tags in the reader's antenna's fields have to first be read. This is done by clicking on the **Read Tags** button. Once the tags are read, clicking on the **List Tags** button will result in the first box in the right hand part of the window being populated with all the tags that were read. Then the tag that the user wants to localize can be selected by checking the box next to it, and then clicking on the **Select** button. Then the unknown tag can be located or tracked by either clicking on **>** or **>>** respectively. A typical localization is shown in Figure 4.15.

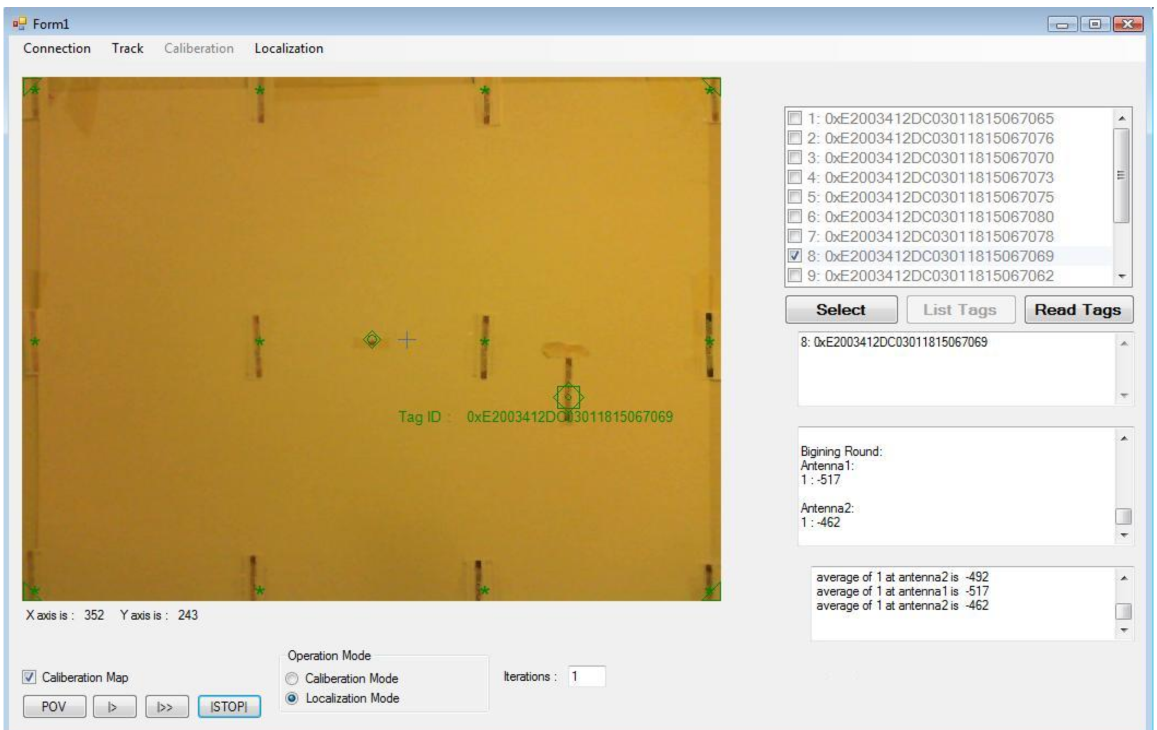


Figure 4.15 Tag Localization Tool Operating in Localization Mode

Notice that in Figure 4.15 the marker which looks like, marks the exact location of the unknown tag. Although usually the marker is not directly on top of the unknown tag most of the time, it is not a rare occurrence. The marker usually points to somewhere near the unknown tag, and sometimes it is dead on, sometimes it is completely off. Since the localization method implements regression analysis or curve fitting, the function estimated does not necessarily pass through the data points, and some data points may vary significantly from the trend of the data. As seen in Figure 4.15 the unknown tag's id is also written under marker.

By going to **Localization →Results**, the user can view further details of the tag localization, as shown in Figure 4.16. This includes the exact pixel coordinates, its average RSSI values, and its distance from each of the antennas.

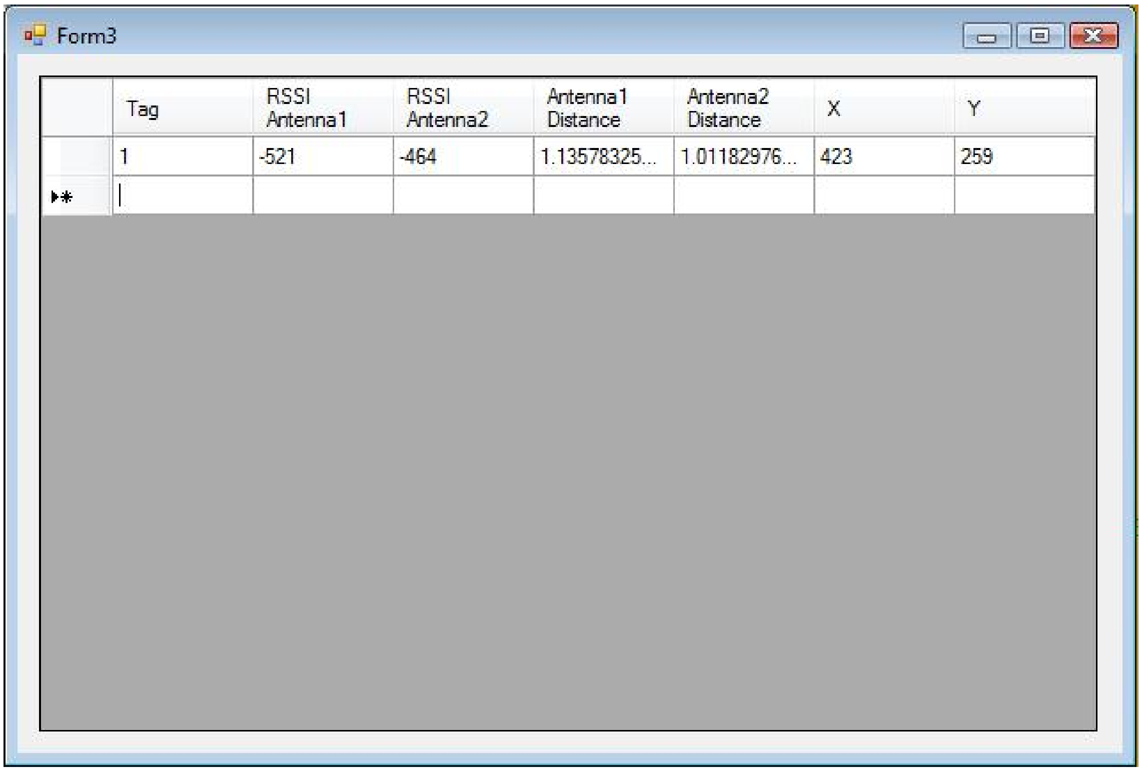


Figure 4.16 Results of the Tag Localization Tool Operating in Localization Mode

With this the localization process is over. The user may select another tag to localize, may run calibration all over again, or may simply exit the program. The calibration parameters will be cleared if the user exits the program. When the program is restarted at a later time, the user will either have to run calibration again, or if the calibration results from previous calibration processes were written down, the user can set the default calibration parameters as shown in Figure 4.9. If the default calibration parameters are defined then it won't be necessary to run the calibration process again. However for greater accuracy it is recommended that the user run the calibration process every time the localization in software starts up. This is because the passive communication in the far field is severely influenced by the environment, and the environment is very dynamic.

CHAPTER 5

RESULTS AND CONCLUSION

Although the operation of the tag localization system varies widely from one environment to the next, some performance analysis was done to give the reader an idea of the accuracy and consistency of the system. To do this, in a series of tests both calibration tags and unknown tags were localized, the results of which are also presented in this chapter. The work done in this thesis is only a stepping stool for further research on this issue. There is definite room for improvements on the system, and the implementation of more techniques. Further research could also be conducted on the passive UHF RFID system as a whole, using the tool developed in this thesis.

5.1 System Performance Analysis

The calibration and localization processes were analyzed separately. The curve fitting technique was implemented in the calibration process, and the results of this are presented in this section. Then two sets of analysis were done. In the first one, the calibration tags used during the calibration process were then localized by using the same parameters resolved during the calibration process. This would give an idea of the accuracy of the system. In another analysis an unknown tag was localized multiple times while its position remained constant. This was done in order to get an idea on the accuracy and consistency of the tag localization tool.

5.1.1 Curve Fitting

The calibration parameters were calculated for each of the reader antennas separately, using linear regression or curve fitting. This process was carried out with the use of twelve calibration tags. As demonstrated in Chapter 2, the simplified path loss formula was converted into a linear form. The regression analysis thus resolves the reference path loss at the distance of one meter; this is the y intercept. The analysis also solves for the slope of the estimated curve, which is ten times the path loss exponent.

After the parameters have been calculated, a function can be formed based on these parameters. The function does not necessarily pass through any of the data points, but rather minimizes the error. This is known as curve fitting. The curve fitting plots are shown in Figure 5.1 for Antenna 1 and Antenna 2. Remember that the plot is not linear because the distance has been converted back to meter format from $-10 \log d$ format.

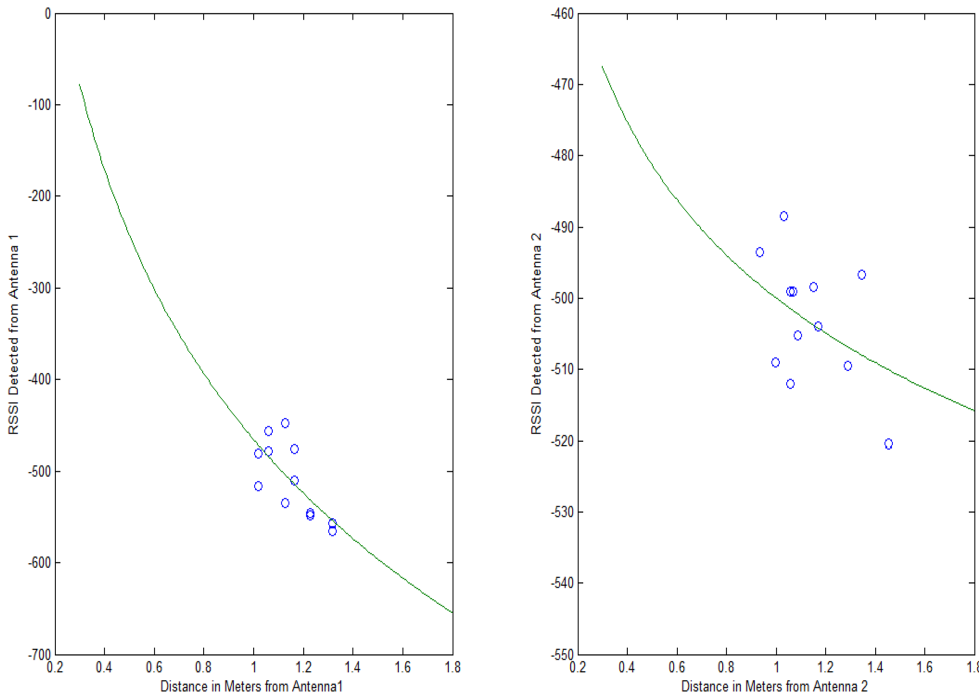


Figure 5.1 Curve Fitting Plots of Antenna1 and Antenna2

Calibration parameters P_{lo}, and *N* are then plugged back into the simplified path loss formula. The RSSIs of the tags are then measured, and plugged in for P_l, in the simplified path loss formula. The distance of the tags from each of the antennas can be resolved. Since the actual positions of the calibration tags are known, we can then compare these distances to the calculated values as shown in Figure 5.2 for Antenna 1 and Antenna 2. The calculated values of any one tag may vary significantly from one ranging routine to the next, so the averages over multiple RSSI measurements were used.

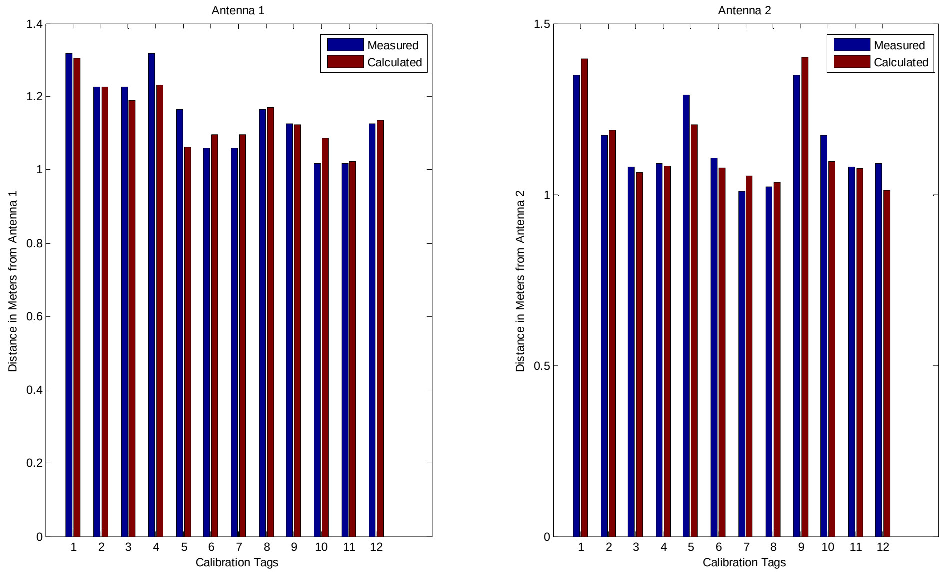


Figure 5.2 Calculated and Measured Distance Comparison Plots for Antenna 1 and Antenna 2

By implementing twelve calibration tags as anchor nodes, multilalteration technique can be used to calculate the unknown tags position. This is done by forming an over determined system of equations. Method of least squares was then implemented in resolving the x and y pixel coordinates of the tags.

Again since the actual coordinates of the calibration tags are known, we can then compare these to the calculated values. These results are shown in Figure 5.3 for the x and y coordinates. The calculated values of any one tag may vary significantly from one localization to the next, so the averages of RSSI measurements were used.

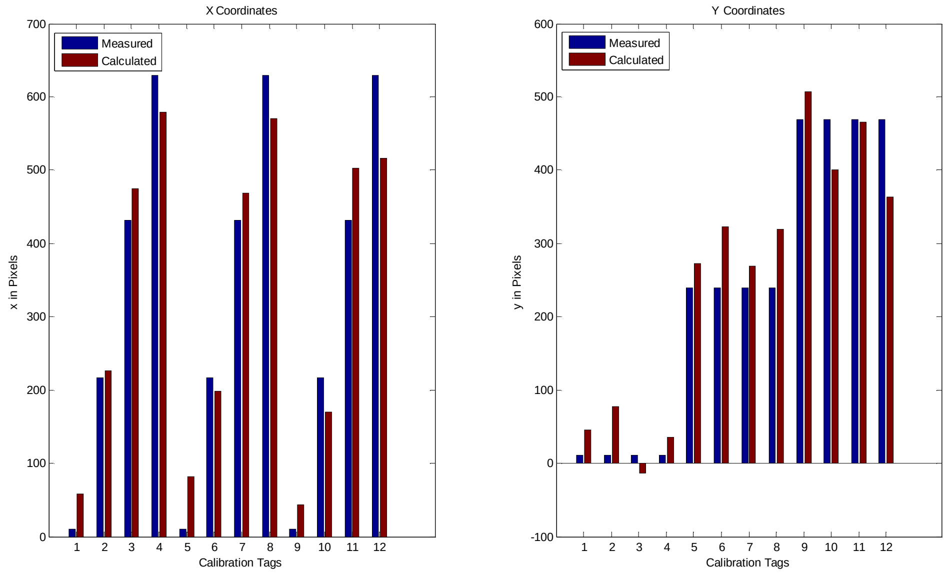


Figure 5.3 Calculated and Measured Coordinate Comparison Plots for the x and y Axis

In the final analysis, an unknown tag was localized twenty times. This was done in order to get an idea of the accuracy and the consistency of the localization tool in calculating the tag's position. The result of this analysis is presented by the scatter plot shown in Figure 5.4.

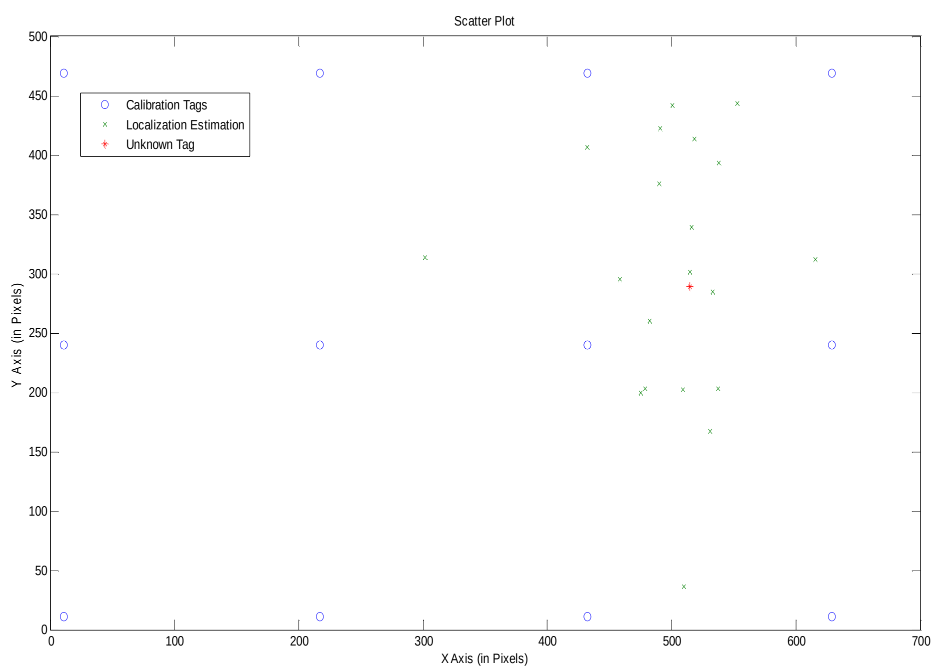


Figure 5.4 Scatter Plot of the Unknown Tag Localization

5.2 Conclusion

The software tool created here is a stepping stool for much more research to come. This research would include both improvements made on the system itself, and also the use of the system as a research tool. This system's aim is not to pinpoint the tag locations, which is difficult to do under the limitations imposed by the environment. Rather this localization tool, presents a much more precise localization process than room level based localization such as presence based localization or localization using choke points. Based on the limited number of data gathered in the previous section the system accuracy was evaluated. In Figure 5.4, the unknown tag's x and y pixel coordinates are (515, 289), and its coordinates in meters are (0.83, 0.46). The following shows the performance of the localization system for the twenty localizations carried out:

- The x coordinates had a mean of 499 pixels with a standard deviation of 60. When converted to meters the mean is 0.8 meters with a standard deviation of 0.096.
- The y coordinates had a mean of 300 pixels with a standard deviation of 108. When converted to meters the mean is 0.48 meters with a standard deviation of 0.173.

One of the objectives of this thesis was to build a prototype for a valuable tool, which can be used by the current industry for RFID applications. This tool would ultimately be a very useful tag localization tool, as well as provide valuable data about a perspective environment. Such a tool would be useful in supply chain management applications by aiding in the tracking of objects. Here localization is done in two dimensions, and the reader antennas are kept at a constant distance to the plane containing the tags. A similar arrangement may be RFID antennas installed on a ceiling, and the ground would be the plane containing the tags. The solution presented in this thesis is a particularly inexpensive and simple to implement, because it utilizes only one reader, and uses cheap passive tags for both calibration and localization.

5.3 Future Research

The tag's performance varies widely in different environments. The tool developed here runs a calibration process to account for some of the environmental factors. This is done by resolving certain parameters. This tag localization tool would also enable the users to make comparisons between different environments by running the calibration routine. This would be an interesting research topic in the future. The results such an analysis may include which environment best suits a passive UHF RFID communication, and what effects certain interferences have on the environment.

The Sirit INfinity 510 reader is a powerful tool that provides the user with spectrum analysis capabilities. This capability was not explored in the research conducted in this thesis, but it may be utilized in the future in order to improve our understanding of the RFID communication environment. The results obtained in this research may be improved further by applying neural networks [42], Kalman filtering [43], or map matching techniques [35].

The system could be further improved by giving the users the option of which localization technique they may want to use. Some of the localization techniques, such as the closest neighbor and scene analysis techniques described in this thesis may be implemented. Research could be conducted to see which technique is most suitable. Future research may also include signal propagation models other than the one explored here.

There is room for improvements in the software capabilities. Future versions of the software will give the user more flexibility in custom design of the experimental arrangement. In the future the software may give the user the ability to select the number of calibration tags, the calibration tag arrangements, and the reader antenna arrangements. Currently only the localization of one unknown tag is conducted at a time; a simple modification of the program would allow the user to locate and multiple unknown tags.

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BIOGRAPHICAL INFORMATION

Nasir Kenarangui finished his undergraduate degree in Electrical Engineering at the University of Texas at Arlington, graduating with *magna cum-laude*. He gained a wide breadth of experience by choosing to work on a variety of different projects at UTA. These projects included, DSP based battery charger design, complete RFID system design (hardware and software), device interface between the microprocessor board and the computer, laser optoacoustic defectoscopy device, and near field antenna design. He is interested in communications, and signal processing. During the first semester as a graduate student, he took advanced Electromagnetic Theory class, and later he took the RFID classes, embedded microcontrollers, and wireless communications.