12-2012

Three-Dimensional Indoor RFID Localization System

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THREE-DIMENSIONAL INDOOR RFID LOCALIZATION SYSTEM

by

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A DISSERTATION

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Doctor of Philosophy

Major: Engineering

(Industrial, Management Systems, and Manufacturing Engineering)

Under the Supervision of Professor Robert E. Williams

Lincoln, Nebraska

December, 2012

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University of Nebraska, 2012

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Radio Frequency Identification (RFID) is an information exchange technology based on radio waves communication. It is also a possible solution to indoor localization. Due to multipath propagation and anisotropic interference in the indoor environment, theoretical propagation models are generally not sufficient for RFID-based localization. In fact, the radio frequency (RF) signal distribution may not even be monotonic and this makes range-based localization algorithms less accurate. On the other hand, range free localization algorithms, such as k Nearest-Neighbor (kNN), require reference tags to be spread throughout the whole three-dimensional (3D) space which is simply not practical. In this work, a hybrid real-time localization algorithm that combines reference tags with Received Signal Strength Indicator (RSSI) ranging is introduced to improve RFID-based 3D localization in high-complexity indoor environments. The experiments demonstrate that the proposed system is more accurate than traditional algorithms under real world constraints. The active RFID system includes 4 readers and 24 reference tags deployed in a fully furnished room. The localization algorithm is implemented in MATLAB and is synchronized with RF signal data collection in real-time. The results show that the novel

hybrid algorithm achieves an average 3D localization error of 1.08m which represents a significant improvement over kNN and RSSI algorithms under the same circumstance. A battery-assisted passive RFID system was deployed side-by-side to the active system for comparison. Furthermore, the reader and tag performance was evaluated in both high-complexity laboratory environment and International Space Station (ISS) mock-up with high-reflection interior surface. In addition, theoretical models on minimum number of required reference tags and localization error prediction were introduced.

Acknowledgements

I wish to thank my advisor Dr. Robert E. Williams for his constant guidance, help, and support. His dedication to research has been a real inspiration.

I am sincerely thankful to Dr. Kamlakar P. Rajurkar, Dr. Michael W. Riley, and Dr. Lance C. Pérez for serving on my Ph.D. committee and providing valuable suggestions and comments to the original manuscript.

The dissertation experimentation would not have been possible without the gracious use of the facilities of Dr. Lance C. Pérez, the MC^2 laboratory in the department of Electrical Engineering. I want to thank Lianlin Zhao, Marques L. King and all associates who were so friendly and helpful to my research there.

I would like to thank all faculty and staff members in the IMSE department and then the MME department since August 2011. Their kindness made my study at UNL much more comfortable.

I also would like to thank my beautiful wife, Bijia, for her love, caring, courage, and support during this research.

Finally, I dedicate this dissertation to my parents, Shuliang Wu and Zhenyun Cao, and to my sister, Jiawei Wu. They had a great influence on my career path and academic motivation and pursuits.

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Nomenclature and Abbreviations

2D	Two-dimensional
3D	Three-dimensional
A-GPS	Assisted-GPS
AOA	Angle of Arrival
APM	Adaptive Power Multilateration
COTS	Commercial off-the-shelf
dBm	Ratio of measured power decibels (dB) to one milliwatt (mW)
EM	Electromagnetic
EPC	Electronic Product Code
Gbps	Giga-bits-per-second
Gen 2	EPCglobal UHF Class 1 Generation 2
GPS	Global Positioning System
GUI	Graphic User Interface
HF	High Frequency, 13.56 MHz
IC	Integrated Circuit
IR	Infrared, 300 GHz to 405 THz
ISS	International Space Station
JSON	JavaScript Object Notation
kNN	k Nearest-Neighbor

LF	Low Frequency, 120–150 kHz
LOS	Line-of-Sight
LSQ	Least Squares Quadratic
MW	Microwave Frequency, 2.4–5.8 GHz
PI	Prediction Interval
QoS	Quality of Service
RF	Radio Frequency, 3 kHz to 300 GHz
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indication (unit: dBm)
RTLS	Real-Time Localization System
TDOA	Time Difference of Arrival
TOA	Time of Arrival
UHF	Ultra High Frequency, 433MHz, 868-870 MHz, and 902-928 MHz
UPC	Universal Product Code
UWB	Ultra Wide Band
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network
XML	Extensible Markup Language

Chapter 1

Introduction

1.1 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a radio wave transmission process between an interrogator and a transponder, also known as a reader and a tag. The tag is identified by responding to the information stored in its internal memory or from the attached sensors. The reader is usually connected to a computer with a database for further processing of received information or sensor data. RFID technology is widely applied in transportation payments, asset management, supply chains, logistics, animal tracking, libraries, and securities [1].

Based on their working mechanism, RFID tags can be categorized as active tags, passive tags and semi-passive tags. The active tags are self-powered and broadcast signals at preset intervals. They usually provide a larger read range. The passive tags and semi-passive tags are only activated by the querying signal from the reader. The semi-passive tags use internal battery power to enhance the broadcasting signal strength, while the passive tags are much cheaper and smaller. The operating frequency bands used for RFID tags vary from kHz, MHz to GHz, which leads to different radio wave coupling modes and performance.

1.2 Real-Time Localization System (RTLS)

An emerging application of RFID is indoor Real-Time Localization Systems (RTLS), where satellite-based navigation techniques are limited by in-building coverage, and wireless network devices are relatively expensive and larger than RFID tags and therefore not suitable for small items. Other non RF-based techniques, such as visual, ultrasonic, infrared and laser localization, are vulnerable to environmental impacts and are restricted to the Line-of-Sight (LOS) readability. Admittedly, the multi-path propagation is an issue for RFID localization.

Due to the variation of RF signals in a real indoor environment, the theoretical propagation model is not applicable for RFID localization. Numerous positioning algorithms have been developed. The multilateration approach utilizes different techniques for estimating distance between the unknown targets and the readers, such as, Received Signal Strength Indication (RSSI), Time of Arrival (TOA), and Angle of Arrival (AOA). The Bayesian inference approach statistically analyzes the dynamical data based on the Markov assumption. It is effective in tracking mobile objects upon calibration and training. In addition, both the k Nearest-Neighbor (kNN) approach by using weighted centroid of certain neighbors and the proximity approach by using intersection of several coverage areas, avoid the distance estimation step, but both heavily rely on the density of reference tags or reader distribution to improve positioning accuracy. Furthermore, most reported RFID-RTLS systems are designed for 2D space only, there is a clear need for a 3D system.

1.3 Purpose of Research

Due to multipath propagation and interference in the indoor environment, theoretical propagation models are generally not sufficient for RFID-based localization. In fact, the RF signal distribution may not even be monotonic and this makes range-based localization algorithms less accurate. On the other hand, range-free localization algorithms, such as kNN, require reference tags to be deployed throughout the whole 3D space which is simply not practical. Besides, the anisotropic environmental impacts in real 3D application are significant and not neglectable.

The first objective of this study is to model the theoretical minimum number of reference tags needed in a localization system. The modeling process is also helpful on identifying the major factor affecting the localization accuracy.

The second objective of this research, therefore, is to build an indoor RFID-based RTLS capable of positioning objects in 3D space in real-time. An active RFID system and a power-assisted passive RFID system were built side-by-side for easy comparison. The systems were deployed in a high-complexity laboratory room to reflect real environmental impacts.

The third objective of this dissertation is to investigate the RFID tag performance difference between the regular laboratory environment and the ISS mock-up. The high-reflection interior surface would be a big challenge for RF signal stability. The investigation result may be valuable for further system design.

1.4 Dissertation Organization

Chapter 2 consists of a literature review describing the background regarding RFID and RTLS technologies, their applications, and common system designs.

Chapter 3 presents a theoretical analysis about the minimum number of reference tags needed in a localization system.

Chapter 4 describes the proposed 3D localization system designs in the high-complexity environment and the localization algorithm being evaluated. The experiment designs of several fundamental tests are mentioned as well.

Chapter 5 contains the results and analysis of the fundamental tests and localization experiments. It also includes a tag performance comparison between active tags versus battery-assisted passive tags in both laboratory and mock-up environments.

Chapter 6 summarizes the conclusions and recommendations.

The appendices include the programming interface to the two types of readers, the Matlab codes used for controlling the whole system, and the data sheets for all experiments.

Chapter 2

Literature Review

2.1 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a popular information exchange technology widely applied in electronic passport [2], animal tracking [3], supply chains [4], industrial automation [5], mining securities [6], hospital [7], asset management [8], and pharmaceuticals [9]. There are numerous RFID applications, and cannot be listed here completely. More examples may be found in the RFID Journal and RFID handbook [1, 10].

A simplest RFID system consists of two major components: a tag and a reader. The tag and the reader communicate via radio waves. The radio frequency (RF) bands commonly used in RFID include 120-150 kHz at Low Frequency (LF), 13.56 MHz at High Frequency (HF), 433MHz, 868-870 MHz, and 902-928 MHz at Ultra High Frequency (UHF), and 2.4-5.8 GHz at Microwave Frequency (MW) [10]. The RFID systems with operating frequency at LF and HF work based on inductive coupling. By contrast, the systems in the range of UHF and MW are coupled using electromagnetic (EM) fields, which brings a significantly higher read range than inductive systems.

These typical frequency bands used in RFID are summarized in Figure 2-1. The 433 MHz UHF and MW tags are usually used for active tags. In addition, the MW tags can be designed to be compatible with existing WiFi systems via the IEEE 802.11 protocols. For common passive RFID applications, the LF and HF tags can be used without license globally, while the UHF frequency bands are restricted by various regulations in different countries. These passive tags are most likely bonded with an Electronic Product Code (EPC), which is designed to enhance the traditional Universal Product Code (UPC) electronically. The international standardization of EPC is mostly led by EPCGlobal, an organization aiming to standardize and promote EPC technology worldwide. According to the latest standard [11], which is also adopted as part of ISO-18000, 868-870 MHz and 902-928 MHz readers and tags communicate using the EPCglobal UHF Class 1 Generation 2 (Gen 2) interface. The new protocol address some problems experienced from previous one used for LF and HF tags, namely Gen 1 tags.

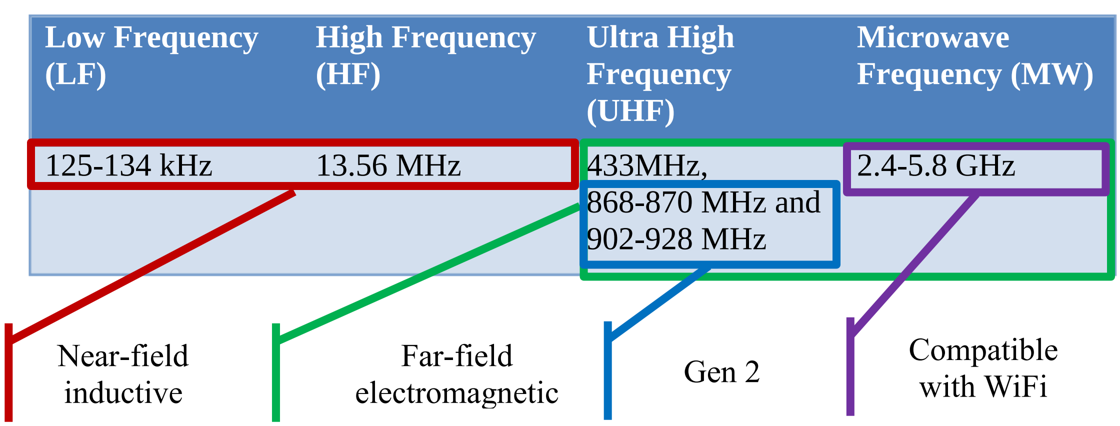


Figure 2-1: Typical frequency bands used for RFID

Normally, a reader initiates an inquiry or update process, as shown in Figure 2-2 part (a). Then, a tag receiving the command carries the order and replies the execution result to the reader. As shown in Figure 2-2 part (b), the self-powered active tag can be programmed to broadcast data periodically, regardless of whether any reader actually exists or not. The basic information reported by a RFID tag may include serial number, manufacturing date, vendor name, asset information, and other customized data [11]. Such static data is stored in the internal memory of the tag. For tags with rewritable memory, the data can be updated upon request. By integrating certain sensors to the tag, some additional information, such as motion status, air pressure, temperature, and humidity can be detected and reported by the tag as well.

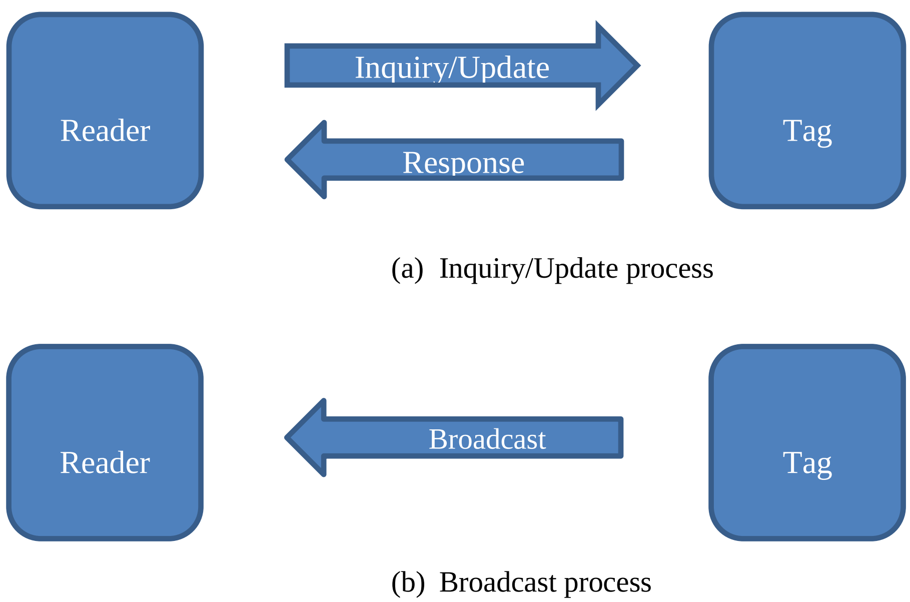


Figure 2-2: Communication models between RFID tags and readers

2.1.1 Tags

Usually, an RFID tag has two key components: an integrated circuit (IC) for executing commands and storing data; and an antenna coil for receiving and transmitting RF signals. Additional components include batteries and/or special sensors as mentioned above. The typical RFID tag structure is demonstrated in Figure 2-3.

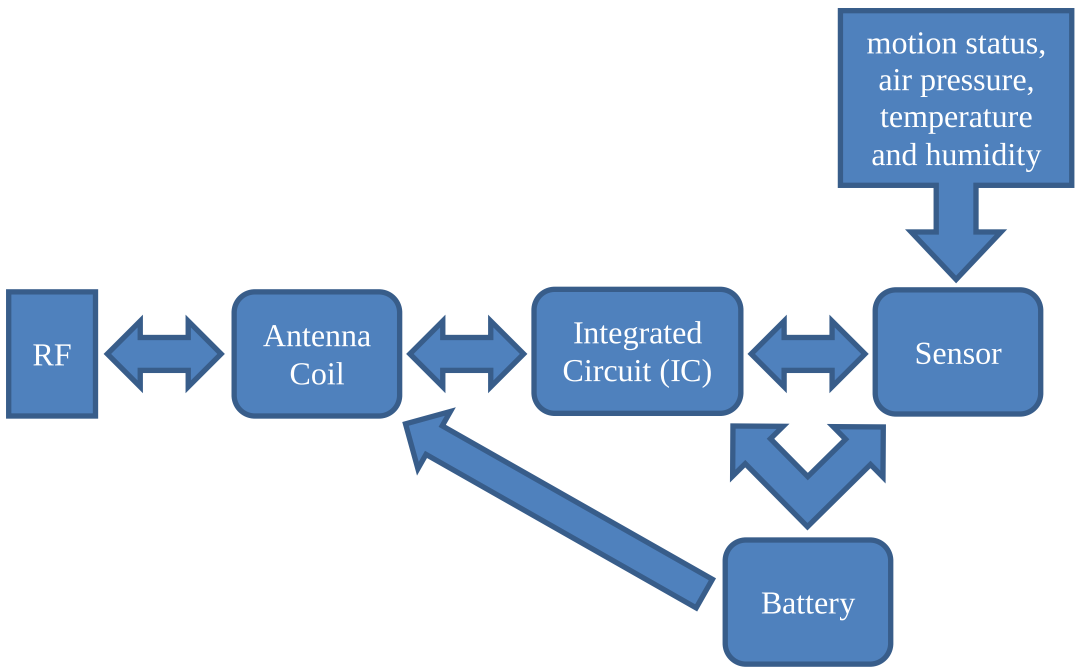


Figure 2-3: Active RFID tag structure

Based on different power source and working mechanism, RFID tags can be categorized into three major types: passive, semi-passive, and active tags. Both passive tag and semi-passive tag are activated by the querying RF signal from the reader. The passive tag is only powered by the energy transformed from the querying RF waves, which significantly decreases its read range, cost and size. On the other hand, the semi-passive tag uses internal battery power to drive the circuits and any existing sensors, and the signal transmission is still powered by the incoming RF waves. An active tag is self-powered and broadcasts signals at preset intervals. It usually provides a larger read range.

All types of tags are used in RFID-based RTLS. Systems using active tags are more commonly reported than passive tag systems due to the larger read range and continuously working ability. On the other hand, the passive tags and semi-passive tags have advantages on security and interference issues, owing to their silent characteristics.

2.1.1.1 Passive Tags

A passive RFID tag has neither battery nor sensor. The RF waves propagated by the reader's antennas are inducted to provide power for the passive tag. It appears to be dormant most of the time, and becomes active after an interrogation from a reader is received. The inquiry/response process limits the passive tag to communicate with only one reader at a time.

Typical operating frequency bands for passive tags are 120-150 kHz and 13.56 MHz. In this case, near-field communication, where the distance traveled in space of the RF signal is much less than its wavelength, acts as the major technology to drive the tag. A relatively larger coil, therefore, is required for the passive tag to generate enough power by inductive coupling. Since the RF signal strength decays along the distance rapidly, the read range of traditional passive tags is limited to 1 to 3 meters, varying by the operating frequency [12]. Due to the reflective characteristics of electromagnetic waves on metal and liquid surfaces, the readability of passive tags is severely affected under such circumstances. The Gen 2 passive tags use 868-870 MHz and 902-928 MHz as operating frequency bands and are able to work in the dual mode of near-field and far-field communication, which improves the overall performance significantly. For instance, the read range can be extended to 10 meters [13].

Lack of a battery and a sensor definitely bring some limitations to passive RFID tags. But it also reduces the cost and size of RFID tags significantly.

2.1.1.2 Semi-passive Tags

A semi-passive RFID tag is essentially a passive tag with additional battery and/or sensor. It is an enhanced edition of a passive tag, but not a silent edition of an active tag. The additional power supply is used to power the circuits and sensors only. In this way, all the power received via the RF waves can be used for RF communication with the reader. It marginally increases the read range since no more power in the received RF signal is shared to drive circuits the way passive tags do. As long as the inquiry signal can be received, the response can be sent back with full strength.

2.1.1.3 Active Tags

With an additional battery as power supply, an active RFID tag has the ability to broadcast its identification information or sensor data actively and periodically. Therefore, active tags are able to communicate with multiple readers concurrently. Additionally, they have the larger read range between 50 to 100 meters as higher frequencies are used and broadcasting RF signal strength is enhanced with the extra battery [14].

Typical operating frequency bands for active tags are 433 MHz and 2.4 – 5.8 GHz, at which the RFID system works in the far-field region where the distance traveled in space of the RF signal is much greater than its wavelength. In such cases, using higher frequency (such as 2.4 GHz) leads to higher data transmitting bandwidth and rate. Therefore, new functionalities, such as tag-to-tag communication and integration to WiFi network, become possible.

The battery life of an active RFID tag is usually around 3 to 5 years. Thus, battery monitoring and maintenance are required. Moreover, the additional battery and related circuits increase both the cost and size of active tags significantly, comparing to passive tags.

2.1.2 Readers

A RFID reader is a device modulating and demodulating RF signals to communicate with supported RFID tags via one or several antennas. Most readers are compatible with either active tags or passive tags of certain operating frequency; only a few are able to work in dual mode. A database for managing all readers and tags, and some complicated control logics, such as noise threshold setting, antennas balance, and active history, may be deployed on the computer connected to the readers.

2.2 Real-Time Localization System (RTLS)

An emerging application of RFID is indoor Real-Time Localization System (RTLS), where the Global Positioning System (GPS) technique is limited by in-building coverage, Wireless Local Area Network (WLAN) devices are relatively expensive and larger than RFID tags and therefore not suitable for small items, and Ultra Wide Band (UWB) systems have a potential interference with some radar systems by sharing a wide range of bandwidth. Other non RF-based techniques, such as ultrasonic, infrared (IR) and laser localization, are vulnerable to environmental impacts and are restricted to the Line-of-Sight (LOS) readability. Admittedly, the multi-path propagation is an issue for RFID localization.

RTLS, especially indoor RTLS, has widespread applications in many areas. Most current systems provide room-level or sub-room level resolution. Low cost rack-level or item-level solution is desired. An uncompleted list of up-to-date RTLS products and their major applications is listed in Table 2-1. All information is collected from the product description available on their official websites.

Table 2-1: RTLS products list

System	Vendor	Technology	Ranging	Accuracy	Applications
AeroScout RTLS	AeroScout	WiFi and Active RFID	TDOA, RSSI	5 meter	Healthcare, Manufacturing, Logistics
ZOMOFI	Albis	Active RFID		0.5 - 2m	
Awarenet	Awarepoint	ZigBee		1-3 meter	Healthcare
Axcess RTLS	Axcess	Active RFID			Logistics, Security
CenTrak RTLS	CenTrak	Infrared and Active RFID		Rack-level	Healthcare
Wireless Location	Cisco	WiFi, Active and Passive RFID			Asset Management
Ekakau RTLS	Ekakau	WiFi	RSSI	Sub-room	Healthcare, Retail, Logictics, Manufacturing
LOST	Essensium	ZigBee	TOA	Sub-meter	Logistics
Argus	Guard RFID	Active RFID		3-5 meter	Industrial, Healthcare
SensorSMART	Identec	Active RFID and WSN			Marine, Oil, Mining, Defense
InSites Locator	Intelligent InSites	Various techniques		Room-level	Healthcare
BizTalk RFID	Microsoft	UWB and RFID			Manufacturing
RTLS ENGINE	Motorola	WiFi, Active and Passive RFID			Asset Management
Omnitrol RTLS	Omnitrol	WiFi, UWB, and RFID			Manufacturing, Retail, Logistics
PanGo Locator	PanGo/Cisco	WiFi and Active RFID	RSSI		Asset Management, Healthcare
PervTrack RTLS	PervCom	Active RFID and WSN			Manufacturing, Mining Industry
PINC RTLS	PINC	Passive RFID		+/- 1 spot	Yard Management
PinPoint RTLS	PinPoint	WiFi and ZigBee			Education, Healthcare, Hospitality
iLocate	Precyse	WSN			Manufacturing, Defense, Retail, Healthcare
Radianse RTLS	Radianse	Active RFID			Healthcare
Asset Manager	RF Code	Active RFID		Sub-room	Asset Management
Room Locator	RF Code	Infrared		Rack-level	Asset Management
RFind RTLS	RFind	Active RFID			Automotive, Logistics, Manufacturing, Public Transit
SmartChain	Savi	Active RFID			Aerospace, Defense, Logistics, Natural Resources
High Definition	Sonitor/IBM	Ultrasound		Sub-room	Healthcare, Homecare
Plus, PlusON	Time Domain	UWB			Retail, Manufacturing, Healthcare, Defense
Ubisense RTLS	Ubisense	UWB	AOA, TDOA	15cm	Manufacturing, Defense, Transpotation
Elpas	Visonic	Infrared, Active and Passive RFID			Healthcare
Wavetrend System	Wavetrend	Active RFID			Construction, Oil and Gas, Defense, Security, Mining
Visibility System	Westico	WiFi		Meters	Logistics, Retail, Manufacturing, Healthcare
MobiWERX	WirelessWERX	Bluetooth			Hospitality, Retail, Attractions, Mobile-gaming
WhereNet	Zebra	WiFi and UWB	TDOA		Asset Tracking, Supply Chain Management

2.2.1 Global Positioning System (GPS) and A-GPS (Assisted GPS)

The Global Positioning System (GPS) is a well-known satellites-based outdoor localization system operated by the U.S. Other similar systems in use include: GLONASS by Russia, Beidou by China, and Galileo by Europe. Assisted GPS (A-GPS) is a GPS application which uses cellular network resources to improve the startup and locating performance of a receiver. By measuring the time difference of arrivals from four or more satellites at the same time, the GPS receiver is able to calculate its three-dimensional (3D) position based on the multilateration approach. For civil applications, the positioning resolution is about 10 meters for outdoor usage [15]. However, neither GPS nor A-GPS is suitable for indoor applications due to weak signals. Furthermore, high energy consuming and expensive receivers limit the GPS or A-GPS to be used for a large scale deployment.

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

The Wireless Local Area Network (WLAN) technique is used for indoor localization due to several advantages against GPS/A-GPS. First, the Wireless Fidelity (WiFi) devices are relatively inexpensive and have low power consumption. Second, WiFi network become an increasingly common infrastructure in many buildings, which help to reduce the deployment cycle and overall cost of a WiFi-based indoor localization system. Nevertheless, the size, cost and power consumption of traditional WLAN devices are still not comparative to RFID tags due to different purpose of use. A technique called

Wireless Sensor Network (WSN) was developed to address such issues. The idea of WSN is to limit the computational power and signal bandwidth of a WSN node to a low level so that the overall performance is just enough for environmental monitoring applications. Then, a new problem emerges. WSN nodes may be interfered by WLAN devices which usually have stronger signals. ZigBee and WiFi are two most important protocols used in WSN. One of WSN's major advantages is inter-communication capability among nodes. The positioning accuracy of the WiFi-based localization systems varies from sub-meter to several meters for different algorithms and deployment densities [16]. According to latest research results, the accuracy could achieve 0.04 meters for 2D and around 0.1 meters for 3D applications [17, 18].

2.2.3 Radio Frequency Identification (RFID)

The biggest advantages of passive or semi-passive RFID tags are the extremely low price and ultra-small size. However, the RTLS applications based on Gen 1 passive/semi-passive RFID tags are limited by the low read range. Dense deployment is required to provide enough coverage. The typical resolution of such a RTLS is at the sub-meter level and highly depends on the density of tag deployment. A system may benefit from the larger read range of Gen 2 passive tags. For all kinds of passive tags, the tag orientation affects the signal reading significantly [19]. A common solution is to fix all tags, both reference tags and target tags, on the same plane (ceiling, floor, or wall) with the same orientation [20, 21]. This certainly causes some limitations in real applications.

Active RFID is similar to WSN but differs in that it has lower operation frequency (except for WiFi-based RFID, which will be discussed later) and lacks tag-to-tag communication feature. Due to similar mechanism, most deployment schemes and positioning algorithms work in almost the same way for both active RFID and WSN localization systems. Consequently, they share the localization resolution from sub-meter to sub-room level as well. The 433 MHz RFID system has a potential to be interfered in real applications because this frequency band is open for amateur radio [10]. The term, WiFi-based RFID particularly refers to a RFID system operates at the frequency of 2.4 GHz and is embedded into or able to communicate with any existing WiFi systems. In this way, the RFID system can be easily deployed and managed. Though, interference and traffic control between RFID signals and regular WiFi signals requires additional Quality of Service (QoS) configuration on the network server [22].

2.2.4 Ultra Wide Band (UWB)

As a totally different approach, Ultra Wide Band (UWB) is a radio technique which has high volume data rate (up to 1 Gbps) as the result of using ultra-short pulses (up to 1-2 giga-pulses per second) over a wide range of frequency spectrum (from 3.1 to 10.6 GHz) [23]. In general, the positioning resolution of a UWB-based localization system can achieve decimeter level, via LOS measurement and multilateration approximation [12]. Some particular algorithms may result in even more accurate resolution, less than 0.04 meters [23]. The pulse radio transmission style ensures UWB have no interference with other narrow-banded wave radio transmissions in the same frequency bands. However, it may be interfered in some environments where air traffic control radio beacon system, airport or maritime surveillance radar, and GPS receivers, are in use [24]. Another concern is that various regulations on this wide spectrum are permitted in different countries [25], because the pulse-based radio technique is originally reserved for military usage, such as radar and satellite systems. This leads to high R&D cost and, therefore, high price for UWB chips.

2.2.5 Non RF-based

Other than the above mentioned radio-based solutions, those non RF-based techniques, such as ultrasonic, infrared (IR) and laser localization, have long been applied in positioning systems and are mature [14]. However, restricted to the Line-of-Sight (LOS) readability, these techniques are vulnerable to environmental impacts, for instance, obstacles and irregular room shapes. On the other hand, such LOS characteristic ensures item-level accuracy, given the tag is detected. Nevertheless, the overall locating resolution is highly determined by the density of reader/antenna deployment, which leads to significantly increased cost of the whole system.

2.2.6 Summary

Upon the above discussion, several interesting characteristics of the indoor RTLS with various techniques are summarized and compared in Table 2-2. The unit accuracy column defines the accuracy level being achieved by a single unit but not the whole system, since some systems' resolution highly relies on the density of tag/reader deployment. It should be noted that the system cost column is comparing the estimated building cost of a system based on comparative overall performance.

Table 2-2: Indoor RTLS comparison based on different frequency bands being used

Category				**Frequency**	**Band**	**Unit Accuracy**	**LOS**	**Multi-path**	**Read Range**
EM	IR/Laser			High	Wide	High	Yes	No	Medium
	RF	UWB		High	Wide	High	No	No	Medium
		Narrow Band	MW*	Medium	Medium	Med/High	No	Yes	High
			UHF	Medium	Medium	Medium	No	Yes	Med/High
			HF	Low	Narrow	Medium	No	Yes	Medium
			LF	Low	Narrow	Low	No	Yes	Low
Ultrasound				Low	Narrow	High	Yes	Yes	High

*Note: Both WLAN/WSN and WiFi-based RFID are included in the MW band.

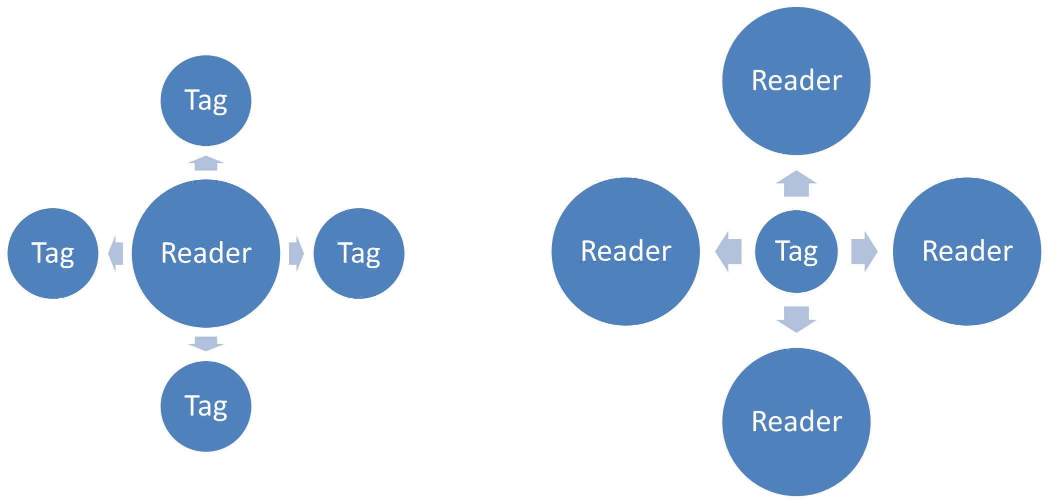
As a whole, the UWB, WSN, and Gen 2 RFID techniques seem to stand out from the others. Due to the low price of tags, Gen 2 RFID technique is very suitable for large scale applications. Though, its localization accuracy is lower than the other two.

2.3 RFID-RTLS

Despite the difference caused by various types of RFID tags, the fundamental system structure, or scheme of RFID-RTLS varies. Also, different positioning logics, namely algorithms, have been reported.

2.3.1 Schemes

RFID-based localization can be classified as fixed-tag localization and fixed-reader/antenna localization, in accordance with different roles of tags and readers/antennas [26], as illustrated in Figure 2-4. In the fixed-tag scheme, the tags are deployed on the ceiling or floor with some rules while the readers/antennas are usually attached to mobile objects. This is cost effective when the objects to be tracked are relatively large, few in numbers, and usually move in a 2D plane or on a certain route. The major application is an auto guided vehicle or robot [27, 28]. In the fixed-reader/antenna scheme, the readers/antennas and tags are placed in an opposite way to the fixed-tag scheme. The readers/antennas are installed at fixed positions while the tags are attached to the items to be tracked. It is useful for most applications where a lot of items need to be tracked and located at the same time because the tags are much cheaper and smaller than the readers/antennas. The following work will be based on this scheme.



(a) Fixed-tag scheme (b) Fixed-reader scheme

Figure 2-4: Two common RTLS schemes

2.3.2 Algorithms

In a real indoor environment, fading, absorbing, reflection, and interference are major issues affecting the RF waves' strength, direction, and distribution. This make the variation of the RF signal propagation not easily modeled. Since the theoretical model is not applicable, numerous positioning algorithms have been developed. Several major types are summarized and introduced as follows, while many varieties exist. The two largest groups are determined by whether the algorithm ranges the RF signal to an estimated distance or not.

The range-based localization algorithms require two steps of work. First, the elementary range results are obtained in several ways: Received Signal Strength

Indication (RSSI), Angle of Arrival (AOA), Time of Arrival (TOA), Time Difference of Arrival (TDOA), or Adaptive Power Multilateration (APM). Then, various approaches on geographical calculations, such as triangulation, trilateration, and multilateration, are applied to estimate the final position.

Both the k Nearest-Neighbor (kNN) approach by using centroid of certain neighbors and the proximity approach by using intersection of several coverage areas avoid the distance estimation step in range-based localization approaches. However, they heavily rely on the density of reference tags or reader/antenna distribution to improve positioning accuracy.

2.3.3 Range-based Localization

2.3.3.1 Received Signal Strength Indicator (RSSI)

Received Signal Strength Indicator (RSSI) is considered the simplest approach for ranging since almost no additional cost is needed to collect the RSSI data which is provided by most systems [29]. It is a measurement of received radio signal power in terms of the ratio of measured power decibels (dB) to one milliwatt (mW). However, it is also a less accurate way due to complicated environmental impacts to the RF signals propagation [30]. No theoretical or empirical model can be applied as a universal solution. Therefore, the RSSI map, which is used to translate the signal strength into distance estimation, should be calibrated for every single antenna to achieve better results. The initial solution is to measure the RSSI values at all possible points with predefined density and renew the mapping periodically. It is not practical to maintain such a system.

Later, a technique called fingerprinting, or profiling is used, which places reference tags at particular positions to serve as anchors. The signal strength collected from these reference tags with known coordinates help to build a dynamic RSSI map reflecting real environmental impacts. For each antenna, this map is used to translate the RSSI value from a tag with unknown coordinates into an estimated distance from this tag to the antenna. Classical lateration can be applied to collective data from several antennas to approximate the position of this unknown tag in space. The idea of RSSI with fingerprinting is demonstrated in Figure 2-5. The improvement on resolution relies on the density of these anchor nodes.

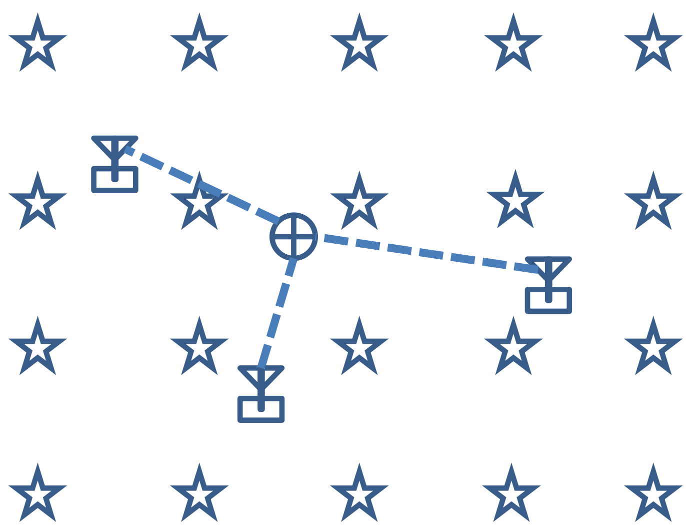


Figure 2-5: RSSI with fingerprinting

2.3.3.2 Angle of Arrival (AOA)

The basic idea of Angle of Arrival (AOA) is simple. Consider a triangle for example. Given the coordinates of any two points are known, the third one can be located if and only if the angles from these two known points to the unknown point are provided. This method is known as triangulation, as illustrated in Figure 2-6. The concept can be extended to 3D space easily. This approach requires customized RF signal modulating/demodulating units which are add-ons to the overall cost. Therefore, precise calibration is needed before use. The LOS requirement is another limitation for applications. The measured angle accuracy is less than 1.7° in a small experimental space, and decreases for larger angles and longer distance between the tag and the antennas [31]. The overall resolution is approximately sub-meter level for a regular room size space, and depends on the density of reader/antenna deployment.

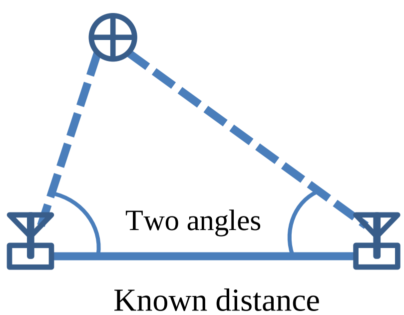


Figure 2-6: Triangulation for AOA

2.3.3.3 Time of Arrival (TOA)

The Time of Arrival (TOA) method is based on a theoretical propagation model of an RF signal. The distance between two points can be determined if the travel time of the signal between them is measurable. Then, the location of an unknown tag can be determined using such measurements from various antennas. Cycle intersection, as shown in Figure 2-7, and nonlinear least-squares approaches are commonly used to get optimal results with minimum errors. However, the velocity of the EM wave is so high that the typical travel time within a room is on the scale of nanoseconds. Hence, the TOA method requires all readers and tags to be strictly precisely synchronized, and all signals to be time-stamped [29]. The theoretical accuracy can be very high. But with affordable commercial synchronizing unit, the system resolution is usually about 1 to 2 meters [32]. Moreover, LOS is required to reduce interference caused by multi-path effects.

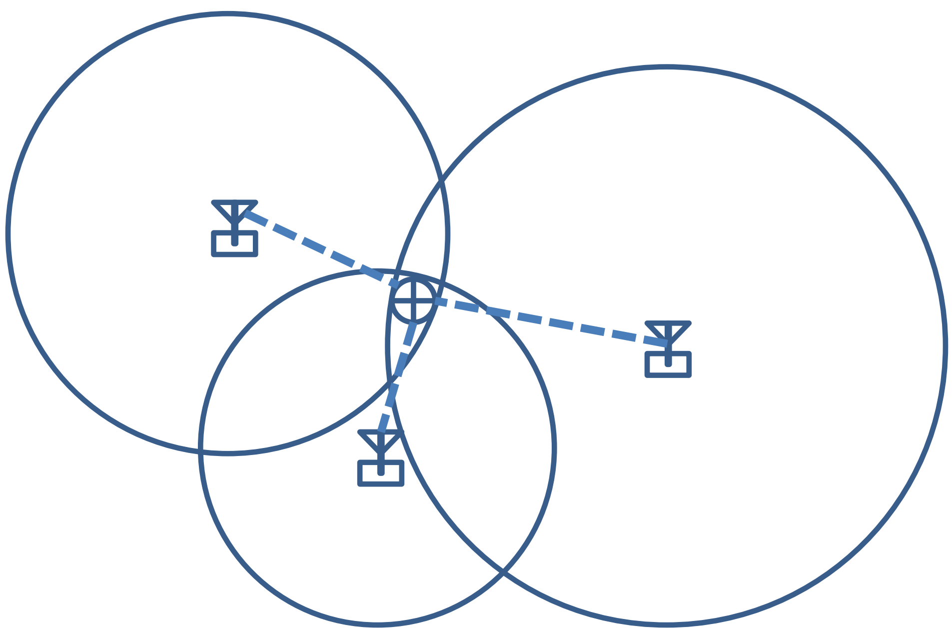


Figure 2-7: Cycle intersection for TOA

2.3.3.4 Time Difference of Arrival (TDOA)

Similar to TOA, the Time Difference of Arrival (TDOA) approach also relies on precisely synchronized readers and tags. But it uses a different methodology to determine the location of the unknown point [33]. For each pair of antennas, given the time difference of the RF signals from them to the tag to be tracked is known, all the possible locations of this tag must fall into one half of a hyperbola in 2D space, as shown in Figure 2-8, or a hyperboloid in 3D space. Then, the tag's location is determined as the intersection of the hyperbolas or hyperboloids generated by all pairs of antennas. The TDOA method has same limitations and drawbacks as TOA.

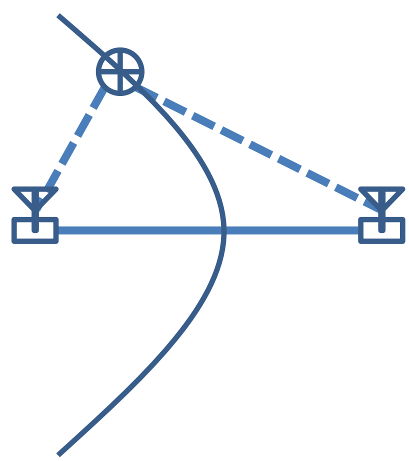


Figure 2-8: First step of multilateration for TDOA

2.3.3.5 Adaptive Power Multilateration (APM)

Another approach is called Adaptive Power Multilateration (APM), which measures the estimated distance from the reader to the tag by reducing or increasing the reader transmission power until the tag disappears or appears, as shown in Figure 2-9. The corresponding power level is then translated into distance based on a pre-calibrated chart. At last, the tag's position is determined using the multilateration method on distances estimated from all readers. The accuracy of APM heavily relays on two things. One is the edge tolerance of the power circle. A perfect clear cut at the edge may not exist. The other one is the environmental impacts. The pre-calibrated chart may not be valid under complex circumstance. Some attempts were reported to improve this method by using reader rotating and some statistical analysis [34, 35].

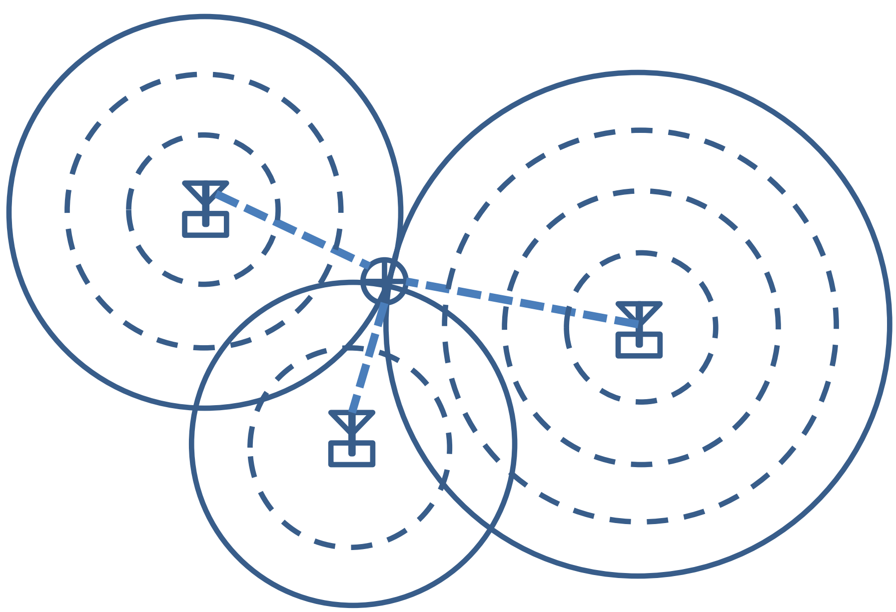


Figure 2-9: Multilateration for APM

2.3.4 Range-free Localization

2.3.4.1 k Nearest-Neighbor (kNN)

The fingerprinting technique applied in the improved RSSI approach is also used in the k Nearest-Neighbor (kNN) method but without ranging. Similarly, the reference anchors are deployed in cells. The Eucledian distances between the RSSI values from the unknown tag and all anchors are calculated. Subsequently, the k anchors with lowest distances to this tag are selected as its k nearest neighbors. The coordinates of this tag can be estimated using the centroid of these anchors, as illustrated in Figure 2-10. An enhanced method call weighted kNN further applies the Eucledian distances from the unknown tag to its k nearest neighbors as weights to improve the approximation [7]. Overall, the kNN approach is suitable for complex non-isotropic and varying environments.

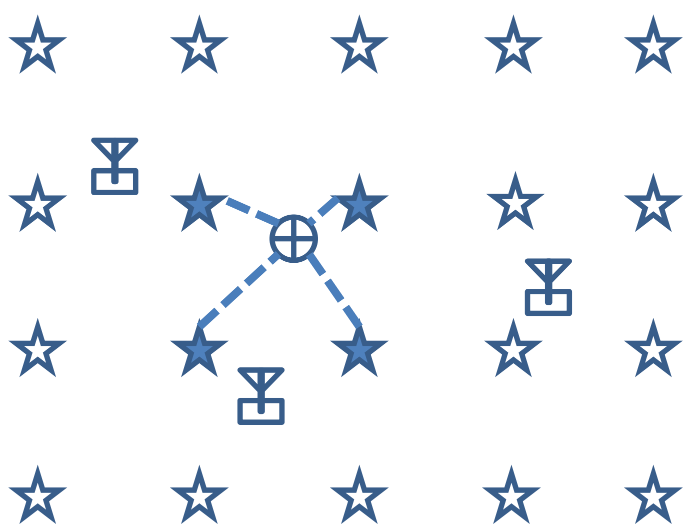


Figure 2-10: kNN

2.3.4.2 Proximity

In the proximity approach [14], each antenna has a predefined coverage area, which may be an approximation or calibrated result. If the unknown tag is detected by more than one antenna, the location of this tag can be estimated by the intersection of the coverage areas of these antennas, as shown in Figure 2-11. The density of antenna deployment heavily affects the system resolution. Furthermore, the coverage area may be difficult to be clearly defined since the RF signals fade away gradually at the edge and the theoretical propagation model may not be an appropriate simulation for real indoor environments.

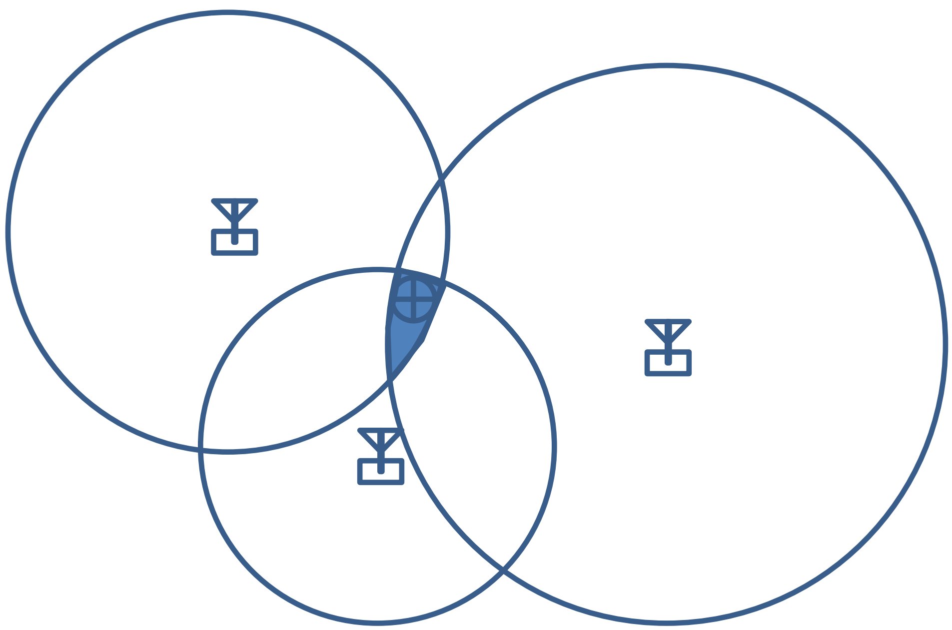


Figure 2-11: Proximity

2.3.5 Summary

Pros and cons of different types of localization algorithms most commonly used in RFID-RTLS are summarized in Table 2-3. Reported localization errors for several systems using these algorithms are also listed.

Table 2-3: Summary of localization algorithms in RFID-RTLS

Algorithms		**Pros**	**Cons**	**Accuracy**
Range-based	RSSI	Low cost; supported by most systems; enhanced with profiling	Low accuracy level; relies on dense deployment of reference tags	0.5 m [36], simulated; 0.72 m [37], measured
	AOA	High accuracy level	High cost for customized hardware; LOS measurement required; pre-calibration need	N/A
	TOA	High accuracy level	High cost for synchronized devices; LOS measurement required	N/A
	TDOA	High accuracy level	High cost for synchronized devices; LOS measurement required	0.2 m [38], measured
	APM	Low cost; no reference tags needed	Low accuracy level; relies on pre-calibrated power versus distance chart; not suitable in complex environments	0.32 m [35], simulated; 0.6 m [34], measured
Range-free	kNN	Low cost; suitable for complex non-isotropic and varying environments	Low accuracy level; relies on dense deployment of reference tags	0.6 m [7], measured
	Proximity	Low cost; easily deployed	Low accuracy level; relies on dense deployment of readers or antennas, coverage areas may not be clearly defined in complex environments	N/A

Overall, the RSSI and kNN approaches are mostly cost effective and reliable for indoor environments. Actually, these two methods are very similar in that they share the fundamental step of fingerprinting the reference tags. They are only different in the final stage for estimating the position of the unknown tag.

Chapter 3

Theoretical Modeling

3.1 Introduction

It is of interest whether there is any statistically significant minimum number of reference tags needed for an indoor, real time localization system based on Gen 2 RFID with battery-assisted passive tags or other active tags. This problem may be solved in two steps.

First, find out a theoretical solution (at least approximation) based on a series of assumptions and experimental data from various sources.

Second, design an experiment which is able to determine the relationship between accuracy level and number of reference tags, and compare the result to the value estimated in first step.

Furthermore, the trend of localization error as the system dimension increases from 1D to 2D and then to 3D is investigated. It may be useful on predicting the 3D localization error based on previous 2D or 1D system performance.

3.2 Assumptions

The following are the assumptions used in this modeling section.

- **Room size.** To simplify the question, the test bed is assumed to be located in a room with the dimension of 3x3x3 meters. In this way, all readers and tags can be deployed symmetrically and evenly in the 3D space. Such deployment policy in 2D is reported to be an optimum solution in terms of maximizing accuracy [39]. Furthermore, $3*\sqrt{5}=6.7$ meter (the maximum distance within a 3x3x3 cube) is a safe distance to cover the read range of common Gen 2 RFID passive tags [40]. Larger room size may require either more readers or higher class tags to ensure the RSSI in a stable range. Either option leads to increased overall system cost.

- **Environment.** In reality, a complex environment is very difficult to be modeled. So, the room is assumed to be absent of large obstructions. All environmental effects, such as radio wave reflection, absorption, and possible interference, are assumed to be isotropic and consistent.

- **Reader.** The amount of readers (and/or extended antennas, which will also be treated as reader for the sake of conciseness) and their deployment will affect the localization algorithm and accuracy. Nevertheless, such variation/optimization is out of the scope of this question. Let’s assume that four readers are placed at the four opposite corners of the room and none of them are located on the same edge of the cube, as illustrated in Figure 3-1. This is one of the symmetric layouts with minimum amount of readers required in a 3D space RTLS system.

- **Tag.** All reference tags are placed evenly and symmetrically on the six faces of the cube. None of them is placed in the inner space of the cube, as this is not practical in any real application. So, the total amount of all reference tags with such criteria cannot be any possible integer. Only certain numbers of tags are possible. Therefore, the minimum amount is 6 for one on each face center. Several possible layouts are illustrated in Figure 3-2. Scheme (a) has one reference tag on each corner point. Scheme (b) has one reference tag on each edge center. Scheme (c) has one reference tag on each corner point, edge center, and face center. More tag layout schemes will be discussed later.

- **Algorithm.** To simplify the solution, the basic RSSI ranging approach is applied to each reader. The RSSI map (based on all reference tags) for each reader is constructed and assumed to be isotropic in 3D space. The distances from the target tag to four readers are then estimated. The Trilateration method is used to determine the final position of the target tag.

- **Measurement.** The accuracy is defined as the distance from the real position and the estimated position of a target tag. Theoretically, the accuracy is not the same everywhere since there is no reference tag in the middle of the room. So, it is best to place the target tag at any random position within the room to calculate the accuracy. However, this may involve complex modeling and simulation. In this solution, therefore, the accuracy is averaged over the whole space with a few measurements.

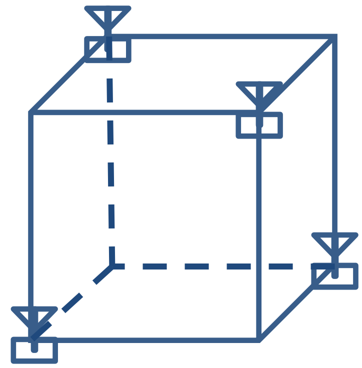
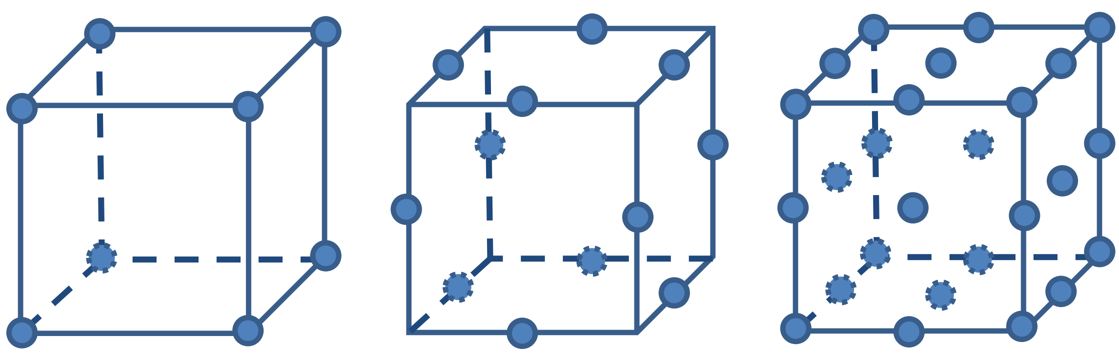


Figure 3-1: Reader layout scheme



(a) n=8 (b) n=12 (c) n=26

Figure 3-2: Tag layout scheme

3.3 Ranging

The theoretical propagation model used most extensively for RSSI ranging is called log-normal propagation model [12], which is valid with previous environmental assumptions. The model is given in Equation (3-1).

$$P_{RX}[dB] = PL(d_0) - 10\eta log_{10}\frac{d}{d_0} + X_\sigma \tag{3-1}$$

where $PL(d_0)$ is the path loss value for a reference distance d_0 (commonly 1.0 meter), η is the path loss exponent, and X_σ is a Gaussian random variable with zero mean and variance, σ^2, that models the random variation of the RSSI value.

According to previous research [41], the RSSI values are approximately linear within a range of 4 meters in the anechoic chamber and to a range of 10 meters in the clear hallway. Therefore, the propagation model in this question may be simplified into Equation (3-2).

$$P_{RX}[dB] = \widehat{PL}(d_0) - \hat{\beta}d + X_\sigma \tag{3-2}$$

where $\hat{\beta}$ is the slope coefficient for distance, which is a value estimated from the linear regression of measured RSSI for a given distance. It is a Gaussian random variable with mean β and variance ${\sigma_\beta}^2 = \frac{1}{n-2}(\sum_{i=1}^{n}\hat{\varepsilon}_i^2)/(\sum_{i=1}^{n}(x_i - \bar{x})^2)$ that models the random variation due to regression estimation. Obviously, more reference tags (larger n) lead to smaller ${\sigma_\beta}^2$ and hence more precise estimation of β. It should be noted that, by definition, the residual $\hat{\varepsilon}_i$ is also a Gaussian random variable with zero mean and variance σ^2 which is same as X_σ. Similarly, $\widehat{PL}(d_0)$ is the intercept coefficient with variance $\sigma_{PL}^2 = \sigma_\beta^2(\frac{1}{n}\sum_{i=1}^{n} x_i^2)$.

In order to predict distance with given RSSI, the Equation (3-2) is transformed into Equation (3-3).

$$d = \frac{\widehat{PL}(d_0) - \hat{P}_{RX}[dB] + X_\sigma}{\hat{\beta}} \tag{3-3}$$

where $\hat{P}_{RX}[dB]$ contains possible measurement error. Then, we have Equation (3-4).

$$\sigma_d^2 = Var\left(\frac{\widehat{PL}(d_0) - \hat{P}_{RX}[dB] + X_\sigma}{\hat{\beta}}\right) \tag{3-4}$$

This can be further calculated via the following equations, referred from [42, 43].

$$Var(X+Y) = Var(X) + Var(Y) + 2Cov(X,Y) \tag{3-5}$$

$$Var(XY) = [E(X)]^2 Var(Y) + [E(Y)]^2 Var(X) + Var(X)Var(Y) \tag{3-6}$$

$$Var\left(\frac{X}{Y}\right) \cong \left[\frac{E(X)}{E(Y)}\right]^2 \left\{\frac{Var(X)}{[E(X)]^2} + \frac{Var(Y)}{[E(Y)]^2} - \frac{2Cov(X,Y)}{E(X)E(Y)}\right\} \tag{3-7}$$

The close form solution of σ_d^2 may be too complicated to be easily interpreted. So, pilot experiment results should be used for further evaluation. The values may vary for different systems and environments, but the derivation steps are the same. For example, based on the experiment results on active RFID tags in 2D space, the estimated regression function (with 9 reference tags) is d = -9.560 - 0.234P_{RX}. The σ_d varies from 0.126 to 0.430 (average 0.278) within the range of 4 meters. The corresponding 95% prediction interval (PI) for ranging varies from 1.858 to 2.690 meters (average 2.274).

A close investigation into the relationship between σ_d^2 and *n* reveals that

$$\sigma_d^2 \cong \alpha(n) \cdot Var(regression) + \beta(n) \cdot Var(nature) + \gamma(n) \cdot Cov(r,n) \qquad (3\text{-}8)$$

where *Var(regression)* is the variance generated from linear regression approximation process, *Var(nature)* in the variance inherited from RSSI variation and measurement error, *Cov(r,n)* is the covariance between them, and *α(n)*, *β(n)*, and *γ(n)* are corresponding coefficients for the three terms, respectively. The three coefficients are functions of *n*.

A proposed hypothesis of σ_d^2 as a function of *n* is that σ_d^2 will decrease to a certain level as *n* increases. After that, *Var(nature)* becomes dominant, and σ_d^2 will keep nearly constant. We may design a series of experiments with various amounts of reference tags to see whether we are able to fit a model to predict such trend or not. If it is found, then the maximum possible RSSI ranging error can be estimated for any given amount of reference tags.

3.4 Localization

After the approximated distances from the target tag to four readers are obtained, the relationship among them may be present in Equation (3-9).

$$\begin{cases}(x-x_1)^2+(y-y_1)^2+(z-z_1)^2=r_1^2\\(x-x_2)^2+(y-y_2)^2+(z-z_2)^2=r_2^2\\(x-x_3)^2+(y-y_3)^2+(z-z_3)^2=r_3^2\\(x-x_4)^2+(y-y_4)^2+(z-z_4)^2=r_4^2\end{cases} \tag{3-9}$$

where (x, y, z) is the target tag coordinate to be estimated, (x_i, y_i, z_i) is the position of four readers, and r_i are the predicted distance from the target tag to the four readers. This group of nonlinear functions can be solved via traditional nonlinear least squares approach, iterative arithmetic method, or some other algorithms [44]. The fundamental idea is to find the best solution of (x, y, z) which minimizes the sum of squared differences between the r_i's and their corresponding modeled values.

The final localization error, e, between the approximated position $(\hat{x}, \hat{y}, \hat{z})$ and the real position (x, y, z) of the target tag is defined in Equation (3-10).

$$(x-\hat{x})^2+(y-\hat{y})^2+(z-\hat{z})^2=e^2 \tag{3-10}$$

According to the performance analysis presented in [44], the variance of the position estimation error is proportional to the square of ranging error, and can be modeled in Equation (3-11).

$$\sigma_{ex}^2=D_x^2\sigma_d^2 \qquad \sigma_{ey}^2=D_y^2\sigma_d^2 \qquad \sigma_{ez}^2=D_z^2\sigma_d^2 \tag{3-11}$$

where σ_d^2 is the random error inherited from the RSSI ranging process, D_x, D_y, and D_z are geometric indices expressing the non-isotropic effect of the system, which can be calculated with the following functions of Equation (3-12).

$$D_x^2 = \frac{\sigma_y^2 + \sigma_z^2}{\sigma_d^2} \qquad D_y^2 = \frac{\sigma_x^2 + \sigma_z^2}{\sigma_d^2} \qquad D_z^2 = \frac{\sigma_x^2 + \sigma_y^2}{\sigma_d^2} \tag{3-12}$$

By assuming isotropic everywhere in previous statement, the variances in three axes are identical, and are equal to the ranging variance σ_d^2. Therefore, the geometric indices D_x, D_y, and D_z are all equal to √2. By further assuming no covariance among the variances in three axes, the overall variance of position estimation error can be determined by Equation (3-13).

$$\sigma_e^2 = 6\sigma_d^2 \tag{3-13}$$

Similarly, the expected value of the localization error, namely bias, is also proved to be proportional to the square of ranging error, and can be modeled by Equation (3-14).

$$b_x = B_x\sigma_d^2 \qquad b_y = B_y\sigma_d^2 \qquad b_z = B_z\sigma_d^2 \tag{3-14}$$

where B_x, B_y, and B_z are geometric factors expressing the nonlinearity effect of the system, which may be defined as the coefficients ratio of the second and first order terms of the nonlinear distribution equation. By assuming linearity everywhere in previous statement, the second order terms are negligible for all three axes. Therefore, the geometric factors B_x, B_y, and B_z and corresponding expected values of position estimation error for all three axes are equal to zero. This means the overall estimation is unbiased, as shown in Equation (3-15).

$$E(e) = \sigma_d^2\sqrt{B_x^2+B_y^2+B_z^2} \tag{3-15}$$

The above result is based on a series of assumption which may not be adequate in a real situation, especially the non-isotropic characteristics of RSSI reading. It is known to be sensitive to the orientation of the tag with respect to the reader. It’s impossible to have all reference tags facing each reader with same orientation at the same time. Multiplicity of reference tags is a possible solution which will not be discussed here. Moreover, the ranging error must be different at various locations in the room since there is no reference tag in the middle of the room and the environmental factors will affect the reading close to the wall, floor, ceiling, or any area using certain materials such as metal. All of these will lead to a higher overall position estimation error than what has been derived here.

Since the 95% prediction interval (PI) is proportional to standard error, the projected 95% PI for 3D localization should be approximately √6 times of the 95% PI for ranging only, based on Equation (3-13). Now, using the pilot result at *n*=9, the estimated 95% PI for 3D localization is about (2.274)*√6 = 5.57 meters. This means, with the linear regression function estimated from 9 reference tags and the position approximation via trilateration, we are 95% confident that the true position is within a 5.57 meters interval, which is the diameter of a globe centered at the approximated position of the target tag. In other words, the maximum possible error of the position estimation is 2.79 meters away from the true value. Moreover, it is possible to estimate this 95% PI with any amount of reference tags via the Equation (3-8) and Equation (3-13).

Please note that this is maximum possible error. It is different from the usually defined average error. Theoretically, the average localization error, e, can be calculated based on the definition in Equation (3-10) and its expected value $\sqrt{2/\pi}\,\sigma_e$ by assuming a normal distribution, as shown in Equation (3-16).

$$\hat{e} = \sqrt{2/\pi}\,\sigma_e = \sqrt{2/\pi}\left(\sqrt{6}\sigma_d\right) = 2\sqrt{3/\pi}\,\sigma_d \cong 2\sigma_d \tag{3-16}$$

The estimated error for 3D localization, $\hat{e}$, is then approximately 2 times of the ranging standard deviation, σ_d. Since the definition of 95% PI is [μ-1.96σ, μ+1.96σ], or approximately [μ-2σ, μ+2σ], Equation (3-16) can be further expressed in terms of 95% PI for ranging only, as shown in Equation (3-17).

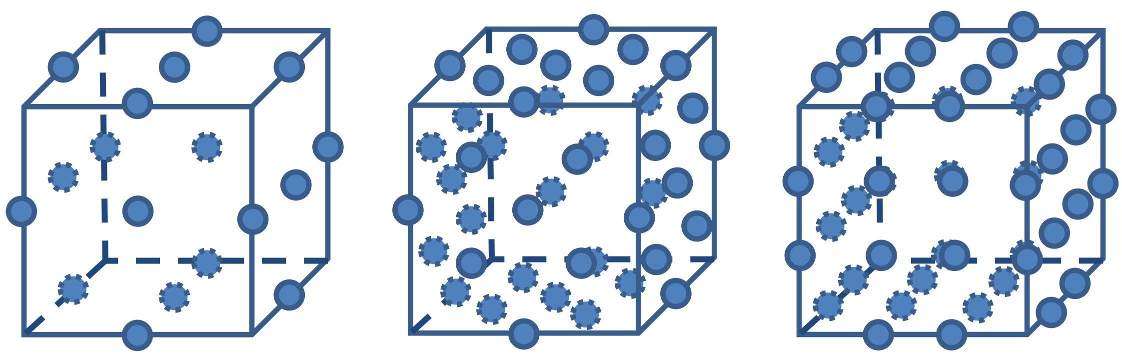
$$\hat{e} \cong half\ 95\%\ PI\ for\ ranging\ only \tag{3-17}$$

Using pilot result at n=9, the estimated localization error for 3D is about (2.274)*0.5=1.137 meters, which is expected to be close to the measured one, e. Though, it is higher than the accuracy assumption of 0.5 meters, which means more reference tags may be desired to increase the accuracy level.

3.5 Experiments

The following proposed experiments involve two parts. The first one is to model the regression function of RSSI ranging variance, σ_d^2, with amount of reference tags *n*. The second one is to model the localization error, *e*, (which is approximately the double of ranging standard deviation) with respect to amount of reference tags, *n*.

For both experiments, the factor being varied is the amount of reference tags. Since *n*=9 was insufficient, we start from *n*=12. Five levels are enough to detect possible high-order polynomial, logarithm, or Hoerl model trend using regression analysis [45]. These five levels (*n*=12, 18, 26, 42, and 48) will be implemented as illustrated in Figure 3-2 and Figure 3-3.



(a) n=18 (b) n=42 (c) n=48

Figure 3-3: Tag layout scheme (more)

For experiment #1, the ultimate response variable is σ_d^2, the variance of distance prediction using the corresponding linear regression estimation. The ultimate predictor variable is *n*, the amount of reference tags. Nevertheless, σ_d^2 is not directly measurable. It should be estimated from the regression process, which is conducted by reader, a block factor B. For each reader of a given scheme (with certain level of n), the RSSI value and distance from every reference tag to the corresponding reader are measured to fit a regression model (assumed to be linear). The σ_d^2 for the four blocks are then averaged for this level of n. By repeating this process for all schemes, we are able to fit the ultimate regression model between σ_d^2 and n for the purpose of predicting σ_d^2 using arbitrary n. The design structure of experiment #1 is summarized in Table 3-1.

Table 3-1: Design of experiment #1

Objective		To fit the best model of $\sigma_d^2 = f(n)$				
Distance = f(RSSI) ↘		n=12	n=18	n=26	n=42	n=48
σ_d^2	B=1					
	B=2					
	B=3					
	B=4					
	Average					

For experiment #2, the ultimate response variable is the localization error, e. The regression function of $e = g(n)$ is easy to model. Though, it is of more interest whether the relationship described in the Equation (3-13) is valid or not. The design structure of experiment #2 is summarized in Table 3-2. Please note that the total number of replicates (by putting target tags at different locations) is designed to be able to catch any sample variation less than or equal to σ_e with the power of 80%.

Table 3-2: Design of experiment #2

Objective 1		To fit the best model of $e = g(n)$				
Measured error ↘		n=12	n=18	n=26	n=42	n=48
e	R=1					
	R=2					
	R=3					
	…					
	R=24					
	R=25					
	Average					

Objective 2	To compare estimated error with measured error				
Estimated error $\hat{e}$, namely $2\sigma_d$					

3.6 Summary

Both theoretical analysis and experimental design are presented to demonstrate the idea of evaluating the statistically confident accuracy as a function of the amount of reference tags for an indoor RTLS with numerous assumptions. Therefore, the statistically significant minimum number of reference tags needed may be obtained in a reverse way. The theoretical model also indicates that a lower-bound of the accuracy level for any given system may exist, due to the natural variation of RFID signal strength. Improved system design and ingenious localization algorithm may help make this lower-bound even smaller.

The experimental results could differ a lot from the theoretical function due to violation of those assumptions or restrictions of the test environment. Revised prediction model is expected to include more variables, rather than the number of reference tags only. Despite these, there are several important conclusions which may benefit further research.

The ranging accuracy is affected by both the regression analysis and the RSSI variation, as shown in Equation (3-8). At some point, the increase in the number of reference tags does not bring any further improvement to the overall accuracy, as the variance from measured RSSI variation becomes dominant, which is the natural characteristic that belongs to a particular RFID system. The estimated localization error for 3D applications is approximately equal to half of the 95% PI for 1D ranging only.

Moreover, from the whole process, it is clear that the estimated localization error is expected to be larger in 3D systems than in 2D or 1D systems. According to the geometric indices defined in Equation (3-12), the theoretical ratio is $\sqrt{6} : \sqrt{2} : 1$, or approximately 2.45 : 1.4 : 1. The ratio will be even larger when the environmental factors, such as non-isotropic and non-linear distribution of RF signals are taken into account.

Lastly, the proposed experiments were not actually conducted for several reasons. Though, a reasonable and relatively safe number of reference tags being used in the following experiments could be set to 24, as it is not too small or too large.

Chapter 4

System and Experimental Designs

4.1 Fundamental Tests for Active System

Some early-stage experiments were conducted to evaluate the active 433 MHz RF Code reader and tag characteristics. These tests are described as follows.

4.1.1 Reader Test

The purpose of the reader test is to evaluate the effects of reader position and antenna orientation. The whole system was setup in room W107 Nebraska Hall, which is a conference room with approximate size of 6.3 by 4.8 by 2.7 meters.

A lot of factors may affect the RSSI reading of a RFID system. To serve the purpose of this experiment, only reader related variables were investigated. According to previous research [41], the distance from reader to ground, the distance from reader to wall, and the antenna orientation may have significant effects on RSSI reading. So, these three factors were chosen to be evaluated in this experiment. In addition, four readers were included as a block factor to separate any potential reader bias. Furthermore, three tags were randomly selected from the 25 tags we have available to serve as non-reader-related replicates. Both reader and tag effects were contained in the evaluation as well. A detailed treatment design is listed in Table 4-1.

Table 4-1: Main factors of reader test

Symbol	Factor	Levels	Comments
A	reader	readers #1	IP address: 192.168.1.101
		readers #2	IP address: 192.168.1.102
		readers #3	IP address: 192.168.1.103
		readers #4	IP address: 192.168.1.104
B	height	0.4 m	Close to the ground
		1.2 m	Far away from either the ground or the ceiling
		2 m	Close to the ceiling
C	depth	0.2 m	Close to the wall
		0.6 m	Neither too close nor too far away to the wall
		1 m	Far away from the wall
D	antenna	[\ /]	Antenna A (the left one when facing the reader) and antenna B (the right one when facing the reader) are both in the vertical plane with 45 degrees to the ground and 90 degrees in between;
		[|_]	Antenna A and B are both in the vertical plane with A in the vertical direction and B in the horizontal direction;
		[. |]	Antenna A is in the horizontal plane and pointing straight forward, while antenna B is in the vertical plane and in the vertical direction as well.
E	tag	tag #1	Tag ID: LOCATE00016492
		tag #2	Tag ID: LOCATE00016488
		tag #3	Tag ID: LOCATE00016502

The reader and tag deployment is demonstrated in Figure 4-1, where reader has 3x3=9 possible positions while tag position was set at a fixed location (1.2 m from the ground, and 2 m from the wall).

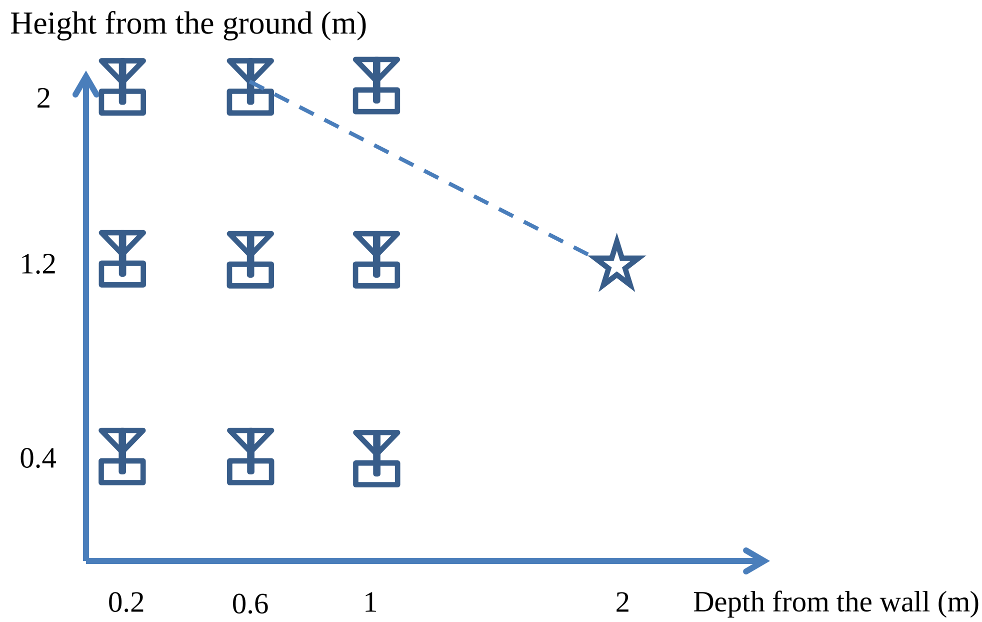


Figure 4-1: Layout scheme of reader test

The desired experimental unit is each possible treatment combination. However, this may be impractical. Overall, the number of all possible treatment and replicate combinations is 4*3*3*3*3=324, which is too large for a preliminary experiment. So, a trade-off was made between the ability to test 2nd order or higher order interactions and the significantly reduced number of total runs to be conducted. The final design consists of 56 runs (only certain treatment and replicate combinations were selected) with the power equal to 0.917 which is judged to be acceptable to test the main effects of each factor. The 56 runs were randomized within each block of readers.

Thirty continuous RSSI data points, with 2 second intervals, were collected for each run; then the following responses, namely dependent variables, were calculated:

- μA: average RSSI for antenna A, unit: dBm;
- μB: average RSSI for antenna B, unit: dBm;
- μAvg: average RSSI of antenna A and B, unit: dBm;
- μMax: maximum RSSI of antenna A and B, unit: dBm;
- μDiff: RSSI difference between antenna A and B, unit: dBm.

4.1.2 Tag Test

The goal of the tag test is to determine how the RSSI reading varies for different tags, their orientations, and the distance from tag to reader. The test location and system setup is exactly same as the above reader test.

To serve the purpose of this experiment, only tag related variables were investigated. According to previous research [41], the distance from tag to reader and the tag orientation have significant effects on RSSI reading. So, these two factors were chosen to be evaluated in this experiment. The three levels of distance are 1, 2, and 3 meters. The six levels of tag orientation were selected to covers major variations and the three axes directions. In addition, three tags were randomly picked from the 25 tags available and served as a block factor to separate any potential tag bias. The tag effect was contained in the further evaluation as well. A detailed treatment design is listed Table 4-2.

Table 4-2: Main factors of tag test

Symbol	Factor	Levels	Comments
A	tag	tag #1	Tag ID: LOCATE00016492
		tag #2	Tag ID: LOCATE00016488
		tag #3	Tag ID: LOCATE00016502
B	distance	1 m	Near distance comparing to room size
		2 m	Medium distance comparing to room size
		3 m	Far distance comparing to room size
C	orientation	Level 1: >	The tag is placed facing the ceiling with its long edge perpendicular to the line connecting reader and tag;
		Level 2: ^	The tag is placed facing the ceiling with its short edge perpendicular to the line connecting reader and tag;
		Level 3: _	The tag is placed sitting on one of its long edges and facing against the reader;
		Level 4: -	The tag is placed sitting on one of its short edges and facing against the reader;
		Level 5: |	The tag is placed sitting on one of its long edges with the facing direction 90 degree different from level 3;
		Level 6: .	The tag is placed sitting on one of its short edges with the facing direction 90 degree different from level 4.

The reader was placed at a fixed position (1.2m from the ground, and 0.6m from the wall). The antenna orientation was setup at the level 2 configuration as used in the previous reader test, that is, antenna A and B are both in the vertical plane with A in the vertical direction and B in the horizontal direction. The reader and tag deployment is illustrated in Figure 4-2.

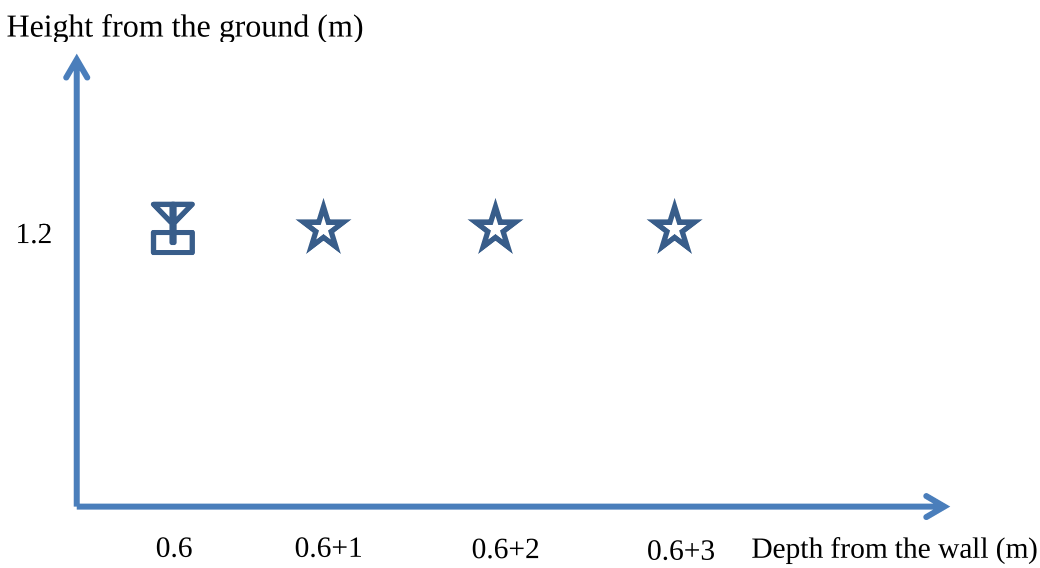


Figure 4-2: Layout scheme of tag test

The desired experimental unit is each possible treatment combination. Overall, the number of all possible treatment combinations is 3*3*6=54, which is acceptable for a preliminary experiment. The 54 runs were randomized within each block of tags.

Similarly, 30 continuous RSSI data points, with 2 second intervals, were collected for each run; then the responses (µA, µB, µAvg, µMax, and µDiff) were calculated. These dependent variables are defined in the previous reader test. Only the µMax (unit: dBm) result was used for further analysis, according to the reader test experience and recommendation, which is explained in Section 5.1.1.

4.1.3 Ranging Test

As a supplement of the above tag test, this ranging test is designed to investigate the relationship between the RSSI and distance from the tag to the reader in more detail. The whole system was setup in room 329B Scott Engineering Center, with approximate size of 4.34 by 8.74 by 2.82 meters.

Only one factor, the distance from the tag to the reader, was used in this experiment. It includes 10 levels, ranging from 0.5m to 5m with a 0.5m interval. Five tags were randomly selected as replicates for each distance level.

The reader was setup at a fixed position, at least 2m away from all walls and exactly 1m from the ground. The antenna orientation was kept in a consistent posture throughout the whole experiment with the left antenna pointing to the ceiling and the right antenna pointing to the wall. The tag was placed at the same height of the reader with the front side facing the reader in a straight line for all distance levels, as illustrated in Figure 4-3.

The basic experiment unit is a single tag with certain distance to the reader. 30 data points with 2 seconds interval were recorded for each run. The results were naturally blocked by 5 randomly selected tags. The total number of all treatment combinations is 10*5=50 runs. They are completely randomized. Still, μMax (unit: dBm) is chosen as the response for analysis as recommended before.

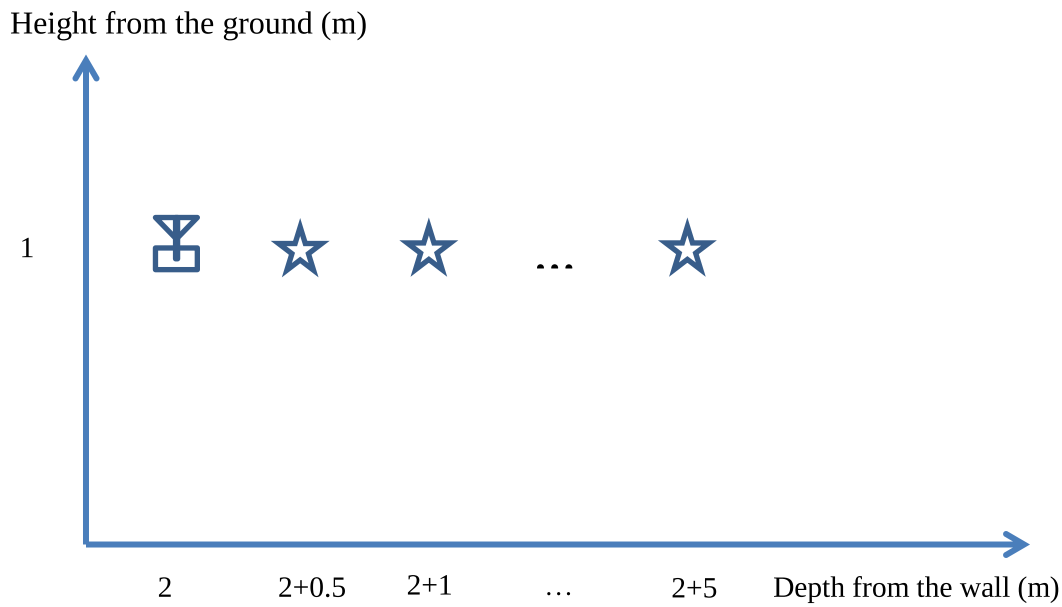


Figure 4-3: Layout scheme of ranging test

4.2 Localization Test for Active System

4.2.1 System Setup

In order to evaluate the performance under realistic conditions, the proposed system was deployed in an experimental environment consisting of a 4x9x3m high-complexity room, furnished with a bed, a sofa, several tables and chairs, and other common household items. The system included 4 active 433 MHz RFID readers deployed at the four edges of the ceiling and 24 reference tags placed on the walls, ceiling and floor, with an average spacing of 1.5m. The readers and tags are all commercial off-the-shelf (COTS) products, as shown in Figure 4-4.

Figure 4-4: RF Code readers and tags

Four readers are mounted on the ceiling. Two antennas of each reader are placed as one pointing to the center of the ceiling and the other pointing to the right of the reader. This setting makes two antennas perpendicular to each other such that the RF signal receiving capability could be maximized. The reader layout scheme is demonstrated in Figure 4-5. It is a ceiling view of the four readers. The coordinates of readers and ceiling corners are marked at corresponding positions in Figure 4-5. The (x,y,z) coordinates are defined with the origin (0,0,0) set at the south-west ground corner of this room.

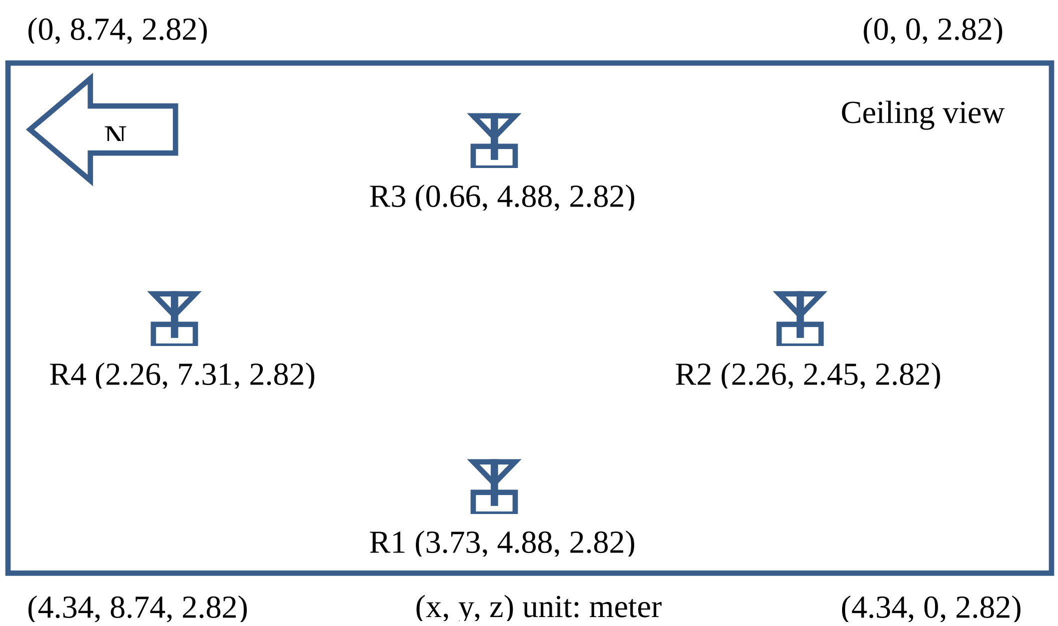


Figure 4-5: Reader layout in room environment

The 24 reference tags are grouped into different layers along each of the x, y and z axes, resulting in 4 layers in the x dimension, 3 layers in the y dimension, and 4 layers in the z dimension. All tags are placed with its front side facing the positive x direction. The tag layout scheme is demonstrated in Figure 4-6. The coordinates of these reference tags are listed in Table 4-3.

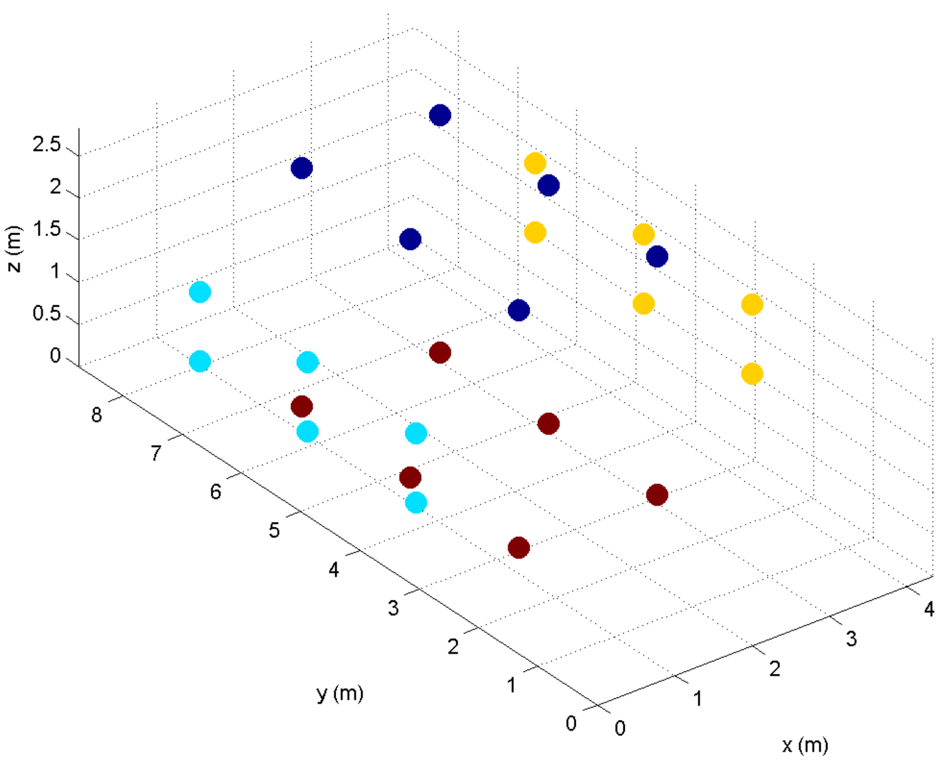


Figure 4-6: Reference tag layout in room environment

Table 4-3: Reference tags ID and positions

#	ID	(x,y,z)	#	ID	(x,y,z)
1	LOCATE00016485	[1.32,6.71,2.82]	2	LOCATE00016486	[3.12,6.71,2.82]
3	LOCATE00016487	[1.32,4.88,2.82]	4	LOCATE00016488	[3.12,4.88,2.82]
5	LOCATE00016489	[1.32,3.05,2.82]	6	LOCATE00016490	[3.12,3.05,2.82]
7	LOCATE00016491	[0.00,6.71,1.82]	8	LOCATE00016492	[0,6.71,1.00]
9	LOCATE00016493	[0.00,4.88,1.82]	10	LOCATE00016494	[0,4.88,1.00]
11	LOCATE00016495	[0.00,3.05,1.82]	12	LOCATE00016496	[0,3.05,1.00]
13	LOCATE00016497	[4.34,6.71,1.82]	14	LOCATE00016498	[4.34,6.71,1.00]
15	LOCATE00016499	[4.34,4.88,1.82]	16	LOCATE00016500	[4.34,4.88,1.00]
17	LOCATE00016501	[4.34,3.05,1.82]	18	LOCATE00016502	[4.34,3.05,1.00]
19	LOCATE00016503	[1.32,6.71,0.00]	20	LOCATE00016504	[3.12,6.71,0.00]
21	LOCATE00016505	[1.32,4.88,0.00]	22	LOCATE00016506	[3.12,4.88,0.00]
23	LOCATE00016507	[1.32,3.05,0.00]	24	LOCATE00016508	[3.12,3.05,0.00]

4.2.2 Software Development

The four RF Code readers were initialized using the Reader Configuration Utility downloaded from the RF Code support website. The reader can be connected to a computer via either Ethernet port or serial port (recommended for first time initialization). The basic parameters of these readers were set to the following values.

- IP address: 192.168.1.101, 192.68.1.102, 192.168.1.103, and 192.168.1.104;
- Subnet mask: 255.255.255.0;
- Gateway: 192.168.1.1; and
- Others settings were kept at factory default.

The control package, Zone Manager, was also downloaded from the official support website. It was installed on the laptop to work as the center node of the RF Code system. Both readers and tags information were configured in the Zone Manager. The package has a web portal which is accessible either from local computer or remote place. The login information is given below.

- Local: http://localhost:6580/rfcode_zonemgr/
- Remote: http://<public_ip_address>:6580/rfcode_zonemgr/

It should be noted that, due to different network security policy, some work may need to be done to setup the correct network and firewall configuration before the remote access feature works.

After being configured in the Zone Manager, the system is ready for use now. Tag information is able to be read from the web portal. It is broadcasted periodically (10 seconds by default, 2 second in motion). The tag freezes at last update and eventually disappears from the list several minutes later after the reader loses track of it. So, there must be a database to support the web portal to provide buffered information. A system scheme is demonstrated in Figure 4-7 to make the whole structure clearer. The database is inaccessible to the end user directly, which makes collecting data over time difficult. So, additional programming using Matlab has to be done to achieve this automatically such that real-time algorithm becomes possible. JavaScript Object Notation (JSON) was used as the programing interface to the RF Code system in Matlab. This is described in Appendix A.1 in details.

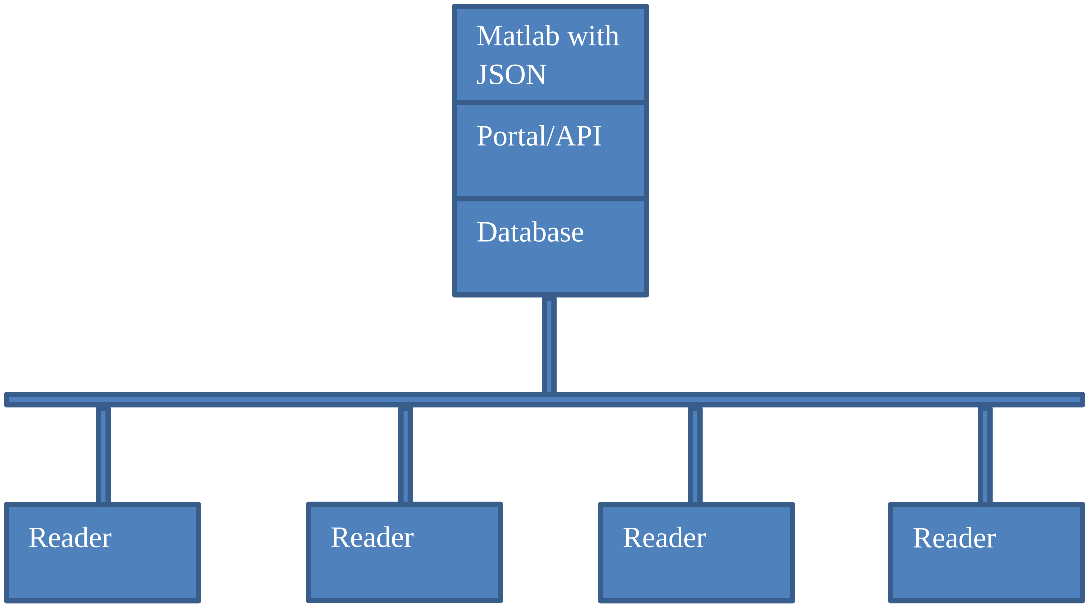


Figure 4-7: Network and software structure of the RF Code system

Based on these preparations, a Matlab package was coded to read and collect RF Code tag information continuously. See Appendix B.2 for codes. This is mainly used in fundamental tests, including the reader test, tag test and ranging test.

The readers and tags are detected and listed when loading the Graphic User Interface (GUI), as illustrated in Figure 4-8. Any of them can be chosen to be included in further evaluation or not. Different channel mode is available to specify the working mechanism of two antennas. The Read SSI button performs a single request of RSSI information of selected tags through selected readers.

The bottom part of the screen is used to collect continuous data. The amount of data points and the interval between two data points can be set at any positive value. By clicking the Start button, the requested RSSI information shows up on the screen continuously. The results can be saved into a text file for further analysis.

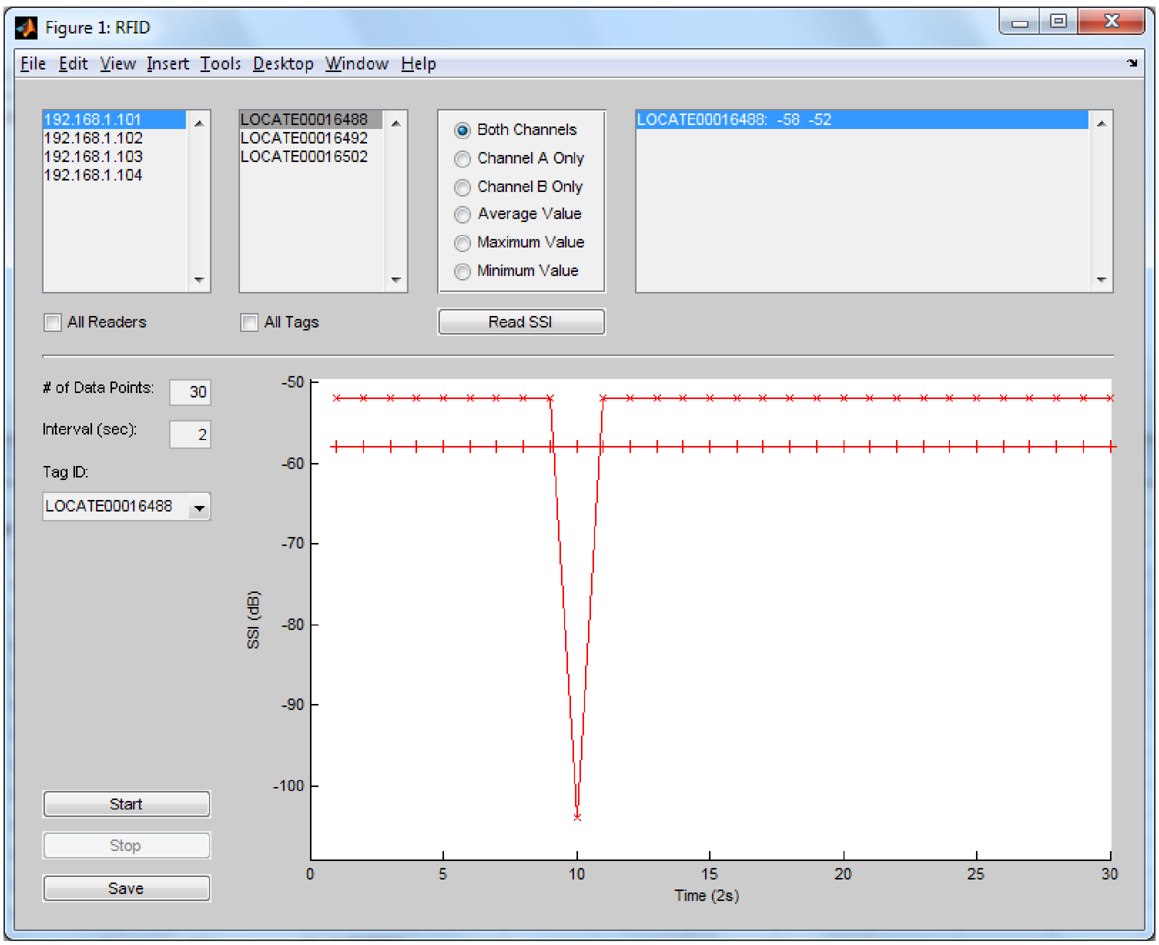


Figure 4-8: RSSI reading GUI

For localization test, another software package is built on top of this one and provides advanced features, such as signal map evaluation, localization presentation, and error decomposition. See Appendix B.3 for codes.

The screen snapshot of the localization GUI is illustrated in Figure 4-9. It mainly shows the real-time estimated (x,y,z) coordinates and localization error versus time.

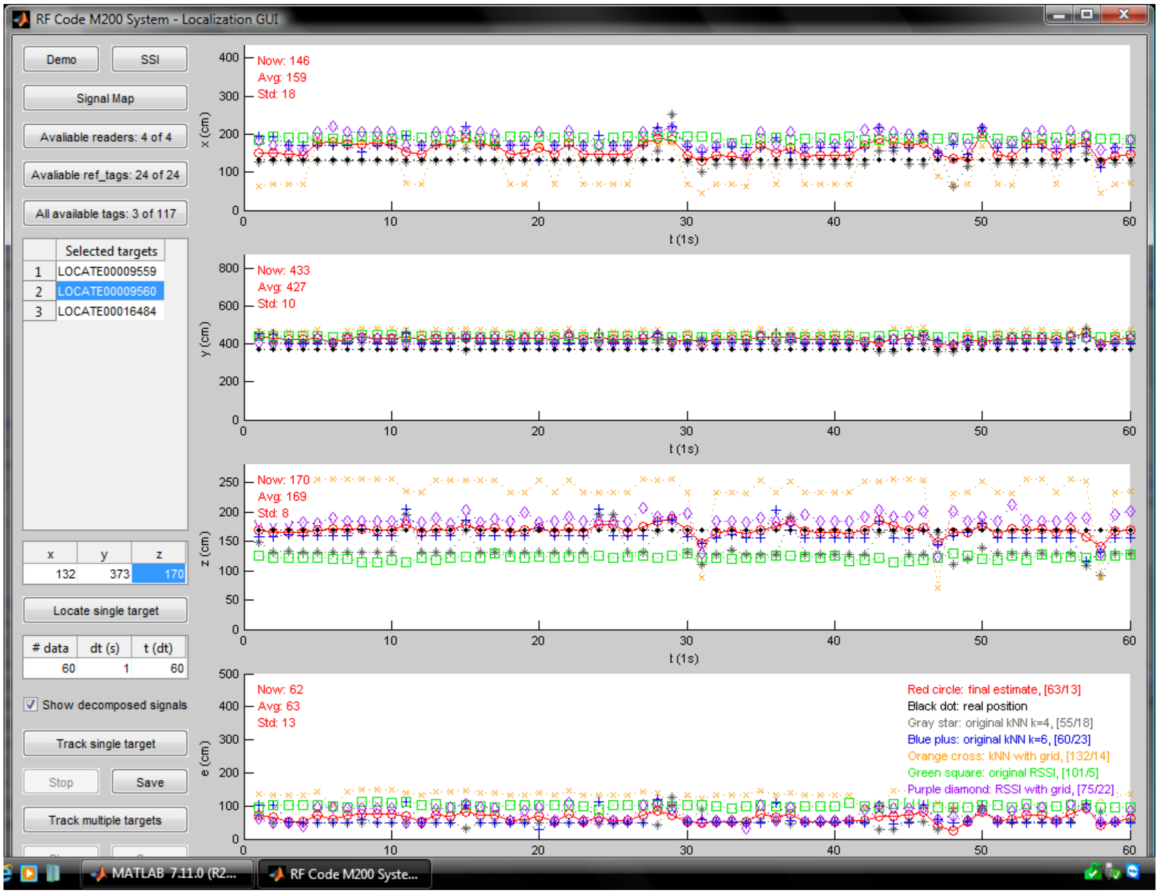


Figure 4-9: Localization GUI

The coordinates of all readers, reference tags and other tags can be modified in pop-up windows by clicking the corresponding buttons. The proposed target tags are listed in the Selected targets area, which can be modified in the All available tags pop-up window. Single selection can be made by clicking on the tag ID. Multiple selection can be made by clicking on the tag ID while pressing the Ctrl or Shift key. The coordinates of the current selected target tag can be revised in the x/y/z zone. Locate single target perform a one-time localization process. To make a continuous localization, the amount of data points, the interval between two data points, and the visible length of the time axis should be defined first. After that, by clicking the Track single target button or the Track multiple targets button, the real-time estimated x/y/z values and localization errors are plotted. To switch targets for multiple tracking, simply click the desired target identification. The Show decomposed signals checkbox allows localization error decomposition based on various algorithms, as shown in the above snapshot. Though, the save data feature is currently not available due to data complexity.

4.2.3 Localization Algorithm

The proposed localization algorithm is a hybrid approach by taking both range-free estimation and range-based measurement into account. This is an improvement based on a 2D solution previously proposed by other student [46], and has been presented as a poster in [47]. The scheme of the 2D algorithm is illustrated in Figure 4-10. It can be broken down into four steps.

- Side detection;
- RSSI ranging;
- Quadrant filtering; and
- Final estimation.

First, the target tag's RSSI values obtained from each reader are compared to all reference tags' RSSI values. Estimation is then made on which side of the room and quadrant the target is expected to be in.

Second, based on the side information (two adjacent sides connected to the estimated quadrant), linear RSSI ranging is conducted using reference tags for each side. This is repeated for all readers. So far, the total number of ranging estimations for the target tag is 2 times the number of readers.

Next, the ranges are filtered out if they do not cross over the estimated quadrant or are totally outside of the room. The rest of them are valid for the next step.

At last, Least Squares Quadratic (LSQ) estimates based on remaining ranges and their intersections points within the estimated quadrant are then averaged to find the single final point estimation.

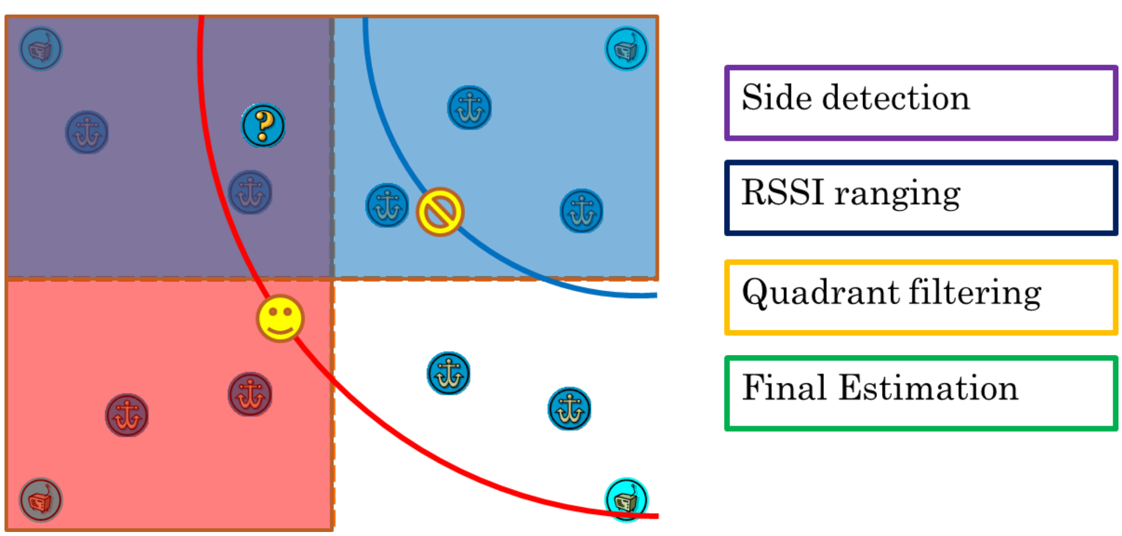


Figure 4-10: 2D algorithm

The above 2D solution is evolved into the 3D algorithm proposed in this work. Not only the dimension increases, but also the kNN approximation is included. Similarly, it can be divided into four steps:

- Layer detection;
- kNN approximation;
- RSSI ranging; and
- Final estimation.

First, recall that all 24 reference tags are grouped into different layers along three axes. By comparing the RSSI of the target tag with the values of the reference tags in different layers, the best fit layer for each axis is decided respectively. Then, the intersection of these three layers is defined as the approximated center of the target area. The surrounding reference tags within a 3x3x3 unit cube are classified as a sub-group reference tags being used in next steps. An example is as illustrated in Figure 4-11. The dimension of the cube, 3 reference tags per side, is chosen based on the consideration of the geometrical distribution of the reference tags. This sub-group of reference tags is believed to have closer performance with the target tag than other reference tags do, as the environmental effects may be complex and non-isotropic.

Second, the sub-group selected in first step is used as the nearest neighbors in the kNN approach in this step. Since the number of tags in the sub-group may be different in each case, the k value in the kNN procedure varies as well. This makes the kNN estimation more reliable.

Then, similarly, this sub-group is also used as the mapping reference tags in the RSSI ranging approach. The ranging estimation is repeated for each reader. Then, LSQ estimate is applied to these ranges.

The final step is taking the average of the step 2 and step 3 results as the target tag coordinates estimation.

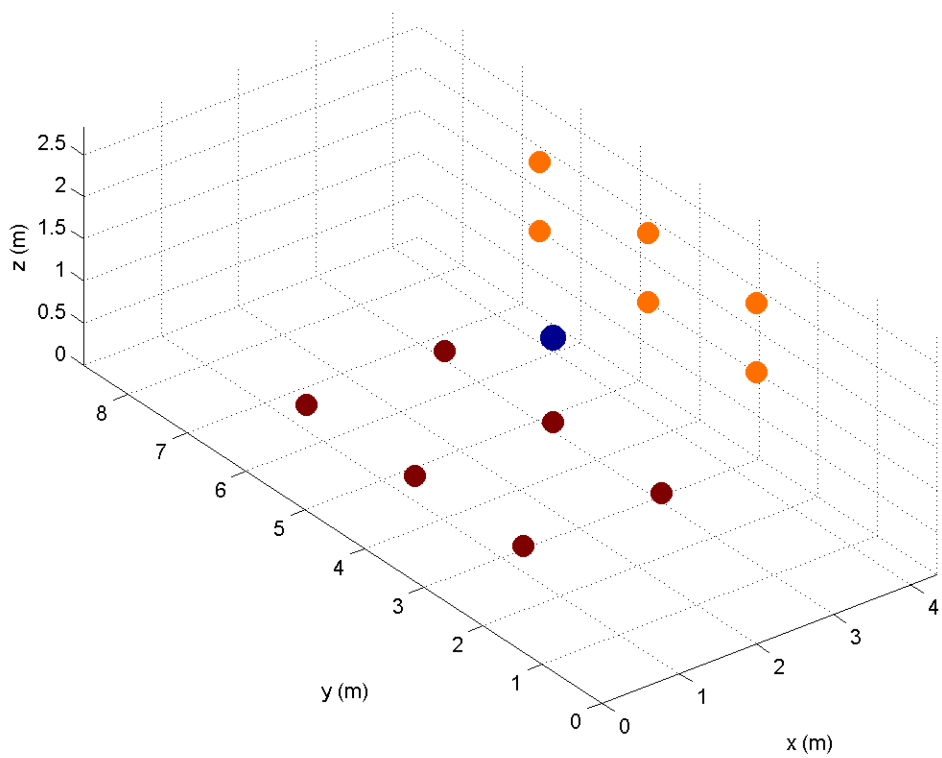


Figure 4-11: Intersection point and surrounding reference tags

4.2.4 Experimental Design

The localization experiment is designed to evaluate the performance of the proposed hybrid algorithm by comparing to the traditional kNN and RSSI algorithms with various tag position and orientation combinations.

Three factors are location, orientation, and algorithm, as defined as in Table 4-4.

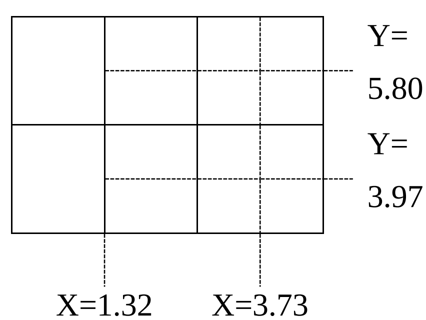
Table 4-4: Main factors of localization test

Factor	**Level**
Position	8 different positions as described as follows
Orientation	3 orientations (X+, Y+, and Z+), defined as putting the tag front side to the positive direction of the three axes, respectively
Algorithm	3 algorithm (Hybrid, kNN, and RSSI), this is also used as a blocking factor to simplify the experiment procedure

Table 4-5: Tag position definition

#	**X (m)**	**Y (m)**	**Z (m)**
1	1.32	3.97	0.70
2	1.32	3.97	1.70
3	1.32	5.80	0.70
4	1.32	5.80	1.70
5	3.73	3.97	0.70
6	3.73	3.97	1.70
7	3.73	5.80	0.70
8	3.73	5.80	1.70

X/Y (with Z = 0.70 and 1.70)



The basic experiment unit is a single tag. Thirty data points with 2 seconds interval are recorded for each run. Three replicates (tags) are used for each treatment. The total number of all treatment combination is then 8*3*3*3=216 runs. They are randomized within each block (namely the algorithm).

The response variable is mean localization error, the distance (unit: meter) between the estimated position and the real position, denoted as e.

The power analysis result shows that, at the confidence level of alpha equal 0.05, the power of detecting the localization error difference at the same scale of standard deviation is 0.868, greater than common critical value 0.8. This means the result obtained from this designed experiment is reliable.

4.3 Additional Tests for Battery-assisted Passive System

The above experiment is based on RF Code active tags system and is deployed in the normal laboratory room environment. Two additional tests are conducted to evaluate the system performance using Intelleflex battery-assisted passive tags and the effects of ISS mock-up to the tag characteristics.

4.3.1 System Setup

These additional tests, laboratory environment investigation, were also conducted in room 329B Scott Engineering Center. Figure 4-12 shows the Intelleflex readers, antennas and tags. The reader being used in this experiment is Intelleflex FMR6000 Passive RFID Reader. Its operating frequency is 902-928 MHz in North America. One or two pairs of antennas are used for sending and receiving signals. The tags being used in this experiment are STT-8000 (general purpose tags) and SMT-8100 (metal environment tags), labeled as STT and SMT, respectively. They are both battery-powered passive tags.

Figure 4-12: Intelleflex readers and tags

A wood-framed International Space Station mock-up, with the size of 1.83(W) by 3.10(D) by 1.83(H) meters, was constructed to simulate the high-reflection environment. The interior surface is covered by aluminum sheet. A metal cabinet is placed at the open end on the left, as demonstrated in Figure 4-13. It is placed on the background of a real International Space Station. The objective of this mock-up is to be able to evaluate the RFID tags and RTLS performance in such circumstance.

Figure 4-13: International space station mock-up

The performance of the battery-assisted passive tags in both the regular laboratory environment and such high-reflection mock-up is of interest. Two types of tags (general purpose tags and metal environment tags) are evaluated to see if they have similar characteristics.

4.3.2 Software Development

The basic parameters of the Intelleflex readers were set to the following values.

- IP address: 192.168.1.11, and 192.68.1.12;
- Subnet mask: 255.255.255.0;
- Gateway: 192.168.1.1; and
- Others settings were kept at factory default.

There is no bundled software provided along with the system. The tag reading functionality of the reader could be verified via a demo webpage by accessing reader directly using its IP address. Also, the readability is not guaranteed since there is no database. The request has to be fulfilled upon real tag feedback every time. This makes the querying time much longer than RF Code system. The system structure is demonstrated in Figure 4-14. Extensible Markup Language (XML) was used as the programing interface to the Intelleflex system in Matlab. See Appendix A.2 for details.

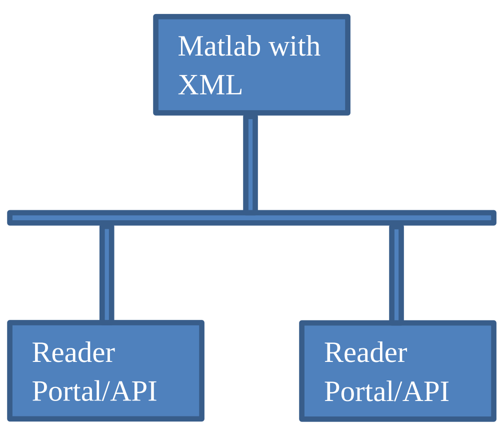


Figure 4-14: Network and software structure of the Intelleflex system

In order to avoid duplication of effort, the GUI for the RF Code system is re-used, which has been described in Section 4.2.2. See Appendix B.2 and B.3 for codes of RSSI reading and localization, respectively. Under the same user interface, different API library is invoked for the two systems. The scheme of the whole system is illustrated in Figure 4-15.

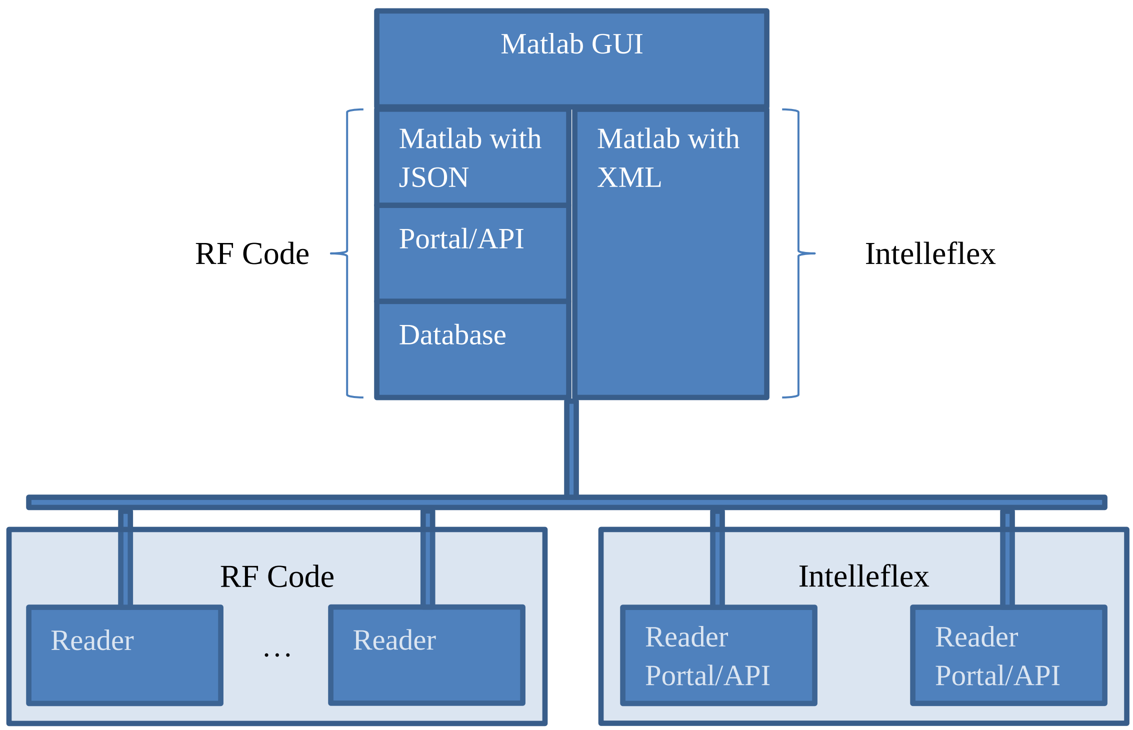


Figure 4-15: Network and software structure of both systems

4.3.3 Experimental Design

Four factors are used in this experiment, as described in the following table.

Table 4-6: Main factors of battery-assisted passive tag test

Factor	**Level**
Location	Laboratory room (Lab) environment and ISS mock-up (Mockup)
Group	General purpose tags (STT) and metal environment tags (MTT)
Orientation	3 orientations (X+, Y+, and Z+), defined as putting the tag front side to the positive direction of the three axes, respectively
Distance	10 levels from 0.5 meters to 5 meters with 0.5 meters interval in the laboratory room environment; 6 levels from 0.5 meters to 3 meters with 0.5 meters interval in the ISS mock-up

The basic experiment unit is a single tag. Thirty data points with 2 seconds interval are recorded for each run. Three replicates (tags) are used for each treatment. The total number of all treatment combination is then 2*3*(6+10)*3=288 runs. They are completely randomized.

No blocking is designed. The response variable is the mean RSSI value (unit: dBm) during each run. The corresponding standard deviation is investigated as well.

4.4 Localization Tests for Battery-assisted Passive System

In order to investigate the performance of battery-assisted passive tag in the proposed localization system, a brief localization test for the battery-assisted passive system was duplicated based on the localization test for the active system.

Due to space limitation, the Intelleflex readers and antennas are placed at different positions. And only two pairs of antennas are used in the localization procedure. Their coordinates are (3.12, 7.71, 1.41) and (1.32, 2.05, 1.41). All reference tags are placed exactly at the same positions as the RF Code reference tags. The treatment design is listed in Table 4-7. Most of them are same as the passive system experiment design, except for the elimination of the factor orientation. The target tags are placed with same orientation as reference tags since the localization test on passive tags shows that this optimizes the localization accuracy. Though, the number of replicates (tags) increases from 3 to 5 such that the power is still higher than 0.8.

Table 4-7: Main factors of localization test (battery-assisted passive sytem)

Factor	**Level**
Position	8 different positions as described in Table 4-5
Algorithm	3 algorithms (Hybrid, kNN, and RSSI), this is also used as a blocking factor to simplify the experiment procedure

4.5 Summary

A localization test bed is built in room 329B Scott Engineering Center. Two RFID systems, a RF Code active system and an Intelleflex battery-assisted passive system, are placed side-by-side for comparison. Both use 24 reference tags. There are 4 readers for the active system, while only one reader plus two separated antennas are used for the battery-assisted passive system due to implementation restriction. The software package is developed using Matlab with JSON and XML programming interface to different readers. It is able to communicate with readers and tags to get RSSI information in real-time. Certain localization algorithm is then applied to estimate the target tag coordinates and localization error.

Besides, a series of fundamental tests, such basic reader, tag, and ranging tests, are designed prior to the formal localization test to help understanding both RFID system better, such as the reader/antenna placement, tag orientation issue, and measured response variable selection.

In addition, an International Space Station mock-up is constructed next to the laboratory environment. Its interior surface is covered by aluminum sheet to simulate the high-reflection environment. The ranging performance of battery-assisted passive tag in such a mock-up is compared to regular laboratory results.

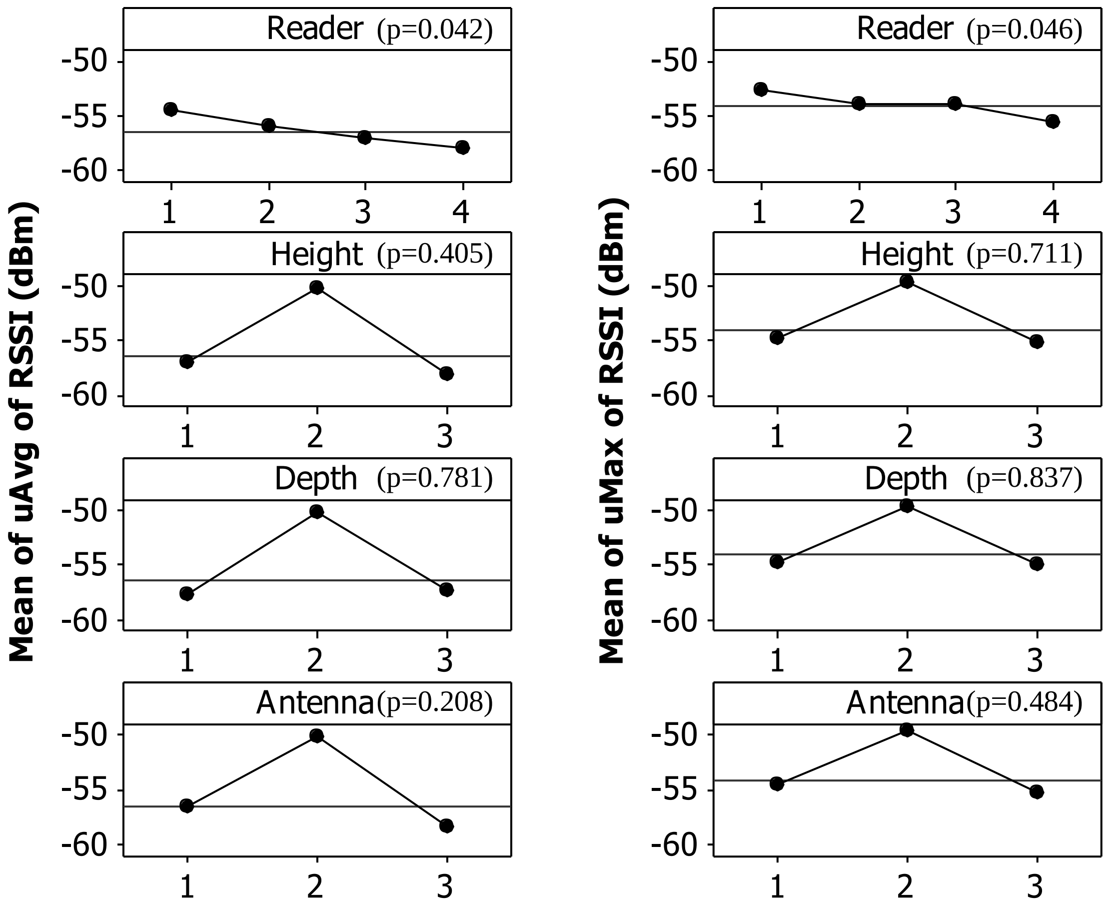
Chapter 5

Results and Analysis

5.1 Fundamental Tests for Active System

5.1.1 Reader Test

The test results are analyzed for main effect only, which is defined as the effect of one factor average over all levels of the others for a particular response. The main effects plot, as shown in Figure 5-1, demonstrates the main effects of the four factors for the two responses in a matrix. The columns are two selected responses: μAvg and μMax. It was found that both the average and maximum value of the RSSI from the two antennas are good candidates as the measurement of RSSI reading for each reader due to the relatively concentrated standard deviation and few outliers. Therefore, other responses are not reported here. The rows are four factors: reader, height, depth, and antenna. The tag is not shown here as it is a replicate factor in this experiment. The individual plot shows how the response varies with different levels of a factor. The x axes are defined levels for each factor. The y axes are corresponding RSSI values (unit: dBm) plotted in the same scale for easier comparison.



(a) μAvg of RSSI (b) μMax of RSSI

Figure 5-1: Main effects plot for reader test

The reader factor is a significant one for both responses, with p-value of 0.042 and 0.046, respectively. This indicates that these 4 readers have different characteristics. It is also possible that the readers are affected by any environmental issues, such as varying radio wave interference or human activities nearby. The Figure 5-2 demonstrates such a case that how the RF signals reacted when a student walked by. So, the reader effect discovered here could actually be a combination of these two.

It is not practical to find any four exactly identical readers with the same signal receiving characteristic. So, as long as the RSSI ranging is based on individual reader, the difference among the readers is not an issue. Though, full randomization will be applied to avoid time-related affects in any future work. It should be noticed that this phenomenon illustrated in Figure 5-2 means the RFID system is under varying environmental impacts. So, simple RSSI mapping or ranging is not a solution to utilize reference tags. Ranging-free based algorithm, such kNN, would be a better choice. This is why kNN is included in the proposed hybrid algorithm.

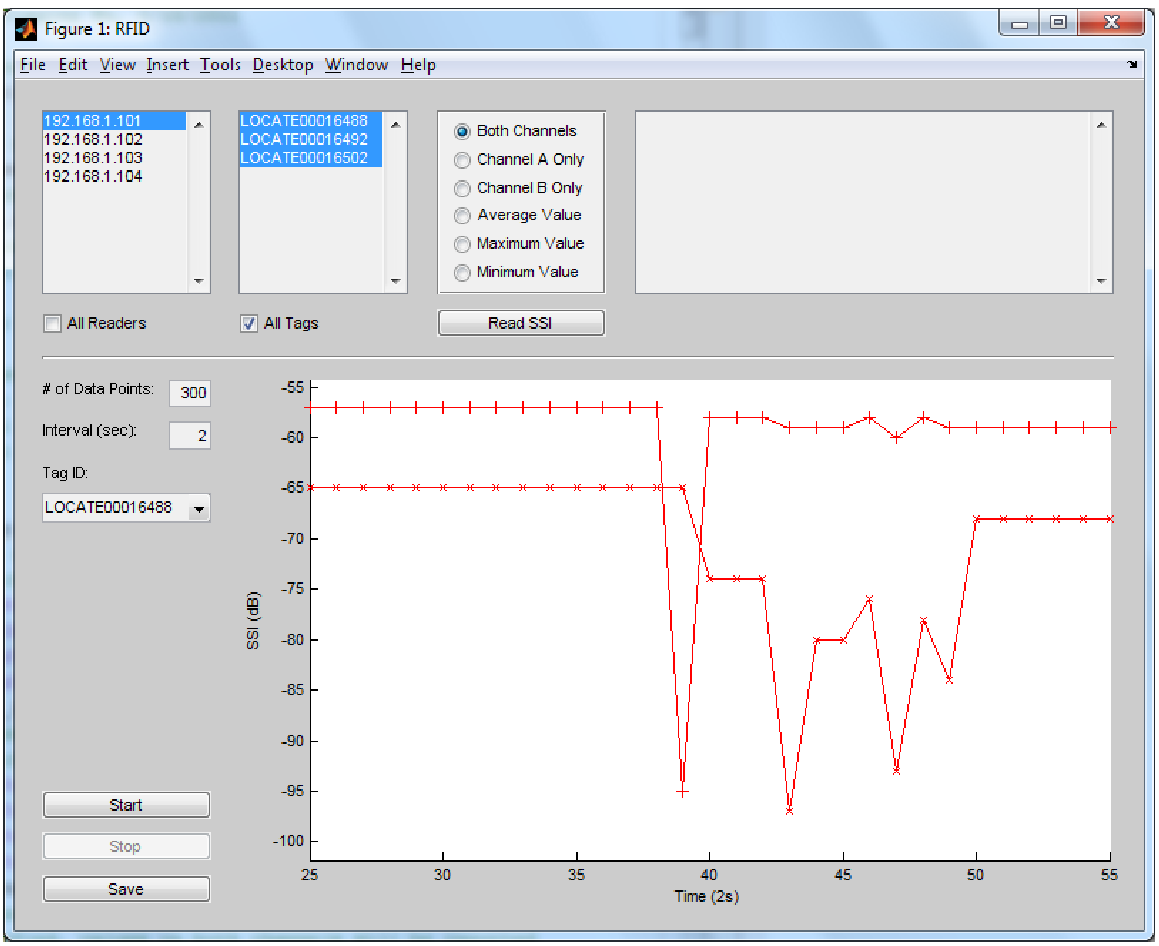


Figure 5-2: Interference caused by human activities nearby

Referring to the height and depth columns, the RSSI values are lower when the reader was placed close to the ground, the ceiling, or the wall. However, as long as this effect is consistent, it is acceptable. So, it is experimentally justified to mount all readers on the ceiling in formal experiments.

Having two antennas perpendicular to each other (one is horizontal and the other is vertical) is provides stable signal receiving, which is also recommended by the manual. So, the two perpendicular antennas design is applied in the research effort.

Furthermore, the maximum value of RSSI is preferred as a response of RSSI evaluation rather than the average value in future work. The experimental experience shows that the maximum value makes the final RSSI ranging estimation more robust and stable as the RF signals may disappear occasionally.

In summary, the reader test leads to the following conclusions.

- The 4 readers may have different RF signal receiving characteristics. Though, environmental interference could be confounded with the reader effect.
- Placing reader close to the edges of the room (especially the wall and the ceiling) does affect the RSSI reading, but not unpredictably.
- Setting one antenna horizontally and the other one vertically is the recommended antennas placement.
- The maximum value of RSSI of two antennas' measurement presents the desired information best.

5.1.2 Tag Test

The main effects plot is shown in Figure 5-3. Overall, these tags have very similar performances (with p-value 0.571), which mean the assumption of no significant bias among the RSSI reading from different tags is acceptable. As distance increases from 1 meter to 3 meters, the RSSI reading decreases almost linearly. The tag orientation has an extremely significant affect (p=0.000). It is also noticed that some orientations have similar performance and may be grouped together to reduce levels being used in further experiments. For example, these 6 orientations may be grouped by the direction of three axes (level 1 and 2 for z, level 3 and 4 for y, and level 5 and 6 for x). The plot shows that such grouping is not perfect but reasonable. Then, only 3 levels are needed.

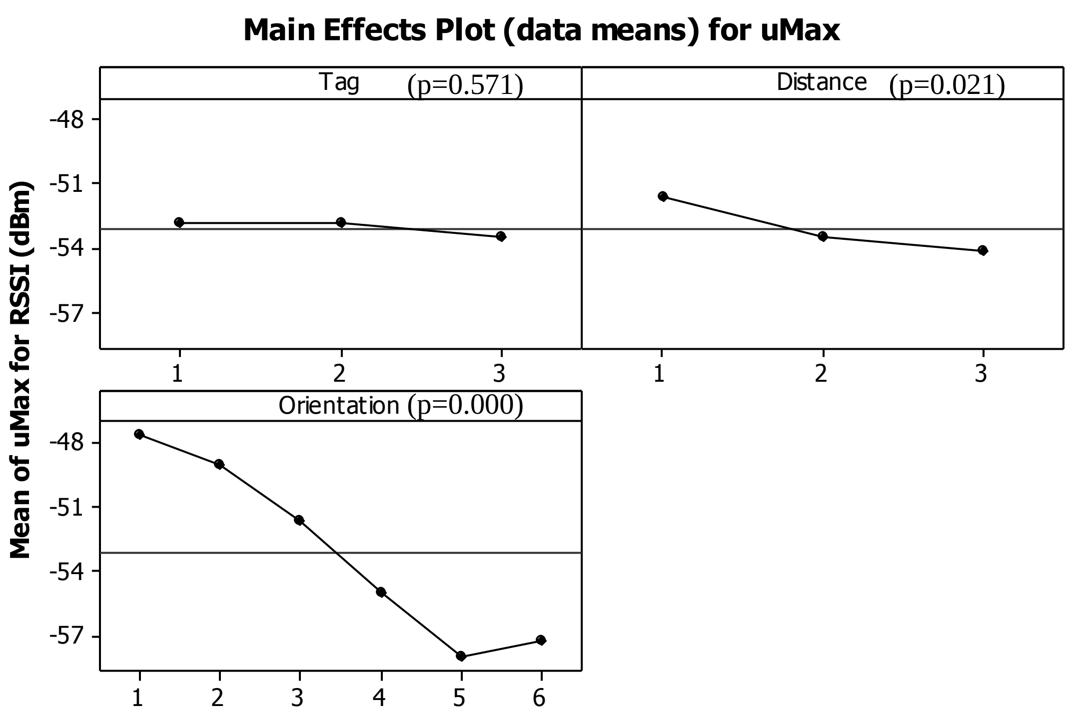


Figure 5-3: Main effects plot for tag test

There is no tag vs. distance or tag vs. orientation interactions, as shown in the Figure 5-4. Those significant interactions are between distance and orientation. This is expected. Most interactions occur when the tag has the minimum size of antenna coil facing directly toward the reader. This means the signals communicated between the reader and tag were most likely reflected from the ceiling, the wall, or the ground. In such situations, the distance between the reader and tag could affect the RSSI significantly since the reflection path changed.

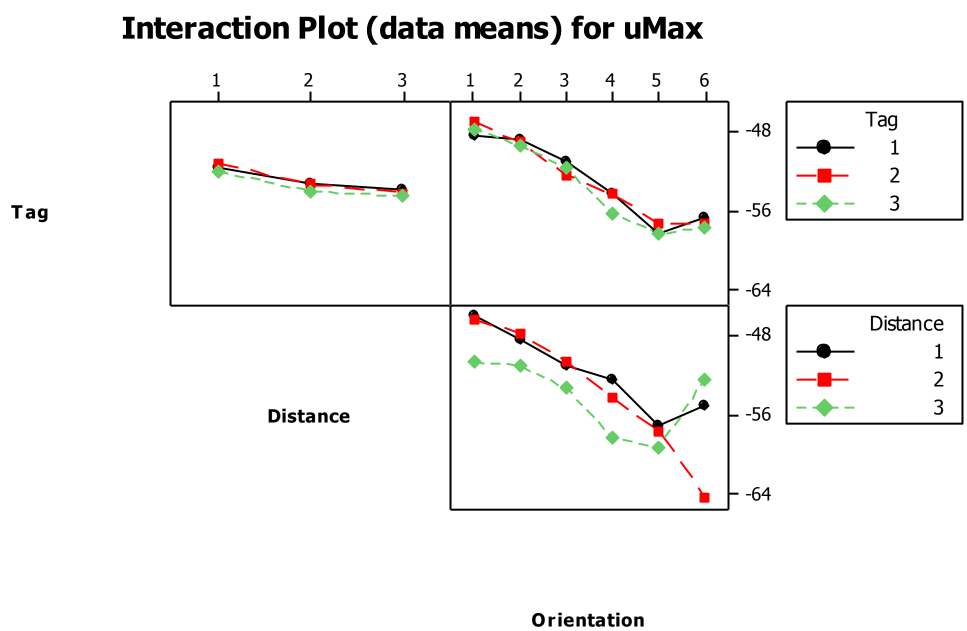


Figure 5-4: Interaction plot for tag test

In summary, the tag test leads to the following conclusions.

- Different tags have similar characteristics in this test. So, it is acceptable to pick any of them as replicates in future tests.
- The distance has an approximately negative linear relationship with RSSI in this 2D experiment, which is expected as normal RF characteristic. Though, smaller intervals and larger range should be investigated further.
- The orientation of any tag is a significant factor and can be further grouped into 3 levels (facing the x, y, and z direction). Therefore, the tag orientation is definitely a must-have factor in further experiment design.
- Interactions mostly occur when the reader and tag are not directly facing each other. However, this may not be easily avoided in a 3D application.

5.1.3 Ranging Test

The RSSI versus distance main effects plot is shown in Figure 5-5. The relationship between RSSI and distance is close to linear in short range. It could be non-linear or even non-monotonic starting from 1 meter. This causes high variance when predicting the actual distance purely based on the RSSI value only. Hence, the proposed hybrid algorithm, a combination of RSSI ranging and kNN approximation, may be more reliable in a complex environment.

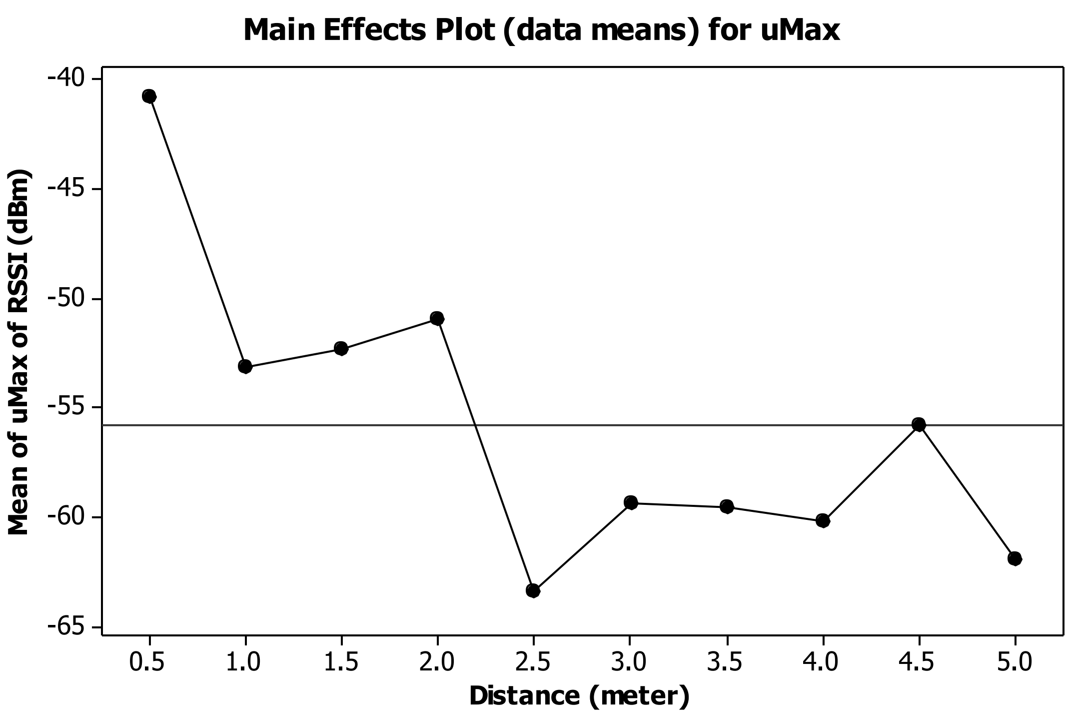


Figure 5-5: Main effects plot for ranging test

The linear regression is performed to determine the goodness of fit. The prediction function based on ranging test result is Distance = - 6.248 - 0.1613 * µMax, as shown in Figure 5-6. The prediction interval varies from 4.09 to 4.28 meters with RSSI ranging from -45 to -70 dBm. This is used in the localization test analysis later.

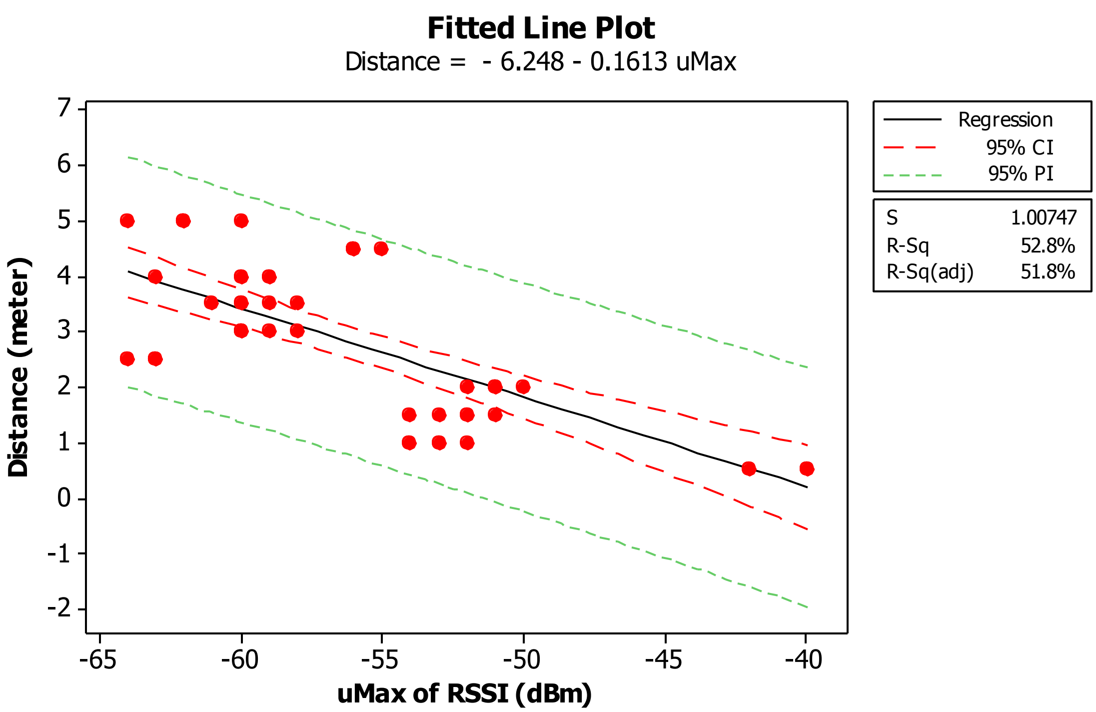


Figure 5-6: Linear regression of ranging test

In summary, the ranging test leads to the following conclusions.

- RSSI does not decrease monotonously as distance increases.
- The linear regression has wide prediction intervals.

5.2 Localization Test for Active System

The proposed system was evaluated by taking measurements at 8 different locations within the room with 3 different tag orientations and 3 different target tags used at each location, as described in Section 4.2.

As shown in Table 5-1, the experiments resulted in mean localization errors of 1.37, 1.67, and 1.69 meters for the hybrid, kNN, and RSSI ranging algorithms, respectively. The corresponding standard deviations are 0.65, 0.84, and 0.46 meters, respectively. The localization error distribution is listed based on error ranges with 0.5 meter intervals. The mean values and standard deviations for each algorithm are presented at the bottom of the table. Statistics test results for comparing these three algorithms are also listed.

The hybrid approach performs better than the other two methods in both aspects of mean and standard deviation. The p-values for mean comparison of the Hybrid method versus kNN approximation and the Hybrid method versus RSSI ranging are 0.003 and 0.000, respectively. And the p-values for standard deviation comparison are 0.030 and 0.010, respectively. Recall that all three different orientations are included here. With mixed orientations, the kNN and RSSI approaches have similar performance in terms of mean localization error.

Table 5-1: Localization error distribution for all orientations

Error Range	**Hybrid**	**kNN**	**RSSI**
$0m < E \leq 0.5m$	5.56%	0.00%	0.00%
$0.5m < E \leq 1m$	26.39%	29.17%	8.33%
$1m < E \leq 1.5m$	36.11%	15.28%	25.00%
$1.5m < E \leq 2m$	9.72%	25.00%	34.72%
$2m < E \leq 2.5m$	18.06%	9.72%	30.56%
$E > 2.5m$	4.17%	20.83%	1.39%
Mean (m)	1.37	1.67	1.69
P-value for Mean Comparison	N/A	0.003	0.000
Stdev (m)	0.65	0.84	0.46
P-value for Stdev Comparison	N/A	0.030	0.010

If only the results with same orientation as reference tags are evaluated, the mean localization errors decrease to 1.08, 1.10, and 1.56 meters for the hybrid, kNN, and RSSI ranging algorithms, respectively, as listed in Table 5-2. The corresponding standard deviations are 0.36, 0.58, and 0.50 meters, respectively. The hybrid approach is not a dominantly best solution this time. But it is significantly better than kNN with smaller standard deviation ($p=0.025$), and is significantly better than RSSI with smaller mean error ($p=0.002$). Overall, with smallest mean and standard deviation, the hybrid approach performs significantly better than the other two methods. This is also illustrated graphically in Figure 5-7. Furthermore, the localization accuracy is much better than using all target tag orientations. This means for the active tag system, the tag orientation makes a difference in signal receiving.

Table 5-2: Localization error distribution for orientation same as reference tags only

Error Range	Hybrid	kNN	RSSI
0m < E ≤ 0.5m	8.33%	0.00%	0.00%
0.5m < E ≤ 1m	25.00%	54.17%	16.67%
1m < E ≤ 1.5m	54.17%	29.17%	29.17%
1.5m < E ≤ 2m	12.50%	8.33%	29.17%
2m < E ≤ 2.5m	0.00%	0.00%	25.00%
E > 2.5m	0.00%	8.33%	0.00%
Mean (m)	1.08	1.10	1.56
P-value for Mean Comparison	N/A	0.895	0.002
Stdev (m)	0.36	0.58	0.50
P-value for Stdev Comparison	N/A	0.025	0.115

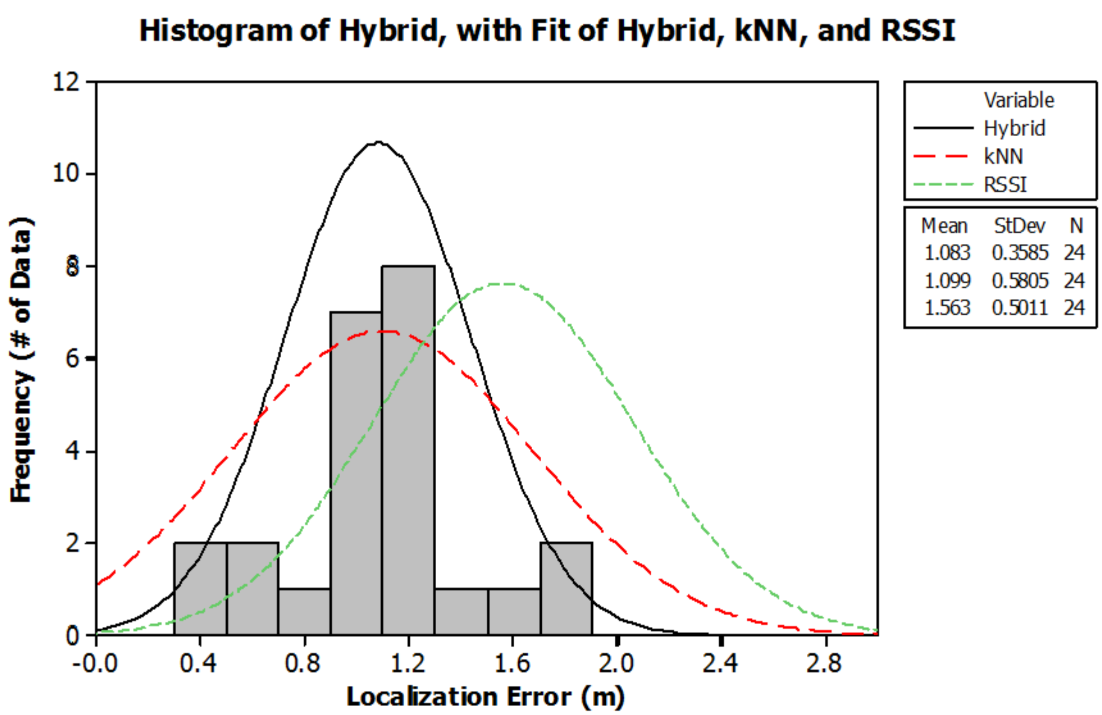
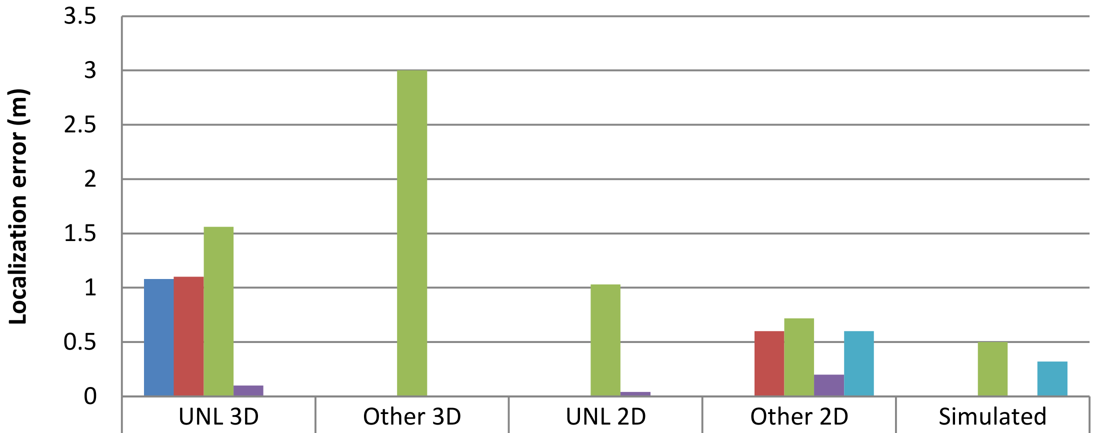


Figure 5-7: Localization error histogram with fit

Recall that, in 2D, RFID-based RTLSs achieve an accuracy of around 1 meter in high-complexity indoor environments [41, 46]. Accuracies of less than 1 meter, around half meter, can be achieved with a higher density of reference tags and/or more complicated hardware [14]. There is also a clear need for RFID-based 3D indoor RTLSs [48]. And as summarized in Section 3.6, theoretical results predict that the localization error in 3D will be at least 1.7 times that in 2D, if isotropic RF propagation and environmental impacts are accounted for [44]. Therefore, the performance of the proposed 3D RTLS is aligned with theoretical prediction and is competitive with other current 2D systems when taking the dimension difference into account.

A localization error comparison chart among various reported RFID-based RTLS is illustrated in Figure 5-8. The matrix at the bottom shows the localization errors based on several major algorithms, kNN, RSSI, TDOA, and APM. The results for 3D, 2D, and simulation are separated in different columns. The simulation results are listed here for reference only, and are discussed in details. In the second column, the significantly large value of 3 meters by using RSSI algorithm in 3D is not the focus either. As this is the very initial attempt at 3D RFID localization, a lot of improvements developed later were applied to 2D applications but not 3D applications. It should also be noticed that, all TDOA systems use microware frequency bands, which is an intersection of RFID and WSN. Their high accuracy error levels were benefited from complicated time synchronization mechanism of the devices.



	UNL 3D	Other 3D	UNL 2D	Other 2D	Simulated
Hybrid	1.08 [47]				
kNN	1.1 [47]			0.6 [7]	
RSSI	1.56 [47]	3 [30]	1.03 [46]	0.72 [37]	0.5 [36]
TDOA	0.1 [18]		0.04 [18]	0.2 [38]	
APM				0.6 [34]	0.32 [35]

Figure 5-8: Localization error comparison

First, the RSSI and TDOA rows of the first (UNL 3D) and the third (UNL 2D) columns are compared. These systems were developed in the same high-complexity laboratory room at UNL. So, the comparison between the 2D versus 3D relationship is seen. For RSSI, the ratio of localization error in 3D application versus 2D is 1.56 : 1.03, or equivalently 1.515 : 1. Similarly, the ratio for TDOA is 0.1 : 0.04, or equivalently 2.5 : 1. Recall that the theoretical ratio is $\sqrt{6} : \sqrt{2}$, or equivalently 1.732 : 1, as discussed in Chapter 3. Thus the theoretical prediction is reasonable, and could be used for further evaluation.

Now, if this ratio is applied to the 2D systems reported in the fourth column, the best possible 3D results could be predicted. For kNN, the 3D accuracy prediction is 1.732 * 0.6 = 1.04 meters. The UNL 3D result is 1.1 meters. And for RSSI, the 3D accuracy prediction is 1.732 * 0.72 = 1.25 meters. Though, the UNL 3D result, 1.56 meters, is 25% higher than this prediction. It may be caused by the reference tags deployment strategy. As in other 2D applications, the reference tags are usually placed evenly on the plane being investigated. However, in the UNL 3D system, all reference tags are attached to the walls, ceiling, and floor. There is no reference tag in the middle of the room to reflect real restriction. The proposed hybrid algorithm reduces the localization error to 1.08 meters, even closer to the prediction than the kNN approach. It also brings significantly smaller standard deviation, as mentioned in earlier part of this section. So, this 3D system is a successful attempt. Admittedly, it may be further improved.

In addition, the relationship between the ranging error and localization error was also evaluated to see if it fit the theoretical prediction as expressed in Equation (3-16). The typical RSSI values range from -45 to -70 dBm in this localization test. Therefore, the PI varies from 4.09 to 4.28 meters, as discussed in Section 5.1.3. According to the prediction formula, Equation (3-17) developed in Section 3.4, the theoretical localization error using RSSI ranging in 3D applications should be from 2.05 to 2.14 meters. The actual error measured in this test using RSSI ranging is 1.56 meters, which is smaller than the prediction values. Due to the time constraint, the proposed experiment in Section 3.5 was not conducted in a full set. The above verification is considered a sample value only. This may be completed in future work.

In summary, based on commercial off-the-shelf (COTS) RFID readers and tags and using a novel software based localization algorithm, the proposed system achieves a mean localization error of 1.08 meters, which fits previous theoretical prediction. The proposed hybrid algorithm offers significantly enhanced localization performance compared to other existing algorithms.

5.3 Additional Tests for Battery-assisted Passive System

5.3.1 Battery-assisted Passive System

A similar tag test as conducted with the RF Code active tags was repeated to evaluate the performance of two different types of Intelleflex battery-powered passive Gen 2 RFID tags with different test conditions, as described in Section 4.3.

In order to compare the location effect, all data points measured with distance no higher than 3 meters are taken as a subset of the whole dataset, due to the dimension limitation of the mock-up. The main effects plot for the mean of measured signal strength is illustrated in Figure 5-9.

The two levels of the Location factor are significantly different (p=0.000). Overall, the signal strength in Lab is higher than in Mockup, which represents different environmental impacts. The high-reflection effect of the all-metal-surrounded mock-up causes significant interference to the RF signal propagation, which could lead to lower signal strength.

In general, STT tags have significant higher signal strength than SMT tags (p=0.000). The trend is consistent in all other conditions, including different locations. It may because the additional metal shell of SMT tags act as a protection shield, which seems to be designed to filter RF signals or moderate interference in high-reflection environment. Similar component is not found in STT tags.

The mean of signal strength with tag facing toward the ceiling (the z axis) is lower than the other two orientations. The x and y directions have no difference (p=0.467). Overall, the Orientation factor is significant (p=0.000). Though, the various orientations only lead to slight difference on signal strength, comparing to other factors, such as the Location and the Group, as shown in Figure 5-9. The variations of RSSI caused by Location, Group, and Orientation are 7.121, 8.818, and 2.412 dBm, respectively.

The mean of the signal strength versus distance appears to have a linear trend. This is a desired characteristic in localization experiment. It is discussed later in next section that the high standard deviation diminishes this advantage.

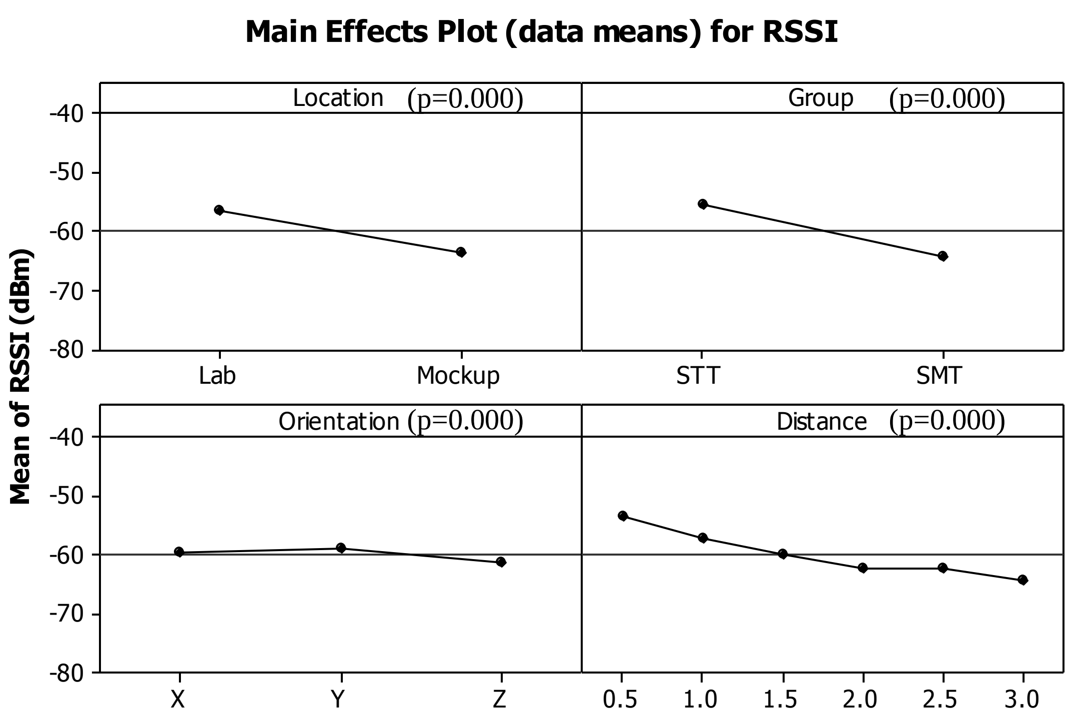


Figure 5-9: Main effects plot for mean

The standard deviation of the signal strength is also investigated. The main effects plot is shown in Figure 5-10.

The Location factor causes significant difference of signal strength over various levels ($p=0.000$). The mock-up environment leads to higher standard deviation, which is expected in high-reflection space due to signal interference.

The SMT tags have no better performance than STT tags in terms of the standard deviation of signal strength. The standard deviations for two types of tags are almost identical ($p=0.913$). The test result does not fully meet the design purpose of SMT tags. The additional metal shell could be helpful when the tag is trying to catch signals from the reader in a metal environment with high signal interference. It may also have a side effect of partially blocking the signal strength broadcasted from the tag. This could cause relatively lower signal strength mean for the SMT tags, as discussed above. But it cannot determine how well the response signal is received by the reader, which means the standard deviation of the signals is not related to the type of the tag. So, only STT tags are used in further in laboratory tests.

The standard deviation of signal strength with tag facing toward the antenna (the y axis) is higher than the other two orientations. The x and z directions have no difference ($p=0.555$). Overall, orientation is still a significant factor ($p=0.000$). Though, it leads to less variation than the Location does (1.397 versus 4.086 dBm), as shown in Figure 5-10.

In general, the standard deviation of signal strength is mostly consistent over distance. It becomes slightly noticeable higher as distance increases to 3 meters. A pair-wise comparison shows that only 3 versus 0.5 and 3 versus 1.5 are significantly different (with p=0.008 and p=0.028, respectively). All other combinations are statistically same.

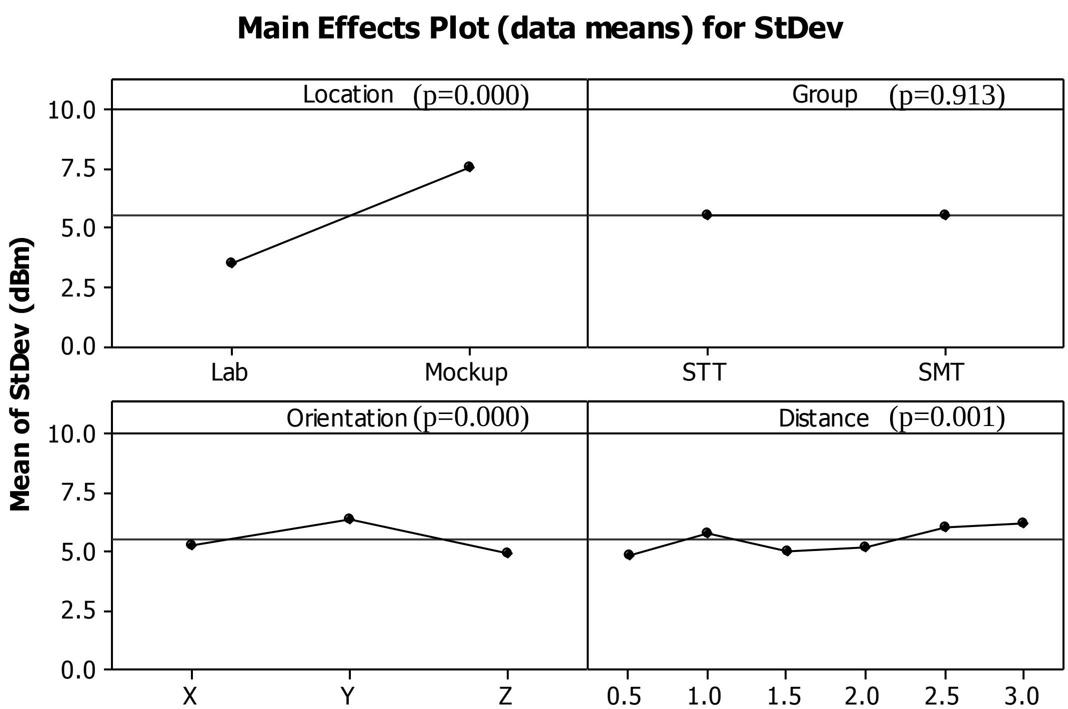


Figure 5-10: Main effects plot for standard deviation

Similarly, a linear regression was performed to the ranging data measured in the laboratory with STT tags, as shown in Figure 5-11. The prediction function based on ranging test result is Distance = - 7.302 - 0.1779 * RSSI, with R^2 equal to 78.7%, which is acceptable. The prediction interval varies from 2.68 to 2.77 meters with RSSI ranging from -40 to -75 dBm. This is used in the localization test analysis later. Even with doubled standard deviation, the PI of the battery-assisted passive system is narrower than the active system (2.68 to 2.77 versus 4.09 to 4.28 meters) due to the stable linear trend of the data (R^2: 78.7% versus 52.8%).

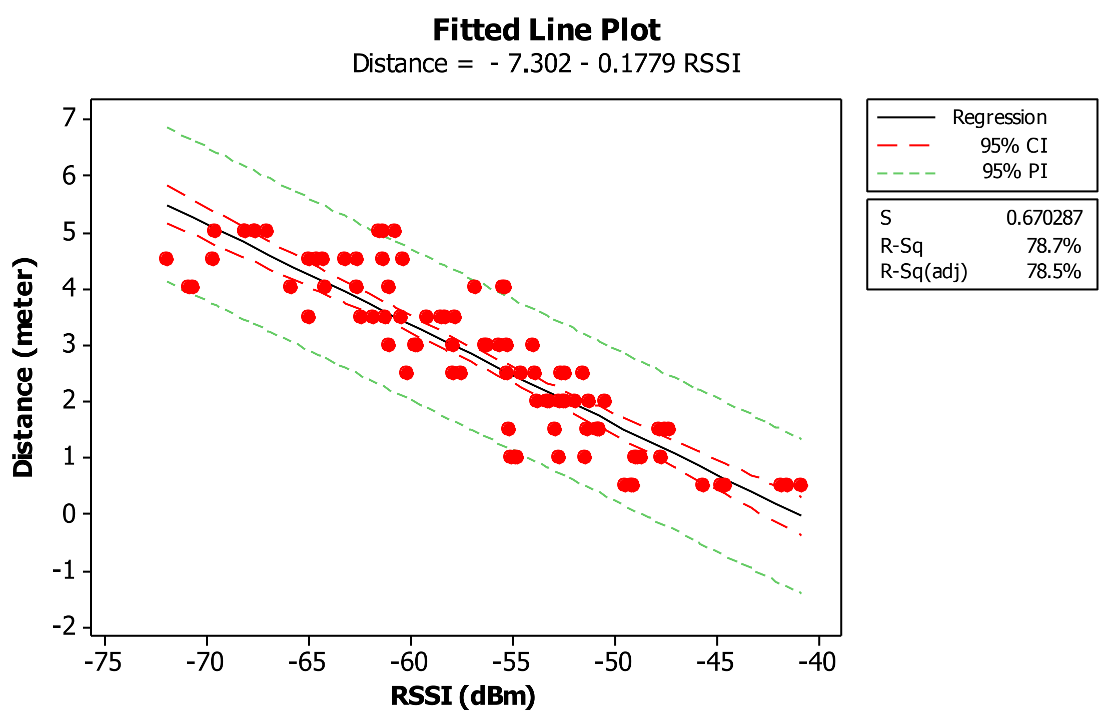


Figure 5-11: Linear regression of ranging test (battery-assisted passive system)

In summary, the battery-assisted passive tag test leads to the following conclusions.

- The mock-up leads to lower RSSI and higher deviation than in the laboratory environment. The signal interference caused by metal reflection is the expected major reason.
- SMT tags have lower RSSI values than STT tags, but they have no difference in terms of standard deviation. This is probably due to the metal shell design of the SMT tags. Though, it should be noted that the SMT tags may have enhanced capability on receiving unstable signals in metal environment, but the response signals being sent out may not benefit from this.
- The Intelleflex tags are not orientation sensitive at all directions in terms of either mean or standard deviation. The orientation causes 2/3 less variation than other factors. The possible reason is the enlarged antenna coil size, which increase broadcasting response signals.
- The signal strength versus distance regression appears to have a linear trend. Though, the high standard deviation makes this advantage less valuable. This is explained in the next section.

5.3.2 Active versus Battery-assisted Passive System

The main effect plots of the signal strength and its deviation versus distance are compared to the RF Code active tags results in Figure 5-12. Overall, Intelleflex tags are better on RSSI linearity but have higher and inconsistent standard deviation.

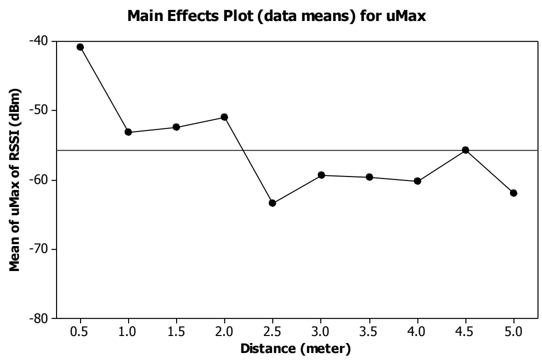
In part (a) comparison, although the average signal strength of the battery-assisted passive system is lower (-57.15 versus -60.94 dBm, p=0.000), the linear trend is more obvious than with the active system. In addition, the average signal strength of the active system does not even monotonously decrease versus distance in most cases.

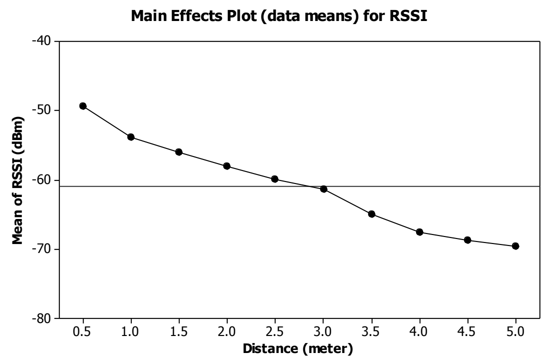
In part (b) comparison, the signal strength deviation for the battery-assisted passive system is almost four times higher than the active system, 4.04 versus 1.11 dBm (p=0.000). This makes the RSSI ranging almost impossible in regular room-size space.

The boxplot comparison in part (c) combines the mean and variation information together to present different characteristics of these two systems. The active system has precise RSSI reading at particular locations but is impacted by the environment. The RSSI measured in the active system does not follow a linear, quadratic, or log trend. It is not even monotonic, which makes RSSI regression less accurate. The RSSI reading of the battery-assisted passive system is distance dependent but less stable at any particular position. As discussed in Chapter 3, such ranging variance is inherited and amplified to final localization error later. So, neither of these two patterns is desired for the purpose of RSSI ranging.

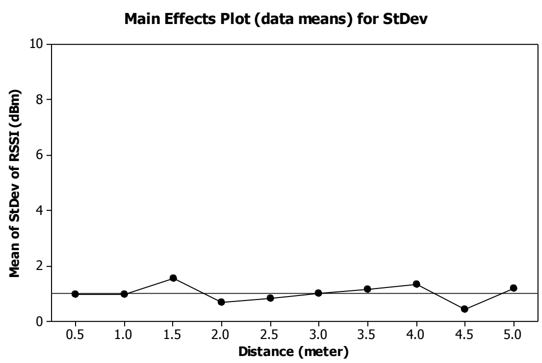
Active system (RF Code)

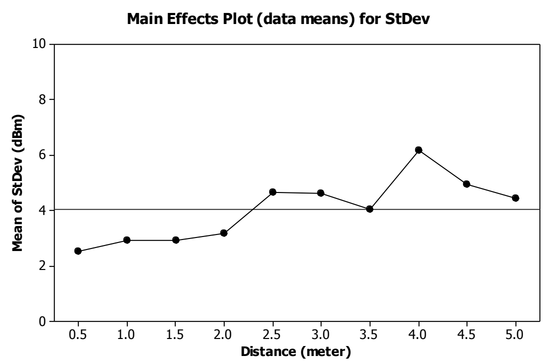
Battery-assisted passive system (Intelleflex)



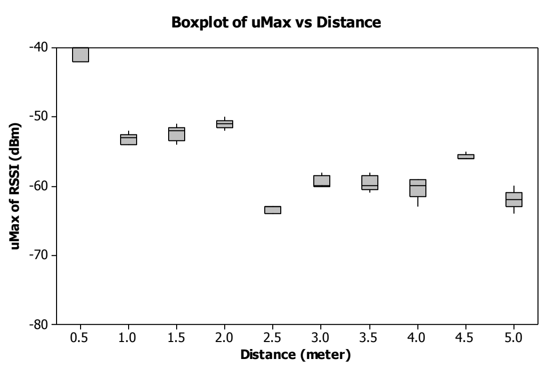


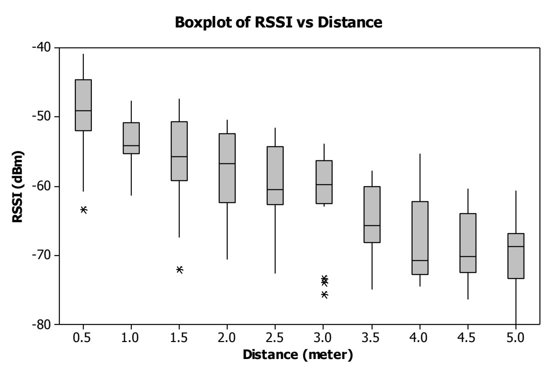
(a) signal strength (mean) versus distance





(b) signal strength (stdev) versus distance





(c) signal strength versus distance using boxplot

Figure 5-12: Active versus battery-assisted passive system

One possible solution to reduce the signal variance of the battery-assisted passive system is to use two pairs of antennas at the same position, just like the active system. Only the maximum value of two antennas measurements is recorded as the official RSSI reading. In this way, the signal variance may decrease. The size of the antennas of the battery-assisted passive system may be an issue. Two panels of a single pair of the antennas, or the two pair of the antennas, require certain space to operate properly. According to the Intelleflex FMR6000 user manual, at least 1 or 2 feet distance is recommended, which is not neglectable to be qualified as the same position.

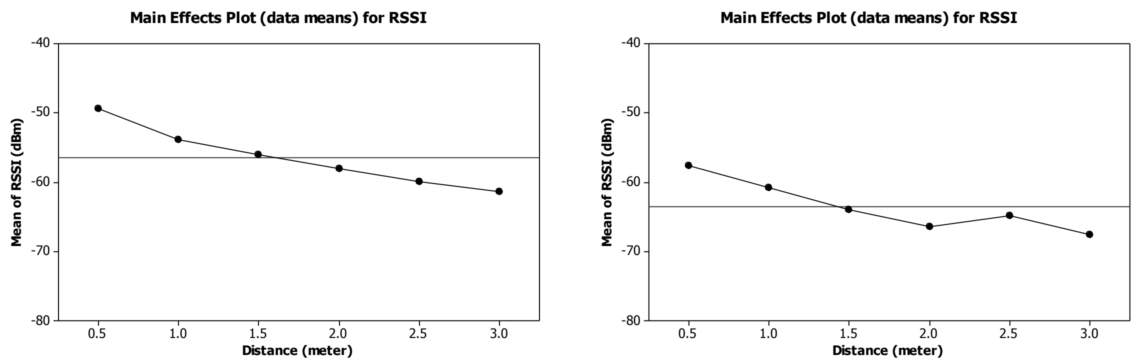
5.3.3 Lab versus Mock-up

The Intelleflex battery-assisted passive system performed differently in the regular laboratory environment and in the ISS mock-up. The main effect plots of signal strength versus distance, and its standard deviation versus distance, are compared to the Lab results within 3 meters, as shown in Figure 5-13. Overall, the RSSI in the laboratory has higher value and lower standard deviation than in the mock-up.

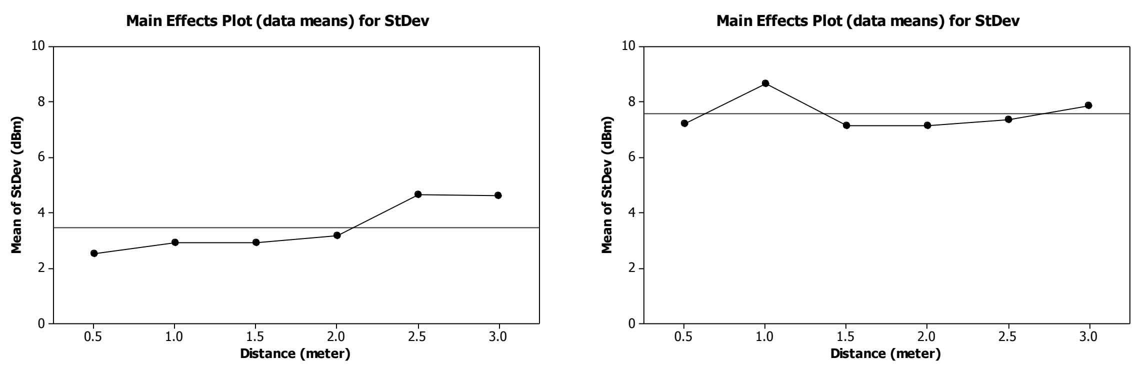
In part (a) comparison, the average signal strength in the mock-up is even lower than in the laboratory, -63.540 versus -56.419 dBm, with p-value 0.000.

In part (b) comparison, the signal strength deviation in the mock-up is significantly higher than in the laboratory, 7.56 versus 3.48 dBm, with p-value 0.000. Recall that the value for the active system is only 1.10 dBm. The high-reflection environment makes the signal receiving satiability even worse for the passive system.

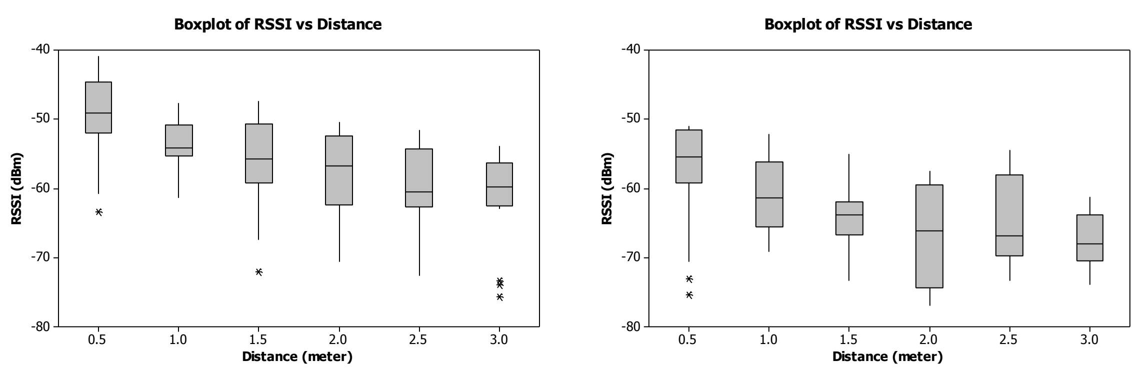
Lab **Mock-up**



(a) signal strength (mean) versus distance



(b) signal strength (stdev) versus distance



(c) signal strength versus distance using boxplot

Figure 5-13: Lab versus Mock-up

The boxplot comparison in part (c) combines the mean and variation information together to present different performance in the two environments. The RSSI reading in the mock-up is more unpredictable than in the laboratory. This means pure RSSI ranging is not reliable in the mock-up. Therefore, range-free algorithms, such as kNN, should be highlighted in future localization tests in the mock-up. For the hybrid algorithm, more weights may be assigned to kNN rather than simple average of kNN and RSSI results in current approach. Moreover, probabilistic modeling may be another candidate.

5.4 Localization Test for Battery-assisted Passive System

As shown in the right column of Table 5-3, this preliminary localization experiment for the battery-assisted passive system resulted in mean localization errors of 2.06, 2.34, and 2.49 meters for the hybrid, kNN, and RSSI ranging algorithms, respectively. The active system results are listed in the left column for comparison. It is very obvious that current battery-assisted passive system produce higher localization error than the active system. Though, the RSSI prediction shows opposite result, which may indicate possible improvement space via further system optimization.

Table 5-3: Localization error comparison

	Active system (RF Code)	**Battery-assisted Passive System (Intelleflex)**
Hybrid	1.08 m	2.06 m
kNN	1.10 m	2.34 m
RSSI	1.56 m	2.49 m
RSSI prediction	2.05 m – 2.14 m	1.34 m – 1.39 m

The localization error prediction was conducted based on RSSI ranging error of both the active system and the battery-assisted passive system based on the Equation (3-17) developed in Section 3.4. Recall that the PIs vary from 4.09 to 4.28 meters and from 2.68 to 2.77 meters for the two systems. This brings the RSSI prediction of 2.05 to 2.14 meters and 1.34 to 1.39 meters, respectively.

For the active system, the real localization error based on RSSI ranging is 1.56 meter, which is around 25% smaller than prediction. This may benefit from the selected reference tags method, which eliminates those reference tags far away from the target tag. In this way, the regression approach is more accurate.

However, for the battery-assisted passive system, the current measured result, 2.49 meter, is over 80% larger than the prediction. Recall that this is only one sample measurement of a whole set of the proposed experiment in Chapter 3. It is possible that current measurement happens to deviate from the predicted mean value. So, it may indicate that the current battery-assisted passive system still has high potential to have its performance improved. One possible solution, mentioned at the end of Section 5.3.2, is to make dual pairs of antennas at the same position.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

According to the research purpose of this dissertation, the conclusions are summarized in accordance with three objectives: theoretical prediction on minimum number of reference tags and localization error, performance evaluation of 3D RFID systems, and high-reflection environmental impacts.

6.1.1 Theoretical Prediction

Based on a series of assumptions and theoretical interpretation, two experiments were designed to evaluate the minimum possible number of reference tags that should be used in a RFID localization test. These experiments per se were not conducted due to a time restraint. However, a localization error prediction function using prediction interval on ranging measurement is developed. That is, $\hat{e} \cong half\ 95\%\ PI\ on\ ranging\ only$ for 3D applications. And the ratio of localization errors for 3D, 2D and 1D ranging only are: $\sqrt{6} : \sqrt{2} : 1$. The measured results in Section 5.2 fit these predictions well. The results from another system, as discussed in Section 5.4, deviated from the prediction. This may be caused by poor design of the second system. Or, it is just a single sample event. Full justification may require more experiments.

6.1.2 Localization Performance

The proposed 3D indoor RFID localization system was built with two types of commercial off-the-shelf (COTS) products. One is the RF Code active system. The other one is the Intelleflex battery-assisted passive system. A hybrid algorithm is developed based upon kNN and RSSI ranging approaches.

For the active system, a mean localization error of 1.08 meters is achieved, which fits previous theoretical prediction, and is better than using kNN or RSSI only. The system is a successful trial on RFID 3D localization. Its performance may be further improved by rearranging reference tags and reader positions.

For the battery-assisted passive system, the mean localization error is 2.06 meters, which is 50% higher than predicted result using RSSI ranging only. However, it is still better than using kNN or RSSI only. Due to space restriction, less readers and antennas than the active system were used in the current system. This may be a major reason causing worse performance than expected.

6.1.3 Environmental Impacts

An ISS mock-up was built to evaluate the RFID performance in a high-reflection environment. It was found that the mock-up did lead to average 7.2 dBm lower RSSI and double the standard deviation of RSSI than in the laboratory environment. The RF signal interference is aggravated in the mock-up. Therefore, RSSI ranging may not be applicable in such environment. The range-free approach may be a better choice.

6.2 Recommendations

Based on the above conclusions, a few recommendations for future work are proposed.

- A complete set of experiments should be conducted to fully justify the conclusion of the theoretical prediction.
- Based on the above experiment results, better reference tags and readers deployment could be assigned to the current system, which may bring better localization performance.
- More readers and antennas should be added to the battery-assisted passive system. Admittedly, certain deployment restrictions may need to be overcome.
- Higher order regressions may be investigated in both the theoretical analysis and the localization algorithm.
- The kNN part of the hybrid algorithm may be emphasized to reduce the impact of strong signal interference in the metal-surrounded ISS mock-up. Probabilistic modeling may be another candidate.

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Appendix A

Programming Interface

A.1 JSON

JSON (JavaScript Object Notation) is a text-based web standard specially designed for data interchange. It is human-readable, and is simpler than XML (Extensible Markup Language), another text-based web standard especially suitable for information exchange, which will be introduced in the Intelleflex section later. The format of JSON makes it easy to be used in various programming languages and applications. Here is an example message of tag information in JSON format.


```
{
    “tag_id”: “LOCATE00016484”,
    “tag_links”:    [
        {“channelid”: 1,
            “ssi”: -56},
        {“channelid”: 2,
            “ssi”: -54}
    ]
}
```


A simple Matlab package, parse_json, contributed by François Glineur in the Matlab Community File Exchange makes the work of parsing JSON message into structure format data much easier.

Most commonly used commands for RF Code (in format of URLs) are:

- List all available readers
    - http://localhost:6580/rfcode_zonemgr/zonemgr/api/readerlist.json
- List all available tags
    - http://localhost:6580/rfcode_zonemgr/zonemgr/api/taglist.json

- List information of one particular tag
    - http://localhost:6580/rfcode_zonemgr/zonemgr/api/tagprint.json?tagid0=<id>

The login information is same as normal web portal access method. Though, special URL reading function should be constructed since Matlab does not support URL authorization. Thanks for Matlab Community again: the urlread_auth and base64encode packages solve this problem. Please note that the urlread_auth must be placed under the “toolbox\matlab\iofun” folder, and the Matlab library cache may need to be re-hashed for the changes to take effect.

The JSON related functions coded for this research are shown as follows for reference. They are pretty much self-explained.

```
function [base_url,login]=zonemgr_portal(hostname,port,username,password)
    % generate base_url and login for rfcode zonemgr web portal
    % all inputs are optional, default values will be applied if not given
    % created by Jiaqing Wu, 3/18/2011

    % check inputs and outputs
    error(nargchk(0,4,nargin));
    error(nargoutchk(2,2,nargout));
    % default rfid zonemgr web portal information
    if (nargin==0), hostname='rfidlab-pc'; end
    if (nargin<=1), port='6580'; end
    if (nargin<=2), username='user'; password='user'; end
    if (nargin==3), password=username; end
    % define a short url
    base_url=['http://',hostname,':',port,'/rfcode_zonemgr/zonemgr/api'];
    % combine username and password to login
    if ~isempty(username) && ~isempty(password)
        login=[username,':',password];
    else
        error('zonemgr_portal:InvalidLogin','Missing login information.');
    end
end

function [reader_status,reader_name,reader_ip]=check_reader(reader_id)
    % check whether queried reader(s) are available or not
    % the input reader_id is optional, but must be a cell array if used
    % all readers will be queried, if reader_id is not given
    % the output reader_status is a vector of (size of reader_id) by 1
    % 1 for online, 0 for offline
    % the output reader_name is a cell array of (# of all readers) by 1
    % the output reader_ip is a cell array of (# of all readers) by 1
    % both of them include all available readers reported by the system
    % created by Jiaqing Wu, 3/18/2011

    % check inputs and outputs
    error(nargchk(0,1,nargin));
```

```
    error(nargoutchk(0,3,nargout));
    % declare global variates
    global base_url login
    % obtain rfid zonemgr web portal information
    if isempty(base_url) && isempty(login)
        [base_url,login]=zonemgr_portal();
    end
    % get reader information
    reader_list=parse_json(urlread_auth([base_url, ...
            '/readerlist.json'],login));
    reader_name=fieldnames(reader_list);
    % initialize cell arrays for purpose of shorter reference length
    reader_state=cell(size(reader_name,1),1);
    reader_ip=cell(size(reader_name,1),1);
    % fulfill actual values
    for i=1:size(reader_name,1)
        reader_state{i}=reader_list.(reader_name{i}).attributes.state;
        reader_ip{i}=reader_list.(reader_name{i}).attributes.hostname;
    end
    % sort reader_name and reader_state in order of ip for easier matching
    reader_sorted=sortrows([reader_ip,reader_name,reader_state]);
    reader_ip=reader_sorted(:,1);
    reader_name=reader_sorted(:,2);
    reader_state=reader_sorted(:,3);
    % reformat the output reader_name
    for i=1:size(reader_name,1)
        reader_name{i}=['$',reader_name{i}(8:end)];
    end
    % set default input if necessary
    if (nargin==0), reader_id=reader_name; end
    % set default output as zeros
    reader_status=zeros(size(reader_id,1),1);
    % locate queried reader(s) in the list, and check connection status
    for i=1:size(reader_id,1)
        [reader_member,member_id]=ismember(reader_id{i},reader_name);
        if reader_member && strcmpi(reader_state{member_id},'ACTIVE')
            reader_status(i,1)=1;
        end
    end
    % report warning if at least one reader is not found or inactive
%     if (sum(reader_status)<size(reader_id,1))
%         disp([num2str(size(reader_id,1)-sum(reader_status)), ...
%             ' queried reader(s) are offline.']);
%     end
end

function [tag_status,tag_name]=check_tag(tag_id)
    % check whether queried tag(s) are available or not
    % tag_id is optional, but must be a cell array if used
    % all tags will be queried, if tag_id is not given
    % the output tag_status is a vector of (size of tag_id) by 1
    % 1 for online, 0 for offline
    % the output tag_name is a cell array of (# of all tags) by 1
    % it includes all available tags reported by the system
    % created by Jiaqing Wu, 3/22/2011

    % check inputs and outputs
    error(nargchk(0,1,nargin));
    error(nargoutchk(0,2,nargout));
```

```
    % declare global variates
    global base_url login
    % obtain rfid zonemgr web portal information
    if isempty(base_url) && isempty(login)
        [base_url,login]=zonemgr_portal();
    end
    % get tag information
    tag_list=parse_json(urlread_auth([base_url, ...
            '/taglist.json'],login));
    tag_name=fieldnames(tag_list);
    % sort tag_name
    tag_name=sortrows(tag_name);
    % set default input if necessary
    if (nargin==0), tag_id=tag_name; end
    % set default output as zeros
    tag_status=zeros(size(tag_id,1),1);
    % locate queried tag(s) in the list, and mark found/unfound ones
    for i=1:size(tag_id,1)
        if ismember(tag_id{i},tag_name)
            tag_status(i,1)=1;
        end
    end
    % report warning if at least one tag is not found
%     if (sum(tag_status)<size(tag_id,1))
%         disp([num2str(size(tag_id,1)-sum(tag_status)), ...
%             ' queried tag(s) are offline.']);
%     end
end

function [ssi,tag_status]=read_ssi(tag_id,reader_id,channel)
    % get ssi for queried tag(s), reader(s) and channel(s)
    % tag_id and reader_id are mandatory input parameters
    % both must be defined as cell arrays
    % the size of reader_id is limited to 4 now, but expandable
    % channel is optional, and can be defined as '', 'A' or 'B' only
    % the output ssi is a matrix with dimension of
    % (# of tag_id) by (# of reader_id * 2)
    % the output tag_status is a vector of (# of tag_id) by 1
    % 1 for online, 0 for offline
    % created by Jiaqing Wu, 3/15/2011
    % add multiple vendors support
    % updated by Jiaqing Wu, 7/23/2012
    % extend reader_id compatibility
    % updated by Jiaqing Wu, 8/1/2012
    global flag

    % for intelleflex only
    if strcmp(flag,'intelleflex')
        reader_id=reader_id(:,end-3:end);
        if (nargin>2) % antenna_id was specified in gui
            switch channel
                case 'A'
                    antenna_id=1;
                case 'B'
                    antenna_id=2;
                otherwise
                    antenna_id=0;
            end
            tagInfo=intelleflex('getTagInfo',reader_id,tag_id,antenna_id);
```

```
    else % antenna_id should be defined via reader sequence
        antenna_id=repmat([1;2],size(reader_id,1)/2,1);
        for i=1:size(reader_id,1)
            tagInfoTemp=intelleflex('getTagInfo', ...
                reader_id(i,:),tag_id,antenna_id(i));
            tagInfo(:,2*i:2*i+1)=tagInfoTemp(:,2:end);
        end
        tagInfo(:,1)=tag_id(:,1);
    end
    ssi=cell2mat(tagInfo(:,2:end));
    tag_status=~(sum(cell2mat(tagInfo(:,2:end)),2)==0);
    return;
end

% check inputs and outputs
error(nargchk(2,3,nargin));
error(nargoutchk(0,2,nargout));
if (nargin>2) && ~strcmpi(channel,'') ... % '' is a hidden option
        && ~strcmpi(channel,'A') && ~strcmpi(channel,'B')
    error('read_ssi:InvalidInput','Channel must be either A or B.');
end
% set default output as zeros
ssi=zeros(size(tag_id,1),size(reader_id,1)*2);
tag_status=check_tag(tag_id); % necessary before querying tag details
% declare global variates
global base_url login
% obtain rfid zonemgr web portal information
if isempty(base_url) && isempty(login)
    [base_url,login]=zonemgr_portal();
end
% get tag details
for i=1:size(tag_id,1)
    % query found tags only
    if (tag_status(i,1)==1)
        tag_detail=parse_json(urlread_auth([base_url, ...
            '/tagprint.json?tagid0=',tag_id{i}],login));
        tag_links=tag_detail.(tag_id{i}).taglinks;
        % put ssi values in sequence
        for j=1:size(tag_links,2)
            k=size(reader_id,1);
            if (k>0) && strcmp(tag_links{j}.channelid, ...
                    [reader_id{1,1},'_channel_A'])
                ssi(i,1)=tag_links{j}.ssi;
            elseif (k>0) && strcmp(tag_links{j}.channelid, ...
                    [reader_id{1,1},'_channel_B'])
                ssi(i,2)=tag_links{j}.ssi;
            elseif (k>1) && strcmp(tag_links{j}.channelid, ...
                    [reader_id{2,1},'_channel_A'])
                ssi(i,3)=tag_links{j}.ssi;
            elseif (k>1) && strcmp(tag_links{j}.channelid, ...
                    [reader_id{2,1},'_channel_B'])
                ssi(i,4)=tag_links{j}.ssi;
            elseif (k>2) && strcmp(tag_links{j}.channelid, ...
                    [reader_id{3,1},'_channel_A'])
                ssi(i,5)=tag_links{j}.ssi;
            elseif (k>2) && strcmp(tag_links{j}.channelid, ...
                    [reader_id{3,1},'_channel_B'])
                ssi(i,6)=tag_links{j}.ssi;
            elseif (k>3) && strcmp(tag_links{j}.channelid, ...
```

```
                        [reader_id{4,1},'_channel_A'])
                    ssi(i,7)=tag_links{j}.ssi;
                elseif (k>3) && strcmp(tag_links{j}.channelid, ...
                        [reader_id{4,1},'_channel_B'])
                    ssi(i,8)=tag_links{j}.ssi;
                else
                    % more information may be detected
                    % duplicate/revise the above code for expansion
                end
            end
        end
    end
    % report values on queried channel only
    % channel = '', given defined in inputs, is treated as both channels
    if (nargin>2) && strcmpi(channel,'A')
        ssi(:,2:2:end)=0;
    elseif (nargin>2) && strcmpi(channel,'B')
        ssi(:,1:2:end)=0;
    end
end
```

A.2 XML

XML (Extensible Markup Language) is provided as API suitable for Matlab programming interface to the Intelleflex system. It is considered more flexible but also more complicated than JSON, in terms of data exchange. An example message of tag information is shown as follows.


```
<findTagsReply>
    <tag>
        <epc>bbaa99887766554400001045</epc>
        <dbm>-88</dbm>
        <roSpecID>0</roSpecID>
    </tag>
    <tag>
        <epc>bbaa99887766554400001045</epc>
        <dbm>-78</dbm>
        <roSpecID>1</roSpecID>
    </tag>
</findTagsReply>
```


There is no existing package perfect for communicating with Intelleflex reader using XML. So, a package, called xml_parse, is coded to use Java socket library to establish a TCP/IP socket connection with the reader via port 80, and then sending and receiving XML messages.

Two simple Matlab packages, struct2xml and xml2struct, contributed by Wouter Falkena in the Matlab Community File Exchange make the work of translating xml format data to/from structure data much easier.

Most commonly used commands for Intelleflex (in format of XML messages) are:

- List status of one particular reader
    - getReaderStatus
- List all available tags or particular tags via filter
    - findTag
- List memory information of one particular tag (not used in this experiment)

- readTagMemory

The XML related functions coded for this research are shown as follows for reference. They are pretty much self-explained.

```
function rx_data=xml_parse(tx_host,tx_port,tx_data,rx_timeout)
    % check inputs and outputs
    error(nargchk(3,4,nargin));
    error(nargoutchk(0,1,nargout));
    % set default values
%     if (nargin==0), tx_host='192.168.1.12'; end
%     if (nargin<=1), tx_port=80; end
%     if (nargin<=2), tx_data=struct('getReaderStatus',struct()); end
    if (nargin<=3), rx_timeout=2; end
    % convert command to xml format
    if isa(tx_data,'struct')
        tx_xml=struct2xml(tx_data);
    else
        tx_xml=tx_data;
    end
    tx_msg=regexprep(tx_xml,'> *\n *<','><');

    % communicate via tcp/ip socket
    rx_msg=xml_socket(tx_host,tx_port,tx_msg,rx_timeout);
%     display(rx_msg);
    if isempty(rx_msg)
        rx_data='';
        return;
    end
    % convert xml message to matlab struct
    rx_xml=javax.xml.parsers.DocumentBuilderFactory.newInstance() ...
        .newDocumentBuilder.parse(java.io.StringBufferInputStream(rx_msg));
    rx_data=xml2struct(rx_xml);
end

function rx_msg=xml_socket(tx_host,tx_port,tx_msg,rx_timeout)
    import java.net.Socket
    import java.io.*
    % check inputs and outputs
    error(nargchk(3,4,nargin));
    error(nargoutchk(0,1,nargout));
    % set default values
    if (nargin==3), rx_timeout=1; end
    tx_socket=[];
    rx_pause=0.2;
    try
        % establish socket connection
        tx_socket=Socket(tx_host,tx_port);
%         fprintf(1,'Connection established\n');
        % send command to reader
%         fprintf(1,'Sending %d bytes <command>\n',length(tx_msg));
        tx_stream=DataOutputStream(tx_socket.getOutputStream);
        tx_stream.writeBytes(char(tx_msg));
        tx_stream.flush;
        % receive data
%         fprintf(1,'Waiting for reply\n');
```

```
        rx_stream=DataInputStream(tx_socket.getInputStream);
        bytes_available=0;
        tic;
        while (bytes_available~=rx_stream.available)||(bytes_available==0)
            bytes_available=rx_stream.available;
            pause(rx_pause);
            if toc>=rx_timeout
                fprintf(1,'Timeout after %5.2f second(s)\n\n', ...
                    rx_timeout);
                break;
            end
        end
        % read response from reader
        rx_buffer=zeros(1,bytes_available,'uint8');
        for i=1:bytes_available
            rx_buffer(i)=rx_stream.readByte;
        end
        if bytes_available>=8092
            while ~strcmp(char(rx_buffer(end-5:end)),'Reply>')
                i=i+1;
                rx_buffer(i)=rx_stream.readByte;
            end
        end
%         fprintf(1,'Receiving %d bytes <response>\n',length(rx_buffer));
%         fprintf(1,'Completed in %5.2f second(s)\n',toc);
        rx_msg=char(rx_buffer);
        % close socket connection
        tx_socket.close;
%         fprintf(1,'Connection closed\n\n');
    catch
        if ~isempty(tx_socket)
            tx_socket.close
        end
        fprintf(1,'Connection terminated\n\n');
    end
end

function returnInfo=intelleflex(cmd,readerID,tagID,antennaID,n,t)
    % check inputs and outputs
    error(nargchk(0,5,nargin));
    error(nargoutchk(0,1,nargout));
    % set default values
    if (nargin<=0), cmd='getReaderInfo'; end
    if (nargin<=1), readerID={'192.168.1.11',80;'192.168.1.12',80}; end
    if (nargin<=2), tagID={}; end
    if (nargin<=3), antennaID=0; end
    if (nargin<=4), n=5; end
    if (nargin<=5), t=2; end
    % choose command to be sent
    switch cmd
        case 'getReaderInfo'
            returnInfo=getReaderInfo(readerID);
        case 'getTagInfo'
            returnInfo=getTagInfo(readerID,tagID,antennaID);
        case 'getTagInfoWithTimer'
            returnInfo=getTagInfo(readerID,tagID,antennaID,n,t);
        otherwise
            returnInfo=getReaderInfo(readerID);
    end
```

```
end

function tagData=findTags(readerID,tagID,antennaID,loop)
    % check inputs and outputs
    error(nargchk(1,4,nargin));
    error(nargoutchk(0,1,nargout));
    % set default values
    if (nargin<=1)
        tagID={};
        selectCmd='';
        Qval=6;
    else
        if (size(tagID,1)==1)
            selectCmd=['<select>', ...
                '<mask>',tagID{1,1},'</mask>', ...
                '</select>'];
        else
            selectCmd='';
        end
        Qval=ceil(log(size(tagID,1)+1)/log(2));
        if isempty(tagID), Qval=6; end
    end
    if Qval>8
        RFProfile=1;
        rx_timeout=90;
    elseif Qval>4
        RFProfile=2;
        rx_timeout=30;
    else
        RFProfile=3;
        rx_timeout=10;
    end
    if (nargin<=2), antennaID=0; end
    if (antennaID==1)||(antennaID==2)
        roSpecCmd=['<roSpec>', ...
            '<id>',num2str(antennaID-1),'</id>', ...
            '<Qval>',num2str(Qval),'</Qval>', ...
            '<txAnt>',num2str(antennaID),'</txAnt>', ...
            '<RFProfile>',num2str(RFProfile),'</RFProfile>', ...
            '</roSpec>'];
    else
        roSpecCmd1=['<roSpec>', ...
            '<id>0</id>', ...
            '<Qval>',num2str(Qval),'</Qval>', ...
            '<txAnt>1</txAnt>', ...
            '<RFProfile>',num2str(RFProfile),'</RFProfile>', ...
            '</roSpec>'];
        roSpecCmd2=['<roSpec>', ...
            '<id>1</id>', ...
            '<Qval>',num2str(Qval),'</Qval>', ...
            '<txAnt>2</txAnt>', ...
            '<RFProfile>',num2str(RFProfile),'</RFProfile>', ...
            '</roSpec>'];
        roSpecCmd=[roSpecCmd1,roSpecCmd2];
    end
    if (nargin<=3)
        loop=0;
        loopCmd='';
    else
```

```
        if (loop>1), loop=1; end
        loopCmd=['<loop>',num2str(loop),'</loop>'];
    end
    % construct command
    tx_data=['<findTags>', ...
        loopCmd, ...
        selectCmd, ...
        roSpecCmd, ...
        '</findTags>'];
    try
        rx_data=xml_parse(readerID{1},readerID{2},tx_data,rx_timeout);
        tagCount=size(rx_data.findTagsReply.tag,2);
    catch
        rx_data='';
        tagCount=0;
    end
    % stop looping if did
    if loop==1
        xml_parse(readerID{1},readerID{2},struct('stopLooping',struct()));
    end
    % decode response
    if isempty(tagID)
        tagID=cell(tagCount,1);
        for i=1:tagCount
            tagID{i}=rx_data.findTagsReply.tag{i}.epc.Text;
        end
        sortrows(tagID);
    end
    tagData=[tagID,num2cell(zeros(size(tagID,1),2))];
    if isempty(rx_data)
        return;
    elseif ~isfield(rx_data.findTagsReply,'tag')
        return;
    end
    for i=1:tagCount
        if tagCount==1
            currentTag=rx_data.findTagsReply.tag;
        else
            currentTag=rx_data.findTagsReply.tag{i};
        end
        [tf,loc]=ismember(currentTag.epc.Text,tagID);
        if tf
            tagData{loc,str2double(currentTag.roSpecID.Text)+2}= ...
                str2double(currentTag.dbm.Text);
%               currentTag.rssi.Text
        end
    end
%     tagData=[tagID,num2cell(-100*rand(size(tagID,1),2))];
end

function tagInfo=getTagInfo(readerID,tagID,antennaID)
    % check inputs and outputs
    error(nargchk(1,3,nargin));
    error(nargoutchk(0,1,nargout));
    % set default values
    if (nargin<=1), tagID={}; end
    if (nargin<=2), antennaID=0; end
    % add column(s)
    tagInfo=[tagID,num2cell(zeros(size(tagID,1),2*size(readerID,1)))];
```

```
    % check reader status validation
    if (size(readerID,2)<=2)
        readerInfo=getReaderInfo(readerID);
    else
        readerInfo=readerID;
    end
    % acquire tag information
    for i=1:size(readerInfo,1)
        if strcmp(readerInfo{i,3},'NOT found')
            tagData=[tagID,num2cell(zeros(size(tagID,1),2))];
        else
            tagData=findTags(readerInfo(i,:),tagID,antennaID);
        end
        if ~isempty(tagData)
            if ~isempty(tagID)
                tagInfo(:,i*2:i*2+1)=tagData(:,2:3);
            else
                tagInfo=[tagInfo,num2cell(zeros(size(tagInfo,1),2)); ...
                    tagData(:,1), ...
                    num2cell(zeros(size(tagData,1),i*2-2)), ...
                    tagData(:,2:3)];
            end
        end
    end
    % refine output
    if isempty(tagID)
        tagInfo=sortrows(tagInfo);
        for k=size(tagInfo,1):-1:2
            if (tagInfo{k,1}==tagInfo{k-1,1})
                tagInfo(k-1,2:end)=num2cell(cell2mat(tagInfo(k,2:end))+ ...
                    cell2mat(tagInfo(k-1,2:end)));
                tagInfo(k,:)=[];
            end
        end
    end
end

function tagInfo=getTagInfoWithTimer(readerInfo,tagID,antennaID,n,t)
    % check inputs and outputs
    error(nargchk(5,5,nargin));
    error(nargoutchk(0,1,nargout));
    % set default values
    tagInfo=[tagID,num2cell(zeros(size(tagID,1),2*size(readerInfo,1)))];
    tagInfo=repmat(tagInfo,[1,1,n]);
    % collect data for n periods
    for i=1:n
        tic; % start the stopwatch timer
        tagInfo(:,:,i)=getTagInfo(readerInfo,tagID,antennaID);
        pause(t-toc); % pause t seconds between intervals
    end
end

function readerData=getReaderStatus(readerID)
    % check inputs and outputs
    error(nargchk(1,1,nargin));
    error(nargoutchk(0,1,nargout));
    % construct command
    tx_data='<getReaderStatus></getReaderStatus>';
    % send command
```

```
    try
        rx_data=xml_parse(readerID{1},readerID{2},tx_data);
        readerName=rx_data.getReaderStatusReply.info.name.Text;
        readerStatus=1;
    catch
        readerName='NOT found';
        readerStatus=0;
    end
    readerData=[readerID,{readerName,readerStatus}];
end

function readerInfo=getReaderInfo(readerID)
    % check inputs and outputs
    error(nargchk(1,1,nargin));
    error(nargoutchk(0,1,nargout));
    % add column(s)
    readerInfo=[readerID,cell(size(readerID,1),2)];
    % acquire reader information
    for i=1:size(readerID,1)
        readerData=getReaderStatus(readerID(i,:));
        readerName=readerData{1,3};
        readerStatus=readerData{1,4};
        readerInfo(i,3:4)={readerName,readerStatus};
%          display(['Reader ',readerID{i,1},' is ',readerName,'.']);
    end
end
```

Appendix B

Matlab Implementation

B.1 Welcome Window

```
function rfcode()
    % access rfcode m200 reader via zonemgr api
    % created by Jiaqing Wu, 3/15/2011
    % add intelleflex fmr6000 reader access via xml interface
    % updated by Jiaqing Wu, 7/23/2012

    global flag
    choice=questdlg('Please choose a system','System Menu', ...
        'RF Code M200','Intelleflex FMR6000','None of them', ...
        'Intelleflex FMR6000');
    switch choice
        case 'RF Code M200'
            flag='rfcode';
        case 'Intelleflex FMR6000'
            flag='intelleflex';
        case 'None of them'
            return;
        otherwise
            return;
    end
    switch flag
        case 'rfcode'
            % declare global variates, and initialize
            global base_url login
            base_url='';    login='';
            % obtain rfid zonemgr web portal information
            if isempty(base_url) && isempty(login)
                % the blank inputs are default for intranet usage only
                [base_url,login]=zonemgr_portal();
                % the ip address or host name is for internet usage only
%                 [base_url,login]=zonemgr_portal('<ip_address or host_name>');
            end
        case 'intelleflex'
%             readerID={'192.168.1.11',80;'192.168.1.12',80};
%             tagID={'330c4de2611002c000160754';'330c4de26110030000124619'};
        otherwise
            display('The vendor is not recognized.');
            return;
    end

    % load ui for visual presentation of xyz coordinates
    load_gui_xyz();
    % clear global variates declaration, better not used for gui
%     clear global
end
```

B.2 RSSI Reading

```
function load_gui_ssi()
    % load gui for monitoring ssi and system debug
    % created by Jiaqing Wu, 3/24/2011
    % add multiple vendors support
    % updated by Jiaqing Wu, 7/23/2012
    global flag

    % create and hide the gui figure as it is being constructed
    fig_main=figure('visible','off','position',[100,100,800,600], ...
        'MenuBar','none','Resize','off','WindowStyle','modal');
    % list all available readers
    reader_title=uicontrol('style','checkbox','string','All Readers', ...
        'position',[20,420,120,20],'callback',@reader_title_callback, ...
        'BackgroundColor',get(fig_main,'color'));
    switch flag
        case 'rfcode'
            [reader_status_all,reader_name_all,reader_ip_all]= ...
                check_reader();
        case 'intelleflex'
            readerID={'192.168.1.11',80;'192.168.1.12',80};
readerID=readerID(1,:);
            readerInfo=intelleflex('getReaderInfo',readerID);
            reader_name_all=readerInfo(:,3);
            reader_ip_all=readerInfo(:,1);
    end
    reader_list_all=uicontrol('style','listbox','string',reader_ip_all, ...
        'position',[20,450,120,130], ...
        'min',0,'max',size(reader_ip_all,1), ...
        'callback',@reader_list_all_callback);
    % list all available tags
    tag_title=uicontrol('style','checkbox','string','All Tags', ...
        'position',[160,420,120,20],'callback',@tag_title_callback, ...
        'BackgroundColor',get(fig_main,'color'));
    switch flag
        case 'rfcode'
            [tag_status_all,tag_name_all]=check_tag();
        case 'intelleflex'
            tagInfo=intelleflex('getTagInfo',readerInfo);
            tag_name_all=tagInfo(:,1);
    end
    tag_list_all=uicontrol('style','listbox','string',tag_name_all, ...
        'position',[160,450,120,130], ...
        'min',0,'max',size(tag_name_all,1), ...
        'callback',@tag_list_all_callback);
    % initialize radio button group for channel
    channel_group=uibuttongroup('visible','off','units','pixels', ...
        'position',[300,450,120,130]);
    channel_both=uicontrol('style','radiobutton','string', ...
        'Both Channels','parent',channel_group, ...
        'HandleVisibility','off','position',[10,105,100,20]);
    channel_a_only=uicontrol('style','radiobutton','string', ...
        'Channel A Only','parent',channel_group, ...
        'HandleVisibility','off','position',[10,85,100,20]);
    channel_b_only=uicontrol('style','radiobutton','string', ...
        'Channel B Only','parent',channel_group, ...
```

```
    'HandleVisibility','off','position',[10,65,100,20]);
channel_average=uicontrol('style','radiobutton','string', ...
    'Average Value','parent',channel_group, ...
    'HandleVisibility','off','position',[10,45,100,20]);
channel_maximum=uicontrol('style','radiobutton','string', ...
    'Maximum Value','parent',channel_group, ...
    'HandleVisibility','off','position',[10,25,100,20]);
channel_minimum=uicontrol('style','radiobutton','string', ...
    'Minimum Value','parent',channel_group, ...
    'HandleVisibility','off','position',[10,5,100,20]);
set(channel_group,'SelectionChangeFcn',@channel_group_callback);
set(channel_group,'SelectedObject',channel_both); % default selection
set(channel_group,'UserData',''); % stand for both channels
set(channel_group,'visible','on');
% initialize command button for reading ssi
read_ssi_button=uicontrol('style','pushbutton','string','Read SSI', ...
    'position',[300,420,120,20],'callback',@read_ssi_button_callback);
% initialize text field for reporting ssi
report_ssi=uicontrol('style','listbox','string','', ...
    'position',[440,450,340,130],'callback',@report_ssi_callback);
% seperate continuously ssi reading from single ssi reading
group_seperator=uipanel('visible','on','units','pixels', ...
    'position',[20,405,760,2],'BackgroundColor',get(fig_main,'color'));
% # of data points, non-negative value only, note: 0 means forever
n_data_label=uicontrol('style','text','string','# of Data Points:', ...
    'HorizontalAlignment','left','position',[20,370,80,20], ...
    'BackgroundColor',get(fig_main,'color'));
n_data=uicontrol('style','edit','HorizontalAlignment','right', ...
    'string','30','position',[110,370,30,20]);
% interval between two samples, unit: second
interval_label=uicontrol('style','text','string','Interval (sec):', ...
    'HorizontalAlignment','left','position',[20,340,80,20], ...
    'BackgroundColor',get(fig_main,'color'));
interval=uicontrol('style','edit','HorizontalAlignment','right', ...
    'string','2','position',[110,340,30,20]);
% drop-down list for selected tags, display plot for one tag each time
tag_group_label=uicontrol('style','text','string','Tag ID:', ...
    'HorizontalAlignment','left','position',[20,310,120,20], ...
    'BackgroundColor',get(fig_main,'color'));
tag_group=uicontrol('style','popupmenu','string', ...
    tag_name_all(get(tag_list_all,'value')), ...
    'position',[20,290,120,20],'callback',@tag_group_callback);
% command buttons
start_button=uicontrol('style','pushbutton','string','Start', ...
    'position',[20,80,120,20],'enable','on', ...
    'callback',@start_button_callback);
stop_button=uicontrol('style','pushbutton','string','Stop', ...
    'position',[20,50,120,20],'enable','off', ...
    'callback',@stop_button_callback);
save_button=uicontrol('style','pushbutton','string','Save', ...
    'position',[20,20,120,20],'enable','off', ...
    'callback',@save_button_callback);
% plot showing continuously collected ssi data
timer_plot=axes('units','pixels','position',[210,50,567,340], ...
    'fontsize',get(report_ssi,'fontsize'));
xlabel('Time (2s)','fontsize',get(report_ssi,'fontsize'));
ylabel('SSI (dB)','fontsize',get(report_ssi,'fontsize'));
set(timer_plot,'XLim',[0,30],'YLim',[-120,-40]);
```

```
% change units to normalized so components resize automatically
set([fig_main,reader_title,reader_list_all,tag_title,tag_list_all, ...
    channel_group,channel_both,channel_a_only,channel_b_only, ...
    channel_average,channel_maximum,channel_minimum, ...
    read_ssi_button,report_ssi,timer_plot,group_seperator,...
    n_data_label,n_data,interval_label,interval, ...
    tag_group_label,tag_group, ...
    start_button,stop_button,save_button], ...
    'units','normalized');
switch flag
    case 'rfcode'
        fig_main_title='RF Code M200 System - Monitoring GUI';
    case 'intelleflex'
        fig_main_title='Intelleflex FMR6000 System - Monitoring GUI';
end
set(fig_main,'numbertitle','off','name',fig_main_title); % rename
movegui(fig_main,'center'); % centralize
set(fig_main,'visible','on'); % make the GUI visible

% select-all function for readers
function reader_title_callback(hObject,eventdata,handles)
    if (get(reader_title,'value')==get(reader_title,'max'))
        % checkbox is checked, select all readers
        set(reader_list_all,'UserData',get(reader_list_all,'value'));
        set(reader_list_all,'value',(1:1:get(reader_list_all,'max')));
    else
        % checkbox is unchecked, unselect all readers
        old_value=get(reader_list_all,'UserData');
        if isempty(old_value)
            set(reader_list_all,'value',1);
        else
            set(reader_list_all,'value',old_value)
        end
    end
end

% clear the select all checkbox as selection changes
function reader_list_all_callback(hObject,eventdata,handles)
    if (get(reader_title,'value')==get(reader_title,'max'))
        set(reader_title,'value',get(reader_title,'min'));
    end
end

% select-all function for tags
function tag_title_callback(hObject,eventdata,handles)
    if (get(tag_title,'value')==get(tag_title,'max'))
        % checkbox is checked, select all readers
        set(tag_list_all,'UserData',get(tag_list_all,'value'));
        set(tag_list_all,'value',(1:1:get(tag_list_all,'max')));
    else
        % checkbox is unchecked, unselect all readers
        old_value=get(tag_list_all,'UserData');
        if isempty(old_value)
            set(tag_list_all,'value',1);
        else
            set(tag_list_all,'value',old_value)
        end
    end
    % also change tag group list
```

```
    tag_group_update();
end

% clear the select all checkbox as selection changes
function tag_list_all_callback(hObject,eventdata,handles)
    if (get(tag_title,'value')==get(tag_title,'max'))
        set(tag_title,'value',get(tag_title,'min'));
    end
    % also change tag group list
    tag_group_update();
end

% change tag group list as selection changes
function tag_group_update()
    set(tag_group,'string',tag_name_all(get(tag_list_all,'value')));
    set(tag_group,'value',1); % choose the first one as default
    % clear current axe and reset x/y axis
    cla;
    set(timer_plot,'XLim',[0,30],'YLim',[-120,-40]);
    % clear temp storage to avoid mismatching plots
    if ~isempty(getappdata(timer_plot,'ssi_read_temp'))
        rmappdata(timer_plot,'ssi_read_temp');
        rmappdata(timer_plot,'line_spec_temp');
        rmappdata(timer_plot,'x_max_temp');
        rmappdata(timer_plot,'i_temp');
    end
end

% select channel for ssi reporting
function channel_group_callback(hObject,eventdata,handles)
    switch get(get(channel_group,'SelectedObject'),'string')
        case 'Both Channels'
            set(channel_group,'UserData','');
        case 'Channel A Only'
            set(channel_group,'UserData','A');
        case 'Channel B Only'
            set(channel_group,'UserData','B');
        case 'Average Value'
            set(channel_group,'UserData','avg');
        case 'Maximum Value'
            set(channel_group,'UserData','max');
        case 'Minimum Value'
            set(channel_group,'UserData','min');
    end
end

% read ssi for selected reader(s), tag(s) and channel(s)
function read_ssi_button_callback(hObject,eventdata,handles)
    % shorten reference
    tag_index=get(tag_list_all,'value');
    reader_index=get(reader_list_all,'value');
    channel_option=get(channel_group,'UserData');
    if strcmpi(channel_option,'avg') ...
            || strcmpi(channel_option,'max') ...
            || strcmpi(channel_option,'min')
        channel='';
    else
        channel=channel_option;
    end
```

```
    % get ssi information
    switch flag
        case 'rfcode'
            ssi=read_ssi(tag_name_all(tag_index), ...
                reader_name_all(reader_index),channel);
        case 'intelleflex'
            ssi=read_ssi(tag_name_all(tag_index), ...
                readerInfo(reader_index,:),channel);
    end
    % revise ssi information
    ssi=revise_ssi(ssi,channel_option);
    % organize data for the text field
    ssi_text=cell(size(ssi,1),1);
    for i=1:size(ssi,1)
        for j=1:size(ssi,2)
            % try to padleft all ssi values
            k=length(num2str(min(ssi(:,j))))-length(num2str(ssi(i,j)));
            ssi_text{i}=[ssi_text{i},blanks(2+k), ...
                num2str(ssi(i,j))];
        end
    end
    report_text=cell(size(tag_index,2),1);
    for i=1:size(tag_index,2)
        report_text{i}=[tag_name_all{(tag_index(i))}, ...
            ':',ssi_text{i}];
    end
    % locate tag being selected last time in new index
    [tf,idx]=ismember(get(report_ssi,'UserData'),tag_index);
    if tf
        set(report_ssi,'value',idx);
    else
        set(report_ssi,'value',1);
    end
    % save tag being selected this time based on new index
    set(read_ssi_button,'UserData',tag_index);
    set(report_ssi,'UserData',tag_index(get(report_ssi,'value')));
    % display ssi information
    set(report_ssi,'string',report_text);
end

% save information
function report_ssi_callback(hObject,eventdata,handles)
    % save tag being selected based on old index
    tag_index_save=get(read_ssi_button,'UserData');
    set(report_ssi,'UserData',tag_index_save(get(report_ssi,'value')));
end

% switch plots for different tags
function tag_group_callback(hObject,eventdata,handles)
    % initialize parameters from temp storage
    ssi_read=getappdata(timer_plot,'ssi_read_temp');
    line_spec_trim=getappdata(timer_plot,'line_spec_temp');
    x_max=getappdata(timer_plot,'x_max_temp');
    i=getappdata(timer_plot,'i_temp');
    % get currently selected tag
    tag_index=get(tag_group,'value');
    % clear current axe and reset x/y axis
    cla;
    set(timer_plot,'XLim',[0,30],'YLim',[-120,-40]);
```

```
    % jump out if data of new tag(s) are not collected yet
    if (tag_index<=size(ssi_read,1))
        % adjust the x axis to dispaly the lastest 31 data points
        if (i>x_max), set(timer_plot,'XLim',[max(1,i-x_max),i]); end
        % adjust the y axis
        if (sum(ssi_read(tag_index,:,:))~=0)
            set(timer_plot,'YLim', ...
                [min(min(ssi_read(tag_index,:,:)))*1.05, ...
                max(max(ssi_read(tag_index,:,:)))/1.05]);
        else % in case of losing signal during the loop
            set(timer_plot,'YLim',[-120,0]);
        end
        % hold for multiple plots
        hold on;
        % plot ssi monitoring data for 31 points at most
        for j=1:size(ssi_read,2)
            plot(max(1,i-x_max):i,shiftdim(ssi_read(tag_index, ...
                j,:)),line_spec_trim{j});
        end
        hold off;
    end
end

% start monitoring
function start_button_callback(hObject,eventdata,handles)
    % validation for n_data and interval inputs
    timer_max=round(str2double(get(n_data,'string')));
    timer=str2double(get(interval,'string'));
    if isnan(timer_max) || isnan(timer)
        errordlg('You must enter numeric values for both inputs.', ...
            'Bad Input','modal');
        return
    elseif (timer_max<0)
        errordlg('The # of data points must be non-negative.', ...
            'Invalid Input','modal');
        return
    elseif (timer<=0)
        errordlg('The interval value must be positive.', ...
            'Invalid Input','modal');
        return
    end
    % toggle buttons
    set([reader_title,reader_list_all,tag_title,tag_list_all, ...
        channel_both,channel_a_only,channel_b_only, ...
        channel_average,channel_maximum,channel_minimum, ...
        n_data,interval,tag_group,start_button,save_button], ...
        'enable','off');
    set(stop_button,'enable','on');
    % reset save button status
    set(save_button,'UserData','unsaved');
    % shorten reference
    tag_name_part=get(tag_group,'string');
    reader_index=get(reader_list_all,'value');
    channel_option=get(channel_group,'UserData');
    if strcmpi(channel_option,'avg') ...
            || strcmpi(channel_option,'max') ...
            || strcmpi(channel_option,'min')
        channel='';
    else
```

```
    channel=channel_option;
end
% define different linespec for each lines
line_spec={'-+r';'-xr';'--ob';'--*b';':sm';':dm';'-.pk';'-.hk'};
% keep monitoring forever if # of data points is not given
if (timer_max==0), timer_max=inf; end
% reset current axe and x/y axis
cla reset;
xlabel(['Time (',get(interval,'string'),'s)'], ...
    'fontsize',get(report_ssi,'fontsize'));
ylabel('SSI (dB)','fontsize',get(report_ssi,'fontsize'));
set(timer_plot,'XLim',[0,30],'YLim',[-120,-40]);
% get ssi information, and plot
for i=1:timer_max
    tic; % start the stopwatch timer
    % jump out from the loop for interruption
    if strcmpi(get(stop_button,'enable'),'off'), break; end
    switch flag
        case 'rfcode'
            ssi=read_ssi(tag_name_part, ...
                reader_name_all(reader_index),channel);
        case 'intelleflex'
            ssi=read_ssi(tag_name_part, ...
                readerInfo(reader_index,:),channel);
    end

    % revise ssi information
    ssi=revise_ssi(ssi,channel_option);
    % trim ssi monitoring data
    ssi_full(:,:,i)=ssi;
    set(timer_plot,'UserData',ssi_full);
    x_max=30; % self-defined
    if (i>x_max) % take the lastest 31 points
        ssi_trim=ssi_full(:,:,i-x_max:i);
    else
        ssi_trim=ssi_full;
    end
    % skip zero values if single channel requested
    if strcmpi(channel,'A')
        ssi_read=ssi_trim(:,1:2:end,:);
        line_spec_trim=line_spec(1:2:end,:);
    elseif strcmpi(channel,'B')
        ssi_read=ssi_trim(:,2:2:end,:);
        line_spec_trim=line_spec(2:2:end,:);
    else
        ssi_read=ssi_trim;
        line_spec_trim=line_spec;
    end
    % save data for external call
    setappdata(timer_plot,'ssi_read_temp',ssi_read)
    setappdata(timer_plot,'line_spec_temp',line_spec_trim);
    setappdata(timer_plot,'x_max_temp',x_max);
    setappdata(timer_plot,'i_temp',i);
    % suspend the tag_index drop-down menu and get current value
    set(tag_group,'enable','off');
    tag_index=get(tag_group,'value');
    % adjust the x axis to dispaly the lastest 31 data points
    if (i>x_max), set(timer_plot,'XLim',[max(1,i-x_max),i]); end
    % adjust the y axis
```

```
        if (sum(ssi_read(tag_index,:,:))~=0)
            set(timer_plot,'YLim', ...
                [min(min(ssi_read(tag_index,:,:)))*1.05, ...
                max(max(ssi_read(tag_index,:,:)))/1.05]);
        else % in case of losing signal during the loop
            set(timer_plot,'YLim',[-120,0]);
        end
        % hold for multiple plots
        hold on;
        % plot ssi monitoring data for 31 points at most
        for j=1:size(ssi_read,2)
            plot(max(1,i-x_max):i,shiftdim(ssi_read(tag_index, ...
                j,:)),line_spec_trim{j});
        end
        hold off;
        % restore the drop-down menu
        set(tag_group,'enable','on');
        % pause between intervals
        if (i~=timer_max), pause(timer-toc); end
    end
    % end the process same as the stop button is pressed
    stop_button_callback();
end

% stop monitoring
function stop_button_callback(hObject,eventdata,handles)
    % toggle buttons
    set([reader_title,reader_list_all,tag_title,tag_list_all, ...
        channel_both,channel_a_only,channel_b_only, ...
        channel_average,channel_maximum,channel_minimum, ...
        n_data,interval,tag_group,start_button,save_button], ...
        'enable','on');
    set(stop_button,'enable','off');
    if strcmpi(get(save_button,'UserData'),'saved')
        set(save_button,'enable','off');
    end
end

% save data to file for backup
function save_button_callback(hObject,eventdata,handles)
    % shorten reference
    name_output=datestr(now,'yyyymmddTHHMMSS');
    time_output=datestr(now,'yyyy-mm-dd HH:MM:SS');
    tag_output=tag_name_all(get(tag_list_all,'value'));
    reader_output=reader_name_all(get(reader_list_all,'value'));
    channel_output=get(get(channel_group,'SelectedObject'),'string');
    ssi_output=get(timer_plot,'UserData');
    n_data_output=num2str(min(str2double(get(n_data,'string')), ...
        size(ssi_output,3)));
    interval_output=get(interval,'string');
    % write data into a txt file under current directory
    file_name=fopen([pwd,'\',name_output,'.txt'],'wt');
    % list date/time
    fprintf(file_name,'%s\n','Date and Time:');
    fprintf(file_name,'%s\n\n',time_output);
    % list all tags
    fprintf(file_name,'%s\n','Tag List:');
    for i=1:size(tag_output,1)
        fprintf(file_name,'%s\n',tag_output{i});
```

```
end
fprintf(file_name,'\n');
% list all readers
fprintf(file_name,'%s\n','Reader List:');
for i=1:size(reader_output,1)
    fprintf(file_name,'%s\n',reader_output{i});
end
fprintf(file_name,'\n');
% list channel option
fprintf(file_name,'%s\n','Channel Option:');
fprintf(file_name,'%s\n\n',channel_output);
% list # of data points
fprintf(file_name,'%s\n','# of data points:');
fprintf(file_name,'%s\n\n',n_data_output);
% list interval
fprintf(file_name,'%s\n','Interval (sec):');
fprintf(file_name,'%s\n\n',interval_output);
% list recorded ssi information
[m,n,p]=size(ssi_output);
for i=1:m
    fprintf(file_name,'%s\n',['SSI Matrix #',num2str(i),':']);
    for k=1:p
        for j=1:n
            if (j==n)
                fprintf(file_name,'%4d\n',ssi_output(i,j,k));
            else
                fprintf(file_name,'%4d\t',ssi_output(i,j,k));
            end
        end
    end
    % seperator
    fprintf(file_name,'%s\n','Mean Value:');
    % mean value for each channel
    for j=1:n
        if (j==n)
            fprintf(file_name,'%4.1f\n',mean(ssi_output(i,j,:)));
        else
            fprintf(file_name,'%4.1f\t',mean(ssi_output(i,j,:)));
        end

    end
    % seperator
    fprintf(file_name,'%s\n','Standard Deviation:');
    % standard deviation for each channel
    for j=1:n
        if (j==n)
            fprintf(file_name,'%4.2f\n',std(ssi_output(i,j,:)));
        else
            fprintf(file_name,'%4.2f\t',std(ssi_output(i,j,:)));
        end
    end
    % seperator
    fprintf(file_name,'%s\n','Mean and Std for AVG(A+B):');
    for j=1:2:n
        if (j==n-1)
            fprintf(file_name,'%4.1f\t', ...
                mean(mean([ssi_output(i,j,:), ...
                ssi_output(i,j+1,:)])));
            fprintf(file_name,'%4.1f\n', ...
```

```
                        std(mean([ssi_output(i,j,:), ...
                        ssi_output(i,j+1,:)])));
                else
                    fprintf(file_name,'%4.1f\t', ...
                        mean(mean([ssi_output(i,j,:), ...
                        ssi_output(i,j+1,:)])));
                    fprintf(file_name,'%4.1f\t', ...
                        std(mean([ssi_output(i,j,:), ...
                        ssi_output(i,j+1,:)])));
                end
            end
            % seperator
            fprintf(file_name,'%s\n','Mean and Std for MAX(A+B):');
            for j=1:2:n
                if (j==n-1)
                    fprintf(file_name,'%4.1f\t', ...
                        mean(max([ssi_output(i,j,:), ...
                        ssi_output(i,j+1,:)])));
                    fprintf(file_name,'%4.1f\n', ...
                        std(max([ssi_output(i,j,:),ssi_output(i,j+1,:)])));
                else
                    fprintf(file_name,'%4.1f\t', ...
                        mean(max([ssi_output(i,j,:), ...
                        ssi_output(i,j+1,:)])));
                    fprintf(file_name,'%4.1f\t', ...
                        std(max([ssi_output(i,j,:),ssi_output(i,j+1,:)])));
                end
            end
            % seperate ssi matrices for different tags
            if (i~=m), fprintf(file_name,'\n'); end
        end
        % close file
        fclose(file_name);
        % reset save button status
        set(save_button,'enable','off','UserData','saved');
    end
end

function ssi_rev=revise_ssi(ssi,channel_option)
    % revise ssi information based on channel option
    % created by Jiaqing, 3/22/2011

    ssi_rev=ssi;
    for i=1:2:size(ssi,2)
        % revise if requested
        switch channel_option
            case 'avg'
                ssi_rev(:,i)=round(mean(ssi(:,i:i+1),2));
                ssi_rev(:,i+1)=ssi_rev(:,i);
            case 'max'
                ssi_rev(:,i)=max(ssi(:,i:i+1),[],2);
                ssi_rev(:,i+1)=ssi_rev(:,i);
            case 'min'
                ssi_rev(:,i)=min(ssi(:,i:i+1),[],2);
                ssi_rev(:,i+1)=ssi_rev(:,i);
        end
    end
end
```

B.3 Localization

```
function load_gui_xyz()
    % load  gui for visual presentation of xyz coordinates
    % created by Jiaqing Wu, 9/29/2011
    % add multiple vendors support
    % updated by Jiaqing Wu, 7/23/2012
    global flag

    % get monitor screen size(s)
    scr_size=get(0,'MonitorPosition');
    % use the main monitor as default screen
    for i=1:size(scr_size,1)
        if scr_size(i,1)==1
            scr_main=scr_size(i,:);
            break;
        end
    end
    % minimum acceptable screen resolution is 1024*768
    if scr_main(3)<1024 || scr_main(4)<768
        disp('Warning: The screen resolution is lower than 1024*768.');
        disp(' ');
    end
    % create and hide the gui figure as it is being constructed
    fig_main_gui=figure('Visible','off','Position',[1,1,1024,768], ...
        'MenuBar','none','Resize','off','WindowStyle','modal');

    % entrances to other functions
    btn_demo=uicontrol('Style','pushbutton','Position',[10,735,70,25], ...
        'String','Demo','TooltipString','3D Demo', ...
        'Callback',@btn_demo_cbk);
    btn_ssi=uicontrol('Style','pushbutton','Position',[90,735,70,25], ...
        'String','SSI','TooltipString','Read SSI', ...
        'Callback',@btn_ssi_cbk);
    btn_map=uicontrol('Style','pushbutton','Position',[10,700,150,25], ...
        'String','Signal Map','TooltipString','Show Distribution', ...
        'Callback',@btn_map_cbk);
    % check readers avalibility
    switch flag
        case 'rfcode'
            readers=init_readers();
            [readers_status,readers_name,readers_ip]= ...
                check_reader(readers(:,1));
        case 'intelleflex'
            readers=init_readers();
            readerID=readers(:,7:8);
            readers=readers(:,1:6);
readers=readers(1:2,:);
readerID=readerID(1:2,:);
            readerInfo=intelleflex('getReaderInfo',readerID);
            readers_status=cell2mat(readerInfo(:,4));
            readers_name=readerInfo(:,3);
            readers_ip=readerInfo(:,1);
            readers=[readerInfo(:,3),readers(:,2:6),readerInfo(:,:)];
    end
    % report warning if at least one reader is not found or inactive
    if (sum(readers_status)<size(readers,1))
```

```
    disp(['Warning: ', ...
        num2str(size(readers,1)-sum(readers_status)), ...
        ' designated reader(s) are offline.']);
    disp(' ');
end
btn_readers=uicontrol('Style','pushbutton', ...
    'Position',[10,665,150,25], ...
    'String',['Avaliable readers: ',num2str(sum(readers_status)), ...
    ' of ',num2str(size(readers,1))], ...
    'TooltipString','Click for more details', ...
    'Callback',@btn_readers_cbk);
% check reference tags avalibility
switch flag
    case 'rfcode'
        ref_tags=init_ref_tags();
        ref_tags_group=init_ref_tags_group(ref_tags);
        [ref_tags_status,ref_tags_name]=check_tag(ref_tags);
    case 'intelleflex'
        ref_tags=init_ref_tags();
        ref_tags_group=init_ref_tags_group(ref_tags);
        tagID=ref_tags(:,1);
        tagInfo=intelleflex('getTagInfo',readerInfo,tagID);
        ref_tags_status=~(sum(cell2mat(tagInfo(:,2:end)),2)==0);
        ref_tags_name=tagInfo(:,1);
end
% report warning if at least one reference tag is not detected
if (sum(ref_tags_status)<size(ref_tags,1))
    disp(['Warning: ', ...
        num2str(size(ref_tags,1)-sum(ref_tags_status)), ...
        ' designated reference tag(s) are offline.']);
    disp(' ');
end
btn_ref_tags=uicontrol('Style','pushbutton', ...
    'Position',[10,630,150,25], ...
    'String',['Avaliable ref_tags: ',num2str(sum(ref_tags_status)), ...
    ' of ',num2str(size(ref_tags,1))], ...
    'TooltipString','Click for more details', ...
    'Callback',@btn_ref_tags_cbk);
% list all availabe tags
switch flag
    case 'rfcode'
        [tags_status,tags_name]=check_tag();
        [tags,tags_flag]=init_tags(tags_name);
    case 'intelleflex'
        tagInfo=intelleflex('getTagInfo',readerID);
        tags_status=~(sum(cell2mat(tagInfo(:,2:end)),2)==0);
        tags_name=tagInfo(:,1);
        [tags,tags_flag]=init_tags(tags_name);
end
btn_tags=uicontrol('Style','pushbutton', ...
    'Position',[10,595,150,25], ...
    'String',['All available tags: ', ...
        num2str(sum(cell2mat(tags_flag),1)), ...
        ' of ',num2str(size(tags,1))], ...
    'TooltipString','Click for more details', ...
    'Callback',@btn_tags_cbk);

% real xyz for precision evaluation
tbl_real_xyz=uitable('Position',[10,270,150,41],'Enable','off');
```

```
tbl_real_xyz_col_name={'x','y','z'};
tbl_real_xyz_col_format={'numeric','numeric','numeric'};
tbl_real_xyz_col_edit=[true true true];
tbl_real_xyz_col_width={49 49 49};
set(tbl_real_xyz, ...
    'Data',{[],[],[]}, ...
    'ColumnName',tbl_real_xyz_col_name, ...
    'ColumnFormat',tbl_real_xyz_col_format, ...
    'ColumnEditable',tbl_real_xyz_col_edit, ...
    'ColumnWidth',tbl_real_xyz_col_width, ...
    'RowName',[], ...
    'TooltipString','Enter real coordinates for selected target');
% button for on-demand positioning
btn_plot_single=uicontrol('Style','pushbutton', ...
    'Position',[10,235,150,25],'Enable','off', ...
    'String','Locate single target', ...
    'Callback',@btn_plot_single_cbk);

% default t axis units
dt=1; % how many second(s) each t axis unit means by default
dt_lbl=['t (',num2str(dt),'s)'];
ut=60; % how many units each t axis has by default
ut_lmt=[0,ut];
% x value plot
axis_plot_x=axes('Units','pixels','Position',[210,610,800,150], ...
    'FontSize',get(btn_tags,'FontSize'));
x_x=xlabel(axis_plot_x,dt_lbl,'FontSize',get(btn_tags,'FontSize'));
x_y=ylabel(axis_plot_x,'x (cm)','FontSize',get(btn_tags,'FontSize'));
set(axis_plot_x,'XLim',ut_lmt,'YLim',[0,434]);
% y value plot
axis_plot_y=axes('Units','pixels','Position',[210,420,800,150], ...
    'FontSize',get(btn_tags,'FontSize'));
y_x=xlabel(axis_plot_y,dt_lbl,'FontSize',get(btn_tags,'FontSize'));
y_y=ylabel(axis_plot_y,'y (cm)','FontSize',get(btn_tags,'FontSize'));
set(axis_plot_y,'XLim',ut_lmt,'YLim',[0,874]);
% z value plot
axis_plot_z=axes('Units','pixels','Position',[210,230,800,150], ...
    'FontSize',get(btn_tags,'FontSize'));
z_x=xlabel(axis_plot_z,dt_lbl,'FontSize',get(btn_tags,'FontSize'));
z_y=ylabel(axis_plot_z,'z (cm)','FontSize',get(btn_tags,'FontSize'));
set(axis_plot_z,'XLim',ut_lmt,'YLim',[0,282]);
% error plot
axis_plot_e=axes('Units','pixels','Position',[210,40,800,150], ...
    'FontSize',get(btn_tags,'FontSize'));
e_x=xlabel(axis_plot_e,dt_lbl,'FontSize',get(btn_tags,'FontSize'));
e_y=ylabel(axis_plot_e,'e (cm)','FontSize',get(btn_tags,'FontSize'));
set(axis_plot_e,'XLim',ut_lmt,'YLim',[0,500]);

% timer for continuous tracking
n=60; % default # of data points
tbl_timer=uitable('Position',[10,185,150,40],'Enable','off', ...
    'CellEditCallback',@tbl_timer_cbk);
tbl_timer_col_name={'# data','dt (s)','t (dt)'};
tbl_timer_col_format={'numeric','numeric','numeric'};
tbl_timer_col_edit=[true true true];
tbl_timer_col_width={49 49 49};
set(tbl_timer, ...
    'Data',{n,dt,ut}, ...
    'ColumnName',tbl_timer_col_name, ...
```

```
    'ColumnFormat',tbl_timer_col_format, ...
    'ColumnEditable',tbl_timer_col_edit, ...
    'ColumnWidth',tbl_timer_col_width, ...
    'RowName',[], ...
    'TooltipString','Enter # of data, intervals, and t axis units');
% decomposition option
chk_decompose=uicontrol('Style','checkbox', ...
    'Position',[10,150,150,25],'Enable','off', ...
    'BackgroundColor',get(fig_main_gui,'Color'), ...
    'String','Show decomposed signals', ...
    'Callback',@chk_decompose_cbk);
% button for continuous tracking - start
btn_plot_timer_start=uicontrol('Style','pushbutton', ...
    'Position',[10,115,150,25],'Enable','off', ...
    'String','Track single target', ...
    'Callback',@btn_plot_timer_start_cbk);
% button for continuous tracking - stop
btn_plot_timer_stop=uicontrol('Style','pushbutton', ...
    'Position',[10,80,70,25], ...
    'String','Stop','Enable','off', ...
    'Callback',@btn_plot_timer_stop_cbk);
% button for continuous tracking - save
btn_plot_timer_save=uicontrol('Style','pushbutton', ...
    'Position',[90,80,70,25], ...
    'String','Save','Enable','off', ...
    'Callback',@btn_plot_timer_save_cbk);


% list of multiple targets
tbl_multiple=uitable('Position',[10,320,150,265], ...
    'CellSelectionCallback',@tbl_multiple_cbk);
set(tbl_multiple, ...
    'Data',{}, ...
    'ColumnName','Selected targets', ...
    'ColumnFormat',{'char'}, ...
    'ColumnEditable',false, ...
    'ColumnWidth',{98}, ...
    'TooltipString','Click target ID to make selection');
% intialize the list of target tags
targets_name=tags_name;
for s=size(targets_name,1):-1:1
    if not(tags_flag{s,1}), targets_name(s,:)=[]; end;
end
set(tbl_multiple,'Data',targets_name);
% button for multiple continuous tracking - start
btn_plot_multiple_timer_start=uicontrol('Style','pushbutton', ...
    'Position',[10,45,150,25], ...
    'String','Track multiple targets','Enable','off', ...
    'Callback',@btn_plot_multiple_timer_start_cbk);
% button for multiple continuous tracking - stop
btn_plot_multiple_timer_stop=uicontrol('Style','pushbutton', ...
    'Position',[10,10,70,25], ...
    'String','Stop','Enable','off', ...
    'Callback',@btn_plot_multiple_timer_stop_cbk);
% button for multiple continuous tracking - save
btn_plot_multiple_timer_save=uicontrol('Style','pushbutton', ...
    'Position',[90,10,70,25], ...
    'String','Save','Enable','off', ...
    'Callback',@btn_plot_multiple_timer_save_cbk);
```

```
% change units to normalized so components resize automatically
set([fig_main_gui, ...
    btn_readers,btn_ref_tags,btn_tags,btn_plot_single, ...
    axis_plot_x,axis_plot_y,axis_plot_z,axis_plot_e, ...
    x_x,x_y,y_x,y_y,z_x,z_y,e_x,e_y,tbl_real_xyz,tbl_timer, ...
    btn_plot_timer_start,btn_plot_timer_stop,btn_plot_timer_save, ...
    tbl_multiple,btn_plot_multiple_timer_start, ...
    btn_plot_multiple_timer_stop,btn_plot_multiple_timer_save, ...
    btn_demo,btn_ssi,btn_map,chk_decompose], ...
    'Units','normalized');
set([btn_readers,btn_ref_tags,btn_tags,btn_plot_single, ...
    axis_plot_x,axis_plot_y,axis_plot_z,axis_plot_e, ...
    x_x,x_y,y_x,y_y,z_x,z_y,e_x,e_y,tbl_real_xyz,tbl_timer, ...
    btn_plot_timer_start,btn_plot_timer_stop,btn_plot_timer_save, ...
    tbl_multiple,btn_plot_multiple_timer_start, ...
    btn_plot_multiple_timer_stop,btn_plot_multiple_timer_save, ...
    btn_demo,btn_ssi,btn_map,chk_decompose], ...
    'FontUnits','normalized');
% finalize the figure
switch flag
    case 'rfcode'
        fig_main_gui_title= ...
            'RF Code M200 System - Localization GUI';
    case 'intelleflex'
        fig_main_gui_title= ...
            'Intelleflex FMR6000 System - Localization GUI';
end
set(fig_main_gui,'NumberTitle','off', ...
    'Name',fig_main_gui_title); % rename
movegui(fig_main_gui,'center'); % centralize
set(fig_main_gui,'Visible','on'); % make the GUI visible

function btn_readers_cbk(hObject,eventdata,handles)
    % Display more details about available readers
    % Created by Jiaqing Wu, 9/30/2011

    % Construct a new figure
    fig_readers=figure('Visible','off','MenuBar','none', ...
        'Position',[1,1,350,200],'Resize','off', ...
        'WindowStyle','modal');
    % display all readers
    lbl_readers=uicontrol('Style','text', ...
        'Position',[10,180,340,20], ...
        'BackgroundColor',get(fig_main_gui,'Color'), ...
        'HorizontalAlignment','left', ...
        'String',[num2str(sum(readers_status)),' of ', ...
            num2str(size(readers,1)), ...
            ' designated reader(s) are online.']);
    tbl_readers=uitable('Position',[10,65,340,110], ...
        'CellEditCallback',@tbl_readers_cbk);
    tbl_rdr_col_name={'ON','IP','X','Y','Z','A','B'};
    tbl_rdr_col_format={'logical','char', ...
        'numeric','numeric','numeric','numeric','numeric'};
    tbl_rdr_col_edit=[false false true true true true true];
    tbl_rdr_col_width={40 90 32 32 32 32 32};
    set(tbl_readers, ...
        'Data',cat(2,num2cell(logical(readers_status)), ...
            readers_ip,readers(:,2:6)), ...
        'ColumnName',tbl_rdr_col_name, ...
```

```
            'ColumnFormat',tbl_rdr_col_format, ...
            'ColumnEditable',tbl_rdr_col_edit, ...
            'ColumnWidth',tbl_rdr_col_width);
        lbl_readers_note=uicontrol('Style','text', ...
            'Position',[10,40,340,20], ...
            'BackgroundColor',get(fig_main_gui,'Color'), ...
            'HorizontalAlignment','left', ...
            'String','Note: X, Y, Z, A and B are editable.');
        % prepare save and close buttons
        btn_readers_save=uicontrol('Style','pushbutton', ...
            'Position',[190,10,75,25], ...
            'String','Save','Enable','off', ...
            'CallBack',@btn_readers_save_cbk);
        btn_readers_close=uicontrol('Style','pushbutton', ...
            'Position',[275,10,75,25], ...
            'String','Close','Enable','on', ...
            'CallBack',@btn_readers_close_cbk);
        % finalize the figure
        set(fig_readers,'NumberTitle','off', ...
            'Name','View and Edit Readers Information'); % rename
        movegui(fig_readers,'center'); % centralize
        set(fig_readers,'Visible','on'); % make the GUI visible

        function tbl_readers_cbk(source,eventdata)
            % toggle the save button to active
            set(btn_readers_save,'Enable','on');
        end

        function btn_readers_save_cbk(hObject,eventdata,handles)
            % save changes to both the variable and txt file (later)
            readers_new=get(tbl_readers,'Data');
            readers(:,2:end)=readers_new(:,3:end);
            % not finished yet
            set(btn_readers_save,'Enable','off');
%             msgbox('Fail to save updated data to txt file.','Sorry');
        end

        function btn_readers_close_cbk(hObject,eventdata,handles)
            % close current figure
            close(fig_readers);
        end
    end

    function btn_ref_tags_cbk(hObject,eventdata,handles)
        % Display more details about available reference tags
        % Created by Jiaqing Wu, 9/30/2011

        % Construct a new figure
        fig_ref_tags=figure('Visible','off','MenuBar','none', ...
            'Position',[1,1,350,300],'Resize','off', ...
            'WindowStyle','modal');
        % display all reference tags
        lbl_ref_tags=uicontrol('Style','text', ...
            'Position',[10,280,340,20], ...
            'BackgroundColor',get(fig_main_gui,'Color'), ...
            'HorizontalAlignment','left', ...
            'String',[num2str(sum(ref_tags_status)),' of ', ...
                num2str(size(ref_tags,1)), ...
```

```
            ' designated reference tag(s) are online.']);
    tbl_ref_tags=uitable('Position',[10,65,340,210], ...
        'CellEditCallback',@tbl_ref_tags_cbk);
    tbl_rtg_col_name={'ON','ID','X','Y','Z','O'};
    tbl_rtg_col_format={'logical','char', ...
        'numeric','numeric','numeric','numeric'};
    tbl_rtg_col_edit=[false false true true true true];
    tbl_rtg_col_width={40 120 32 32 32 32};
    set(tbl_ref_tags, ...
        'Data',cat(2,num2cell(logical(ref_tags_status)),ref_tags), ...
        'ColumnName',tbl_rtg_col_name, ...
        'ColumnFormat',tbl_rtg_col_format, ...
        'ColumnEditable',tbl_rtg_col_edit, ...
        'ColumnWidth',tbl_rtg_col_width);
    lbl_ref_tags_note=uicontrol('Style','text', ...
        'Position',[10,40,340,20], ...
        'BackgroundColor',get(fig_main_gui,'Color'), ...
        'HorizontalAlignment','left', ...
        'String','Note: X, Y, Z, and O are editable.');
    % prepare save and close buttons
    btn_ref_tags_save=uicontrol('Style','pushbutton', ...
        'Position',[190,10,75,25], ...
        'String','Save','Enable','off', ...
        'CallBack',@btn_ref_tags_save_cbk);
    btn_ref_tags_close=uicontrol('Style','pushbutton', ...
        'Position',[275,10,75,25], ...
        'String','Close','Enable','on', ...
        'CallBack',@btn_ref_tags_close_cbk);
    % finalize the figure
    set(fig_ref_tags,'NumberTitle','off', ...
        'Name','View and Edit Reference Tags Information'); % rename
    movegui(fig_ref_tags,'center'); % centralize
    set(fig_ref_tags,'Visible','on'); % make the GUI visible

    function tbl_ref_tags_cbk(source,eventdata)
        % toggle the save button to active
        set(btn_ref_tags_save,'Enable','on');
    end

    function btn_ref_tags_save_cbk(hObject,eventdata,handles)
        % save changes to both the variable and txt file (later)
        ref_tags_new=get(tbl_ref_tags,'Data');
        ref_tags(:,:)=ref_tags_new(:,2:end);
        % not finished yet
        set(btn_ref_tags_save,'Enable','off');
%         msgbox('Fail to save updated data to txt file.','Sorry');
    end

    function btn_ref_tags_close_cbk(hObject,eventdata,handles)
        % close current figure
        close(fig_ref_tags);
    end
end

function btn_tags_cbk(hObject,eventdata,handles)
    % Display more details about all available tags
    % Created by Jiaqing Wu, 10/2/2011
```

```
% Construct a new figure
fig_tags=figure('Visible','off','MenuBar','none', ...
    'Position',[1,1,350,300],'Resize','off', ...
    'WindowStyle','modal');
% display all tags
lbl_tags=uicontrol('Style','text', ...
    'Position',[10,280,340,20], ...
    'BackgroundColor',get(fig_main_gui,'Color'), ...
    'HorizontalAlignment','left', ...
    'String',[num2str(sum(cell2mat(tags_flag),1)),' of ', ...
        num2str(size(tags,1)), ...
        ' available tag(s) are selected.']);
tbl_tags=uitable('Position',[10,65,340,210], ...
    'CellEditCallback',@tbl_tags_cbk);
tbl_tags_col_name={'ON','ID','X','Y','Z','O'};
tbl_tags_col_format={'logical','char', ...
    'numeric','numeric','numeric','numeric'};
tbl_tags_col_edit=[true false true true true true];
tbl_tags_col_width={40 120 32 32 32 32};
set(tbl_tags, ...
    'Data',cat(2,tags_flag,tags), ...
    'ColumnName',tbl_tags_col_name, ...
    'ColumnFormat',tbl_tags_col_format, ...
    'ColumnEditable',tbl_tags_col_edit, ...
    'ColumnWidth',tbl_tags_col_width);
lbl_tags_note=uicontrol('Style','text', ...
    'Position',[10,40,340,20], ...
    'BackgroundColor',get(fig_main_gui,'Color'), ...
    'HorizontalAlignment','left', ...
    'String','Note: X, Y, Z, and O are editable.');
% prepare save and close buttons
btn_tags_save=uicontrol('Style','pushbutton', ...
    'Position',[190,10,75,25], ...
    'String','Save','Enable','off', ...
    'CallBack',@btn_tags_save_cbk);
btn_tags_close=uicontrol('Style','pushbutton', ...
    'Position',[275,10,75,25], ...
    'String','Close','Enable','on', ...
    'CallBack',@btn_tags_close_cbk);
% finalize the figure
set(fig_tags,'NumberTitle','off', ...
    'Name','View and Edit All Tags Information'); % rename
movegui(fig_tags,'center'); % centralize
set(fig_tags,'Visible','on'); % make the GUI visible

function tbl_tags_cbk(source,eventdata)
    % toggle the save button to active
    set(btn_tags_save,'Enable','on');
    tags_temp=get(tbl_tags,'Data');
    set(lbl_tags,'String', ...
        [num2str(sum(cell2mat(tags_temp(:,1)),1)), ...
        ' of ',num2str(size(tags,1)), ...
        ' available tag(s) are selected.']);
end

function btn_tags_save_cbk(hObject,eventdata,handles)
    % save changes to both the variable and txt file (later)
    tags_new=get(tbl_tags,'Data');
    tags_flag=tags_new(:,1);
```

```
            tags=tags_new(:,2:end);
            set(btn_tags,'String',['All available tags: ', ...
                num2str(sum(cell2mat(tags_flag),1)), ...
                ' of ',num2str(size(tags,1))]);
            % update the list of target tags
            targets_name=tags_new;
            for t=size(targets_name,1):-1:1
                if not(targets_name{t,1}), targets_name(t,:)=[]; end;
            end
            targets_name=targets_name(:,2);
            set(tbl_multiple,'Data',targets_name);
            if size(targets_name,1)>=2
                set(btn_plot_multiple_timer_start,'Enable','on');
            else
                set(btn_plot_multiple_timer_start,'Enable','off');
            end
            % not finished yet
            set(btn_tags_save,'Enable','off');
%             msgbox('Fail to save updated data to txt file.','Sorry');
        end

        function btn_tags_close_cbk(hObject,eventdata,handles)
            % close current figure
            close(fig_tags);
        end
    end

    function tbl_multiple_cbk(source,eventdata)
        % define currently selected target tag (the only one)
        % created by Jiaqing Wu, 9/30/2011

        % get the most recent target tag id (one only)
        if isempty(eventdata.Indices)
            target_name={};
            set(tbl_real_xyz,'Data',{[],[],[]});
            set([tbl_real_xyz,btn_plot_single,chk_decompose, ...
                tbl_timer,btn_plot_timer_start,btn_plot_timer_save, ...
                btn_plot_multiple_timer_start, ...
                btn_plot_multiple_timer_save],'Enable','off');
            set([btn_plot_timer_save, ...
                btn_plot_multiple_timer_save],'UserData','saved');
            % reset
            h_xyze=[axis_plot_x;axis_plot_y;axis_plot_z;axis_plot_e];
            for j=1:4
                cla(h_xyze(j));
                axis(h_xyze(j),[0,ut,get(h_xyze(j),'YLim')]);
            end
        else
            target_name=targets_name(eventdata(1).Indices(1));
            [tf,loc]=ismember(target_name,tags(:,1));
            set(tbl_real_xyz,'Data',tags(loc,2:4));
            if not(strcmpi(get(btn_plot_multiple_timer_save, ...
                    'UserData'),'unsaved'))
                set([tbl_real_xyz,btn_plot_single,chk_decompose, ...
                    tbl_timer,btn_plot_timer_start],'Enable','on');
                if size(targets_name,1)>=2
                    set(btn_plot_multiple_timer_start,'Enable','on');
                end
            end
```

```
        end
        set(btn_plot_single,'Userdata',target_name);
    end

    function btn_plot_single_cbk(hObject,eventdata,handles)
        % call knn algorithm
%         target=knn(get(btn_plot_single,'Userdata'),readers,ref_tags);
        % call 2-pass knn approach
%         target=xyz_grid(get(btn_plot_single,'Userdata'), ...
%             readers,ref_tags,ref_tags_group);
        % call ssi ranging approach
%         target=ssi_range(get(btn_plot_single,'Userdata'), ...
%             readers,ref_tags);
        % call hybrid approach
        target=hybrid(get(btn_plot_single,'Userdata'), ...
            readers,ref_tags,ref_tags_group);
        % avoid empty selection
        if isempty(target)
            msgbox('Please click one desired tag ID first.','Warning');
            return;
        else % renew plots
            plot_xyz(target);
            plot_e(target,get(tbl_real_xyz,'Data'));
        end;
    end

    function plot_xyz(target)
        % show estimated xyz of selected target
        % created by Jiaqing Wu, 10/1/2011

        % plot x y z values
        h_xyz=[axis_plot_x;axis_plot_y;axis_plot_z];
        for j=1:3
            axes(h_xyz(j));
            cla;
            axis([0,ut,get(h_xyz(j),'YLim')]); % reset
            hold on;
            plot(1,target{1,j+1},'-ro');
            text('Position',[2,target{1,j+1}], ...
                'String',num2str(target{1,j+1}), ...
                'BackgroundColor','white','Color','red', ...
                'FontUnits','normalized', ...
                'FontSize',get(h_xyz(j),'FontSize'));
            % also plot real values
            real_xyz=get(tbl_real_xyz,'Data');
            if not(isempty(real_xyz{1}) || isempty(real_xyz{2}) ...
                    || isempty(real_xyz{3}))
                plot(1,real_xyz{j},'-k.');
            end
            hold off;
        end
    end

    function plot_e(target,real_xyz)
        % show distance between estimated and real xyz of selected target
        % created by Jiaqing Wu, 10/2/2011

        % clear plot
```

```
    axes(axis_plot_e);
    cla;
    axis([0,ut,get(axis_plot_e,'YLim')]); % reset
    % plot e value
    %e=sum((cell2mat(target(1,2:4))-cell2mat(real_xyz(1,1:3))).^2).^0.5
    if not(isempty(real_xyz{1}) || isempty(real_xyz{2}) ...
            || isempty(real_xyz{3}))
        e=norm(cell2mat(target(1,2:4))-cell2mat(real_xyz(1,1:3)));
        e=round(e);
    else
        e=0;
    end
    hold on;
    plot(1,e,'-ro');
    text('Position',[2,e], ...
        'String',num2str(e), ...
        'BackgroundColor','white','Color','red', ...
        'FontUnits','normalized', ...
        'FontSize',get(axis_plot_e,'FontSize'));
    hold off;
end

function tbl_timer_cbk(hObject,eventdata,handles)
    timer_new=cell2mat(get(tbl_timer,'Data'));
    % renew variable
    n=timer_new(1);
    dt=timer_new(2);
    ut=timer_new(3);
    % renew t axes
    x_x=xlabel(axis_plot_x,['t (',num2str(dt),'s)']);
    y_x=xlabel(axis_plot_y,['t (',num2str(dt),'s)']);
    z_x=xlabel(axis_plot_z,['t (',num2str(dt),'s)']);
    e_x=xlabel(axis_plot_e,['t (',num2str(dt),'s)']);
    set([axis_plot_x,axis_plot_y,axis_plot_z,axis_plot_e], ...
        'XLim',[0,ut]);
end

function chk_decompose_cbk(hObject,eventdata,handles)
    % do nothing
end

function btn_plot_timer_start_cbk(hObject,eventdata,handles)
    % call knn algorithm and renew plots with defined timer
    % created by Jiaqing Wu, 10/3/2011
    % add signals decomposition support
    % updated by Jiaqing Wu, 3/19/2012

    % avoid invalid inputs of n and dt, could be validated after input
    if n<0 || mod(n,1)~=0
        msgbox('Set # data to an integer greater than 1.','Warning');
        return;
    elseif dt<=0
        msgbox('Set dt (s) to a positive value.','Warning');
        return;
    elseif n==0
        n=inf; % set for endless loop, means non-stop monitoring
    end
    % toggle buttons
    set([btn_readers,btn_ref_tags,btn_tags,tbl_multiple, ...
```

```
            tbl_real_xyz,btn_plot_single,tbl_timer, ...
            btn_plot_timer_start,btn_plot_timer_save, ...
            btn_plot_multiple_timer_start, ...
            btn_plot_multiple_timer_save, ...
            btn_demo,btn_ssi,btn_map,chk_decompose], ...
            'Enable','off');
        set(btn_plot_timer_stop,'Enable','on');
        set(btn_plot_timer_save,'UserData','unsaved');
        % initialize target_timer and e_timer array
        target_timer=cell(1,4,n);
        target_dc=zeros(4,3,n);
        e_timer=cell(1,1,n);
        e_dc=zeros(4,1,n);
        % timer
        for t=1:n
            tic; % start the stopwatch timer
            % jump out from the loop for interruption
            if strcmpi(get(btn_plot_timer_stop,'Enable'),'off'), break; end
            % call knn algorithm
%             target_t=knn(get(btn_plot_single,'Userdata'),readers,ref_tags);
            % call 2-pass knn approach
%             target_t=xyz_grid(get(btn_plot_single,'Userdata'), ...
%                 readers,ref_tags,ref_tags_group);
            % call ssi ranging approach
%             target_t=ssi_range(get(btn_plot_single,'Userdata'), ...
%                 readers,ref_tags);
            % call hybrid approach
            [target_t,target_d]=hybrid(get(btn_plot_single,'Userdata'), ...
                readers,ref_tags,ref_tags_group);
            % exclude outliers
            target_t=check_outlier(target_timer,target_t,t);
            target_d=check_outlier( ...
                [cat(3,repmat(target_t(:,1),[4,1,t-1]),cell(4,1,n-t+1)), ...
                    num2cell(target_dc)], ...
                [repmat(target_t(:,1),[4,1,1]),num2cell(target_d)],t);
            target_d=cell2mat(target_d(:,2:end));
            target_timer(:,:,t)=target_t;
            target_dc(:,:,t)=target_d;
            % estimate error
            real_xyz=get(tbl_real_xyz,'Data');
            if not(isempty(real_xyz{1}) || isempty(real_xyz{2}) ...
                || isempty(real_xyz{3}))
                e_timer(1,:,t)={round(norm(cell2mat( ...
                    target_timer(1,2:4,t))- ...
                    cell2mat(real_xyz(1,1:3))))};
                for r=1:4
                    e_dc(r,:,t)=round(norm(target_dc(r,1:3,t)- ...
                        cell2mat(real_xyz(1,1:3))));
                end
            else
                e_timer(1,:,t)={0};
                e_dc(:,:,t)=zeros(4,1);
            end
            % plot decomposed signals or not
            if get(chk_decompose,'Value')==get(chk_decompose,'Max')
                plot_xyz_timer(target_timer,t,target_dc);
                plot_e_timer(e_timer,t,e_dc);
            else
                plot_xyz_timer(target_timer,t);
                plot_e_timer(e_timer,t);
```

```
            end
            % pause between intervals
            if (t~=n), pause(dt-toc); end
        end
        % end the process same as the stop button is pressed
        btn_plot_timer_stop_cbk();
        % output localizaiton errors for different algorithms combinations
        print_summary(target_timer,target_dc,real_xyz);
    end

    function btn_plot_timer_stop_cbk(hObject,eventdata,handles)
        % toggle buttons
        set([btn_readers,btn_ref_tags,btn_tags,tbl_multiple, ...
            tbl_real_xyz,btn_plot_single,tbl_timer, ...
            btn_plot_timer_start,btn_plot_timer_save, ...
            btn_demo,btn_ssi,btn_map,chk_decompose], ...
            'Enable','on');
        if size(targets_name,1)>=2
            set([btn_plot_multiple_timer_start, ...
                btn_plot_multiple_timer_save],'Enable','on');
        end
        set(btn_plot_timer_stop,'Enable','off');
        % make sure there is data need to be saved
        if not(strcmpi(get(btn_plot_timer_save,'UserData'),'unsaved'))
            set(btn_plot_timer_save,'Enable','off');
        end
        if not(strcmpi(get(btn_plot_multiple_timer_save,'UserData'), ...
                'unsaved'))
            set(btn_plot_multiple_timer_save,'Enable','off');
        end
    end

    function btn_plot_timer_save_cbk(hObject,eventdata,handles)
        % save data to txt file (to be finished later)

        % reset button status
        set(btn_plot_timer_save,'Enable','off','UserData','saved');
    end

    function plot_xyz_timer(target_timer,t,target_dc)
        % show estimated xyz of selected target over time
        % created by Jiaqing Wu, 10/3/2011
        % add signals decomposition support
        % updated by Jiaqing Wu, 3/19/2012

        % plot x y z values
        h_xyz=[axis_plot_x;axis_plot_y;axis_plot_z];
        for j=1:3
            axes(h_xyz(j));
            cla;
            hold on;
            % adjust the x axis to dispaly lastest data points
%             if (t>ut), set(h_xyz,'XLim',[max(0,t-ut),t]); end
            p=get(h_xyz(j),'XLim');
            q=get(h_xyz(j),'YLim');
            axis([max(0,t-ut),max(t,ut),q]);
            plot(max(1,t-ut):t, ...
                squeeze(cell2mat(target_timer(1,j+1,max(1,t-ut):t))), ...
```

```
                    '-ro');
                % also plot decomposition
                if (nargin==3)
%                       plot(max(1,t-ut):t, ...
%                           squeeze(target_dc(1,j,max(1,t-ut):t)), ...
%                           'Line',':','Color',[0.4,0.4,0.4],'Marker','*');
                    plot(max(1,t-ut):t, ...
                        squeeze(target_dc(1,j,max(1,t-ut):t)), ...
                        'Line',':','Color',[0,0,0.9],'Marker','+');
                    plot(max(1,t-ut):t, ...
                        squeeze(target_dc(2,j,max(1,t-ut):t)), ...
                        'Line',':','Color',[1,0.6,0],'Marker','x');
                    plot(max(1,t-ut):t, ...
                        squeeze(target_dc(3,j,max(1,t-ut):t)), ...
                        'Line',':','Color',[0,0.9,0],'Marker','s');
                    plot(max(1,t-ut):t, ...
                        squeeze(target_dc(4,j,max(1,t-ut):t)), ...
                        'Line',':','Color',[0.6,0,1],'Marker','d');
                end
                % also plot real values
                real_xyz=get(tbl_real_xyz,'Data');
                if not(isempty(real_xyz{1}) || isempty(real_xyz{2}) ...
                        || isempty(real_xyz{3}))
                    plot(max(1,t-ut):t, ...
                        repmat(real_xyz{j},t-max(1,t-ut)+1),':k.');
                end
                % real-time value, average and s.d.
                text('Position',[max(1,t-ut+1),q(2)*0.9], ...
                    'String',['Now: ',num2str(target_timer{1,j+1,t})], ...
                    'BackgroundColor','white','Color','red', ...
                    'FontUnits','normalized', ...
                    'FontSize',get(h_xyz(j),'FontSize'));
                text('Position',[max(1,t-ut+1),q(2)*0.8], ...
                    'String',['Avg: ',num2str(round(mean(squeeze(cell2mat( ...
                        target_timer(1,j+1,:))))))], ...
                    'BackgroundColor','white','Color','red', ...
                    'FontUnits','normalized', ...
                    'FontSize',get(h_xyz(j),'FontSize'));
                text('Position',[max(1,t-ut+1),q(2)*0.7], ...
                    'String',['Std: ',num2str(round(std(squeeze(cell2mat( ...
                        target_timer(1,j+1,:))))))], ...
                    'BackgroundColor','white','Color','red', ...
                    'FontUnits','normalized', ...
                    'FontSize',get(h_xyz(j),'FontSize'));
                hold off;
            end
        end

        function plot_e_timer(e_timer,t,e_dc)
            % show distance between estimated and real xyz of selected target
            % created by Jiaqing Wu, 10/2/2011
            % add signals decomposition support
            % updated by Jiaqing Wu, 3/19/2012

            % clear plot
            axes(axis_plot_e);
            cla;
            % adjust the x axis to dispaly lastest data points
%             if (t>ut), set(axis_plot_e,'XLim',[max(0,t-ut),t]); end
```

```
        axis([max(0,t-ut),max(t,ut),get(axis_plot_e,'YLim')]);
        % plot e value
%         real_xyz=get(tbl_real_xyz,'Data');
%         if not(isempty(real_xyz{1}) || isempty(real_xyz{2}) ...
%                 || isempty(real_xyz{3}))
            hold on;
            plot(max(1,t-ut):t, ...
                squeeze(cell2mat(e_timer(1,1,max(1,t-ut):t))), ...
                '-ro');
            if (nargin==3)
%                 plot(max(1,t-ut):t,squeeze(e_dc(1,1,max(1,t-ut):t)), ...
%                     'Line',':','Color',[0.4,0.4,0.4],'Marker','*');
                plot(max(1,t-ut):t,squeeze(e_dc(1,1,max(1,t-ut):t)), ...
                    'Line',':','Color',[0,0,0.9],'Marker','+');
                plot(max(1,t-ut):t,squeeze(e_dc(2,1,max(1,t-ut):t)), ...
                    'Line',':','Color',[1,0.6,0],'Marker','x');
                plot(max(1,t-ut):t,squeeze(e_dc(3,1,max(1,t-ut):t)), ...
                    'Line',':','Color',[0,0.9,0],'Marker','s');
                plot(max(1,t-ut):t,squeeze(e_dc(4,1,max(1,t-ut):t)), ...
                    'Line',':','Color',[0.6,0,1],'Marker','d');
            end
            p=get(axis_plot_e,'XLim');
            q=get(axis_plot_e,'YLim');
            text('Position',[p(2)*0.75,q(2)*0.9], ...
                'String', ['Red circle: final estimate, [', ...
                num2str(round(mean(squeeze(cell2mat( ...
                    e_timer(1,1,:)))))),'/', ...
                num2str(round(std(squeeze(cell2mat( ...
                    e_timer(1,1,:)))))),']'], ...
                'BackgroundColor','white','Color','red', ...
                'FontUnits','normalized', ...
                'FontSize',get(axis_plot_e,'FontSize'));
            text('Position',[p(2)*0.75,q(2)*0.8], ...
                'String', 'Black dot: real position', ...
                'BackgroundColor','white','Color','black', ...
                'FontUnits','normalized', ...
                'FontSize',get(axis_plot_e,'FontSize'));
            if (nargin==3)
%                 text('Position',[p(2)*0.75,q(2)*0.7], ...
%                     'String', ['Gray star: original kNN, [', ...
%                     num2str(round(mean(squeeze(e_dc(1,1,1:t))))),'/', ...
%                     num2str(round(std(squeeze(e_dc(1,1,1:t))))),']'], ...
%                     'BackgroundColor','white','Color',[0.4,0.4,0.4], ...
%                     'FontUnits','normalized', ...
%                     'FontSize',get(axis_plot_e,'FontSize'));
                text('Position',[p(2)*0.75,q(2)*0.6], ...
                    'String', ['Blue plus: original kNN, [', ...
                    num2str(round(mean(squeeze(e_dc(1,1,1:t))))),'/', ...
                    num2str(round(std(squeeze(e_dc(1,1,1:t))))),']'], ...
                    'BackgroundColor','white','Color',[0,0,0.9], ...
                    'FontUnits','normalized', ...
                    'FontSize',get(axis_plot_e,'FontSize'));
                text('Position',[p(2)*0.75,q(2)*0.5], ...
                    'String', ['Orange cross: kNN with grid, [', ...
                    num2str(round(mean(squeeze(e_dc(2,1,1:t))))),'/', ...
                    num2str(round(std(squeeze(e_dc(2,1,1:t))))),']'], ...
                    'BackgroundColor','white','Color',[1,0.6,0], ...
                    'FontUnits','normalized', ...
                    'FontSize',get(axis_plot_e,'FontSize'));
                text('Position',[p(2)*0.75,q(2)*0.4], ...
```

```
                'String', ['Green square: original RSSI, [', ...
                num2str(round(mean(squeeze(e_dc(3,1,1:t))))),'/', ...
                num2str(round(std(squeeze(e_dc(3,1,1:t))))),']'], ...
                'BackgroundColor','white','Color',[0,0.9,0], ...
                'FontUnits','normalized', ...
                'FontSize',get(axis_plot_e,'FontSize'));
            text('Position',[p(2)*0.75,q(2)*0.3], ...
                'String',['Purple diamond: RSSI with grid, [', ...
                num2str(round(mean(squeeze(e_dc(4,1,1:t))))),'/', ...
                num2str(round(std(squeeze(e_dc(4,1,1:t))))),']'], ...
                'BackgroundColor','white','Color',[0.6,0,1], ...
                'FontUnits','normalized', ...
                'FontSize',get(axis_plot_e,'FontSize'));
        end
        text('Position',[max(1,t-ut+1),q(2)*0.9], ...
            'String',['Now: ',num2str(e_timer{1,1,t})], ...
            'BackgroundColor','white','Color','red', ...
            'FontUnits','normalized', ...
            'FontSize',get(axis_plot_e,'FontSize'));
        text('Position',[max(1,t-ut+1),q(2)*0.8], ...
            'String',['Avg: ',num2str(round(mean(squeeze(cell2mat( ...
                e_timer(1,1,:))))))], ...
            'BackgroundColor','white','Color','red', ...
            'FontUnits','normalized', ...
            'FontSize',get(axis_plot_e,'FontSize'));
        text('Position',[max(1,t-ut+1),q(2)*0.7], ...
            'String',['Std: ',num2str(round(std(squeeze(cell2mat( ...
                e_timer(1,1,:))))))], ...
            'BackgroundColor','white','Color','red', ...
            'FontUnits','normalized', ...
            'FontSize',get(axis_plot_e,'FontSize'));
        hold off;
%       end
    end

    function btn_plot_multiple_timer_start_cbk(hObject,eventdata,handles)
        % call knn algorithm and renew plots with defined timer
        % created by Jiaqing Wu, 10/3/2011

        % avoid invalid inputs of n and dt, could be validated after input
        if n<0 || mod(n,1)~=0
            msgbox('Set # data to an integer greater than 1.','Warning');
            return;
        elseif dt<=0
            msgbox('Set dt (s) to a positive value.','Warning');
            return;
        elseif n==0
            n=inf; % set for endless loop, means non-stop monitoring
        end
        % toggle buttons
        set([btn_readers,btn_ref_tags,btn_tags,tbl_multiple, ...
            tbl_real_xyz,btn_plot_single,tbl_timer, ...
            btn_plot_timer_start,btn_plot_timer_save, ...
            btn_plot_multiple_timer_start, ...
            btn_plot_multiple_timer_save, ...
            btn_demo,btn_ssi,btn_map,chk_decompose], ...
            'Enable','off');
        set(btn_plot_multiple_timer_stop,'Enable','on');
        set(btn_plot_multiple_timer_save,'UserData','unsaved');
```

```
        set(tbl_multiple,'Enable','on', ...
            'TooltipString','Click target ID to switch plots');
        % initialize targets_timer and es_timer array
        m=size(targets_name,1);
        targets_timer=cell(m,4,n);
        es_timer=cell(m,1,n);
        % timer
        for t=1:n
            tic; % start the stopwatch timer
            % jump out from the loop for interruption
            if strcmpi(get(btn_plot_multiple_timer_stop,'Enable'),'off')
                break;
            end
            % call knn algorithm to get latest xyz
            target_name=get(btn_plot_single,'Userdata');
            [tf,loc]=ismember(target_name,targets_name);
%             targets_t=knn(targets_name,readers,ref_tags);
            % call 2-pass knn approach
%             targets_t=xyz_grid(targets_name, ...
%                 readers,ref_tags,ref_tags_group);
            % call ssi ranging approach
%             targets_t=ssi_range(targets_name,readers,ref_tags);
            % call hybrid approach
            targets_t=hybrid(targets_name, ...
                readers,ref_tags,ref_tags_group);
            % exclude outliers
            targets_t=check_outlier(targets_timer,targets_t,t);
            targets_timer(:,:,t)=targets_t;
            plot_xyz_timer(targets_timer(loc,:,:),t);
            for r=1:m
                [tf,l]=ismember(targets_name(r),tags(:,1));
                real_xyz=tags(l,2:4);
                if not(isempty(real_xyz{1}) || isempty(real_xyz{2}) ...
                    || isempty(real_xyz{3}))
                    es_timer(r,:,t)={round(norm(cell2mat( ...
                        targets_timer(r,2:4,t))- ...
                        cell2mat(real_xyz(1,1:3))))};
                else
                    es_timer(r,:,t)={0};
                end
            end
%             target_name=get(btn_plot_single,'Userdata');
%             [tf,loc]=ismember(target_name,targets_name);
            plot_e_timer(es_timer(loc,:,:),t);
            % pause between intervals
            if (t~=n), pause(dt-toc); end
        end
        % end the process same as the stop button is pressed
        btn_plot_multiple_timer_stop_cbk();
    end

    function btn_plot_multiple_timer_stop_cbk(hObject,eventdata,handles)
        % toggle buttons
        set([btn_readers,btn_ref_tags,btn_tags,tbl_multiple, ...
            tbl_real_xyz,btn_plot_single,tbl_timer, ...
            btn_plot_timer_start,btn_plot_timer_save, ...
            btn_plot_multiple_timer_start, ...
            btn_plot_multiple_timer_save, ...
            btn_demo,btn_ssi,btn_map,chk_decompose], ...
```

```
                'Enable','on');
            set(btn_plot_multiple_timer_stop,'Enable','off');
            set(tbl_multiple,'TooltipString', ...
                'Click target ID to make selection');
            % make sure there is data need to be saved
            if not(strcmpi(get(btn_plot_timer_save,'UserData'),'unsaved'))
                set(btn_plot_timer_save,'Enable','off');
            end
            if not(strcmpi(get(btn_plot_multiple_timer_save,'UserData'), ...
                    'unsaved'))
                set(btn_plot_multiple_timer_save,'Enable','off');
            end
        end

        function btn_plot_multiple_timer_save_cbk(hObject,eventdata,handles)
            % save data to txt file (to be finished later)

            % reset button status
            set(btn_plot_multiple_timer_save, ...
                'Enable','off','UserData','saved');
        end

        function btn_demo_cbk(hObject,eventdata,handles)
            % construct a 3d model for demostration
            demo_3d();
        end

        function btn_ssi_cbk(hObject,eventdata,handles)
            % load gui for monitoring ssi and system debug
            load_gui_ssi();
        end

        function btn_map_cbk(hObject,eventdata,handles)
            % construct a 3d map of signal distribution
            map_3d();
        end
    end

    function readers=init_readers()
        % initialize readers information
        % created by Jiaqing Wu, 9/29/2011
        % add intelleflex readers information
        % updated by Jiaqing Wu, 8/7/2012
        global flag

        % designated # of readers
        n_readers=4;
        % 6 columns for id, 3d coordinates (x,y,z), and antenna orientation
        % antenna orientation is defined by its direction along which axis
        % 1: x; 2: y; 3: z; -1: -x; -2: -y; -3: -z
        readers=cell(n_readers,6);
        % enter information for each reader
        % may be loaded from txt file for easier configuration (later)
        if strcmp(flag,'rfcode')
            readers(1,1)={'$zReaderM200_89dec2ea'};
            readers(1,2:4)=num2cell([373,488,282]);
            readers(1,5)=num2cell(2);
            readers(1,6)=num2cell(-1);
```

```
        readers(2,1)={'$zReaderM200_a15c7b43'};
        readers(2,2:4)=num2cell([226,245,282]);
        readers(2,5)=num2cell(1);
        readers(2,6)=num2cell(2);
        readers(3,1)={'$zReaderM200_f5afb811'};
        readers(3,2:4)=num2cell([66,548,282]);
        readers(3,5)=num2cell(-2);
        readers(3,6)=num2cell(1);
        readers(4,1)={'$zReaderM200_d81e664b'};
        readers(4,2:4)=num2cell([226,731,282]);
        readers(4,5)=num2cell(-1);
        readers(4,6)=num2cell(-2);
%          readers % read information of all readers
    else
        readers(1,1)={'Reader #1 Antenna #1'};
        readers(1,2:4)=num2cell([312,771,141]);
        readers(1,5)=num2cell(2);
        readers(1,6)=num2cell(-1);
        readers(2,1)={'Reader #1 Antenna #2'};
        readers(2,2:4)=num2cell([132,205,141]);
        readers(2,5)=num2cell(1);
        readers(2,6)=num2cell(2);
        readers(3,1)={'Reader #2 Antenna #1'};
        readers(3,2:4)=num2cell([0,0,0]);
        readers(3,5)=num2cell(-2);
        readers(3,6)=num2cell(1);
        readers(4,1)={'Reader #2 Antenna #2'};
        readers(4,2:4)=num2cell([0,0,0]);
        readers(4,5)=num2cell(-1);
        readers(4,6)=num2cell(-2);
        readers=cat(2,readers,{'192.168.1.11',80;'192.168.1.11',80; ...
            '192.168.1.12',80;'192.168.1.12',80});
        readers=cat(2,readers,{'',0;'',0;'',0;'',0});
    end
end

function ref_tags=init_ref_tags()
    % intialize reference tags information
    % created by Jiaqing Wu, 9/29/2011
    % add intelleflex readers information
    % updated by Jiaqing Wu, 8/7/2012
    global flag

    % designated # of reference tags
    n_ref_tags=24; % 6*3 so far, => 6*4 now
    % 5 columns for id, 3d coordinates (x,y,z), and tag orientation
    % tag orientation is defined by the facing side to the x-y plane
    % 1: front/back; 2: top/bottom; 3: left/right
    ref_tags=cell(n_ref_tags,5);
    % enter information for each reference tag
    % may be loaded from txt file for easier configuration (later)
    if strcmp(flag,'rfcode')
        ref_tags(1,1)={'LOCATE00016485'};
        ref_tags(1,2:4)=num2cell([132,671,282]);
        ref_tags(1,5)=num2cell(2);
        ref_tags(2,1)={'LOCATE00016486'};
        ref_tags(2,2:4)=num2cell([312,671,282]);
        ref_tags(2,5)=num2cell(2);
        ref_tags(3,1)={'LOCATE00016487'};
```

```
ref_tags(3,2:4)=num2cell([132,488,282]);
ref_tags(3,5)=num2cell(2);
ref_tags(4,1)={'LOCATE00016488'};
ref_tags(4,2:4)=num2cell([312,488,282]);
ref_tags(4,5)=num2cell(2);
ref_tags(5,1)={'LOCATE00016489'};
ref_tags(5,2:4)=num2cell([132,305,282]);
ref_tags(5,5)=num2cell(2);
ref_tags(6,1)={'LOCATE00016490'};
ref_tags(6,2:4)=num2cell([312,305,282]);
ref_tags(6,5)=num2cell(2);
ref_tags(7,1)={'LOCATE00016491'};
ref_tags(7,2:4)=num2cell([0,671,182]);
ref_tags(7,5)=num2cell(2);
ref_tags(8,1)={'LOCATE00016492'};
ref_tags(8,2:4)=num2cell([0,671,100]);
ref_tags(8,5)=num2cell(2);
ref_tags(9,1)={'LOCATE00016493'};
ref_tags(9,2:4)=num2cell([0,488,182]);
ref_tags(9,5)=num2cell(2);
ref_tags(10,1)={'LOCATE00016494'};
ref_tags(10,2:4)=num2cell([0,488,100]);
ref_tags(10,5)=num2cell(2);
ref_tags(11,1)={'LOCATE00016495'};
ref_tags(11,2:4)=num2cell([0,305,182]);
ref_tags(11,5)=num2cell(2);
ref_tags(12,1)={'LOCATE00016496'};
ref_tags(12,2:4)=num2cell([0,305,100]);
ref_tags(12,5)=num2cell(2);
ref_tags(13,1)={'LOCATE00016497'};
ref_tags(13,2:4)=num2cell([434,671,182]);
ref_tags(13,5)=num2cell(2);
ref_tags(14,1)={'LOCATE00016498'};
ref_tags(14,2:4)=num2cell([434,671,100]);
ref_tags(14,5)=num2cell(2);
ref_tags(15,1)={'LOCATE00016499'};
ref_tags(15,2:4)=num2cell([434,488,182]);
ref_tags(15,5)=num2cell(2);
ref_tags(16,1)={'LOCATE00016500'};
ref_tags(16,2:4)=num2cell([434,488,100]);
ref_tags(16,5)=num2cell(2);
ref_tags(17,1)={'LOCATE00016501'};
ref_tags(17,2:4)=num2cell([434,305,182]);
ref_tags(17,5)=num2cell(2);
ref_tags(18,1)={'LOCATE00016502'};
ref_tags(18,2:4)=num2cell([434,305,100]);
ref_tags(18,5)=num2cell(2);
ref_tags(19,1)={'LOCATE00016503'};
ref_tags(19,2:4)=num2cell([132,671,0]);
ref_tags(19,5)=num2cell(2);
ref_tags(20,1)={'LOCATE00016504'};
ref_tags(20,2:4)=num2cell([312,671,0]);
ref_tags(20,5)=num2cell(2);
ref_tags(21,1)={'LOCATE00016505'};
ref_tags(21,2:4)=num2cell([132,488,0]);
ref_tags(21,5)=num2cell(2);
ref_tags(22,1)={'LOCATE00016506'};
ref_tags(22,2:4)=num2cell([312,488,0]);
ref_tags(22,5)=num2cell(2);
ref_tags(23,1)={'LOCATE00016507'};
```

```
        ref_tags(23,2:4)=num2cell([132,305,0]);
        ref_tags(23,5)=num2cell(2);
        ref_tags(24,1)={'LOCATE00016508'};
        ref_tags(24,2:4)=num2cell([312,305,0]);
        ref_tags(24,5)=num2cell(2);
%         ref_tags % read information of all tags
    else
        ref_tags(1,1)={'330c4de2611002c000155500'};
        ref_tags(1,2:4)=num2cell([132,671,282]);
        ref_tags(1,5)=num2cell(2);
        ref_tags(2,1)={'330c4de2611002c000174688'};
        ref_tags(2,2:4)=num2cell([312,671,282]);
        ref_tags(2,5)=num2cell(2);
        ref_tags(3,1)={'330c4de2611002c000165000'};
        ref_tags(3,2:4)=num2cell([132,488,282]);
        ref_tags(3,5)=num2cell(2);
        ref_tags(4,1)={'330c4de2611002c000141474'};
        ref_tags(4,2:4)=num2cell([312,488,282]);
        ref_tags(4,5)=num2cell(2);
        ref_tags(5,1)={'330c4de2611002c000158778'};
        ref_tags(5,2:4)=num2cell([132,305,282]);
        ref_tags(5,5)=num2cell(2);
        ref_tags(6,1)={'330c4de2611002c000167962'};
        ref_tags(6,2:4)=num2cell([312,305,282]);
        ref_tags(6,5)=num2cell(2);
        ref_tags(7,1)={'330c4de2611002c000155498'};
        ref_tags(7,2:4)=num2cell([0,671,182]);
        ref_tags(7,5)=num2cell(2);
        ref_tags(8,1)={'330c4de2611002c000163328'};
        ref_tags(8,2:4)=num2cell([0,671,100]);
        ref_tags(8,5)=num2cell(2);
        ref_tags(9,1)={'330c4de2611002c000160756'};
        ref_tags(9,2:4)=num2cell([0,488,182]);
        ref_tags(9,5)=num2cell(2);
        ref_tags(10,1)={'330c4de2611002c000160752'};
        ref_tags(10,2:4)=num2cell([0,488,100]);
        ref_tags(10,5)=num2cell(2);
        ref_tags(11,1)={'330c4de2611002c000160266'};
        ref_tags(11,2:4)=num2cell([0,305,182]);
        ref_tags(11,5)=num2cell(2);
        ref_tags(12,1)={'330c4de2611002c000159980'};
        ref_tags(12,2:4)=num2cell([0,305,100]);
        ref_tags(12,5)=num2cell(2);
        ref_tags(13,1)={'330c4de2611002c000155528'};
        ref_tags(13,2:4)=num2cell([434,671,182]);
        ref_tags(13,5)=num2cell(2);
        ref_tags(14,1)={'330c4de2611002c000157170'};
        ref_tags(14,2:4)=num2cell([434,671,100]);
        ref_tags(14,5)=num2cell(2);
        ref_tags(15,1)={'330c4de2611002c000160738'};
        ref_tags(15,2:4)=num2cell([434,488,182]);
        ref_tags(15,5)=num2cell(2);
        ref_tags(16,1)={'330c4de2611002c000169764'};
        ref_tags(16,2:4)=num2cell([434,488,100]);
        ref_tags(16,5)=num2cell(2);
        ref_tags(17,1)={'330c4de2611002c000160216'};
        ref_tags(17,2:4)=num2cell([434,305,182]);
        ref_tags(17,5)=num2cell(2);
        ref_tags(18,1)={'330c4de2611002c000161148'};
        ref_tags(18,2:4)=num2cell([434,305,100]);
```

```
        ref_tags(18,5)=num2cell(2);
        ref_tags(19,1)={'330c4de2611002c000160510'};
        ref_tags(19,2:4)=num2cell([132,671,0]);
        ref_tags(19,5)=num2cell(2);
        ref_tags(20,1)={'330c4de2611002c000160888'};
        ref_tags(20,2:4)=num2cell([312,671,0]);
        ref_tags(20,5)=num2cell(2);
        ref_tags(21,1)={'330c4de2611002c000160736'};
        ref_tags(21,2:4)=num2cell([132,488,0]);
        ref_tags(21,5)=num2cell(2);
        ref_tags(22,1)={'330c4de2611002c000147520'};
        ref_tags(22,2:4)=num2cell([312,488,0]);
        ref_tags(22,5)=num2cell(2);
        ref_tags(23,1)={'330c4de2611002c000169766'};
        ref_tags(23,2:4)=num2cell([132,305,0]);
        ref_tags(23,5)=num2cell(2);
        ref_tags(24,1)={'330c4de2611002c000159236'};
        ref_tags(24,2:4)=num2cell([312,305,0]);
        ref_tags(24,5)=num2cell(2);
    end
end

function ref_tags_group=init_ref_tags_group(ref_tags)
    % devide all ref_tags into groups along the x, y, and z axes
    % created by Jiaqing Wu, 10/5/2011

    % designed group information: 4 groups for x and z, 5 for y
    % add xyz group info to each ref_tag
    ref_tags_group=cat(2,ref_tags(:,1),cell(size(ref_tags,1),3));
    ref_tags_group(1,2:4)=num2cell([2,3,4]);
    ref_tags_group(2,2:4)=num2cell([3,3,4]);
    ref_tags_group(3,2:4)=num2cell([2,2,4]);
    ref_tags_group(4,2:4)=num2cell([3,2,4]);
    ref_tags_group(5,2:4)=num2cell([2,1,4]);
    ref_tags_group(6,2:4)=num2cell([3,1,4]);
    ref_tags_group(7,2:4)=num2cell([1,3,3]);
    ref_tags_group(8,2:4)=num2cell([1,3,2]);
    ref_tags_group(9,2:4)=num2cell([1,2,3]);
    ref_tags_group(10,2:4)=num2cell([1,2,2]);
    ref_tags_group(11,2:4)=num2cell([1,1,3]);
    ref_tags_group(12,2:4)=num2cell([1,1,2]);
    ref_tags_group(13,2:4)=num2cell([4,3,3]);
    ref_tags_group(14,2:4)=num2cell([4,3,2]);
    ref_tags_group(15,2:4)=num2cell([4,2,3]);
    ref_tags_group(16,2:4)=num2cell([4,2,2]);
    ref_tags_group(17,2:4)=num2cell([4,1,3]);
    ref_tags_group(18,2:4)=num2cell([4,1,2]);
    ref_tags_group(19,2:4)=num2cell([2,3,1]);
    ref_tags_group(20,2:4)=num2cell([3,3,1]);
    ref_tags_group(21,2:4)=num2cell([2,2,1]);
    ref_tags_group(22,2:4)=num2cell([3,2,1]);
    ref_tags_group(23,2:4)=num2cell([2,1,1]);
    ref_tags_group(24,2:4)=num2cell([3,1,1]);
end

function [tags,tags_flag]=init_tags(tags_name)
    % intialize tags information
    % created by Jiaqing Wu, 9/29/2011
    % add intelleflex readers information
```

```
    % updated by Jiaqing Wu, 8/7/2012
    global flag

    % 5 columns for id, 3d coordinates (x,y,z), tag orientation
    % tag orientation is defined by the facing side to the x-y plane
    % 1: front/back; 2: top/bottom; 3: left/right
    s=size(tags_name,1);
    % may be loaded from txt file for easier configuration (later)
    tags=cat(2,tags_name,cell(s,4)); % default empty
    % flag is a indicator of whether the tag is selected or not
    tags_flag=num2cell(false(s,1)); % default selection
    % for test only
    for t=1:s
        if strcmp(flag,'rfcode')
            if strcmp(tags_name{t},'LOCATE00009559')
                tags(t,2:4)=num2cell([89,671,76]);
                tags_flag(t)=num2cell(true);
            elseif strcmp(tags_name{t},'LOCATE00009560')
                tags(t,2:4)=num2cell([89,412,76]);
                tags_flag(t)=num2cell(true);
            elseif strcmp(tags_name{t},'LOCATE00016484')
                tags(t,2:4)=num2cell([363,529,76]);
                tags_flag(t)=num2cell(true);
            end
        else
            if strcmp(tags_name{t},'bbaa99887760030400093417')
                tags(t,2:4)=num2cell([0,0,0]);
                tags_flag(t)=num2cell(true);
            elseif strcmp(tags_name{t},'330c4de2611002c000147514')
                tags(t,2:4)=num2cell([0,0,0]);
                tags_flag(t)=num2cell(true);
            elseif strcmp(tags_name{t},'330c4de2611002c000155598')
                tags(t,2:4)=num2cell([0,0,0]);
                tags_flag(t)=num2cell(true);
            elseif strcmp(tags_name{t},'330c4de2611002c000160202')
                tags(t,2:4)=num2cell([0,0,0]);
                tags_flag(t)=num2cell(true);
            elseif strcmp(tags_name{t},'330c4de2611002c000161154')
                tags(t,2:4)=num2cell([0,0,0]);
                tags_flag(t)=num2cell(true);
            elseif strcmp(tags_name{t},'330c4de2611002c000174664')
                tags(t,2:4)=num2cell([0,0,0]);
                tags_flag(t)=num2cell(true);
            else
                tags(t,2:4)=num2cell([0,0,0]);
                tags_flag(t)=num2cell(false);
            end
        end
    end
end

function targets_t=check_outlier(targets_timer,targets_t,t,n,l)
    % exclude outliers which are n_sigma away from the mean value
    % created by Jiaqing Wu, 10/19/2011

    % check inputs and outputs
    error(nargchk(3,5,nargin));
    error(nargoutchk(1,1,nargout));
    if (nargin==4), l=10; end % moving average of previous 10 data points
```

```
    if (nargin==3), n=3; l=10; end % 3 sigmas by default
    if size(targets_timer,3)<=l, return; end % do nothing to short timer
    if isempty(targets_timer{1,1,l}), return; end % skip initial l data

    % reset outliers to average value
    for r=1:size(targets_t,1)
        for s=1:3 % xyz
            if (targets_t{r,s+1,1}< ...
                    (mean(squeeze(cell2mat(targets_timer( ...
                        r,s+1,t-l:t-1)))) ...
                        -n*std(squeeze(cell2mat(targets_timer( ...
                        r,s+1,t-l:t-1)))))) ...
                    || (targets_t{r,s+1,1}> ...
                    (mean(squeeze(cell2mat(targets_timer( ...
                        r,s+1,t-l:t-1)))) ...
                        +n*std(squeeze(cell2mat(targets_timer( ...
                        r,s+1,t-l:t-1))))))
                % replace estimate with the average of mean and observed
%                 display(['At time ',num2str(t),', the #', ...
%                     num2str(s),' coordinate was changed from ', ...
%                     num2str(targets_t{r,s+1,1}),' to ', ...
%                     num2str(mean([mean(squeeze(cell2mat(targets_timer( ...
%                     r,s+1,t-l:t-1)))),targets_t{r,s+1,1}])), ...
%                     ' for tag #',num2str(r),'.']);
                targets_t{r,s+1,1}= ...
                    mean([mean(squeeze(cell2mat(targets_timer( ...
                    r,s+1,t-l:t-1)))),targets_t{r,s+1,1}]);
            end
        end
    end
end

function ssi_new=refine_ssi(ssi)
    % refine ssi values
    % created by Jiaqing Wu, 1/18/2012
    % change the default outlines threadhold from -80 to -100
    % revised by Jiaqing Wu, 8/7/2012

    % exclude zeros and outliers
    l=-100;% default outliers: -100
    ssi_new=ssi;
    for z=1:size(ssi_new,3)
        [x,y]=find(ssi_new(:,:,z)<=l);
        if ~isempty(x)
            for i=1:size(x,1)
                ssi_new(x(i),y(i),z)=l; % nanmean is not supported in edu
            end
        end
        [x,y]=find(ssi_new(:,:,z)==0);
        if ~isempty(x)
            for i=1:size(x,1)
                ssi_new(x(i),y(i),z)=l; % nanmean is not supported in edu
            end
        end
    end
    % use maximum value as final output
    for z=1:size(ssi_new,3)
        for y=1:2:size(ssi_new,2)
            ssi_new(:,y,z)=max(ssi_new(:,y:y+1,z),[],2);
```

```
            ssi_new(:,y+1,z)=ssi_new(:,y,z);
        end
    end
    % average over time if ssi with timer
    ssi_new=round(mean(ssi_new,3));
    % delete duplicated columns
    for y=size(ssi_new,2):-2:2
        ssi_new(:,y)=[];
    end
end

function [targets,ref_tags_knn]=knn(targets_name,readers,ref_tags,k)
    % use kNN algorithm to estimate the location of target tags
    % created by Jiaqing Wu, 9/30/2011
    % unsolved bug: inappropriate for multiple targets with different grids
    % commented by Jiaqing Wu, 2/23/2012
    % add refine_ssi step to use max only
    % revised by Jiaqing Wu, 3/20/2012
    % add ref_tags_knn output
    % updated by Jiaqing Wu, 3/27/2012

    % check inputs and outputs
    error(nargchk(3,4,nargin));
    error(nargoutchk(0,2,nargout));
    % default k value
    if (nargin==3), k=4; end
    % initialize target tags coordinates
    targets_xyz=num2cell(zeros(size(targets_name,1),3));
    % read ssi
    targets_ssi=read_ssi(targets_name,readers); % readers(:,1)
    ref_tags_ssi=read_ssi(ref_tags(:,1),readers); % readers(:,1)
    % refine ssi
    targets_ssi=refine_ssi(targets_ssi);
    ref_tags_ssi=refine_ssi(ref_tags_ssi);
    % find kNN based on smallest k Euclidean distance (2-norm distance)
    k_ed=zeros(size(ref_tags,1),size(targets_name,1));
    k_ssi=k_ed;
    k_idx=k_ed;
    for j=1:size(targets_name,1)
        for i=1:size(ref_tags,1)
            k_ed(i,j)=norm(targets_ssi(j,:)-ref_tags_ssi(i,:));
        end
        [k_ssi(:,j),k_idx(:,j)]=sort(k_ed(:,j),1);
    end
    k_ssi=k_ssi(1:k,:);
    k_idx=k_idx(1:k,:);
    ref_tags_knn=ref_tags(k_idx,:);
    % calculate weighted centroid of the kNN ref_tags
    for j=1:size(targets_name,1)
        % convert Euclidean distances to weights
        k_ssi(:,j)=sum(k_ssi(:,j))./k_ssi(:,j);
        if sum(isinf(k_ssi(:,j)))==0
            targets_xyz(j,:)=num2cell(round(k_ssi(:,j)'* ...
                cell2mat(ref_tags(k_idx(:,j),2:4))/sum(k_ssi(:,j))));
        else % the target ssi is exactly same with one reference tag
            for i=1:k
                if isinf(k_ssi(i,j))
                    targets_xyz(j,:)=ref_tags(k_idx(i,j),2:4);
%                     display(ref_tags{k_idx(i,j),1}); % verification
```

```
                    break;
                end
            end
        end
    end
    % finalize target tags information
    targets=cat(2,targets_name,targets_xyz);
end

function [targets,ref_tags_knn]= ...
    xyz_grid(targets_name,readers,ref_tags,ref_tags_group)
    % use grid information to estimate the location of target tags
    % created by Jiaqing Wu, 10/5/2011
    % unsolved bug: inappropriate for multiple targets with different grids
    % commented by Jiaqing Wu, 2/23/2012
    % avoid duplicated minimum
    % revised by Jiaqing Wu, 3/16/2012
    % add refine_ssi step to use max only
    % revised by Jiaqing Wu, 3/20/2012

    % check inputs and outputs
    error(nargchk(4,4,nargin));
    error(nargoutchk(0,2,nargout));
%     targets_name=ref_tags(:,1); % for test only
    % initialization
    groups=cell2mat(ref_tags_group(:,2:4));
    xm=max(groups(:,1));
    ym=max(groups(:,2));
    zm=max(groups(:,3));
    targets_grid=zeros(size(targets_name,1),3);
    targets=cell(size(targets_name,1),4);
    % read ssi
    targets_ssi=read_ssi(targets_name,readers); % readers(:,1)
    ref_tags_ssi=read_ssi(ref_tags(:,1),readers); % readers(:,1)
    % refine ssi
    targets_ssi=refine_ssi(targets_ssi);
    ref_tags_ssi=refine_ssi(ref_tags_ssi);
    % calculate Euclidean distance (2-norm distance)
    all_ed=zeros(size(ref_tags,1),size(targets_name,1));
    for j=1:size(targets_name,1)
        for i=1:size(ref_tags,1)
            all_ed(i,j)=norm(targets_ssi(j,:)-ref_tags_ssi(i,:));
        end
    end
    % first pass, find closest ref_tag by grid in 3 axes each
    for j=1:size(targets_name,1)
        % compare each target ssi with ref_tags ssi by group x
        x_weighted=zeros(xm,1);
        for x=1:xm
            x_id=find(groups(:,1)==x);
            x_ed=sum(all_ed(x_id,j))./all_ed(x_id,j);
            if sum(isinf(x_ed))==0
                x_weighted(x)=x_ed'*all_ed(x_id,j)/sum(x_ed);
            else % the target ssi is exactly same with one reference tag
                for i=1:size(x_id,1)
                    if isinf(x_ed(i))
                        x_weighted(x)=all_ed(x_id(i),j);
                        break;
                    end
```

```
                end
            end
        end
        x_grid=find(x_weighted==min(x_weighted));
        % compare each target ssi with ref_tags ssi by group y
        y_weighted=zeros(ym,1);
        for y=1:ym
            y_id=find(groups(:,2)==y);
            y_ed=sum(all_ed(y_id,j))./all_ed(y_id,j);
            if sum(isinf(y_ed))==0
                y_weighted(y)=y_ed'*all_ed(y_id,j)/sum(y_ed);
            else % the target ssi is exactly same with one reference tag
                for i=1:size(y_id,1)
                    if isinf(y_ed(i))
                        y_weighted(y)=all_ed(y_id(i),j);
                        break;
                    end
                end
            end
        end
        y_grid=find(y_weighted==min(y_weighted));
        % compare each target ssi with ref_tags ssi by group z
        z_weighted=zeros(zm,1);
        for z=1:zm
            z_id=find(groups(:,3)==z);
            z_ed=sum(all_ed(z_id,j))./all_ed(z_id,j);
            if sum(isinf(z_ed))==0
                z_weighted(z)=z_ed'*all_ed(z_id,j)/sum(z_ed);
            else % the target ssi is exactly same with one reference tag
                for i=1:size(z_id,1)
                    if isinf(z_ed(i))
                        z_weighted(z)=all_ed(z_id(i),j);
                        break;
                    end
                end
            end
        end
        z_grid=find(z_weighted==min(z_weighted));
        % avoid duplicated minimum, use first one only
        targets_grid(j,:)=[x_grid(1),y_grid(1),z_grid(1)];
    end
    % second pass, use ref_tags nearby as k nearest neighbors
    for j=1:size(targets_name,1)
        % extend to neighbors within 2 blocks away (not work very well)
%         knn_grid=zeros(15,3);
%         knn_grid(1:5,:)=[(targets_grid(j,1)-2:targets_grid(j,1)+2)', ...
%             repmat(targets_grid(j,2:3),5,1)];
%         knn_grid(6:10,:)=[repmat(targets_grid(j,1),5,1), ...
%             (targets_grid(j,2)-2:targets_grid(j,2)+2)', ...
%             repmat(targets_grid(j,3),5,1)];
%         knn_grid(11:15,:)=[repmat(targets_grid(j,1:2),5,1), ...
%             (targets_grid(j,3)-2:targets_grid(j,3)+2)'];
        % extend to neighbors within a 3^3 cube
        knn_grid=zeros(27,3);
        knn_grid(:,1)=[repmat(targets_grid(j,1)-1,9,1); ...
            repmat(targets_grid(j,1),9,1); ...
            repmat(targets_grid(j,1)+1,9,1)];
        knn_grid(:,2)=repmat([repmat(targets_grid(j,2)-1,3,1); ...
            repmat(targets_grid(j,2),3,1); ...
            repmat(targets_grid(j,2)+1,3,1)],3,1);
```

```
        knn_grid(:,3)=repmat([targets_grid(j,3)-1; ...
            targets_grid(j,3);targets_grid(j,3)+1],9,1);
        % match possible grid to existing ref_tags
        [tf,loc]=ismember(knn_grid,cell2mat(ref_tags_group(:,2:4)),'rows');
        knn_id=unique(loc(any(loc,2)),'rows');
        ref_tags_knn=ref_tags(knn_id,:);
        % finalize target tags information
        targets(j,:)= ...
            knn(targets_name(j),readers,ref_tags_knn,size(knn_id,1));
    end
end

function [targets,targets_range]= ...
    ssi_range(targets_name,readers,ref_tags,op)
    % use ssi information to estimate the location of target tags
    % created by Jiaqing Wu, 1/18/2012
    % add targets_range output for further estimation purpose
    % updated by Jiaqing Wu, 2/21/2012
    % unsolved bug: inappropriate for multiple targets with different grids
    % commented by Jiaqing Wu, 2/23/2012
    % add refine_ssi step to use max only
    % revised by Jiaqing Wu, 3/20/2012
    % exclude -40db as origin point
    % revised by Jiaqing Wu, 3/27/2012
    % include 2 readers and 4 readers scenarios
    % updated by Jiaqing Wu, 7/23/2012
    % limit y values to real range
    % updated by Jiaqing Wu, 8/18/2012

    % check inputs and outputs
    error(nargchk(3,4,nargin));
    error(nargoutchk(0,2,nargout));
    % initialization
    if nargin==3, op=0; end % include origin point by default
    xm=434; ym=874; zm=282; % maximum values of x, y, and z
    y1=305; y2=671; % real range of y
    readers_xyz=cell2mat(readers(:,2:4));
    ref_tags_xyz=cell2mat(ref_tags(:,2:4));
    targets=cell(size(targets_name,1),4);
    targets_xyz=zeros(size(targets_name,1),3);
    % read ssi
    targets_ssi=read_ssi(targets_name,readers); % readers(:,1)
    ref_tags_ssi=read_ssi(ref_tags(:,1),readers); % readers(:,1)
    % refine ssi
    targets_ssi=refine_ssi(targets_ssi);
    ref_tags_ssi=refine_ssi(ref_tags_ssi);
    % check ssi
    if any(any(isnan(targets_ssi))) || any(any(isnan(ref_tags_ssi)))
        return;
    end
    % calculate distance
    dis=zeros(size(ref_tags_xyz,1),size(readers_xyz,1));
    for i=1:size(ref_tags_xyz,1)
        for j=1:size(readers_xyz,1)
            dis(i,j)=sqrt(sum((ref_tags_xyz(i,:)-readers_xyz(j,:)).^2));
        end
    end
    ref_tags_dis=round(dis);
    % regression analysis
```

```
    b=zeros(2,size(readers,1));
    for i=1:size(readers,1)
        if op~=0
            % excluding -40db as origin point
            b(:,i)=[ones(size(ref_tags,1),1),[ref_tags_ssi(:,i)]]\ ...
                [ref_tags_dis(:,i)];
        else
            % including -40db as origin point
            b(:,i)=[ones(size(ref_tags,1)+1,1),[ref_tags_ssi(:,i);-40]]\ ...
                [ref_tags_dis(:,i);0];
        end
        % regress is not supported in edu
%           b(:,i)=regress([ref_tags_dis(:,i);0], ...
%               [ones(size(ref_tags,1)+1,1),[ref_tags_ssi(:,i);-40]]);
    end
    targets_range=repmat(b(1,:),size(targets,1),1)+ ...
        repmat(b(2,:),size(targets,1),1).*targets_ssi;
    % quit if one reader only
    if size(readers,1)==1
        targets=cat(2,targets_name,num2cell(round(targets_xyz)));
        return;
    end
    % target optimization
    for i=1:size(targets,1)
        switch size(readers_xyz,1)
            case 2
        targets_xyz(i,:)=fmincon(@(x) ...
            (sqrt((x(1)-readers_xyz(1,1))^2+(x(2)-readers_xyz(1,2))^2+ ...
            (x(3)-readers_xyz(1,3))^2)-targets_range(i,1))^2+ ...
            (sqrt((x(1)-readers_xyz(2,1))^2+(x(2)-readers_xyz(2,2))^2+ ...
            (x(3)-readers_xyz(2,3))^2)-targets_range(i,2))^2, ...
            [0 0 0],[],[],[],[],[0 y1 0],[xm y2 zm],[], ...
            optimset('Algorithm','active-set'));
            case 4
        targets_xyz(i,:)=fmincon(@(x) ...
            (sqrt((x(1)-readers_xyz(1,1))^2+(x(2)-readers_xyz(1,2))^2+ ...
            (x(3)-readers_xyz(1,3))^2)-targets_range(i,1))^2+ ...
            (sqrt((x(1)-readers_xyz(2,1))^2+(x(2)-readers_xyz(2,2))^2+ ...
            (x(3)-readers_xyz(2,3))^2)-targets_range(i,2))^2+ ...
            (sqrt((x(1)-readers_xyz(3,1))^2+(x(2)-readers_xyz(3,2))^2+ ...
            (x(3)-readers_xyz(3,3))^2)-targets_range(i,3))^2+ ...
            (sqrt((x(1)-readers_xyz(4,1))^2+(x(2)-readers_xyz(4,2))^2+ ...
            (x(3)-readers_xyz(4,3))^2)-targets_range(i,4))^2, ...
            [0 0 0],[],[],[],[],[0 y1 0],[xm y2 zm],[], ...
            optimset('Algorithm','active-set'));
        end
    end
    % finalize target tags information
    targets=cat(2,targets_name,num2cell(round(targets_xyz)));
end

function [targets,targets_xyz]= ...
    hybrid(targets_name,readers,ref_tags,ref_tags_group)
    % use ssi information to estimate the location of target tags
    % created by Jiaqing Wu, 1/18/2012
    % estimate knn based on individual reader
    % revised by Jiaqing Wu, 2/21/2012
    % unsolved bug: inappropriate for multiple targets with different grids
    % commented by Jiaqing Wu, 2/23/2012
```

```
    % check inputs and outputs
    error(nargchk(4,4,nargin));
    error(nargoutchk(0,2,nargout));
    % average of kNN, kNN with grid, RSSI, and RSSI with grid
    targets1=knn(targets_name,readers,ref_tags,6);
    targets1_xyz=cell2mat(targets1(:,2:4));
    [targets2,ref_tags_knn]= ...
        xyz_grid(targets_name,readers,ref_tags,ref_tags_group);
    targets2_xyz=cell2mat(targets2(:,2:4));
    targets3=ssi_range(targets_name,readers,ref_tags);
    targets3_xyz=cell2mat(targets3(:,2:4));
    targets4=ssi_range(targets_name,readers,ref_tags_knn,1);
    targets4_xyz=cell2mat(targets4(:,2:4));
    targets=cat(2,targets_name,num2cell(round((targets1_xyz+ ...
        targets2_xyz+targets3_xyz+targets4_xyz)/4)));
    targets_xyz=[targets1_xyz; ...
        targets2_xyz;targets3_xyz;targets4_xyz];
end

function print_summary(target_timer,target_dc,real_xyz)
    % output localizaiton errors for different algorithms combinations
    % created by Jiaqing Wu, 8/17/2012
    target_id=target_timer{1,1,1};
    t=size(target_timer,3);
    target_full=zeros(15,3,t);
    e_full=zeros(15,1,t);
    e_summary=zeros(15,2);
    target_full(1,:,:)=(target_dc(1,:,:)+target_dc(2,:,:)+ ...
        target_dc(3,:,:)+target_dc(4,:,:))/4;
    target_full(2:5,:,:)=target_dc(:,:,:);
    target_full(6,:,:)=(target_dc(1,:,:)+target_dc(2,:,:))/2;
    target_full(7,:,:)=(target_dc(1,:,:)+target_dc(3,:,:))/2;
    target_full(8,:,:)=(target_dc(1,:,:)+target_dc(4,:,:))/2;
    target_full(9,:,:)=(target_dc(2,:,:)+target_dc(3,:,:))/2;
    target_full(10,:,:)=(target_dc(2,:,:)+target_dc(4,:,:))/2;
    target_full(11,:,:)=(target_dc(3,:,:)+target_dc(4,:,:))/2;
    target_full(12,:,:)=(target_dc(1,:,:)+target_dc(2,:,:)+ ...
        target_dc(3,:,:))/3;
    target_full(13,:,:)=(target_dc(1,:,:)+target_dc(2,:,:)+ ...
        target_dc(4,:,:))/3;
    target_full(14,:,:)=(target_dc(1,:,:)+target_dc(3,:,:)+ ...
        target_dc(4,:,:))/3;
    target_full(15,:,:)=(target_dc(2,:,:)+target_dc(3,:,:)+ ...
        target_dc(4,:,:))/3;
    if not(isempty(real_xyz{1}) || isempty(real_xyz{2}) ...
        || isempty(real_xyz{3}))
        for s=1:t
            for r=1:15
                e_full(r,:,s)=round(norm(target_full(r,:,s)- ...
                    cell2mat(real_xyz(1,1:3))));
            end
        end
    else
        e_full(:,:,t)=zeros(15,1);
    end
    for r=1:15
        e_summary(r,1)=round(mean(squeeze(e_full(r,1,:))));
        e_summary(r,2)=round(std(squeeze(e_full(r,1,:))));
```

```
    end
    e_summary_all=cat(2,repmat(' ',15,5), ...
        ['ABCD';'A___';'_B__';'__C_';'___D'; ...
        'AB__';'A_C_';'A__D';'_BC_';'_B_D';'__CD'; ...
        'ABC_';'AB_D';'A_CD';'_BCD'],repmat(' ',15,15), ...
        num2str(e_summary));
    save_option=questdlg(e_summary_all,target_id(end-5:end), ...
        'save','exit','save');
    switch save_option
        case 'save'
%             disp('save');
            m_file=fopen([pwd,'\mean.txt'],'at');
            s_file=fopen([pwd,'\std.txt'],'at');
            fprintf(m_file,'%s\n',[datestr(now,'yyyy-mm-dd HH:MM:SS'), ...
                ' <',target_id,'> ',num2str(e_summary(:,1)')]);
            fprintf(s_file,'%s\n',[datestr(now,'yyyy-mm-dd HH:MM:SS'), ...
                ' <',target_id,'> ',num2str(e_summary(:,2)')]);
            fclose(m_file);
            fclose(s_file);
        case 'exit'
%             disp('exit');
            return;
        otherwise
%             disp('exit');
            return;
    end
end
```

Appendix C

Data Sheets

C.1 Reader Test Data Sheet

Table C-1: Reader test data sheet

StdOrder	RunOrder	Reader	Height	Depth	Antenna	Tag	uMax
42	1	3	2	2	2	2	-51
37	2	3	1	1	1	3	-50
29	3	3	3	1	3	1	-55
31	4	3	1	3	3	1	-56
36	5	3	1	1	3	3	-53
40	6	3	1	1	1	1	-52
41	7	3	2	2	2	2	-48
30	8	3	3	3	1	3	-53
35	9	3	1	3	3	3	-56
33	10	3	3	3	1	3	-53
38	11	3	3	1	1	1	-62
39	12	3	1	3	1	1	-55
34	13	3	3	3	3	1	-55
32	14	3	3	1	3	3	-57
45	15	4	1	3	3	1	-57
48	16	4	3	3	3	1	-58
50	17	4	1	1	3	3	-56
53	18	4	1	3	1	1	-61
54	19	4	1	1	1	1	-54
46	20	4	3	1	3	3	-57
52	21	4	3	1	1	1	-60
51	22	4	1	1	1	3	-52
55	23	4	2	2	2	2	-51
44	24	4	3	3	1	3	-54
49	25	4	1	3	3	3	-59
47	26	4	3	3	1	3	-53
56	27	4	2	2	2	2	-53
43	28	4	3	1	3	1	-53

22	29	2	1	1	3	3	-54
25	30	2	1	3	1	1	-60
16	31	2	3	3	1	3	-49
17	32	2	1	3	3	1	-53
23	33	2	1	1	1	3	-49
19	34	2	3	3	1	3	-52
24	35	2	3	1	1	1	-63
28	36	2	2	2	2	2	-50
21	37	2	1	3	3	3	-59
15	38	2	3	1	3	1	-56
18	39	2	3	1	3	3	-57
26	40	2	1	1	1	1	-53
27	41	2	2	2	2	2	-50
20	42	2	3	3	3	1	-52
4	43	1	3	1	3	3	-54
2	44	1	3	3	1	3	-52
8	45	1	1	1	3	3	-52
12	46	1	1	1	1	1	-51
7	47	1	1	3	3	3	-55
3	48	1	1	3	3	1	-55
5	49	1	3	3	1	3	-53
10	50	1	3	1	1	1	-57
14	51	1	2	2	2	2	-46
11	52	1	1	3	1	1	-56
1	53	1	3	1	3	1	-53
6	54	1	3	3	3	1	-53
9	55	1	1	1	1	3	-54
13	56	1	2	2	2	2	-47

C.2 Tag Test Data Sheet

Table C-2: Tag test data sheet

StdOrder	RunOrder	Tag	Distance	Orientation	uMax
18	1	1	3	6	-52
5	2	1	1	4	-53
16	3	1	3	5	-60
2	4	1	1	2	-48
13	5	1	3	1	-51
12	6	1	2	6	-63
10	7	1	2	5	-58
4	8	1	1	5	-57
1	9	1	1	1	-47
15	10	1	3	3	-53
17	11	1	3	4	-56
7	12	1	2	1	-47
3	13	1	1	3	-50
6	14	1	1	6	-55
11	15	1	2	4	-54
8	16	1	2	2	-47
9	17	1	2	3	-50
14	18	1	3	2	-51
37	19	3	1	1	-46
42	20	3	1	6	-56
40	21	3	1	5	-57
50	22	3	3	2	-51
53	23	3	3	4	-61
54	24	3	3	6	-52
49	25	3	3	1	-50
45	26	3	2	3	-51
38	27	3	1	2	-49
48	28	3	2	6	-65
43	29	3	2	1	-47
52	30	3	3	5	-60
39	31	3	1	3	-51
41	32	3	1	4	-53
44	33	3	2	2	-48
46	34	3	2	5	-58
51	35	3	3	3	-53
47	36	3	2	4	-55

24	37	2	1	6	-54
34	38	2	3	5	-58
26	39	2	2	2	-48
28	40	2	2	5	-57
35	41	2	3	4	-58
25	42	2	2	1	-45
31	43	2	3	1	-51
29	44	2	2	4	-54
19	45	2	1	1	-45
32	46	2	3	2	-51
21	47	2	1	3	-52
27	48	2	2	3	-51
30	49	2	2	6	-65
20	50	2	1	2	-48
23	51	2	1	4	-51
33	52	2	3	3	-54
36	53	2	3	6	-53
22	54	2	1	5	-57

C.3 Ranging Test Data Sheet

Table C-3: Ranging test data sheet

StdOrder	RunOrder	Tag	Distance	uMax
11	1	2	0.5	-49
13	2	2	1.5	-62
18	3	2	4	-61
31	4	4	0.5	-51
14	5	2	2	-54
37	6	4	3.5	-59
4	7	1	2	-54
35	8	4	2.5	-54
33	9	4	1.5	-60
32	10	4	1	-55
5	11	1	2.5	-54
28	12	3	4	-61
9	13	1	4.5	-66.5
24	14	3	2	-54
44	15	5	2	-54
21	16	3	0.5	-51
22	17	3	1	-55
42	18	5	1	-58
38	19	4	4	-63
36	20	4	3	-60
45	21	5	2.5	-55
26	22	3	3	-61
20	23	2	5	-62.1
46	24	5	3	-61
3	25	1	1.5	-60
8	26	1	4	-61
47	27	5	3.5	-60
2	28	1	1	-55
41	29	5	0.5	-52
34	30	4	2	-52
29	31	3	4.5	-64
25	32	3	2.5	-56
30	33	3	5	-59.9
39	34	4	4.5	-66
17	35	2	3.5	-59
48	36	5	4	-61

1	37	1	0.5	-50
10	38	1	5	-61.7
27	39	3	3.5	-59
6	40	1	3	-61
15	41	2	2.5	-55
49	42	5	4.5	-66.1
23	43	3	1.5	-60
7	44	1	3.5	-60
16	45	2	3	-61
50	46	5	5	-62.9
43	47	5	1.5	-60
40	48	4	5	-61.6
12	49	2	1	-55
19	50	2	4.5	-64

C.4 Localization Test Data Sheet

Table C-4: Localization test data sheet

StdOrder	RunOrder	Position	Orientation	Tag	Hybrid	kNN	RSSI
51	1	1	Z	3	1.44	2.9	1.32
47	2	8	Y	2	2.12	2.56	2.19
68	3	7	Y	3	2.43	3.46	2.56
71	4	8	Y	3	2.16	2.23	2.24
30	5	2	Z	2	0.99	2.16	1.34
45	6	7	Z	2	2.31	1.62	2.03
23	7	8	Y	1	1.58	2.84	2.29
67	8	7	X	3	1.06	0.78	1.47
20	9	7	Y	1	2.2	3.03	2.38
64	10	6	X	3	0.65	0.56	1.02
29	11	2	Y	2	2.36	1.66	2.01
34	12	4	X	2	0.85	0.77	2.26
48	13	8	Z	2	0.99	0.7	2.1
5	14	2	Y	1	2	2	2.24
70	15	8	X	3	0.91	0.64	1.88
8	16	3	Y	1	0.69	1.63	0.79
43	17	7	X	2	1.17	1.04	1.6
16	18	6	X	1	0.35	0.62	2.26
13	19	5	X	1	1.09	1.03	1.53
4	20	2	X	1	1.24	1.33	2.44
58	21	4	X	3	1.28	0.94	2.07
18	22	6	Z	1	0.3	1.55	1.97
6	23	2	Z	1	1.14	2.45	1.58
59	24	4	Y	3	0.99	1.05	1.98
63	25	5	Z	3	3.15	2.77	1.65
36	26	4	Z	2	1.3	0.82	2.15
50	27	1	Y	3	1.11	1.07	1.23
31	28	3	X	2	1.75	2.8	1.23
66	29	6	Z	3	0.45	2.02	1.61
46	30	8	X	2	0.95	1	1.83
40	31	6	X	2	0.52	0.64	1.27
28	32	2	X	2	1.2	1.15	1.75
41	33	6	Y	2	0.94	1.7	1.76
57	34	3	Z	3	1.28	1.89	1.27
49	35	1	X	3	1.44	1	0.74
22	36	8	X	1	1.1	0.53	2.08

42	37	6	Z	2	0.75	1.87	1.33
62	38	5	Y	3	1.04	3.09	1.65
32	39	3	Y	2	0.62	1.55	1.18
56	40	3	Y	3	0.72	1.66	0.57
65	41	6	Y	3	0.72	1.89	1.72
33	42	3	Z	2	1.17	1.83	1.28
25	43	1	X	2	1.07	1.1	0.76
3	44	1	Z	1	2.12	2.75	1.4
60	45	4	Z	3	1.37	0.84	1.52
61	46	5	X	3	1.18	1.28	1.39
37	47	5	X	2	1.28	0.84	1.55
19	48	7	X	1	1.72	0.52	1.49
21	49	7	Z	1	2.03	1.54	2.08
53	50	2	Y	3	2.17	2.17	2.06
72	51	8	Z	3	2.47	0.66	2.07
54	52	2	Z	3	1.81	2.6	1.59
11	53	4	Y	1	1.21	1.06	2.46
17	54	6	Y	1	1.23	2.15	1.84
9	55	3	Z	1	1.08	1.82	1.29
69	56	7	Z	3	2.21	1.29	1.95
24	57	8	Z	1	1.63	0.77	2.14
2	58	1	Y	1	0.73	1.62	1.69
27	59	1	Z	2	2.35	3.14	1.16
10	60	4	X	1	0.96	1.07	2.16
52	61	2	X	3	0.44	2.62	1.78
12	62	4	Z	1	1.15	0.96	1.9
15	63	5	Z	1	2.84	1.97	1.86
14	64	5	Y	1	1.29	3.31	1.52
35	65	4	Y	2	0.96	1	2.06
38	66	5	Y	2	1	3.33	1.55
1	67	1	X	1	1.04	0.93	0.85
39	68	5	Z	2	2.87	2.32	1.77
7	69	3	X	1	1.6	1.56	1.14
26	70	1	Y	2	0.82	0.92	1.45
44	71	7	Y	2	2.25	3.46	2.32
55	72	3	X	3	1.13	1.63	0.97

C.5 Battery-assisted Passive System Test Data Sheet

Table C-5: Battery-assisted passive system test data sheet

StdOrder	RunOrder	Tag	Location	Group	Orientation	Distance	dBm	StDev
270	1	3	Lab	STT	Z	5	-60.7	1.94
256	2	3	Lab	STT	Y	3	-57.9	2.6
245	3	3	Lab	STT	X	2.5	-55.2	5.64
283	4	3	Lab	SMT	Y	1.5	-57	1.86
261	6	3	Lab	STT	Z	0.5	-41.5	2.28
311	7	3	Mockup	STT	Y	0.5	-51.1	7.68
298	9	3	Lab	SMT	Z	4	-72.9	7.43
260	10	3	Lab	STT	Y	5	-67	3.62
352	11	3	Mockup	SMT	Z	1	-66.7	7.07
315	12	3	Mockup	STT	Y	2.5	-55	8.1
304	13	3	Mockup	STT	X	2	-64.8	5.59
343	14	3	Mockup	SMT	Y	1.5	-65.1	8.31
292	15	3	Lab	SMT	Z	1	-60.6	2.06
287	16	3	Lab	SMT	Y	3.5	-66.7	4.16
295	17	3	Lab	SMT	Z	2.5	-72.7	3.35
277	19	3	Lab	SMT	X	3.5	-69.3	4.52
302	20	3	Mockup	STT	X	1	-52.2	6.39
262	21	3	Lab	STT	Z	1	-51.4	4.13
279	22	3	Lab	SMT	X	4.5	-74.4	5.86
288	23	3	Lab	SMT	Y	4	-72.1	4.04
314	24	3	Mockup	STT	Y	2	-61	11.64
268	25	3	Lab	STT	Z	4	-55.4	3.8
286	26	3	Lab	SMT	Y	3	-63	4.8
276	27	3	Lab	SMT	X	3	-62.3	3.52
303	28	3	Mockup	STT	X	1.5	-62.2	6.26
243	32	3	Lab	STT	X	1.5	-51.3	2.82
284	33	3	Lab	SMT	Y	2	-63.3	3.25
335	34	3	Mockup	SMT	X	2.5	-73.4	5.95
334	36	3	Mockup	SMT	X	2	-75.4	5.94
267	37	3	Lab	STT	Z	3.5	-58.5	2.44
291	39	3	Lab	SMT	Z	0.5	-63.4	2.07
353	40	3	Mockup	SMT	Z	1.5	-73.4	6.07
316	41	3	Mockup	STT	Y	3	-62.5	6.9
313	42	3	Mockup	STT	Y	1.5	-63.5	7.86
325	43	3	Mockup	STT	Z	2.5	-54.5	4.78
242	44	3	Lab	STT	X	1	-55	0.8
333	45	3	Mockup	SMT	X	1.5	-64.1	7.37

253	47	3	Lab	STT	Y	1.5	-55.1	6.66
332	48	3	Mockup	SMT	X	1	-63.9	6.89
272	49	3	Lab	SMT	X	1	-56.1	2.21
322	51	3	Mockup	STT	Z	1	-60.1	6.94
293	52	3	Lab	SMT	Z	1.5	-72	1.6
294	53	3	Lab	SMT	Z	2	-70.6	1.75
257	54	3	Lab	STT	Y	3.5	-62.4	2.99
278	55	3	Lab	SMT	X	4	-74.5	4.14
351	56	3	Mockup	SMT	Z	0.5	-75.4	7.07
356	57	3	Mockup	SMT	Z	3	-72.6	6.11
289	58	3	Lab	SMT	Y	4.5	-74.6	6.42
280	59	3	Lab	SMT	X	5	-74.3	3.43
355	60	3	Mockup	SMT	Z	2.5	-66.7	6.57
251	61	3	Lab	STT	Y	0.5	-45.6	5.09
271	62	3	Lab	SMT	X	0.5	-52.2	1.3
281	63	3	Lab	SMT	Y	0.5	-51.9	2.38
244	64	3	Lab	STT	X	2	-52.7	3.26
247	66	3	Lab	STT	X	3.5	-61.2	2.63
323	67	3	Mockup	STT	Z	1.5	-55	4.32
336	68	3	Mockup	SMT	X	3	-70.6	8.78
263	69	3	Lab	STT	Z	1.5	-47.8	2.35
275	71	3	Lab	SMT	X	2.5	-63	4.14
312	72	3	Mockup	STT	Y	1	-62.6	9.32
301	73	3	Mockup	STT	X	0.5	-51.6	8.16
248	74	3	Lab	STT	X	4	-70.8	13.1
246	75	3	Lab	STT	X	3	-55.6	2.9
249	76	3	Lab	STT	X	4.5	-64.5	2.96
342	78	3	Mockup	SMT	Y	1	-65.8	8.52
344	79	3	Mockup	SMT	Y	2	-75.3	7.25
331	81	3	Mockup	SMT	X	0.5	-58.4	7.3
306	82	3	Mockup	STT	X	3	-61.2	5.47
252	84	3	Lab	STT	Y	1	-47.7	2.49
254	85	3	Lab	STT	Y	2	-52.4	5.82
346	88	3	Mockup	SMT	Y	3	-73.1	9.03
273	89	3	Lab	SMT	X	1.5	-60.5	2.3
266	90	3	Lab	STT	Z	3	-59.7	7.09
341	91	3	Mockup	SMT	Y	0.5	-59	6.29
290	92	3	Lab	SMT	Y	5	-73	4.45
305	93	3	Mockup	STT	X	2.5	-68	8.24
241	94	3	Lab	STT	X	0.5	-49.4	3.3
258	96	3	Lab	STT	Y	4	-62.6	6.84
326	98	3	Mockup	STT	Z	3	-68.5	6.12

264	99	3	Lab	STT	Z	2	-53.7	1.99
324	100	3	Mockup	STT	Z	2	-57.6	6.22
321	101	3	Mockup	STT	Z	0.5	-51	5.61
300	102	3	Lab	SMT	Z	5	-81.1	7.43
250	103	3	Lab	STT	X	5	-68.1	7.24
274	104	3	Lab	SMT	X	2	-62.1	4.12
297	105	3	Lab	SMT	Z	3.5	-75	5.04
296	106	3	Lab	SMT	Z	3	-75.7	3.41
285	108	3	Lab	SMT	Y	2.5	-61.3	4.69
354	110	3	Mockup	SMT	Z	2	-67.7	5.53
255	111	3	Lab	STT	Y	2.5	-57.5	6.92
265	112	3	Lab	STT	Z	2.5	-52.6	1.66
299	115	3	Lab	SMT	Z	4.5	-76.4	4.27
269	116	3	Lab	STT	Z	4.5	-62.6	4.57
345	118	3	Mockup	SMT	Y	2.5	-72.7	8
259	119	3	Lab	STT	Y	4.5	-60.3	1.72
282	120	3	Lab	SMT	Y	1	-54.2	2.39
216	121	2	Mockup	SMT	X	3	-68.5	8.16
146	122	2	Lab	STT	Z	3	-59.6	7.8
205	124	2	Mockup	STT	Z	2.5	-56.6	5.6
206	125	2	Mockup	STT	Z	3	-63.1	8.39
174	127	2	Lab	SMT	Z	2	-68	1.76
132	128	2	Lab	STT	Y	1	-48.6	2.92
130	129	2	Lab	STT	X	5	-67.6	4.51
212	130	2	Mockup	SMT	X	1	-64.3	6.26
163	131	2	Lab	SMT	Y	1.5	-57.2	2.73
154	132	2	Lab	SMT	X	2	-60.4	3.39
150	133	2	Lab	STT	Z	5	-61.5	1.37
152	134	2	Lab	SMT	X	1	-54.1	2.34
129	136	2	Lab	STT	X	4.5	-64.9	2.62
138	137	2	Lab	STT	Y	4	-64.1	6.25
183	138	2	Mockup	STT	X	1.5	-61.3	7.46
191	139	2	Mockup	STT	Y	0.5	-52.4	8.31
158	140	2	Lab	SMT	X	4	-73.9	3.54
215	142	2	Mockup	SMT	X	2.5	-72.1	5.14
233	144	2	Mockup	SMT	Z	1.5	-69.8	6.8
170	146	2	Lab	SMT	Y	5	-69.7	2.99
162	147	2	Lab	SMT	Y	1	-53.7	5.13
155	148	2	Lab	SMT	X	2.5	-62.5	5.41
180	149	2	Lab	SMT	Z	5	-77.6	7.43
175	151	2	Lab	SMT	Z	2.5	-71	4.72
148	152	2	Lab	STT	Z	4	-55.3	3.54

142	153	2	Lab	STT	Z	1	-48.8	4.65
124	154	2	Lab	STT	X	2	-50.4	3.87
145	155	2	Lab	STT	Z	2.5	-51.5	1.54
121	156	2	Lab	STT	X	0.5	-49.1	2.63
186	157	2	Mockup	STT	X	3	-70.5	8.09
127	158	2	Lab	STT	X	3.5	-61.8	2.28
234	160	2	Mockup	SMT	Z	2	-66.6	5.91
164	161	2	Lab	SMT	Y	2	-59.7	2.79
147	162	2	Lab	STT	Z	3.5	-57.8	2.22
226	163	2	Mockup	SMT	Y	3	-69.5	7.29
160	164	2	Lab	SMT	X	5	-71.5	4.57
223	165	2	Mockup	SMT	Y	1.5	-67.4	8.28
131	166	2	Lab	STT	Y	0.5	-44.5	3.89
236	167	2	Mockup	SMT	Z	3	-73.9	6.91
196	168	2	Mockup	STT	Y	3	-67.6	9.29
181	169	2	Mockup	STT	X	0.5	-51.3	6.26
172	172	2	Lab	SMT	Z	1	-58.9	3.18
211	173	2	Mockup	SMT	X	0.5	-57.5	7.19
221	174	2	Mockup	SMT	Y	0.5	-59.7	6.25
151	176	2	Lab	SMT	X	0.5	-49.3	1.95
179	177	2	Lab	SMT	Z	4.5	-72.2	4.21
224	179	2	Mockup	SMT	Y	2	-74.1	7.37
125	180	2	Lab	STT	X	2.5	-54.5	4.46
165	181	2	Lab	SMT	Y	2.5	-61.1	4.7
231	182	2	Mockup	SMT	Z	0.5	-70.6	6.98
144	183	2	Lab	STT	Z	2	-53.3	1.71
167	185	2	Lab	SMT	Y	3.5	-67.7	5.24
193	186	2	Mockup	STT	Y	1.5	-62.6	5.76
178	187	2	Lab	SMT	Z	4	-73.3	8.43
126	188	2	Lab	STT	X	3	-56.2	3.43
137	189	2	Lab	STT	Y	3.5	-64.9	4.17
122	190	2	Lab	STT	X	1	-54.8	0.96
173	191	2	Lab	SMT	Z	1.5	-67.5	1.95
168	192	2	Lab	SMT	Y	4	-70.2	4.95
235	193	2	Mockup	SMT	Z	2.5	-64.6	6.56
201	195	2	Mockup	STT	Z	0.5	-51.3	6.25
139	196	2	Lab	STT	Y	4.5	-71.9	5.4
136	197	2	Lab	STT	Y	3	-56.3	3.02
161	198	2	Lab	SMT	Y	0.5	-48.7	1.25
204	199	2	Mockup	STT	Z	2	-59.6	8.76
194	200	2	Mockup	STT	Y	2	-58	10.04
166	201	2	Lab	SMT	Y	3	-60.1	3.91

203	203	2	Mockup	STT	Z	1.5	-57.7	6.36
149	204	2	Lab	STT	Z	4.5	-61.3	6.8
182	205	2	Mockup	STT	X	1	-54.8	7.16
192	209	2	Mockup	STT	Y	1	-56.5	7.71
177	211	2	Lab	SMT	Z	3.5	-74.5	6.15
153	212	2	Lab	SMT	X	1.5	-58.7	1.98
195	213	2	Mockup	STT	Y	2.5	-61.3	5.43
140	215	2	Lab	STT	Y	5	-67.6	4.28
156	216	2	Lab	SMT	X	3	-60	3.2
225	217	2	Mockup	SMT	Y	2.5	-70.1	10.62
185	218	2	Mockup	STT	X	2.5	-68	9.24
169	219	2	Lab	SMT	Y	4.5	-71.1	5.8
157	221	2	Lab	SMT	X	3.5	-66.6	5.78
134	222	2	Lab	STT	Y	2	-51.2	4.88
171	223	2	Lab	SMT	Z	0.5	-60.8	2.24
232	224	2	Mockup	SMT	Z	1	-69.2	8.94
133	225	2	Lab	STT	Y	1.5	-52.9	6.64
128	226	2	Lab	STT	X	4	-65.8	9.05
214	227	2	Mockup	SMT	X	2	-72.9	4.81
222	228	2	Mockup	SMT	Y	1	-65.5	7.71
159	229	2	Lab	SMT	X	4.5	-73.4	6.82
184	231	2	Mockup	STT	X	2	-65.7	6.79
202	232	2	Mockup	STT	Z	1	-57	8.58
135	233	2	Lab	STT	Y	2.5	-57.9	9.86
176	235	2	Lab	SMT	Z	3	-74	4.07
143	236	2	Lab	STT	Z	1.5	-47.5	1.8
141	237	2	Lab	STT	Z	0.5	-40.8	2.56
213	238	2	Mockup	SMT	X	1.5	-66.5	7.75
123	239	2	Lab	STT	X	1.5	-50.7	4.02
96	241	1	Mockup	SMT	X	3	-65.6	7.1
60	242	1	Lab	SMT	Z	5	-76.5	7.3
12	244	1	Lab	STT	Y	1	-48.9	2.09
76	245	1	Mockup	STT	Y	3	-63.6	6.7
42	247	1	Lab	SMT	Y	1	-54.4	5.56
103	248	1	Mockup	SMT	Y	1.5	-65.1	14.97
51	250	1	Lab	SMT	Z	0.5	-59.9	2.47
115	252	1	Mockup	SMT	Z	2.5	-65.3	6.64
21	253	1	Lab	STT	Z	0.5	-44.7	3.82
50	254	1	Lab	SMT	Y	5	-66.4	2.48
40	255	1	Lab	SMT	X	5	-71.6	2.75
33	259	1	Lab	SMT	X	1.5	-57.8	2.41
91	261	1	Mockup	SMT	X	0.5	-58.6	7.35

106	262	1	Mockup	SMT	Y	3	-66.3	14.96
41	264	1	Lab	SMT	Y	0.5	-46.3	1.46
101	265	1	Mockup	SMT	Y	0.5	-58.3	6.69
73	266	1	Mockup	STT	Y	1.5	-62.5	6.44
71	267	1	Mockup	STT	Y	0.5	-52.3	8.6
16	268	1	Lab	STT	Y	3	-55.2	3.17
24	269	1	Lab	STT	Z	2	-53.2	2.46
5	270	1	Lab	STT	X	2.5	-53.8	5.09
112	273	1	Mockup	SMT	Z	1	-69.2	11.25
52	274	1	Lab	SMT	Z	1	-61.4	5.15
34	275	1	Lab	SMT	X	2	-60.3	2.61
22	276	1	Lab	STT	Z	1	-52.7	3.2
13	277	1	Lab	STT	Y	1.5	-50.7	5.22
10	278	1	Lab	STT	X	5	-69.5	7.12
30	279	1	Lab	STT	Z	5	-61.3	1.94
20	280	1	Lab	STT	Y	5	-68.1	5.04
82	281	1	Mockup	STT	Z	1	-55.1	8.44
1	282	1	Lab	STT	X	0.5	-49	2.76
105	283	1	Mockup	SMT	Y	2.5	-69.7	10.35
43	284	1	Lab	SMT	Y	1.5	-56.3	2.08
111	285	1	Mockup	SMT	Z	0.5	-73.1	8.92
7	286	1	Lab	STT	X	3.5	-60.4	1.62
72	288	1	Mockup	STT	Y	1	-53.8	6.9
45	289	1	Lab	SMT	Y	2.5	-60.9	3.67
39	290	1	Lab	SMT	X	4.5	-70.3	6.73
32	291	1	Lab	SMT	X	1	-52.6	1.62
18	293	1	Lab	STT	Y	4	-61	5.69
53	294	1	Lab	SMT	Z	1.5	-67.1	2.45
61	295	1	Mockup	STT	X	0.5	-53.3	9.08
74	296	1	Mockup	STT	Y	2	-59.1	9.85
113	297	1	Mockup	SMT	Z	1.5	-70	6.81
23	298	1	Lab	STT	Z	1.5	-47.3	1.34
17	299	1	Lab	STT	Y	3.5	-59.1	3.14
49	300	1	Lab	SMT	Y	4.5	-70	6.25
58	301	1	Lab	SMT	Z	4	-72.4	8.75
102	302	1	Mockup	SMT	Y	1	-63.7	11.27
36	303	1	Lab	SMT	X	3	-61.9	4.2
94	304	1	Mockup	SMT	X	2	-75.5	6.78
63	306	1	Mockup	STT	X	1.5	-62.3	6.76
84	307	1	Mockup	STT	Z	2	-57.5	6.66
31	308	1	Lab	SMT	X	0.5	-49.4	2.14
44	309	1	Lab	SMT	Y	2	-59.8	3.72

92	310	1	Mockup	SMT	X	1	-56.8	17.71
35	311	1	Lab	SMT	X	2.5	-61.5	4.94
56	312	1	Lab	SMT	Z	3	-73.3	4.2
55	313	1	Lab	SMT	Z	2.5	-69.4	3.17
64	314	1	Mockup	STT	X	2	-61.6	6.28
75	316	1	Mockup	STT	Y	2.5	-58.6	8.3
19	317	1	Lab	STT	Y	4.5	-69.6	3.56
66	318	1	Mockup	STT	X	3	-63.9	8.44
81	319	1	Mockup	STT	Z	0.5	-52.1	5.69
25	320	1	Lab	STT	Z	2.5	-52.4	3.89
6	321	1	Lab	STT	X	3	-53.9	2.56
28	322	1	Lab	STT	Z	4	-56.8	5.41
86	323	1	Mockup	STT	Z	3	-65.6	8.07
2	324	1	Lab	STT	X	1	-54.7	1.78
85	326	1	Mockup	STT	Z	2.5	-56	5.51
114	327	1	Mockup	SMT	Z	2	-66.6	6.71
27	328	1	Lab	STT	Z	3.5	-58.3	3.26
46	329	1	Lab	SMT	Y	3	-59.4	12.33
95	330	1	Mockup	SMT	X	2.5	-68.6	8.87
116	332	1	Mockup	SMT	Z	3	-68.9	5.78
59	333	1	Lab	SMT	Z	4.5	-71.8	3.48
29	334	1	Lab	STT	Z	4.5	-63.2	8.76
14	337	1	Lab	STT	Y	2	-52.5	4.83
54	339	1	Lab	SMT	Z	2	-68.6	1.62
57	340	1	Lab	SMT	Z	3.5	-72.3	6.6
9	341	1	Lab	STT	X	4.5	-64.2	2.57
65	343	1	Mockup	STT	X	2.5	-67.1	8.38
62	344	1	Mockup	STT	X	1	-57.3	9.21
48	345	1	Lab	SMT	Y	4	-72	3.77
8	346	1	Lab	STT	X	4	-70.6	7.71
11	347	1	Lab	STT	Y	0.5	-41.8	2.11
3	348	1	Lab	STT	X	1.5	-50.8	2.48
47	350	1	Lab	SMT	Y	3.5	-66.6	5.17
37	351	1	Lab	SMT	X	3.5	-66.4	5.1
15	352	1	Lab	STT	Y	2.5	-60.1	6.15
26	353	1	Lab	STT	Z	3	-61	7.19
38	354	1	Lab	SMT	X	4	-72.8	4.65
83	355	1	Mockup	STT	Z	1.5	-56.9	5.33
93	356	1	Mockup	SMT	X	1.5	-65.7	5.45
4	357	1	Lab	STT	X	2	-51.9	3.22
104	360	1	Mockup	SMT	Y	2	-76.9	6.53