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RFID Emergency System for Tumble Detection of Solitary People

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Abstract

RFID (Radio Frequency Identification) system is a wireless system without any kinds of mechanical or optical connection between identifying and detected objects. It consists of two basic devices: a reader and tag. Recently with the development of the technology, SAW-RFID (Surface Acoustic Wave Radio Frequency Identification) tags come into market with acceptable price, as well as its size tends to miniaturization.

We propose to use 3D wireless indoor localization system to detect the position of the tags. The reader converts radio waves returned from the SAW-RFID tag into a form, which can be useful to process the information. The system consists of SAW-RFID tags placed on the object and several RF Readers in the room. The readers sequentially transmit the impulse signals which are then reflected from different tags and received by readers. Then a signal round-trip TOA (Time of Arrival) between tags and readers can be estimated. We define a 3D coordinate system of the readers and calculate the positions of the tags using suitable specific algorithm.

Our system is design to monitor a human body position. The goal is to detect a tumble of solitary living people. A case when the tag positions are identified to be below a per-set threshold means that something happened, and maybe a man has fallen on the ground. This emergency situation can be detected by the monitoring system which then sends information to an alarm system which can call the health centre to take care of the patient.

In this paper, a 5 m×5 m×3 m indoor localization system is implemented in Matlab. The simulation results show a correct identification of a fallen man and accuracy of the high measurement below 30 cm.

Keywords

Emergency Monitoring System, Tumble Detection, Indoor Localization System, TOA, RFID, SAW-RFID TAG, Trilateration

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List of Acronyms

A-GPS	Assisted-GPS
AIR ID	Adjustable Long Range Active ID
AOA	Angle of Arrival
FPGA	Field Programmable Gate Array
GCMD	Graph Colouring with Merging and Deletion
GPS	Global Positioning System
ID	Identification
LANDMARC	Location Identification based on Dynamic Active RFID Calibration
REMA	Ranging using Environment and Mobility Adaptive RSSI
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
TDOA	Time Difference of Arrival
TOA	Time of Arrival
TOF	Time of Flight
SAW	Surface Acoustic Wave
UWB	Ultra-wide Bandwidth

Chapter 1
Introduction

Population aging has been a well-known problem of our society. This situation happens not only in European countries, but also in China and other countries. Statistics show 167 million people aged over 60 years old in China when about half of them are "empty-nesters" who live on their own. Old people who live alone are afraid of an accident especially of falling down when they are alone at home. How to use modern technologies to help solitary elderly or disabled people to keep safe becomes a nowadays challenge.

In this thesis, we propose an emergency monitoring system using RFID (Radio Frequency Identification) technology for tumble detection of solitary people. The indoor system consists of several RF (Radio Frequency) readers installed in a flat and passive SAW RFID (Surface Acoustic Wave Radio Frequency Identification) tags wearing on the body. The localization system is based on ranging measurement. We prefer to use round-trip TOA (Time of Arrival) method to get the distances between readers and a tag. Then we get the tag position by using algebraic algorithms. A time-based ranging measurement system gets results with some uncertainty dependent on environmental factors, system absolute accuracy and time delay. The system has been implemented and simulated in Matlab.

The thesis is organized as follows. Chapter 2 reviews works related to indoor localization techniques and medical alarm systems. Chapter 3 briefly states our problem. Some theoretical background, system configuration and our feasible scenarios are introduced in the Chapter 4. In Chapter 5, we analyse system accuracy, make selection of the scenarios and put out simulation results in Matlab. This is followed by final conclusions and future work in Chapter 6. Matlab codes and simulation data for our indoor localization system are shown in the appendix.

Chapter 2
Survey of Related Work

The most known method for localization is LANDMARC [1] where the location is estimated from the known coordinates of landmarks, based on the ranging and/or bearing measurements between the object and the landmarks. The accuracy of LANDMARC depends on landmark layout, landmark number, target location distribution, and ranging error type.

Abdelmoula Bekkali et al. have worked out an indoor positioning system using landmarks [2]. Their algorithm estimates the target location from a measure of the reader-tags distance and target-landmarks distance based on RSS (Received Signal Strength). They also use Kalman filter and probabilistic map matching to make the system more accurate. The disadvantage of this method is that it requires many reference tags in order to get a good accuracy.

Jeffrey Hightower and Gaetano Borriello use SpotON-a finegrained indoor location sensing system based on RF signal strength for 3-D location sensing [3]. Their method is based on radio signal strength analysis. They designed and analysed a fine-grained indoor location sensing system using AIR ID (Adjustable Long Range Active ID). This approach combines the advantages of wireless location systems with that of infrared-based systems.

Diggelen put forward an indoor GPS theory and implementation [4]. He combined A-GPS (Assisted-GPS) into a system to localize the position of people. He created and implemented a new GPS receiver architecture in cell phones without significant effects on the size, cost or power consumption. In virtue of the cell-phone’s properties, this method can be realized in any common environment in daily life.

Most of localization systems are based on distance estimation. At present, there are several distance measurement methods using RFID techniques. Generally, the localization process is based on measurements in terms of RSSI (Received Signal Strength Indicator), AOA (Angle of Arrival), TOA (Time of Arrival) and TDOA (Time Difference of Arrival).

Srividya Iyer proved that RSSI is helpful in 2-D identification [5]. He uses the degree of signal attenuation to calculate the distance between tag and reader. If the tag is far away from the reader, the signal strength has big fading. On the contrary, if the tag is close to the reader the signal get stronger. Through this features and a geometric method, tag position can be found.

Zhou et al. used AOA measurement method to determine a radio-frequency wave incident on an antenna array [6]. Their modelling and experimental results show that the phase difference of two antennas can be used to estimate the AOA with satisfactory accuracy.

Gardner and Chen introduced a new class of method for signal selective TDOA estimation [7]. They propose a method with high tolerance to interference and noise in localization. Zou et al. use a passive UWB-RFID system and TDOA measurements to find the distance between each tag and reader [8]. For ED-based TOA estimation [8] using passive UWB-RFID tag, 0.3 ns mean absolute error corresponding to 10 cm is possible. Bechteler and Yenigün use SAW ID-Tags at 2.5 GHz and TOA in their distance estimation [9]. Due to the good time resolution of SAW ID-tag, their results show a distance accuracy of 15 cm.

Many works try to use the RSSI to calculate the position. However it is extremely difficult to define a relationship between RSSI and distance which can be used to gain the location. The signal strength attenuation is easily affected by the environment conditions. The RSSI depends more on many factors and the method accuracy is rather poor. The AOA method is more convenient and simpler when is implemented in 2-D area, but more complicated in 3-D. Also it is highly range dependent and small uncertainty in the angle measurement will result in a large location uncertainty. Under the high time resolution, TOA and TDOA are proved to have a very good accuracy [10].

Chapter 3
Problem Statement and Main Contributions

In a case of downfall of solitary elderly people, there is a strong demand to find a way to detect the emergency situations and inform the medical staff or guardians timely and automatically. So our main research problem is to find an accurate localization method to identify whether a person accidently falls. To realize the task, the precise position of body has to be estimated. Therefore, the main objective of our research is to find an accurate indoor body localization method.

In this paper, we presuppose an indoor area of 5 m×5 m×3 m. The two SAW-RFID tags are wearied on two relatively stable positions on a body. One can be placed on the waistband; the other one can be on the collar. Several RF readers placed in a room, to measure their distances to each tag using TOA. After getting the measurement results, applying matching algorithms such as trilateration or multilateration, the precise tag position can be estimated. Each distance obtained from TOA measurement, means that the tag lies on the spherical surface whose centre is the reader and radius is the range away from the reader to the tag. So the searched tag position is located at the intersection of the spherical surfaces with readers in centres. To get a 3-D location there is a need for at least three readers. The quantity of readers and where they are placed affect the feasibility and localization accuracy.

We analysed and then choose the most suitable number of readers and their positions. We proposed two scenarios: Scenarios A and B using 3 and 4 readers respectively. We define a height threshold which can be used to judge whether a person fell down or not. If all detected tags are below the threshold, the system concludes that the person felt down. The emergency message is sent to a suitable information centre.

The main contribution of our paper is to combine different methods in a way to get the accurate position of a body using SAW-RFID tags. The indoor localization algorithm is implemented in Matlab. We estimate the tag position coordinates using TOA measurements and solving spherical equations. We simulate and analyse the different readers' position setting, and find an optimum one.

Chapter 4
System design

4.1 Theoretical background

Localization techniques have been actively researched in recent years. GPS has been the most widely used tool for outdoor localization, however it is not suitable for indoor application. RFID is a good choice for indoor localization due to its price, feasibility and miniaturization. RFID has been invented and developed since 1948. One of the earliest papers exploring RFID was written by Harry Stockman "Communication by Means of Reflected Power" published in 1948 [11].

The RFID system is formed by three components, which are: tags, readers with transceivers and an enterprise system. There are two kinds of tags: passive tag and active tag. The passive tags draw their power from the received signal from a RFID reader through inductive coupling and then respond to the enquiry. The active tags normally run through transmission coupling and answer to the reader using internal power.

Using a conventional RFID-based localization system it is difficult to achieve a good performance and the positioning accuracy. We propose to use a particular kind of passive RFID-based tag which is so-called SAW-RFID or SAW-ID tag.

The SAW-RFID tag receives an incoming electromagnetic pulse and transmits corresponding outgoing signal which has been coded through reflectors in its inside acoustic path [12]. The tag generates a surface acoustic wave (SAW) after receiving an impulse signal through its antenna. Then the SAW is coded and reflected back to the transducer by the reflectors, and the tag transmits the regenerated outgoing signal through its antenna. Tags electrical components can consist of digital gauge to measure the time. The FPGA device used in the time counter can measure the time at resolution of 100 ps [13]. Thomas F. B. et al. using such a component applied to SAW-RFID tags, realize the time resolution of 500 ps [9]. This kind of tag can work under harsh environmental conditions and only needs low power pulse signals. The tag size and price are also reasonable for our specific case.

Trilateration is the most widely used localization method. Main idea of trilateration is to find relative location relationship between known reference nodes and detected node and then estimate the node position using a proper algorithm. Location information can be disclosed from the measured distances between searched node and each reference node. In a RFID case we measure the radio signal propagation time between the transmitters and the receiver, and then the distance is calculated as product of the propagation time and radio signal speed. After getting distances between several readers and one tag, different algorithms are used to gain the position of the tag. To get position in 3-D coordinates, at least three measurements are needed. Then, geometric algorithms extract location information from the measured distances. The trilateration equations can be described in many ways such as circles, spheres or triangles. Here, we represent a basic three spherical equations (1)-(3). Figure 4-1 illustrates a simple model of trilateration system.

$$R_1 = \sqrt{(X_1 - x)^2 + (Y_1 - y)^2 + (Z_1 - z)^2} \tag{1}$$

$$R_2 = \sqrt{(X_2 - x)^2 + (Y_2 - y)^2 + (Z_2 - z)^2} \tag{2}$$

$$R_3 = \sqrt{(X_3 - x)^2 + (Y_3 - y)^2 + (Z_3 - z)^2} \tag{3}$$

where (x,y,z) represents the tag position; (X_i,Y_i,Z_i) represents the known coordinates of the i-th RF reader. The tag position can be calculated from (1)-(3).

4.2 System structure

In this chapter, we present a model of indoor localization system using TOA based trilateration method. In free space, direct wave is the only path that exists. There is no multipath propagation such as reflected waves or diffractive waves. The used constants and variables are shown Tables 1 and Table 2 respectively.

Table 1. Constant Parameters

Name	Symbol	unit
Room length size	a	m
Room width size	b	m
Room height size	c	m
Light speed	C	m/s
Jitter	Jitter	ps
Time resolution	Δt	ns

Table 2. Variable

Name	Symbol	Unit
Tag position	(x,y,z)	m
i-th Reader's position	(X_i,Y_i,Z_i)	m
Distance between a detected Tag and Reader *i*	R_i	m
Real distance between Tag and Reader *i*	$R_i^{'}$	m
Distance from Tag to room edge	L	m
Distance from tag to room edge (critical value)	l	m
Uncertainty of the estimated distance between a tag and a reader	Δd	m
Round-trip TOA	t_i	s

4.2.1 Hardware arrangement

Our system consists of three basic components: SAW-RFID tags, readers and a controller. Each reader is connected to the central controller as shown in Figure 4-1. The readers send a pulse signals which are recognized by the SAW-RFID tag. The pulse signal form SAW-RFID tag is reflected to the reader.

The whole system is controlled by the central controller. It decides when and how often the readers should send pulse signals. The propagation time can be estimated by readers. Then the round-trip TOAs are transmitted to the central controller. Finally, the precise tag position is obtained using the TOAs and matched algebraic algorithm.

The schematic arrangement of the hardware is shown in Figure 4-1. We set readers at corners of the room to avoid interference of daily life.

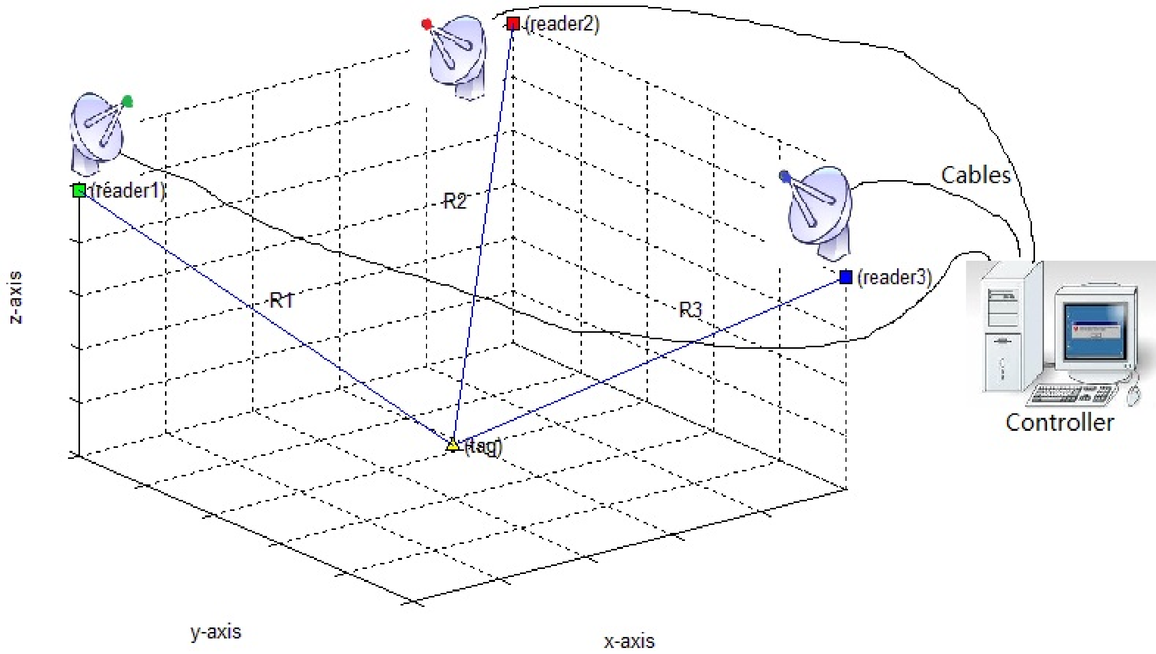

Figure 4-1. A simplified model of trilateration system for 3 readers

4.3 Localization Scenarios

Based on the theories and techniques of indoor localization, we conceive several ways to get the tag position. We choose two typical scenarios among them. In following subchapters, we firstly present a common solution as Scenario A, then based on scenario A, a relatively advanced scenario B is proposed.

4.3.1 Scenario A

In scenario A, the tag position is got from 3 distance estimations based on round-trip TOA measurements. For a 3-D indoor localization system, the three reader method is the simplest way to find the tag position.

To reduce complexity of the computational process, we set three readers at 3 top corners of the room (shown in Figure 4-2). The coordinates of three readers are as follow $Reader1=[0,b,c]$, $Reader2=[a,b,c]$, and $Reader3=[a,0,c]$. Using the coordinates into the algebraic equation set (1)-(3) it turns into:

$$R_1 = C \cdot \frac{t_1}{2} = \sqrt{(0-x)^2 + (b-y)^2 + (c-z)^2} \tag{4}$$

$$R_2 = C \cdot \frac{t_2}{2} = \sqrt{(a-x)^2 + (b-y)^2 + (c-z)^2} \tag{5}$$

$$R_3 = C \cdot \frac{t_3}{2} = \sqrt{(a-x)^2 + (0-y)^2 + (c-z)^2} \tag{6}$$

where t_i (i=1,2,3) represents the round-trip signal propagation time between the i-th RF reader and the tag.

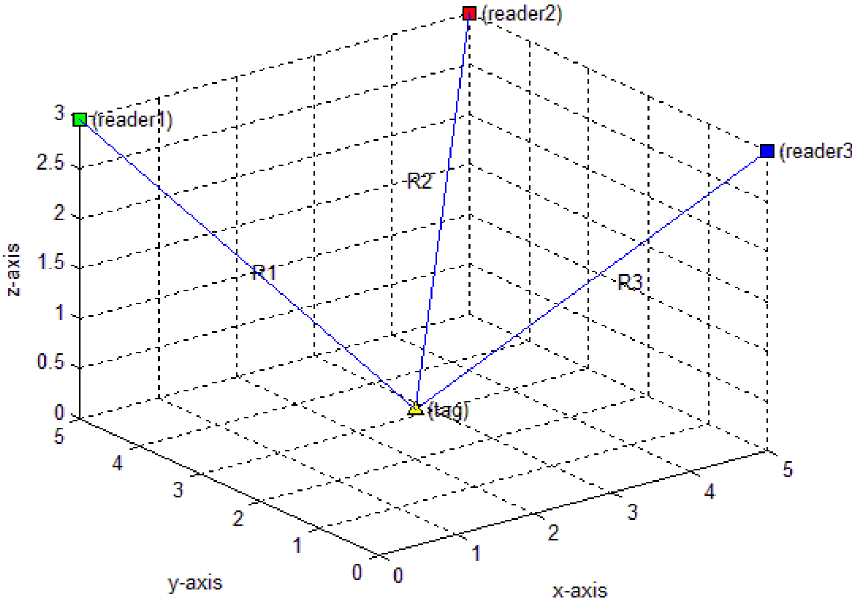

Figure 4-2. A model of Scenario A

Solving the equation set (4)-(6) we get:

$$\Rightarrow \begin{cases} x = \dfrac{R_1^{\,2} - R_2^{\,2} + a^2}{2a} \\ y = \dfrac{R_3^{\,2} - R_2^{\,2} + b^2}{2b} \\ z = c \pm \sqrt{R_1^{\,2} - \left(\dfrac{R_1^{\,2} - R_2^{\,2} + a^2}{2a}\right)^2 - \left(\dfrac{R_3^{\,2} - R_2^{\,2} + b^2}{2b} - b\right)^2} \end{cases} \tag{7}$$

The solution depicts two points. However due to room boundaries, z must be smaller than *c* (the height of the room), then:

$$\Rightarrow \begin{cases} x = \dfrac{R_1^{\ 2} - R_2^{\ 2} + a^2}{2a} \\ y = \dfrac{R_3^{\ 2} - R_2^{\ 2} + b^2}{2b} \\ z = c - \sqrt{R_1^{\ 2} - \left(\dfrac{R_1^{\ 2} - R_2^{\ 2} + a^2}{2a}\right)^2 - \left(\dfrac{R_3^{\ 2} - R_2^{\ 2} + b^2}{2b} - b\right)^2} \end{cases} \quad (8)$$

4.3.2 Scenario B

In scenario B, 4 readers shown in Figure 4-3 are used. The coordinates of the readers are: *Reader*1=[0,*b*,*c*], *Reader*3=[*a*,0,*c*], *Reader*4=[*a*,0,0] and *Reader*5=[0,*b*,0]. For convenience, we group *Reader*3 and *Reader*4 as *Group*1; *Reader*1 and *Reader*5 as *Group*2.

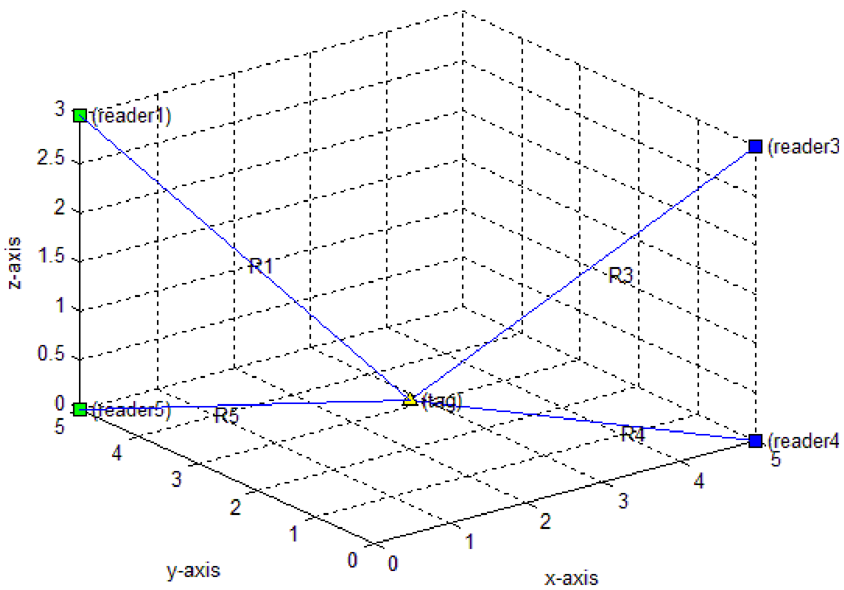

Figure 4-3. A model of Scenario B

In the Scenario B, as shown in the Figure 4-4 where *Reader*3 is placed at a top corner of the room and *Reader*4 is placed at the corresponding down corner. From data of these two readers we can get a z-coordinate of the tag which we depict as z'. To decrease the estimation uncertainty of tag height, we add another group of *Reader*1 and *Reader*5 as shown in Figure 4-3. Similarly, a tag z-coordinate got from *Reader*1 and *Reader*5 is depicted as z''. Then final z-coordinate is the mean value of z' and z''.

The tag lies on cross points of two spheres whose radii are R_3 and R_4 and their centres are the positions of *Reader*3 and *Reader*4 respectively. By analogy to 3 tag scenario, for 2 tags we can define a set of equations:

$$R_3 = \sqrt{(a-x)^2 + (0-y)^2 + (c-z')^2} \tag{9}$$

$$R_4 = \sqrt{(a-x)^2 + (0-y)^2 + (0-z')^2} \tag{10}$$

Solving the equation set (9) -(10) we get:

$$\Rightarrow z' = \frac{R_4{}^2 - R_3{}^2 + c^2}{2c} \tag{11}$$

From the Figures 4-4 and 4-5, and (11) we conclude that the intersection of two surfaces is a circle which is parallel to x-y plane. It means that the tag is located at a certain position on the circle. Using the same algorithm for z'', we get:

$$R_1 = \sqrt{(0-x)^2 + (b-y)^2 + (c-z'')^2} \tag{12}$$

$$R_5 = \sqrt{(0-x)^2 + (b-y)^2 + (0-z'')^2} \tag{13}$$

$$\Rightarrow z'' = \frac{R_5{}^2 - R_1{}^2 + c^2}{2c} \tag{14}$$

Then, the final average z-coordinate is:

$$z = \frac{z' + z''}{2} \tag{15}$$

$$z = \frac{R_4{}^2 - R_3{}^2 + R_5{}^2 - R_1{}^2 + 2c^2}{4c} \tag{16}$$

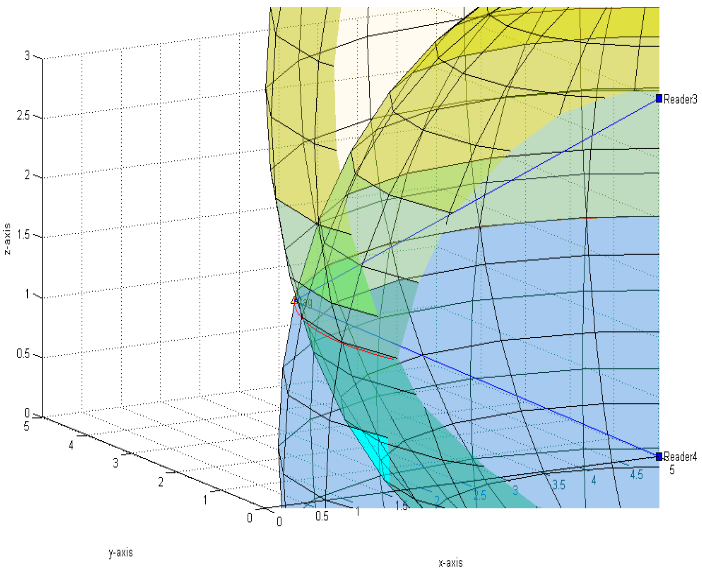

Figure 4-4. A model for intersection of two spherical surfaces

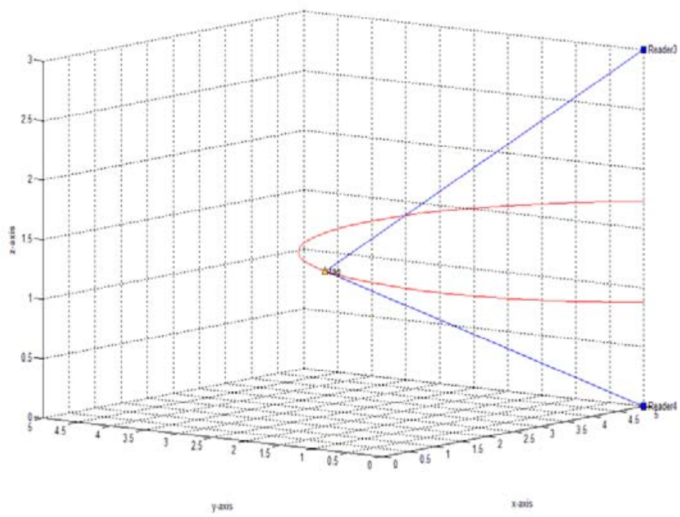

Figure 4-5. A circle (red line) formed by points of intersection

4.4 Analysis of method limitations

For the real time-based localization system, the TOA measurement uncertainty results from resolution of time counter and processing jitters of the system. This uncertainty directly affects the distance measurement uncertainty. The uncertainty in range measurement may increase in a case when no intersection points of spherical surfaces can be found. Due to disturbances in radio propagation path, the premise of the proposed two scenarios validity is that the spherical surfaces are tangent or intersect. Here we discuss whether non-intersection case can exist and how to solve this problem when it happens or how to avoid the problem situation. First, we discuss about a case of non-intersection for Scenario B. Then we analyze Scenario A.

In scenario B, spherical surfaces whose radii are R_3, R_4 and are centred on *Reader*3, *Reader*4 (*Group*1) respectively should intersect. The same should happen with spherical surfaces whose radii are R_1, R_4 and are centred on *Reader*1, *Reader*5 (*Group*2) respectively. Because the same algorithm are used for *Group*1 and *Group*2 (described in section 4.4), we consider only the non-intersection for *Group*1 (*Reader*3 and 4). For the 5 m×5 m×3 m indoor localization system, the distance between *Reader*3 and *Reader*4 is 3 m, and the line connecting the readers is perpendicular to the ground surface. Let L be the horizontal distance shown in Figure4-6, from the real tag to the room vertical edge where we set the two readers.

Here, we presume the maximum distance measurement uncertainty is $\pm \Delta d_{\max}$ =0.16 m which is found from a time measure resolution Δt =0.5 ns and maximum jitters. The detail uncertainty analysis is presented in Section 5.1. Then we need to find the region where the non–intersection case can happen. To simplify the analysis, we approach the problem in the 2-D plane. To find the whole region of the possible non-intersection case, we set the $\Delta d_{\max}$ in a way that the detected distance is shorter than real distance of $|\Delta d_{\max}|$, as shown in Figure 4-6. Figure 4-6 also shows the location of detected tag at the intersection points of the two spherical surfaces.

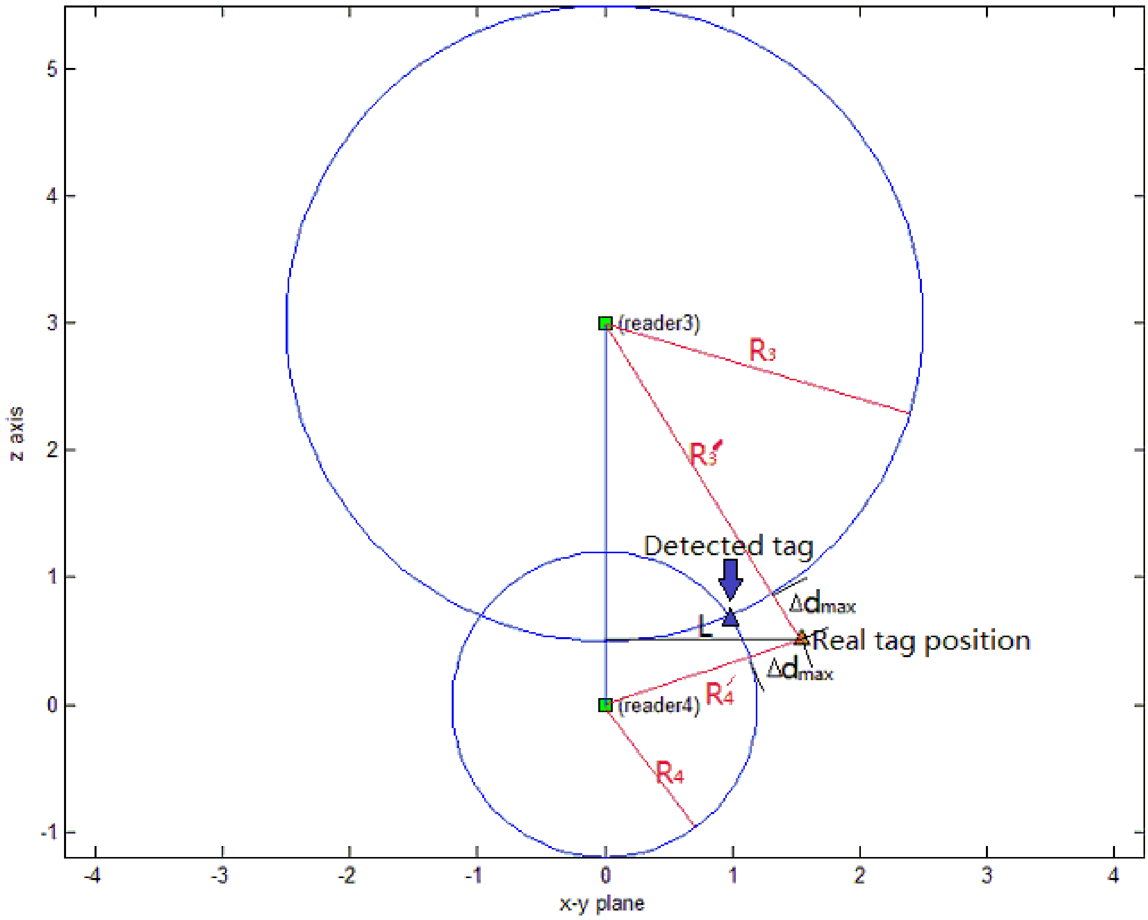

Figure 4-6. Intersection illustration for the cross case in 2-D

For the special case shown in Figure 4-7, the real tag is located very close to the vertical wall edge and the two spheres are tangent. We set the value *L* at this moment as critical value *l* (shown in Figure 4-7) such that for the same tag height value, if *L* is bigger than *l*, there must exist a cross point of the two spheres. Otherwise, if the tag is closer to the wall edge, there no exist cross point due to the distance measurement uncertainty what is illustrated in Figure4-8.

The equations (17) and (18) describe the boundary case that the circles are tangent at the point which is located on the wall edge (shown in Figure 4-7).

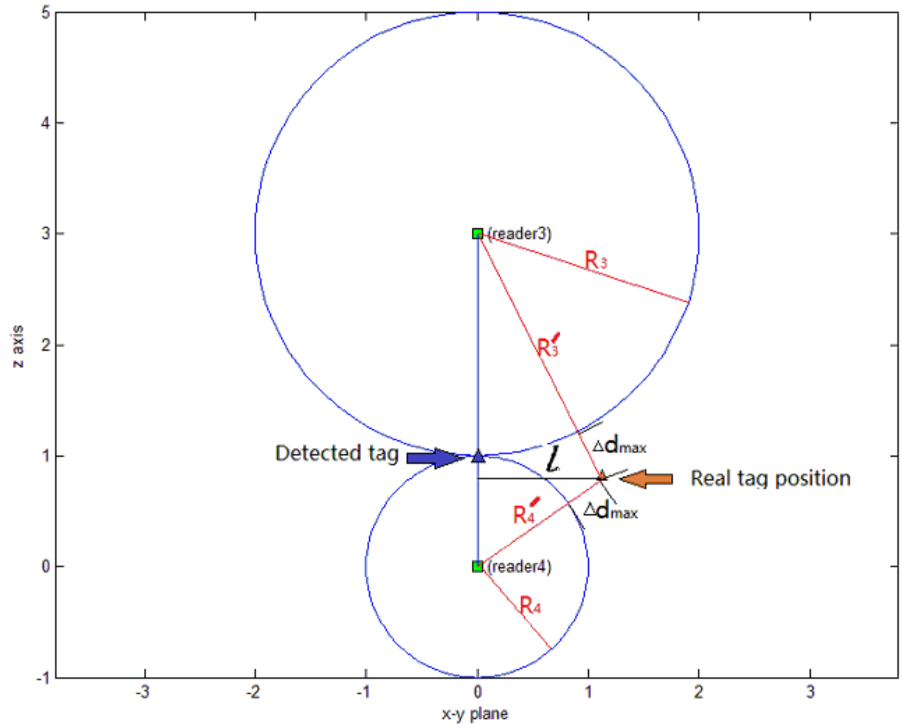

Figure 4-7. Intersection illustration for the tangent case in 2-D

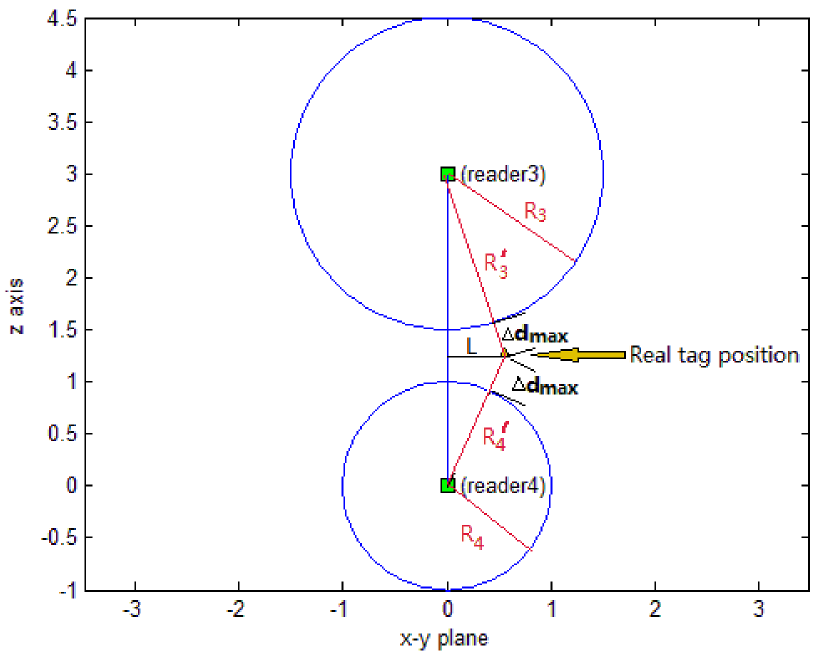

Figure 4-8. Intersection illustration for the non-intersection case in 2-D

$$\begin{cases} R_3'^2 = l^2 + (c-z)^2 \\ R_4'^2 = l^2 + z^2 \\ R_3 + R_4 = c \end{cases} \quad (17)$$

where $R_3 = R_3' - |\Delta d_{max}|$; $R_4 = R_4' - |\Delta d_{max}|$

$$\Rightarrow \sqrt{l^2 + z^2} + \sqrt{l^2 + (c-z)^2} - (2 \times |\Delta d_{max}| + c) = 0 \quad (18)$$

Now we consider the tangent situation for different *z* since find *l* as a function of *z*. From equation (18), for each *z* value, there always exists a corresponding value of *l*, as shown in Figure 4-9. It shows how *l* changes when the height of the tag varies. And when the height (*z*-coordinate of the tag) gets to the half of the room height, *l* reaches the biggest value of approximate 0.7 m what can be treated as the limitation of the method field of view.

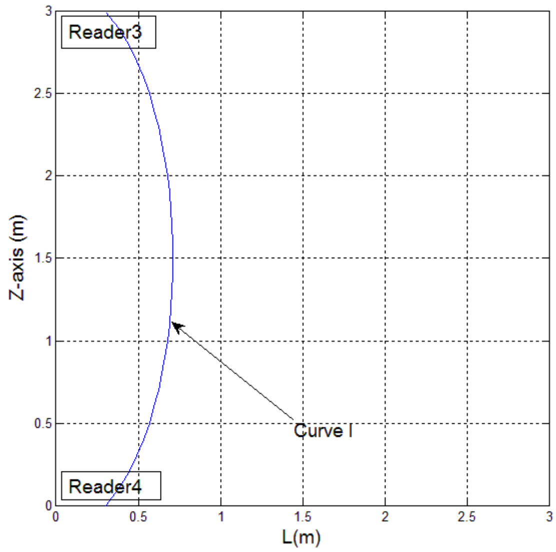

Figure 4-9. Region where non-intersection cases probably happen (left of blue curve)

When the tangent case (Figure 4-7) happens, the sum R_3+R_4 can be considered as equal to the distance between *Reader*3 and *Reader*4 equal to the room height *c*.

$$c = R_3 + R_4 \quad (19)$$

Inserting equation (19) into (11) we get:

$$z' = \frac{R_4^{\ 2} - R_3^{\ 2} + c^2}{2c} = \frac{R_4^{\ 2} - R_3^{\ 2} + (R_3 + R_4)^2}{2(R_3 + R_4)} = R_4 \qquad (20)$$

In this case, R_4 can be considered as tag height $h = R_4$, the height uncertainty of tag would be manageable and float under a controlled value.

When the non-intersection case (Figure 4-8) happens, the real tag position must be close to the wall edge. Using the previous solution (11) to get position is feasible, since the room height *c* is close to R_3+R_4, and the tag height position can be close to R_4 which is the solution (20).

The condition of Scenario A is that three spherical surfaces centred on *Reader*1, 2 and 3 must intersect. If not, a big uncertainty would happen. The three readers are set at top corners of the room. Three spherical surfaces are centred in *Reader*1, 2 and 3. The distance between *Reader*1 and *Reader*2 is 5 m. So when in the equation (18) *a* replaces *c* which is the distance between readers; and *x* replaces *z*, we get:

$$\Rightarrow \sqrt{l^2 + x^2} + \sqrt{l^2 + (a - x)^2} - (2 \times |\Delta d_{\max}| + a) = 0 \qquad (21)$$

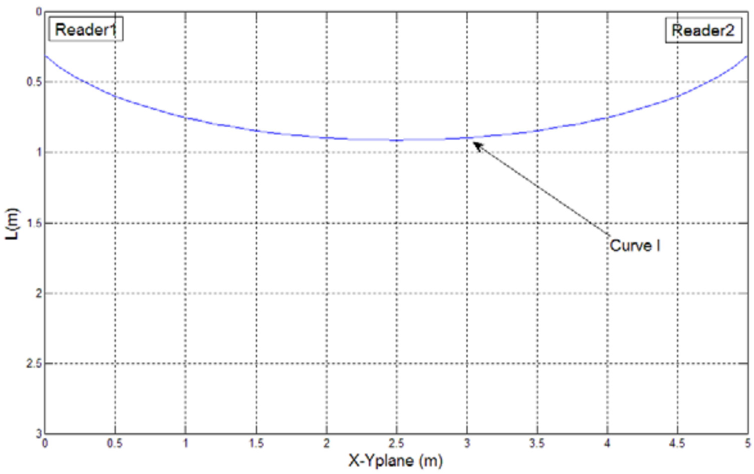

Figure 4-10. Region where non-intersection cases probably happen (above blue curve)

Then the maximum *l* of 0.9 m is found as shown in Figure4-10. Analogically, the maximum *L* can be evaluated for *Reader*2 and 3. Then for the situation of 5 m×5 m×3 m indoor area, the tag position cannot be closer to the ceiling than 0.9 m and man's height should be smaller than 1.8 m.

It can be concluded that for the thesis application field, the spherical surfaces centred on *Reader*1, *Reader*2 always intersect. The same case could also happen on *Reader*2 and *Reader*3. So the *x* and *y*-coordinates always can be found.

In reality a common-intersection of three spherical surfaces may not exist as shown in Fig4-11, then the value of *z*-coordinate can be found using interpolation algorithms.

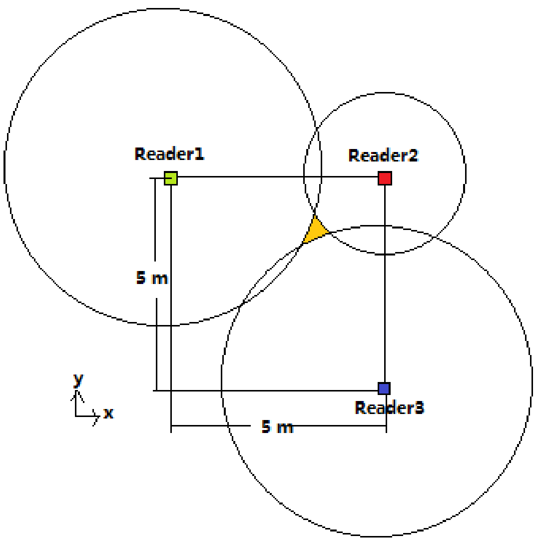

Figure 4-11. Non-intersection case of Scenario A

Chapter 5
Method verification

In this chapter, we validate the indoor localization system using TOA based-trilateration method. In this work, we assume the room size is 5 m×5 m×3 m and the system works under an ideal environmental condition, in free space, and direct wave is the only path that exists. There is no any multipath propagation such as reflected wave or diffractive wave. We set the parameters in the Tables 3.

Table 3. Values of Constant Parameters

Name	Symbol	Value	Unit
Room length size	a	5	m
Room width size	b	5	m
Room height size	c	3	m
Light speed	C	2.99792458×10^{8}	m/s
Jitter	Jitter	-600~+600	ps
Time resolution	Δt	0.1~5.0	ns

5.1 Accuracy analysis

TOA-based distance measurement uncertainty has been analysed in section 4.5. In this section, we study the accuracy of tag position detection. First, a real tag position (2.50, 2.50, 1.00) m is defined and the maximum TOA measurement uncertainty is assumed as Δt_{max}=(3.00+0.25) ns which is the combination of maximum jitters and half value of time resolution. This time accuracy results in a distance uncertainty of $\pm\Delta R_{max}$=±0.16 m.

5.1.1 Accuracy analysis of scenario A

For each TOA-based measurement distance, the distance can be defined as: $R_i = R_i' \pm \Delta R_{\max}$ (i=1, 2, 3…); here, R_i' is the real distance and R_i is the estimated distance. The hexahedron, a region, where the tag may be located, can be got from intersection of 3 spherical shells whose outer radii are $R_i' + \Delta R_{max}$ and inner radii are $R_i' - \Delta R_{max}$. The size of the hexahedron in z-axis differs when the position of the tag varies. For the worst case size and

$\pm\Delta R_{max}$=±0.16 m, the uncertainty between real tag and detected tag is less than 0.4 m. Figure 5-1 shows the area of probable position of detected tag in 3D which is approximately a hexahedron with curved surfaces.

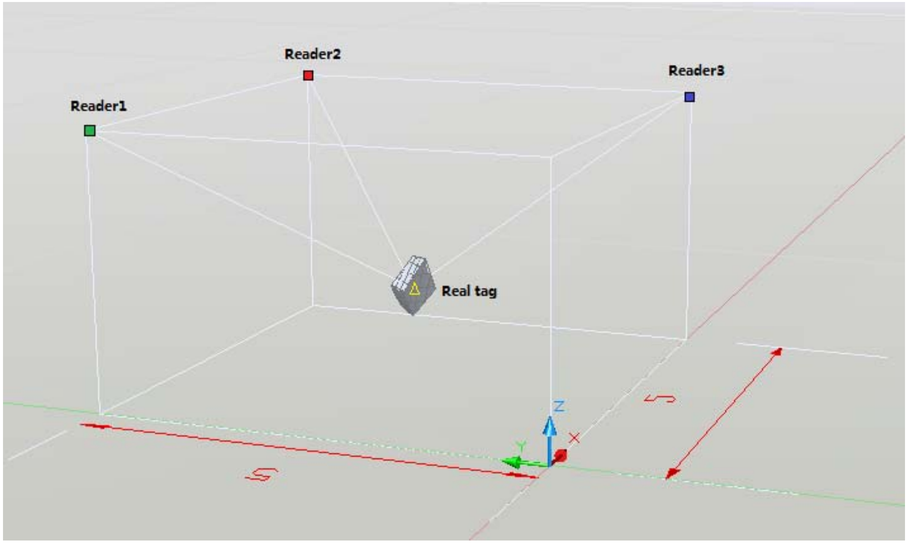

Figure 5-1. Probable positions of detected tag for Scenario A in 3-D

5.1.2 Accuracy analysis of Scenario B

In the same way as in section 5.1.1, the Scenario B real tag position is also set at (2.50, 2.50, 1.00) and $R_i = R_i' \pm \Delta R_{\max}$ (i=3, 4) where $\pm\Delta R_{max}$=±0.16 m, are the estimated distances.

The diamond area, shown in the Figure 5-2, represents the region where the detected tag could exist in the 2D model, where L is a distance to the room edge where we set *Reader*3 and *Reader*4. In Figure 5-3 the region is shown in 3-D. It is the intersection of two spherical shells. Here, the result also shows a maximum height uncertainty of 30 cm.

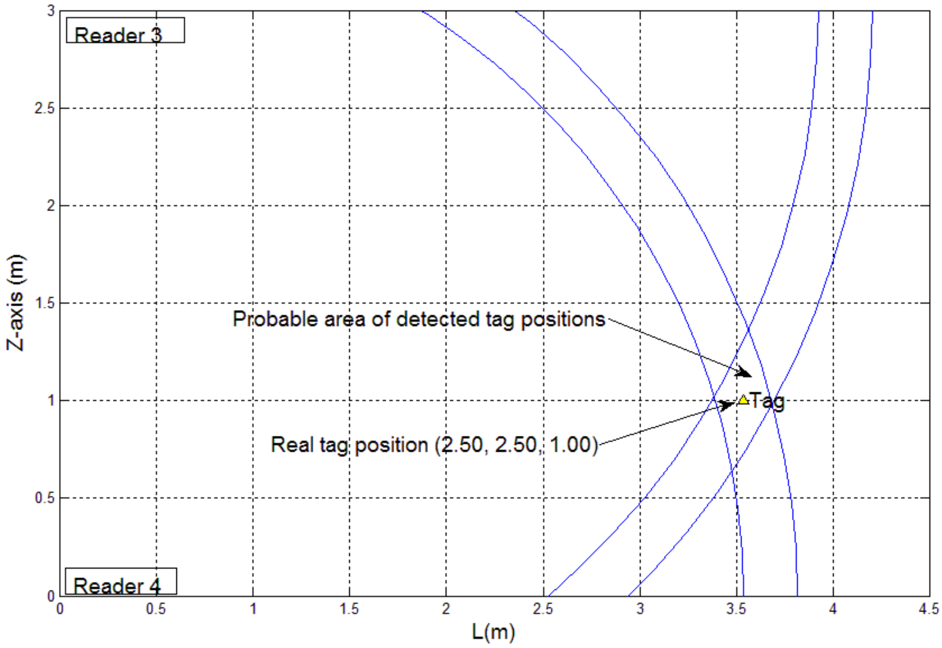

Figure 5-2. Area of possible positions of detected tag for Scenario B in 2-D

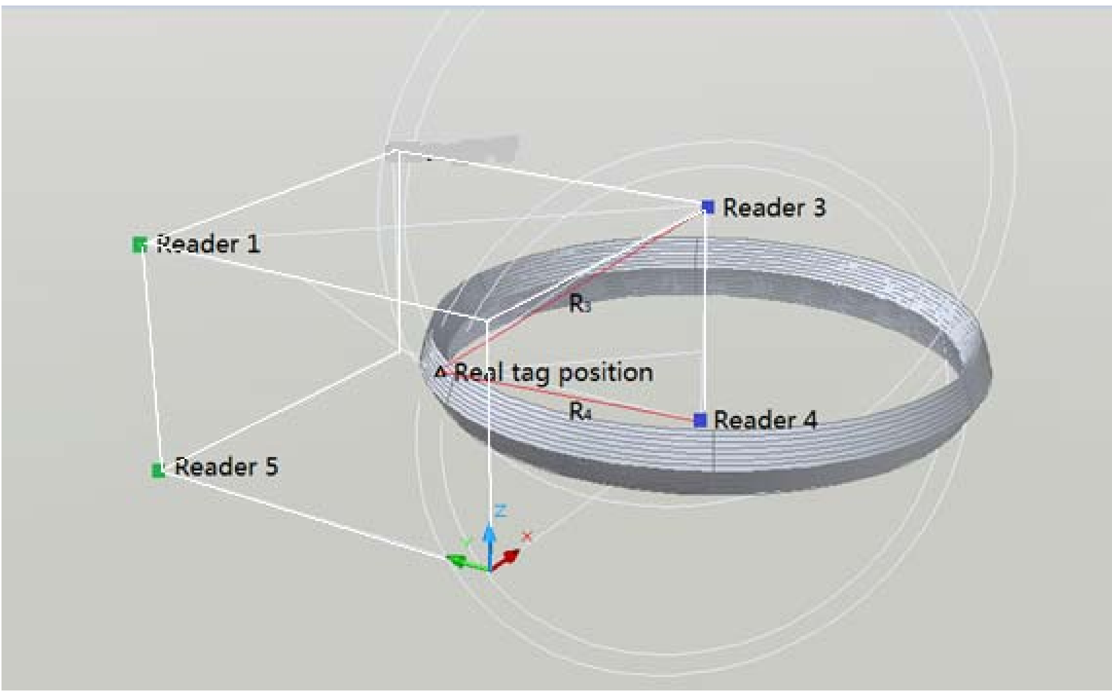

Figure 5-3. Probable positions of detected tag for Scenario B in 3-D

5.2 Choice of scenario and time resolution

To judge an influence of time resolution on the location accuracy we choose different time resolution with a step of 0.1 ns in an interval from 0.1 to 2.0 ns. For each time resolution, we put 100 000 random tag positions to find the maximum uncertainty of tag height. The same random positions are analysed for each time resolution.

Figure5-4 shows the simulation results for the two scenarios. The uncertainty in scenario A is much bigger than that in scenario B. The absolute uncertainty in scenario A is always larger than 1.25 m and it does not suit our system accuracy request. The blue line representing scenario B, suits our system requirements. The maximum absolute height uncertainty of tag goes to 30 cm corresponding.

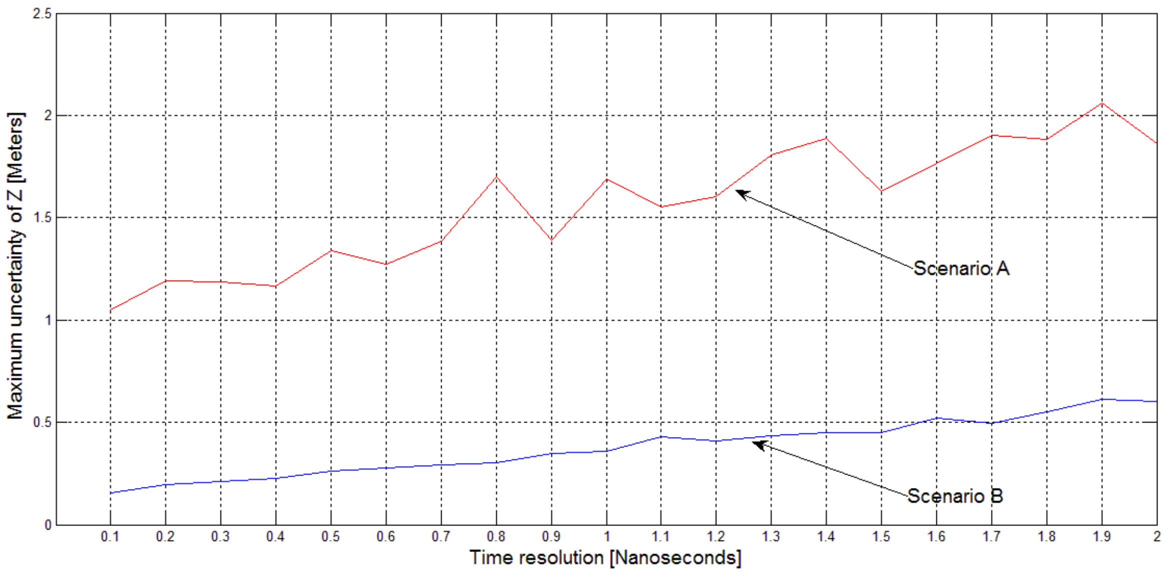

Figure 5-4. Absolute maximum height uncertainty of Scenario A and B
(the maximum absolute height uncertainty chosen from 100000 random tags)

Figure 5-5 shows *z*-coordinate uncertainty of tag using Scenario A and B with 100 running samples under the same time resolution of 0.5 ns, respectively. Compare the two uncertainty data, the Scenario B demonstrates a better quality than the Scenario A. The Scenario B shows also a relative gentle fluctuation less than 20 cm. The Scenario A does not avoid extreme case which is larger than 60 cm, but the most of cases are manageable under 40 cm.

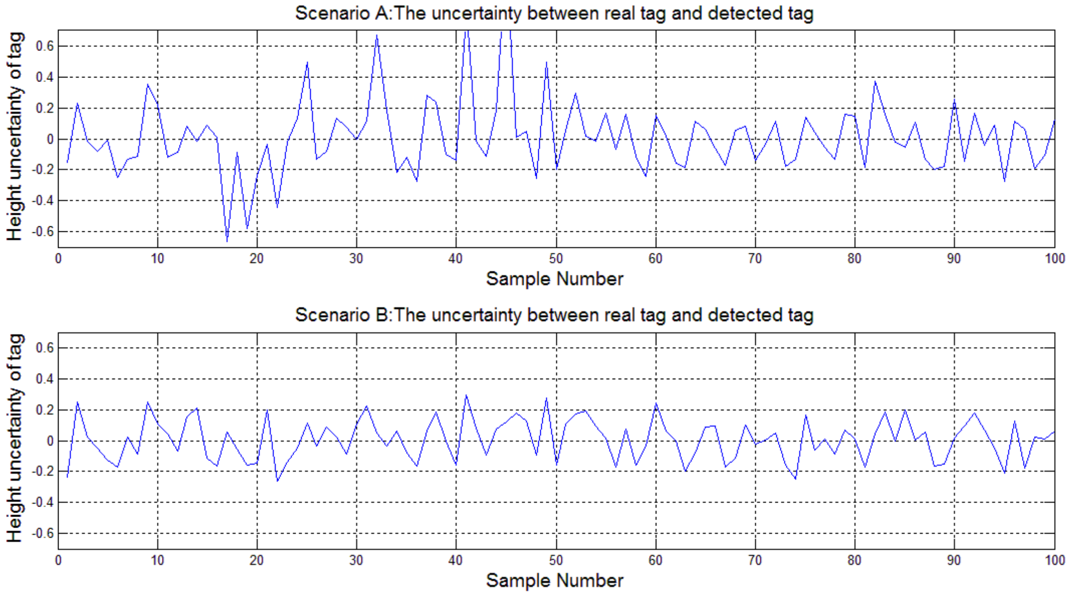

Figure 5-5. *z*-coordinate uncertainties for 100 samples
(uper Figure for the Scenario A and the lower Figure for Scenario B)

The simulation results shown in Figure 5-4, proves that scenario B has about 1 m smaller maximum uncertainty of *z*-coordinate than in Scenario A. This can be seen also in Figure 5-5 where Scenario B shows less uncertainty fluctuation. From the data in Figure 5-5, the mean value of absolute high estimation uncertainty for Scenario A is 0.014 m and for Scenario B is 0.009 m. And the standard deviation values of absolute uncertainty are 0.249 m and 0.136 m for Scenario A and Scenario B respectively. Because the mean values are nearly equal to 0 in both Scenario A and Scenario B in figure 5-5, so we consider another way to see the difference between two scenarios, using absolute value. Then we get absolute uncertainty values from the data in Figure 5-5, the mean value of absolute high estimation uncertainty for Scenario A is 0.17 m and for Scenario B is 0.11 m (shown in appendix). The uncertainty analyses come to a conclusion that the Scenario B is more appropriate solution for our application. Therefore we select scenario B to be our final scheme.

5.3 Case studies

In this section, we list the probable situation in Scenario B. We firstly define a height threshold value under height uncertainty allowance of 30 cm under the condition of time resolution $\Delta t = 0.5$ ns. Table 4 is the summary of all possible situations we considered.

Table 4. Definitions of height range of detected tags
(*Tag*1 on collar, *Tag*2 on waistband, the person is 180 cm tall)

	Standing on the floor	**Sitting on the chair**	**Falling on the floor**
*Tag*1	120~180 cm	80~140 cm	0~50 cm
*Tag*2	60~120 cm	20~80 cm	0~50 cm

We assume the monitored person is 180 cm tall. If the person stands on the floor, the tag on the waistband is found around 80 cm above the floor and the tag on collar is placed about 150 cm above the floor. Then for the distance estimation uncertainty below 30 cm, the tag on waistband can localized between 60 cm and 120 cm above the floor and the height of the tag on collar should be localized between 120 cm and 180 cm above the floor. If the person is sitting on the chair of about 40 cm high, it means one tag is localized approximately at 50 cm high and the other one is at about 110 cm. The estimated height of tag on waistband should be found between 20 cm and 80 cm and the height of the tag on collar should be found between 80 cm and 140 cm. In these two normal circumstances there is at least one tag which is found above 50 cm height.

So in our system, we choose the tumble detection threshold as 50 cm. If estimated heights of two tags are below 50 cm, the alarm function should be initiated. Through the above analysis, several cases can be defined:

1. Normal cases:
   1.1. Normal Case 1: *z*-coordinates of two tags are estimated above 50 cm;
   1.2. Normal Case 2: *z*-coordinate of one tag is localized upper than 50 cm and *z*-coordinate of another tag is below 50 cm.
2. Emergency Case: *z*-coordinates of two tags are localized below 50 cm high.

Actually, to realize the alarm function in Scenario B, one does not need to know the *x* and *y*-coordinates. But here we set extra *Reader*2 and use the same algorithm as in Scenario A to get *x* and *y*-coordinates to localize the tags in 3-D space. Accordingly to the equations (7), *x*-coordinate is got from R_1, R_2, and *y*-coordinate is get from R_2, R_3.

5.3.1 Validation of Normal Case 1

In this case, the position of two tags is above the tumble detection threshold. We assume that the person is standing on the floor. To validate the case we simulate in Matlab localisations of two tags, see Table 5. Figure 5-6 shows that the two tags are placed both above the assumed threshold 50 cm defined to judge the localization of the person.

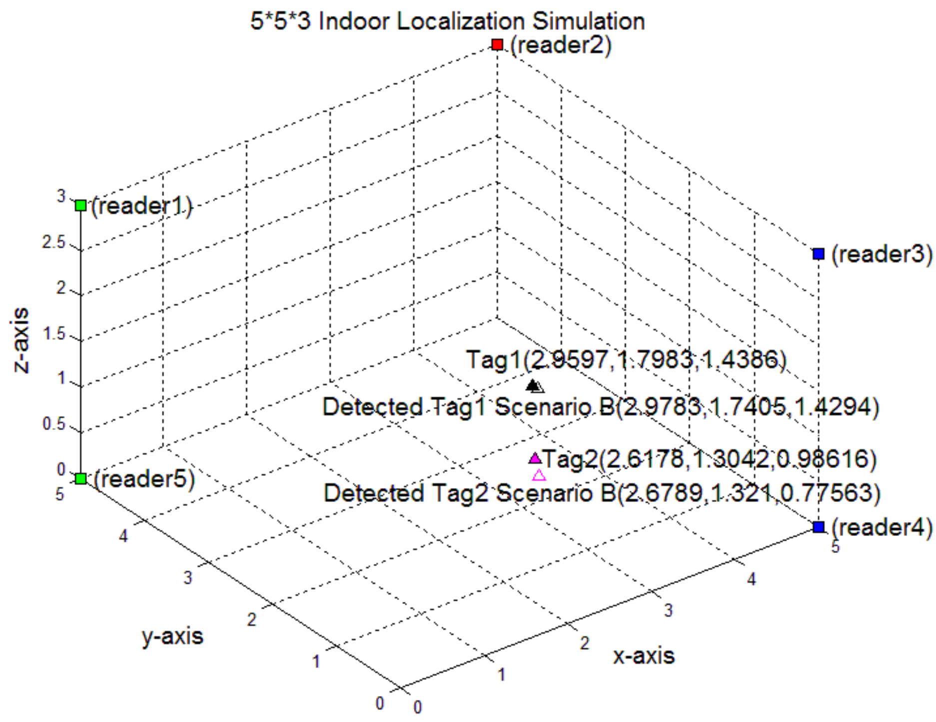

Figure 5-6. Matlab simulation result for Normal Case 1
(Solid triangles represent real tag position and hollow triangles represent detected tag position)

The difference in *z*-coordinate between real tag and detected tag is shown in Table 5. The table shows the uncertainties of tags and the method precision is sufficient for judging the position of a person.

Table 5. Matlab simulation results for Normal Case 1

	***Tag*1 (m)**	***Tag*2 (m)**
Real Position (x,y,z)	(2.96, 1.80, 1.44)	(2.62, 1.30, 0.99)
Scenario B (x,y,z)	(2.98, 1.74, 1.43)	(2.68, 1.32, 0.78)
x-coordinate estimation uncertainty	0.02	0.06
y-coordinate estimation uncertainty	0.06	0.02
z-coordinate estimation uncertainty	0.01	0.21
State Judgement	Standing on the floor	

5.3.2 Validation of Normal Case 2

In this case, the position of one tag is above the tumble detection threshold and the position of the second tag is below the threshold. We assumed that the person is seating in the armchair. To validate the case we simulate in Matlab placements of two tags, see Table 6. Figure 5-7 and Table 6 show that Tag1 is detected at the high upper than the threshold value and the other one below the value. From the information got from the tags, we can conclude that the person probably sits on the chair or bedside.

Table 6. Matlab simulation results for Normal Case 2

	***Tag*1 (m)**	***Tag*2 (m)**
Real Position (*x*,*y*,*z*)	(1.50, 2.55, 1.11)	(1.11, 2.23, 0.39)
Scenario B (*x*,*y*,*z*)	(1.43, 2.55, 0.97)	(1.13, 2.42, 0.43)
x-coordinate estimation uncertainty	0.07	0.02
y-coordinate estimation uncertainty	0.00	0.19
Height estimation uncertainty	0.14	0.04
State Judgement	Sitting on the chair	

5.3.3 Emergency Case

In this case, the positions of two tags are below the tumble detection threshold. We assumed that the person felt down. To validate the case we simulate in Matlab placements of two tags, see Table 7. Figure5-8 and Table 7 show two tags placed and detected below the tumble detection threshold value 50 cm. We can conclude, the person is tumbling over the floor and the alarm function should start to work.

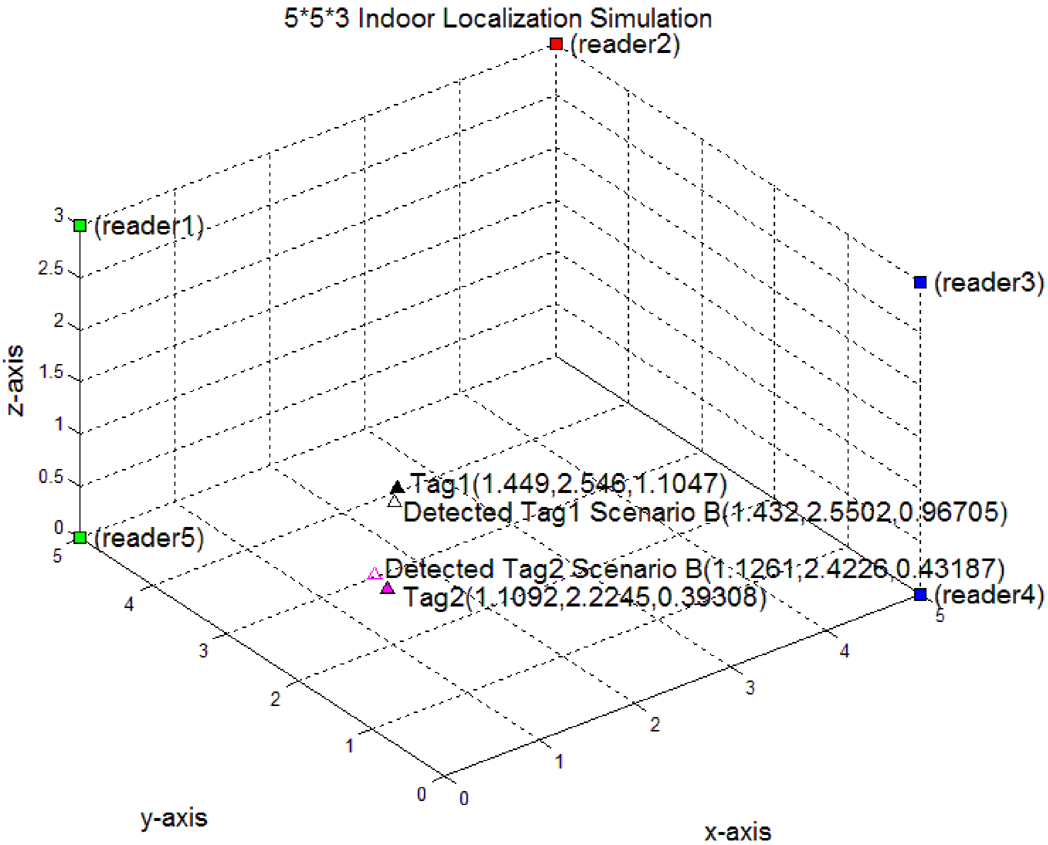

Figure 5-7. Matlab simulation result for case 2
(Solid triangles represent real tag position and hollow triangles represent detected tag position)

Table 7. Matlab simulation results for case 3

	***Tag*1 (m)**	***Tag*2 (m)**
Real Position (*x*,*y*,*z*)	(0.73, 3.73, 0.15)	(1.16, 3.65, 0.28)
Scenario B (*x*,*y*,*z*)	(0.85, 3.83, 0.09)	(1.24, 3.56, 0.37)
x-coordinate estimation uncertainty	0.12	0.08
y-coordinate estimation uncertainty	0.10	0.09
Height Uncertainty of Scenario B	0.06	0.09
State Judgement	Tumbling over the floor	

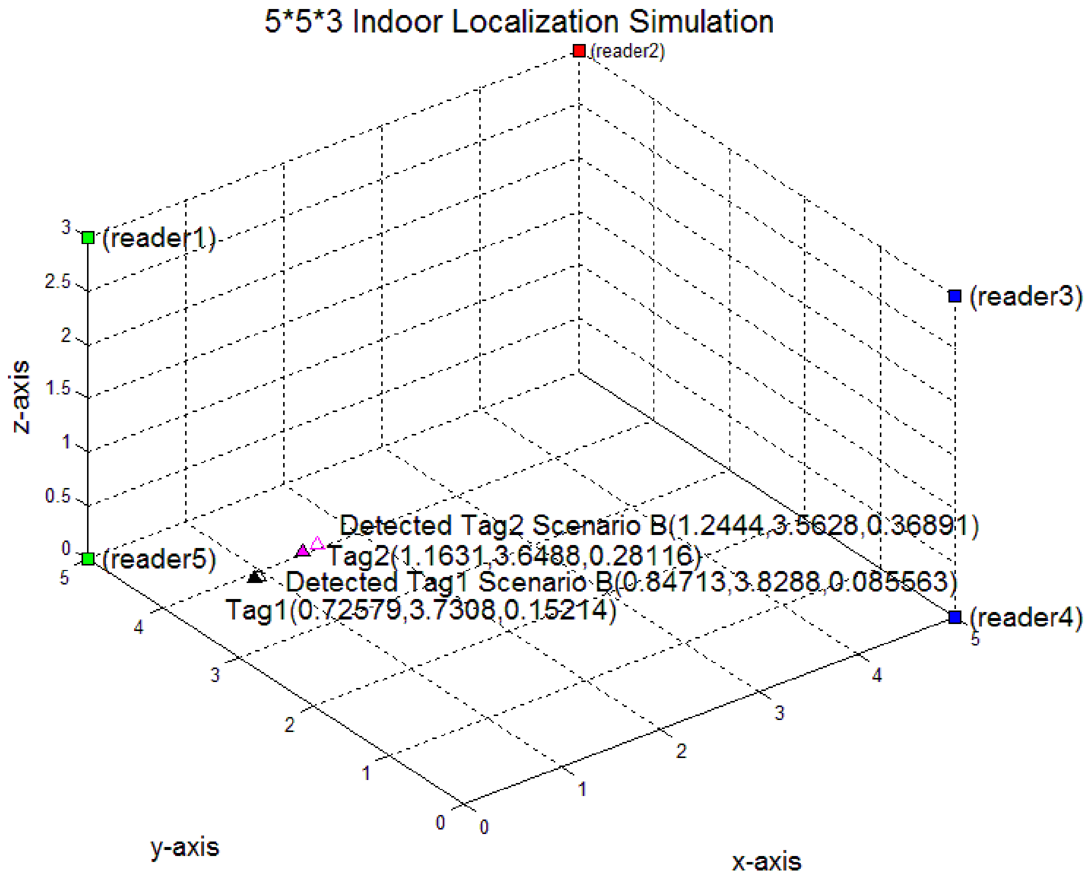

Figure 5-8. Matlab simulation result for case 3
Solid triangles represent real tag position and hollow triangles represent detected tag position

Normal Case 1 and 2 correspond to the normal positions of the person when there are no emergency circumstances and the person is safe. In Emergency Case the two detected tags are localized below the critical high threshold which was defined beforehand. From Figures 5.6-5.8 and Tables 5-7, it can be concluded that the localization system performs correctly in the assumed height estimation uncertainties of 30 cm. The tumble detection function of a person works properly and accomplishes the anticipated goal.

Chapter 6
Conclusion and Future Work

Many systems and designs based on RFID technology are proposed for indoor localization. In this work, we present an indoor wireless localization method applied for emergency monitoring. Many people consider location tracking to be a threat to personal privacy and security, especially when cameras are used. However due to a used technology our solution decreases the threat of individual privacy.

Exploiting round-trip TOA measurement and trilateration-based algorithm, we are able to detect position of RFID tags. For time-based location detection techniques, resolution of time measurement is the greatest barrier of accurate localization. The SAW ID-tag technology contributes to the accuracy enhancements.

Emergency system for tumble detection of solitary people using SAW-RFID tags is proposed in our paper. As shown by all theoretical analysis, simulation results and uncertainty analysis, our system demonstrates a good quality of a height estimation uncertainty under 30 cm. The simulation data are got under conditions that the time counter has resolution of 0.5 ns and jitters is ± 600 ps.

In the future, our localization system can be prototyped and the experimental results should verify presented theoretical analysis and simulation results. The analysis could be complemented with statistical approach. The location system can be completed by a telecommunication part to become an autonomous mobile remote monitoring system.

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Appendix

Matlab codes

```
clc
clear all
close all
a=5;b=5;c=3;%The size of the room,a is in direction of x-coordinate, b is
in direction of y-coordinate
xreader1=0;%Reader 1
yreader1=b;
zreader1=c;
plot3 (xreader1,yreader1,zreader1, 'ks', 'MarkerFaceColor','g')
Reader1=[xreader1,yreader1,zreader1];
xreader2=a;%Reader 2
yreader2=b;
zreader2=c;
Reader2=[xreader2,yreader2,zreader2];
hold on
plot3 (xreader2,yreader2,zreader2, 'ks', 'MarkerFaceColor','r')
xreader3=a;%Reader 3
yreader3=0;
zreader3=c;
Reader3=[xreader3,yreader3,zreader3];
plot3 (xreader3,yreader3,zreader3, 'ks', 'MarkerFaceColor','b')
xreader4=a;%Reader 4
yreader4=0;
zreader4=0;
Reader4=[xreader4,yreader4,zreader4];
plot3 (xreader4,yreader4,zreader4, 'ks', 'MarkerFaceColor','b')
xreader5=0;%Reader 5
yreader5=b;
zreader5=0;
Reader5=[xreader5,yreader5,zreader5];
plot3 (xreader5,yreader5,zreader5, 'ks', 'MarkerFaceColor','g')

axis equal
xlabel('x-axis');
ylabel('y-axis');
zlabel('z-axis');


r1=rand(1,3)*5;%Tag 1
xtag1=r1(1);
ytag1=r1(2);
ztag1=r1(3)*2/5;
P1=[xtag1 ytag1 ztag1];

r2=rand(1,3)*5;%Tag 2
xtag2=r2(1);
ytag2=r2(2);
ztag2=r2(3)*2/5;
P2=[xtag2 ytag2 ztag2];
```

```
D=sqrt((xtag1-xtag2)^2+(ytag1-ytag2)^2+(ztag1-ztag2)^2);

%make the distance between tag1 and tag2 is smaller than 1m
while D>1
r1=rand(1,3)*5;
xtag1=r1(1);
ytag1=r1(2);
ztag1=r1(3)*2/5;
P1=[xtag1 ytag1 ztag1];

r2=rand(1,3)*5;
xtag2=r2(1);
ytag2=r2(2);
ztag2=r2(3)*2/5;
P2=[xtag2 ytag2 ztag2];
D=sqrt((xtag1-xtag2)^2+(ytag1-ytag2)^2+(ztag1-ztag2)^2);
   if D<1
       break
   end
end
% format long
% D
% fprintf('The distance of two tags is %6.16f\r\n',D);

plot3 (xtag1,ytag1,ztag1, 'k^', 'MarkerFaceColor','k')
text(xtag1,ytag1,ztag1,[' Tag1' '(' num2str(xtag1) ','  num2str(ytag1) ','
num2str(ztag1) ')']);
plot3 (xtag2,ytag2,ztag2, 'k^', 'MarkerFaceColor','m')
text(xtag2,ytag2,ztag2,[' Tag2' '(' num2str(xtag2) ','  num2str(ytag2) ','
num2str(ztag2) ')']);

%real distance between two tags and readers
Dt1r1=sqrt((xtag1-xreader1)^2+(ytag1-yreader1)^2+(ztag1-
zreader1)^2);%actual distance between tag1 and reader1
Dt1r2=sqrt((xtag1-xreader2)^2+(ytag1-yreader2)^2+(ztag1-
zreader2)^2);%actual distance between tag1 and reader2
Dt1r3=sqrt((xtag1-xreader3)^2+(ytag1-yreader3)^2+(ztag1-
zreader3)^2);%actual distance between tag1 and reader3
Dt1r4=sqrt((xtag1-xreader4)^2+(ytag1-yreader4)^2+(ztag1-
zreader4)^2);%actual distance between tag1 and reader4
Dt1r5=sqrt((xtag1-xreader5)^2+(ytag1-yreader5)^2+(ztag1-
zreader5)^2);%actual distance between tag1 and reader5

Dt2r1=sqrt((xtag2-xreader1)^2+(ytag2-yreader1)^2+(ztag2-
zreader1)^2);%actual distance between tag2 and reader1
Dt2r2=sqrt((xtag2-xreader2)^2+(ytag2-yreader2)^2+(ztag2-
zreader2)^2);%actual distance between tag2 and reader2
Dt2r3=sqrt((xtag2-xreader3)^2+(ytag2-yreader3)^2+(ztag2-
zreader3)^2);%actual distance between tag2 and reader3
Dt2r4=sqrt((xtag2-xreader4)^2+(ytag2-yreader4)^2+(ztag2-
zreader4)^2);%actual distance between tag2 and reader4
Dt2r5=sqrt((xtag2-xreader5)^2+(ytag2-yreader5)^2+(ztag2-
zreader5)^2);%actual distance between tag2 and reader5
```

```
%create temporary distance(unreal) between tag1 and readers.....
%antenna frequency is 2.45GHZ,T=1/2.45*1e-9
%dt(m)r(n)is the distance contain E errors, it is a calculate
%value.m-tag number,n-readernumber
C=2.99792458*1e8;
T=0.5*1e-9;
jitter=600e-12;%new add
E=(T+jitter)/2*C;
tp=0.5e-3;
Tstep=T+jitter;

for t1=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt1r1=(t1-tp)/2*C;
    if abs(Dt1r1-dt1r1)<=E
        break
    end
end

for t2=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt1r2=(t2-tp)/2*C;
    if abs(Dt1r2-dt1r2)<=E
        break
    end
end
for t3=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt1r3=(t3-tp)/2*C;
    if abs(Dt1r3-dt1r3)<=E
        break
    end
end
for t4=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt1r4=(t4-tp)/2*C;
    if abs(Dt1r4-dt1r4)<=E
        break
    end
end
for t5=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt1r5=(t5-tp)/2*C;
    if abs(Dt1r5-dt1r5)<=E
        break
    end
end

%create temporary distance between tag2 and readers

for t6=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt2r1=(t6-tp)/2*C;
    if abs(Dt2r1-dt2r1)<E
        break
    end
end
for t7=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt2r2=(t7-tp)/2*C;
    if abs(Dt2r2-dt2r2)<E
        break
    end
```

```
end
for t8=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt2r3=(t8-tp)/2*C;
    if abs(Dt2r3-dt2r3)<E
        break
    end
end
for t9=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt2r4=(t9-tp)/2*C;
    if abs(Dt2r4-dt2r4)<E
        break
    end
end
for t10=tp:Tstep:2*sqrt(a^2+b^2+c^2)/C+tp
    dt2r5=(t10-tp)/2*C;
    if abs(Dt2r5-dt2r5)<E
        break
    end
end
%Tag1
%Scenario A
% radiit1r1=sqrt((x-r1x)^2+(y-r1y)^2+(z-r1z)^2);
% radiit1r2=sqrt((x-r2x)^2+(y-r2y)^2+(z-r2z)^2);
% radiit1r3=sqrt((x-r2x)^2+(y-r1y)^2+(z-r2z)^2);
%calcuate the fomular x,y,z
%condition1 tag1 and reader 123
x11=(dt1r1^2-dt1r2^2+a^2)/(2*a);%x1,y1,z1
y11=(dt1r3^2-dt1r2^2+b^2)/(2*b);
z11=c-sqrt(dt1r1^2-x11^2-(y11-b)^2);
% abs(z11-ztag1)
% z11,ztag1

%Scenario B
%condition2 tag1 and reader 34
% radiit1r3=sqrt((x-a)^2+(y-0)^2+(z-c)^2);
% radiit1r4=sqrt((x-a)^2+(y-0)^2+(z-0)^2);
z12=(dt1r4^2-dt1r3^2+c^2)/(2*c);
%condition3 tag1 and reader 15
% radiit1r1=sqrt((x-0)^2+(y-b)^2+(z-c)^2);
% radiit1r5=sqrt((x-0)^2+(y-b)^2+(z-0)^2);
z13=(dt1r5^2-dt1r1^2+c^2)/(2*c);
format long
zaverage1=(z12+z13)/2;%average Tag1

%Tag2
%Scenario A
%condition1 tag2 and reader 123
x21=(dt2r1^2-dt2r2^2+a^2)/(2*a);
y21=(dt2r3^2-dt2r2^2+b^2)/(2*b);
z21=c-sqrt(dt2r1^2-x21^2-(y21-b)^2);
% z21,ztag2,

%Scenario B
%condition2 tag2 and reader 34
% radiit1r3=sqrt((x-a)^2+(y-0)^2+(z-c)^2);
% radiit1r4=sqrt((x-a)^2+(y-0)^2+(z-0)^2);
```

```
z22=(dt2r4^2-dt2r3^2+c^2)/(2*c);
%condition3 tag2 and reader 15
% radiit1r1=sqrt((x-0)^2+(y-b)^2+(z-c)^2);
% radiit1r5=sqrt((x-0)^2+(y-b)^2+(z-0)^2);
z23=(dt2r5^2-dt2r1^2+c^2)/(2*c);
format long
zaverage2=(z22+z23)/2;% average Tag2
% abs(z21-ztag2)

plot3(x11,y11,z11,'ks')
text(x11,y11,z11,[' Detected Tag1 Scenario A' '(' num2str(x11) ','
num2str(y11) ',' num2str(z11) ')'])
plot3(x21,y21,z21,'ms')
text(x21,y21,z21,[' Detected Tag2 Scenario A' '(' num2str(x21) ','
num2str(y21) ',' num2str(z21) ')'])
plot3 (x11,y11,zaverage1, 'k^')
text(x11,y11,zaverage1,[' Detected Tag1 Scenario B' '(' num2str(x11) ','
num2str(y11) ',' num2str(zaverage1) ')']);
plot3 (x21,y21,zaverage2, 'm^')
text(x21,y21,zaverage2,[' Detected Tag2 Scenario B' '(' num2str(x21) ','
num2str(y21) ',' num2str(zaverage2) ')']);

% fprintf('Scenario A: The uncertainty between random tag1(real) and
detected tag1 is %6.16f meters\r\n',abs(z11-ztag1));
% fprintf('Scenario A: The uncertainty between random tag2(real) and
detected tag2 is %6.16f meters\r\n',abs(z21-ztag2));
fprintf('Scenario B: The uncertainty between random tag1(real) and detected
tag1 is %6.16f meters\r\n',abs(zaverage1-ztag1));
fprintf('Scenario B: The uncertainty between random tag2(real) and detected
tag2 is %6.16f meters\r\n',abs(zaverage2-ztag2));

text(xreader1,yreader1,zreader1,['  (' 'reader1' ')']);
text(xreader2,yreader2,zreader2,['  (' 'reader2' ')']);
text(xreader3,yreader3,zreader3,['  (' 'reader3' ')']);
text(xreader4,yreader4,zreader4,['  (' 'reader4' ')']);
text(xreader5,yreader5,zreader5,['  (' 'reader5' ')']);
axis([0 a 0 b 0 c])
grid on
hold off


if zaverage1<0.5&&zaverage2<0.5
     fprintf('The person falls down the floor-ALarm: Two tags all below 0.5
meters\r\n ')
end
if zaverage1>0.5&&zaverage2>0.5
      fprintf('The person stands on the floor-Normal state: Two tags all up
0.5 meters\r\n')
end

 if (zaverage1<0.5&&zaverage2>0.5)||(zaverage1>0.5&&zaverage2<0.5)
     fprintf('The person sits on the chair-Normal state: One tag up 0.5
meters, the other below 0.5 meters\r\n')
 end
```

```
fprintf('Detected Z-coordinate of tag1 is %6.16f meters\r\n',zaverage1)
fprintf('Detected Z-coordinate of tag2 is %6.16f meters\r\n',zaverage2)
fprintf('Real Z-coordinate of tag1 is %6.16f meters\r\n',ztag1)
fprintf('Real Z-coordinate of tag2 is %6.16f meters\r\n',ztag2)
title('5*5*3 Indoor Localization Simulation')
```