Performance Study of MTx Motion Tracker Technology for Indoor Geolocation

A Major Qualifying Project, submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science

Submitted by:

Giselle Lewars ______________________________

Minh Truong ______________________________

Submitted to:

____

Project Advisor: Professor Kaveh Pahlavan

Abstract

The objective of this project is to explore the characteristics of inertial systems by using the MTx Motion Tracker technology for indoor geolocation. MTx is an inertial sensing technology that can be used to provide position data without the use of external reference sources. Xsens Technologies from Netherlands has developed this device to record parameters relating to dynamic movements. This inertial measurement unit includes three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular orientation with respect to a fixed coordinates and acceleration in the coordinate of the device. We used these parameters to track the relative positioning and orientation of the device with respect to a known starting location in an indoor environment. We developed a test-bed for performance evaluations to determine the precision of the MTx Motion Tracker. This test-bed is based on two conducted experiments carried out to evaluate the operation of the device. In each experiment, raw acceleration and relative angles data are collected and implemented in our algorithms through the MATLAB software to evaluate the MTx performance.

Acknowledgements

We would like to sincerely thank individually the efforts of the people that aided in making this Major Qualifying Project a very memorable and interesting experience.

Firstly, we would like to thank our advisor, Dr Kaveh Pahlavan, for extending the opportunity of learning about this new industry. For all of the time and effort he put into ensuring that he was there to help us in meetings. Thank you for keeping us motivated.

Secondly, we would like to show our gratitude to Doctor of Philosophy students, Ferit Akgul and Yunxing Ye for trying to help us along during Dr. Pahlavan's absence. Thank you for being so positive towards our project and trying to help in any way possible.

Lastly, we would like to thank Graduate student, Yi Wang for contributing ideas to the project and Brian Roberts for introducing the project to the team.

We would like to extend our gratitude and express our thanks once again.

Table of Contents

Acknowledgements 3

Table of Contents 4

Table of Figures 6

1. Introduction 7

 1.1 Motivations for the Project 7

 1.2 Description of the Project 9

 1.3 Structure of the Project Report 11

2. Overview of Localization Techniques 13

 2.1 The Localization Industry and its Challenges 13

  2.1.1 Direction-Based Techniques 15

  2.1.2 Distance-Based Techniques 16

  2.1.3 Fingerprinting-Based Techniques 19

 2.2 Performance Measures of Geolocation Systems 20

 2.3 Comparing Geolocation Techniques 20

3. Principle of Operation of MTx Motion Tracking System 21

 3.1 An Overview of Inertial Systems using the MTx System 21

 3.2 The Motion Tracker Output 25

  3.2.1 Calibrated Data Coordinate System 25

  3.2.2 Orientation Coordinate System 26

4. Exploration and Test of MTx Motion Tracker 33

 4.1 Exploration of the MTx Technology 33

  4.1.1 Previous Work 33

  4.1.2 Understanding of the MTx Motion Tracker 33

 4.2 Test Experiments for Performance Accuracy 37

5. Experimental Results 39

 5.1 Device and Fixed Coordinates 39

 5.2 Plots of Acceleration, Euler Angles, Velocity and Distance 39

  5.2.1 Acceleration 40

  5.2.2 Euler Angles 42

5.2.3 Velocity 44

5.2.4 Distance.. 46

5.3 Final Mappings 48

6. Summary and Conclusion.. 50

6.1 Future Recommendations 51

References 52

Appendix 53

Table of Figures

Figure 1 -The Complete Xsens Motion Tracker Device Kit 10
Figure 2 - Angle of Arrival Geolocation Technique 16
Figure 3 - Direction Based Geolocation Technique 18
Figure 4 - MTx System Overview 22
Figure 5 - MTx with Sensor-fixed Coordinate System Overlaid 26
Figure 6 -Device Coordinate Reference Frame versus Earth Fixed Reference Coordinate Frame 27
Figure 7 - three Dimensional Orientation Output 28
Figure 8 -The fixed coordinate system of Euler Angles 29
Figure 9 - MTx Motion Tracker Setup 34
Figure 10 – MT Manager Output Sample 35
Figure 11 - Sample Display of Measurement Values 36
Figure 12 - Routes of Experiments 38
Figure 13 – Acceleration vs Time for Left Turn Experiment 40
Figure 14 - Acceleration vs Time for Right Turn Experiment 41
Figure 15 - Euler Angles vs Time for Left Turn Experiment 42
Figure 16 - Euler Angles vs Time for Right Turn Experiment 43
Figure 17 - Velocity vs Time for Left Turn Experiment 44
Figure 18 - Velocity vs Time for Right Turn Experiment 45
Figure 19 – Distance vs Time for Left Turn Experiment 46
Figure 20 - Distance vs Time for Right Turn Experiment 47
Figure 21 – Final Mapping for Left Turn Experiment 48
Figure 22 – Final Mapping for Right Turn Experiment 49

1. Introduction

In today's world, technology is constantly being developed to better suit the everyday lives of people. A field of technology that is rapidly gaining interest and being further researched and explored is wireless systems. Wireless systems are enabled to allow a wireless network to be expanded using multiple access points without the need for a wired connection to connect them as was required in the past. As we look to the future, most industries perceive wireless networks as a form of communication that is necessary for further advancement.

Wireless geolocation is the term used to refer to a system put in place to provide mobile users with access to their location or position. Indoor geolocation is the method of tracking navigation of an electronic device that is indoors. Indoor geolocation is mainly used to locate people and property within buildings for emergency purposes. The personal locator services locate a person's position and the locator device locates property. There are many outdoor geolocation applications that have been introduced which provide mapping services such as directions and information services such as traffic flow or the weather. The most commonly used geolocation technology is the GPS.

1.1 Motivations for the Project

Global Positioning System (GPS) is a recent breaking technology that is a part of the wireless field. GPS uses a constellation of twenty-four medium Earth orbit satellites that transmit precise microwave signals that enable receivers to determine its location, time, and velocity. Today's society is very dependent on GPS to determine location and its users vary from domestic, commercial and military industries. Though GPS is very effective and has been very successful, there is one thing this technology currently lacks which is deemed necessary to a large market of users. This inefficiency is its ability to determine location within buildings. A navigation system that locates its users indoors is valuable to people with impaired vision, hospitals needing to locate equipment, locating children and firefighters during rescues as well as other emergency responders. For this purpose, it is very important to find a method for evaluating indoor geolocation and the concept of localization may be applicable to the devices that strive to determine location in unknown surroundings. Localization is the technique using computer software to determine location of an electronic device or transceiver wireless transceiver.

The limitation of outdoor geolocation technologies such as GPS is the main motivation for indoor geolocation development. Ultimately, developing an application that is combined with GPS to provide both indoor and outdoor location tracking fulfills the location need. To indicate the path of an electronic device indoors, we use inertial systems. An inertial system is a navigation tool that uses the aid of a computer to detect location by gathering data without the use of external sources. An inertial system seeks to aid those in adapting to unfamiliar environments

Wireless geolocation is acquainted with emergency services because currently it is the main market that seeks a device with technology that locates people or property that is indoors. The system architecture of geolocation consists of a service provider which gives the location information and location aware services to subscribers. The service provider contacts a location control center which figures out the coordinates of a mobile station. The location control center collects the information required to calculate the mobile stations location using parameters such as received signal strength (RSS), angle of arrival (AOA), carrier signal phase of arrival (POA) and time of arrival (TOA) of signals. The location control center is then able to determine the location of the mobile to the service provider which visually displays the location to the user.

1.2 Description of the Project

In a progression targeted to developing the area of wireless geolocation to access the needs of the emergency services market, the company Xsens has developed a product known as the MTx Motion Tracker technology. The project focuses on using MTx in indoor geolocation through the use of inertial sensing for orientation tracking. One of the major applications of MTx is to develop the Navshoe technology. “The Navshoe system is able to navigate its users in arbitrary environments with or without the use of GPS by using a miniature inertial or magnetometer package wirelessly coupled to a PDA”.[1] The MTx technology produces data that can be used to tabulate the orientation of its user through its small wireless inertial sensor. It can be further integrated with GPS for the use of location tracking in outdoor areas.

The goal of this major qualifying project was two-fold. The first part was to research, explore and investigate the characteristics of the Xsens Motion Tracker device for indoor geolocation. The second part was to use the knowledge gained from the research of the technology to create a test-bed for the information collected from the MTx. This information collected are parameters used to test for performance evaluation of the device and our algorithms. This test-bed collects field data that is then processed by MATLAB codes to determine the coordinates and evaluate its accuracy in relative positioning.

[1] Moving Mixed Reality into the Real World – Pedestrian Tracking with Shoe-Mounted Inertial Sensors, Eric Foxlin, November/December 2005, Page 1.

Figure 1 -The Complete Xsens Motion Tracker Device Kit

The Xsens device is a small box shown in Figure 1, which is comprised of accelerometers, magnetometers, and gyroscopes. The device is used to record measurements of a set of parameters in the route taken by the user. The parameters recorded from the device are the acceleration in the x, y, and z direction as well as three orientation angles. These parameters are analyzed and used in localization algorithms using MATLAB. The distance is found by using the three-dimensional acceleration and the direction is found by using the orientation angles. In this project we used two fundamental experiments. The first was a complete left ninety degree turn and the second was a complete right ninety degree turn. The combination of the distance and direction is computed in the software program to display a final mapping of the left and right turns.

By analyzing the data recorded by the device, creating algorithms and using software programming, this project showed through the creation of a test-bed and its results that there is the potential of using the MTx to track a person's location inside a building.

1.3 Structure of the Project Report

This project aims to expand on inertial systems and consists of an in depth investigation of the MTx Motion Tracker and analysis of the data obtained from the device. The following chapters of the report involve an explanation of the sequence of steps taken in the project in achieving the objectives.

The second chapter introduces the readers to localization and the challenges of the industry by defining outdoor and indoor geolocation. It expresses reasons for a development in this field and the markets it will affect. It gives the system architecture of geolocation and methods to determining a user's position. These methods are the techniques that calculate positioning of an electronic device such as a mobile telephone.

The third chapter gives a complete overview of the Xsens Motion Tracker. It defines the components that the device is made up of and the functions of each component in the device. It includes descriptions of the parameters used and how they must be calibrated when being applied to this project.

The fourth chapter shows the test-bed developed to analyze the device. It consists of the output of the device and understanding the output by doing other experiments. It also introduces the two fundamental experiments that were used to evaluate the potential of the device to aid in the indoor geolocation field.

The fifth chapter consists of the results of the test-bed. It gives the breakdown of each step taken in producing the final mapping. It shows the graphs of each step and includes the mathematical computation necessary to achieve the expected output.

The sixth and seventh chapter is the conclusion and future recommendations of the project. It summarizes the entire project and its results as well as gives recommendations for future work on this device.

2. Overview of Localization Techniques

The world has been exposed to and adapted to the use of outdoor geolocation in the form of GPS and depend on it to determine information based on their location. The effectiveness of GPS is very apparent outdoors but has weak or non-existent signal indoors. There are markets that still require a device that can provide indoor geolocation. This has proved very challenging and a number of technologies can be used for developing implementations.

This chapter introduces an overview of localization techniques. It addresses the localization industry and its challenges, gives the system architecture, discusses performance measure of geolocation and describes three techniques for determining positioning. These techniques are direction-based, distance-based, and fingerprinting-based. The techniques are also compared to decide on which ones are superior to the others.

2.1 The Localization Industry and its Challenges

Geolocation is the performance of accessing locations or gathering information to calculate an estimation of a mobile station or position. Locating a user's position through means of a wired connection is extremely fast because the position is easily identified with accuracy due to the other rooms in the building. Locating users through means of a wireless connection is more difficult because there is no fixed location for reference. It is very important to access ones location in cases of emergency and because of this, wireless geolocation has gained significant interest and numerous markets depend on its advancement for services.

Geolocation may be divided into two categories, indoor and outdoor geolocation. As the name suggests, outdoor geolocation refers to wireless location outside and indoor geolocation refers to wireless location within buildings. Outdoor geolocation is more common than indoor geolocation and have introduced mapping services that entail giving directions or information services that include traffic flow, etc. The most common outdoor geolocation application used is the Global Positioning System that is installed in most cellular devices or automobiles being made. While outdoor applications continue to grow, the need for a technology that gives accurate location for indoor geolocation still exists.

Indoor geolocation aims to provide location for emergency services. There is a high demand for indoor geolocation devices by emergency services market such as public safety, nursing homes, visually impaired and children. The importance of such an application may be seen in public safety that requires its location tracking indoors for firefighters. The police force and fire fighters require a device that can locate victims within buildings. In the commercial market, there is a need for a device that is able to track children or the elderly as well as an aid for those with impaired vision or those that are blind for navigation purposes. There is also a need for indoor location for hospitals or large corporations that require finding equipment at critical times. However, despite the high demand for indoor tracking, there is still a lack of applications to address this demand.

The system architecture of geolocation consists of a geolocation service provider, a location control center, and a display system. Together these three systems combine information gathered to produce a person's location visually. The geolocation service provider receives information from the location control center to measure metrics relative to the position of the mobile station to the reference point. The location control center collects the data needed to work out the position of the mobile station. The data provided by the location control center is the information for the positioning algorithm. This is the process of using metrics to determine the location coordinate of the mobile station using angles of arrival (AOA), received signal strength (RSS), phase of arrival (POA), and time of arrival (TOA). After the location is determined and sent to the service provider, the mobile stations location is visually displayed to the user through means of the display system.

The location control center is the ‘brain’ of the geolocation system architecture that calculates an estimation of location using metrics to determine methods to develop a user’s position. These methods are classified under three categories; Direction-Based Techniques, Distance-Based Techniques and Fingerprinting-Based Techniques.

2.1.1 Direction-Based Techniques

The direction-based technique consists of the Angle of Arrival Method (AOA) which uses the Ling of Sight (LOS) approach.

Angle of Arrival

“The angle of arrival geolocation technique uses the direction of arrival of the received signal to determine the location of the mobile station”. The direction of the incoming signals are received and measured from the target transmitter to a direction using directional antennas or antenna arrays in Figure 2.

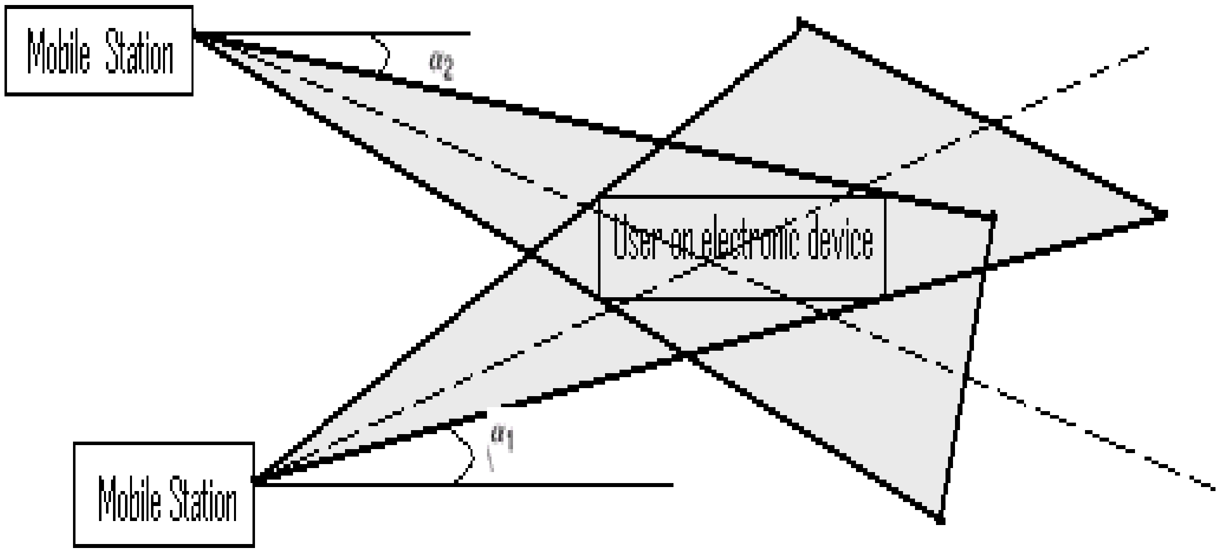

Figure 2 - Angle of Arrival Geolocation Technique

If the line of sight signal path is blocked, then the angle of arrival being used is a reflected or scattered signal for its direction estimation. This technique is not feasible when dealing with indoor geolocation because often times there will be walls or objects blocking the line of sight signal path. To eliminate the blocking of the line of sight signal path, a very large amount of array antennas would need to be placed at all the receivers to track the arrival signal direction to ensure accuracy which is extremely expensive.

2.1.2 Distance-Based Techniques

The Distance-Based Techniques involve the following methods:

- Time of Arrival (TOA)

- Time Difference of Arrival (TDOA)

- Signal Strength

- Received Signal Phase

<u>Time of Arrival</u>

The time of arrival technique uses the distance between the mobile station and receiver to estimate location. At least three measurements are necessary to calculate the possible position of the user. The measurements estimate the position in two dimensions and four measurements estimate the position in three dimension. By estimating the distance between the receiver and the mobile to be d, the mobile is located on a circle with radius d centered on the receiver. Distance is equal to the velocity of light multiplied by the time taken by the signal to reach the base station. ($d = c * t$; where c is the velocity of light and t is the time taken by the signal to reach the base station) Three measurements of d provide a location of the mobile accurately as seen in Figure 3.

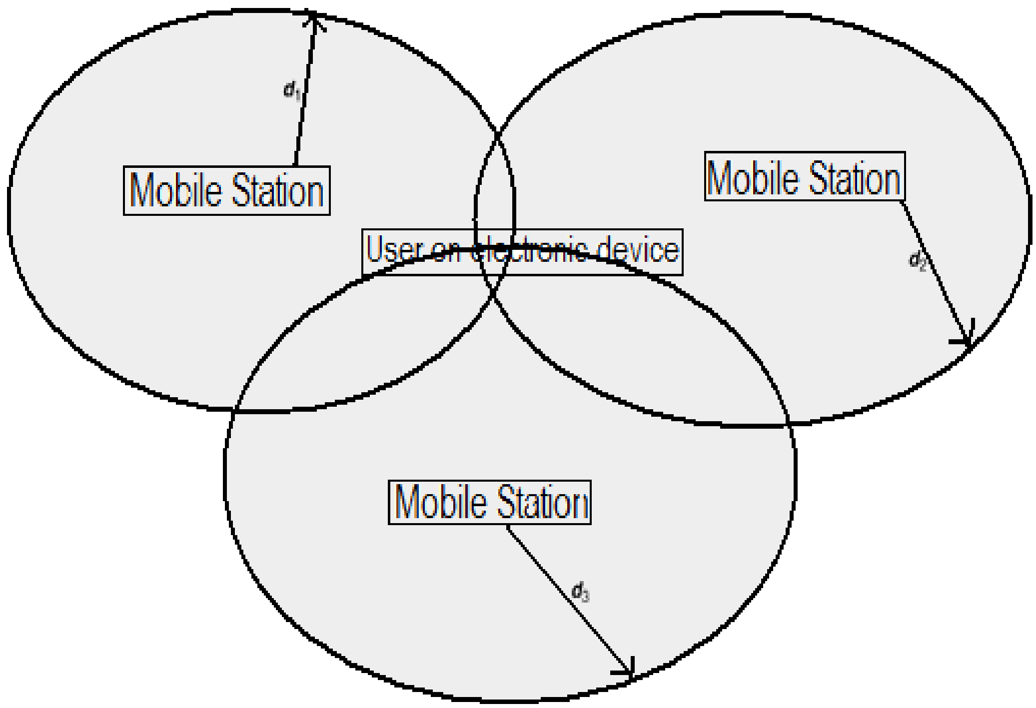

Figure 3 - Direction Based Geolocation Technique

<u>Time Difference of Arrival</u>

Some outdoor geolocation applications use the time difference of arrival technique. This is where the differences of the time of arrivals are use to locate the mobile. "The time difference of arrival technique is similar to that of the time of arrival technique but instead of using circles, the time difference of arrival uses hyperbolas on which the transmitter must be located with foci at the receivers". [2] At least three measurements are needed to calculate a fixed position at the intersection of the hyperbolas.

[2] Principles of Wireless Networks, Kaveh Pahlavan, Prashant Krishnamurthy, Wireless Geolocation Systems Chapter 14, Page 540.

Signal Strength

The signal strength technique uses the transmitted power at the mobile station and the received signal strength at the base station to provide an estimate of the distance between the transmitter and the receiver. Similar to the time of arrival technique, the distance gives the circle centered on the receiver which the mobile transmitter is on.

Received Signal Phase

"The received signal phase technique used with reference receivers measures the carrier phase. Differential Global Positioning System improves location accuracy within twenty meters to one meter as compared with Global Positioning Systems which uses range measurements. In indoor geolocation systems, it is possible to use signal phase methods with time of arrival, time difference of arrival or received signal strength techniques to better estimate the location.

2.1.3 Fingerprinting-Based Techniques

Another technique that estimates position location is signal fingerprinting. "The multipath structure of the channel is unique to every location and may be considered a 'fingerprint' or 'signature' of the location if the same radio frequency signal is transmitted from that location. This technique may be used in indoor geolocation applications where a location pattern develops from multipath rays in a multipath structure in an area"[3].

[3] Principles of Wireless Networks, Kaveh Pahlavan, Prashant Krishnamurthy, Wireless Geolocation Systems Chapter 14, Page 545.

2.2 Performance Measures of Geolocation Systems

"The performances of geolocation systems are tested on similar criterion as telecommunication systems. The most important performance measure for a geolocation system to be successful is accuracy of the location defined. The accuracy of the system may include the percentage of calls within an accuracy of 8 meters or the distribution of distance error at the receiver. The location availability of a system is important because it includes the percent of location requests not fulfilled and the unacceptable uncertainty of locations. Other categories used to determine the performance measurement of geolocation systems are the coverage of the system, the reliability of the system and the delay in location computation"[4].

2.3 Comparing Geolocation Techniques

The time of arrival technique estimate location by calculating the position of the mobile by using circles centered on the mobile or the fixed transceiver. The time difference of arrival does a similar technique using hyperbolas and does not require the knowledge of transmit time from the transmitter. To create estimates of time, TOA and TDOA techniques employ pulse transmission, phase information, or spread spectrum to arrive at locations of mobile stations.

The time of arrival techniques are seen as superior to angle of arrival techniques because the AOA method is not appropriate for indoor geolocation systems. The angle of arrival is suited for outdoor geolocation but has poor accuracy. It has a low delay but may be costly due to the need for antenna arrays that need to be installed in areas. The signal strength method cannot be used in situations where the precision of the location needs to be within accuracy of a few meters.

---

[4] Principles of Wireless Networks, Kaveh Pahlavan, Prashant Krishnamurthy, Wireless Geolocation Systems Chapter 14, Page 547.

3. Principle of Operation of MTx Motion Tracking System

The limitation of GPS calls for an inertial system that is able to be used where GPS becomes ineffective or fails. One such application that attempts to resolve the restriction of the GPS technology is a motion tracking device developed by Xsens, a company in the Netherlands. This device can be used in fields such as biomechanics, exercise and sports, virtual reality, animation, and motion capture. It gathers and records data from which algorithms may be created to produce an application to go hand in hand with GPS for tracking location indoors.

This chapter provides an in-depth description of the Xsens Motion Tracker and how it works. It provides function descriptions for each component and how they work together to deliver the data needed to calculate relative positioning. It includes the parameters recorded by the device and the calculations that need to occur before using the data. This chapter concludes with how these parameters are used in order to get a final mapping.

3.1 An Overview of Inertial Systems using the MTx System

The MTx is a miniature three-degrees-of-freedom (3DoF) inertial orientation tracker device developed by Xsens Technologies. This tracker device is a measurement unit for collecting dynamic movements. It provides three-dimension magnetometers which may be viewed as a three dimensional compass with an embedded processor capable of calculating roll, pitch and yaw in real time, as well as outputting three dimensional linear acceleration rate of turn with use of a gyroscope and earth-magnetic field data.

The MTx device takes the signals of the rate gyroscopes, accelerometers and magnetometers to calculate an accurate statistical optimal three dimensional orientation estimate for dynamic movements. A system overview of the Xsens MTx can be seen in Figure 3 – MTx System Overview.

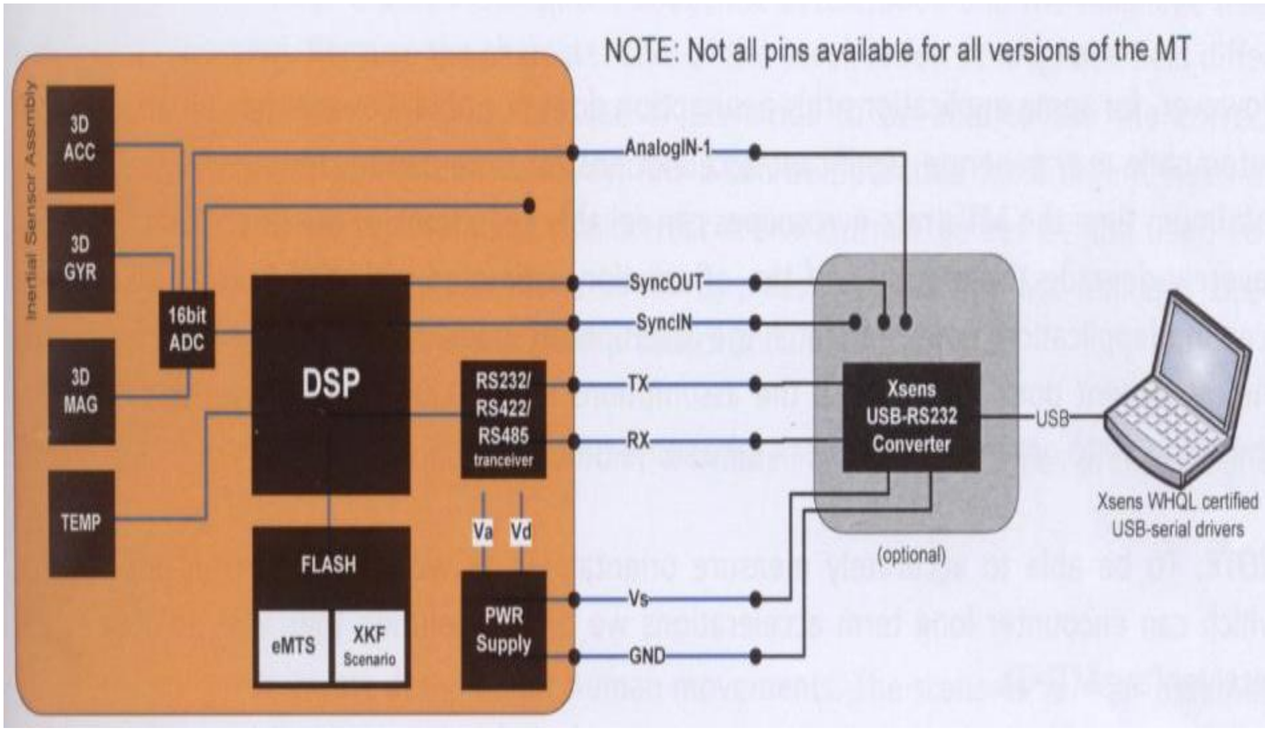

Figure 4 - MTx System Overview[5]

The motion tracker system shown in Figure 4 above is comprised of three main components that enable us to track the devices movements. These are accelerometers, magnetometers, and gyroscopes. It is also able to give the temperature of the devices surroundings which may be important for some of the users such as firefighters.

The MTx uses the accelerometer, gyroscope, and magnetometer to record the information from these components and stores all measurements in the devices memory. This memory is shown in Figure 4 as the 'FLASH' section in the diagram.

[5] MTi and MTx User Manual and Technical Documentation, Xsens Technologies B.V., MTi and MTx System Overview Chapter 2, July 1, 2008, Page 5.

The ADC is the analog to digital converter. This converts the input analog voltage to a digital number. This converter is shown as '16 bit ADC' in the system overview diagram.

The power supply is the source of power to load the device. It provides the energy to power the components running in the device. It is shown as 'PWR Supply' in the system overview diagram.

The transceiver is a device that has a transceiver as well as a receiver. This allows for the device to be connected and receive and send signals to the converter or straight to the computer aid needed to use the motion tracker. It is viewed as 'RS232/RS422/RS485 transceiver' in the system overview diagram.

The digital signal processor is a microchip that is used to measure or process signals. This component is seen as 'DSP' on the system overview diagram. After uploading the information the user is then able to manipulate their algorithm to process the data.

The accelerometers measure gravitational acceleration as well as the acceleration due to the movement of the object with respect to its surroundings. An assumption that the device makes is that on average the acceleration due to the movement is zero. The three dimensional acceleration measurements recorded by the accelerometer in the x, y, and z direction is in respect to the device's reference coordinate frame and will need to be converted to the Earth's fixed reference coordinate. This acceleration is manipulated to calculate the distance of the recorded data which is needed in the final computation of the devices movements.

In addition to the three accelerations in the x, y, and z direction, three orientation angles are needed to calculate the positioning. They are known as Euler angles. These angles are referred to as the roll, pitch and yaw. The roll is defined as the rotation around the x-axis from -

180º to 180º. The pitch is defined as the rotation around y-axis from -90º to 90º. The yaw is defined as the rotation around the z-axis from -180º to 180º.

The magnetometers measure the Earth magnetic field. This means that it is similar to treating it as a compass. Therefore, it stabilizes the heading (yaw). When the Earth magnetic field is disturbed, the MTx will track the disturbance and include it in its estimation. But in case of structural magnetic disturbance, a 'new' local magnetic north will be used to compute the yaw. The gyroscopes and the magnetometers measure the orientation angles.

To obtain orientation, the MTx uses the assumptions about the acceleration and the magnetic field. Based on the application the device is used for, the characteristics of the acceleration or magnetic field will differ. The device may be set for different scenario based on the types of movement. The different scenarios are divided in 'human', 'machine' and 'marine' types of motion. The MTx application for which our project focuses on is human motion.

For 'human' type of motion, the scenario assumes that it is slower movements while also capturing the magnetic disturbances typically for an indoor environment. 'Machine' type of motion includes scenarios where acceleration are slower and of longer periods of time than acceleration of humans. These scenarios are designed for situations where the local earth magnetic field is too distorted to be useful. To adjust to these situations, the 'machine' type of motion does not make use of the local earth magnetic field to obtain a heading estimate. Lastly, the 'marine' type of motion is used for low, long term accelerations and mild magnetic disturbances.

3.2 The Motion Tracker Output

There are two main modes of output produced by the MTx. These methods of output are the Orientation Output and the Calibrated Data Output. The two modes may be combined to view orientation data and inertial data together.

3.2.1 Calibrated Data Coordinate System

The sensor readings given in the calibrated data are the accelerations (from the accelerometer), the rate of turns (from the gyroscope), and the earth magnetic field (from the magnetometer). The readings collected are in the right handed Cartesian coordinate system. The system is in three dimensions and is body-fixed to the device as seen in the Figure 5. The blue arrow represents the x-axis, the yellow represents the y-axis and the green represents the z-axis. The coordinate system is defined as the sensor coordinate system which is referred to as 'S'. The three-dimensional output of the acceleration, the rate of turn, and the magnetic field data have orthogonal XYZ readings within $<0.1^{o}$.

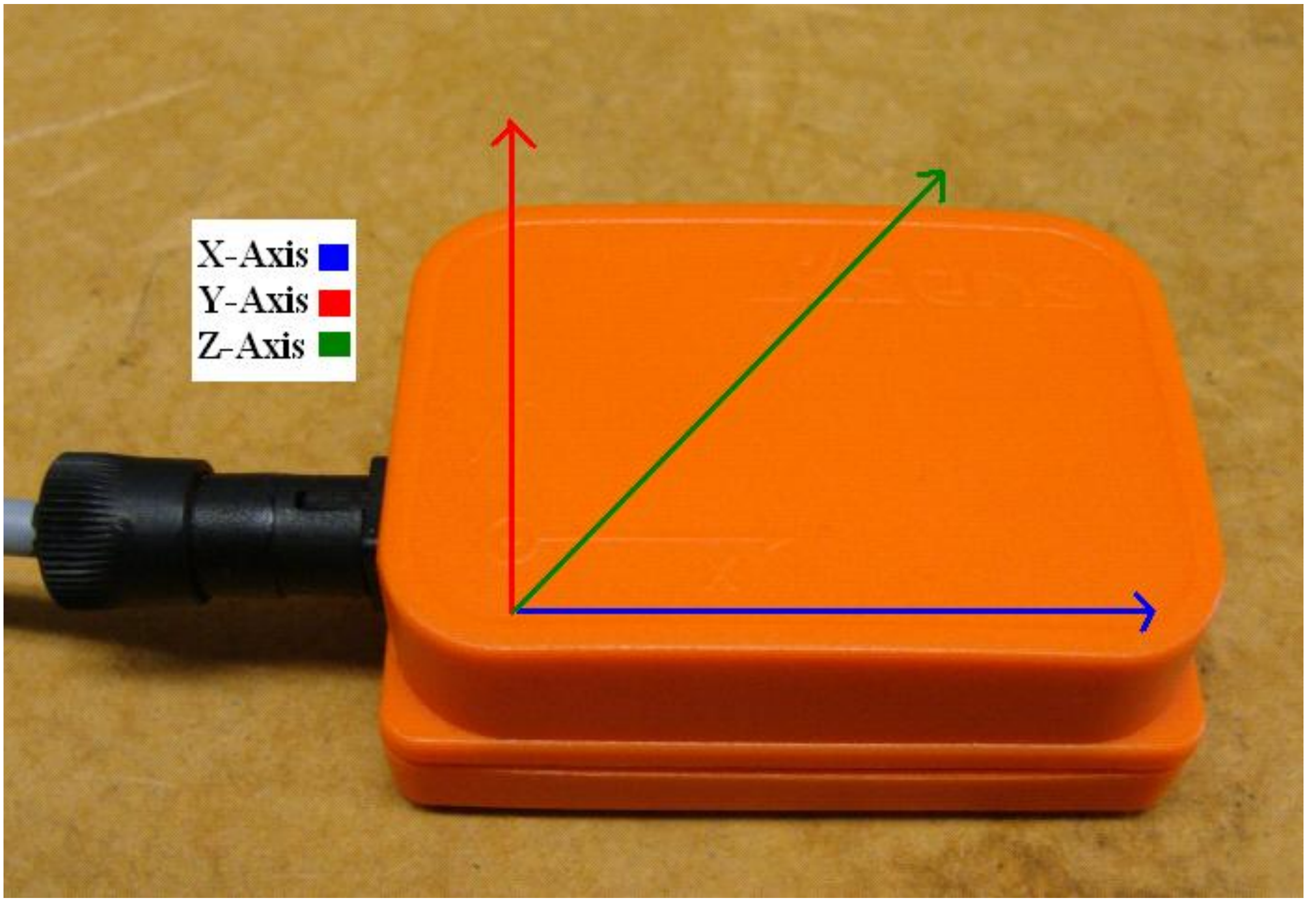

Figure 5 - MTx with Sensor-fixed Coordinate System Overlaid

3.2.2 Orientation Coordinate System

The MTx calculates the orientation between the sensor-fixed coordinate system, S, and an earth-fixed reference coordinate system which is defined as G which may be viewed in Figure 6. The three accelerations, x, y, and z are recorded in respect to the sensor-fixed coordinate system. For example, if the navy blue arrow is an acceleration a(t) being recorded, it is in respect with the red axis which is the rotating axis. The three orientation angles, the roll, pitch, and yaw are recorded in respect to the earth-fixed reference coordinate system and are represented in the figure below by the beta, gamma, and alpha. It is in respect with the light blue axis which is the earth's fixed axis.

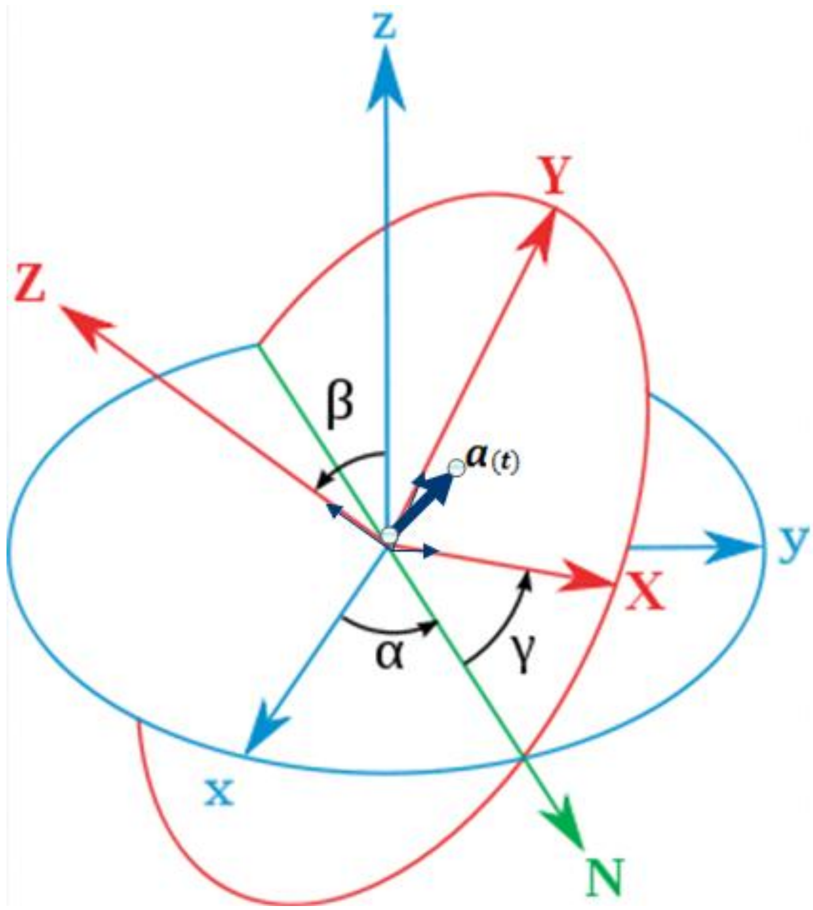

Figure 6 -Device Coordinate Reference Frame versus Earth Fixed Reference Coordinate Frame[6]

The local earth-fixed reference coordinate system used is the right handed Cartesian coordinate system. The three dimensional coordinate system used is shown in Figure 7. The figure shows the coordinate system of an x, y and z axis when the device is at an angle. The x axis is positive when pointing to the Local Magnetic North. The y axis is west according to the right handed coordinate. The z axis is positive when pointing up.

[6] Lionel Brits. Vector of Euler Angles. January 09, 2008

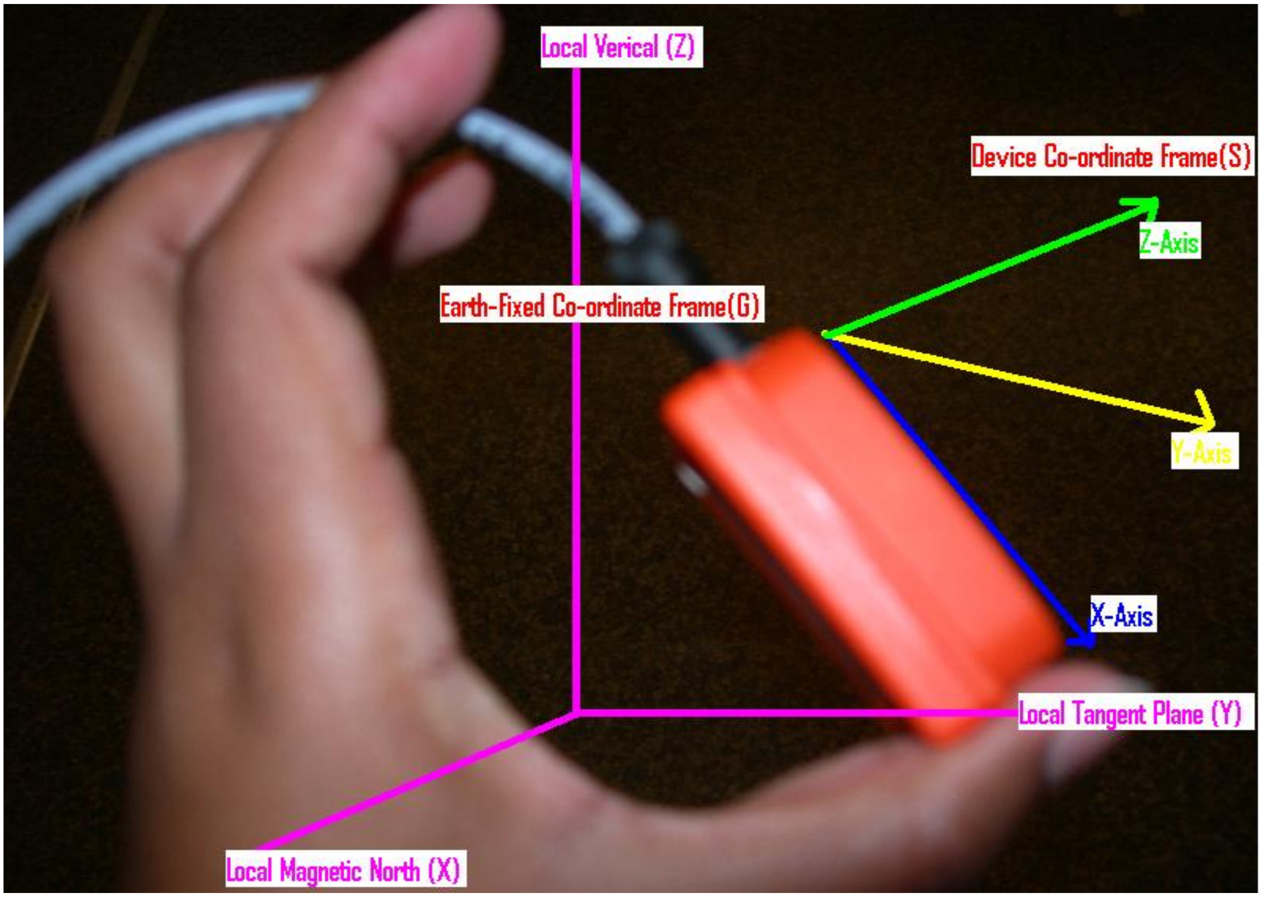

Figure 7 - three Dimensional Orientation Output

<u>Euler Angles</u>

The Euler Angles are known as the roll or bank, pitch or elevation or tilt, and yaw or heading or pan. They are with respect to the fixed coordinate of the Earth. They are in reference to the fixed coordinate system unlike the acceleration which is in reference to the device's coordinate system. In this report, we represent roll with Φ, pitch with Θ, and yaw with Ψ. These rotations of roll, pitch and yaw around the x, y, and z axis respectively may be viewed in Figure 8.

The Euler-angles may be expressed in terms of the components of the rotation matrix, R_{GS} as well as in the unit quaternion Q_{GS}. For this project, we use the rotation matrixR_{GS}.

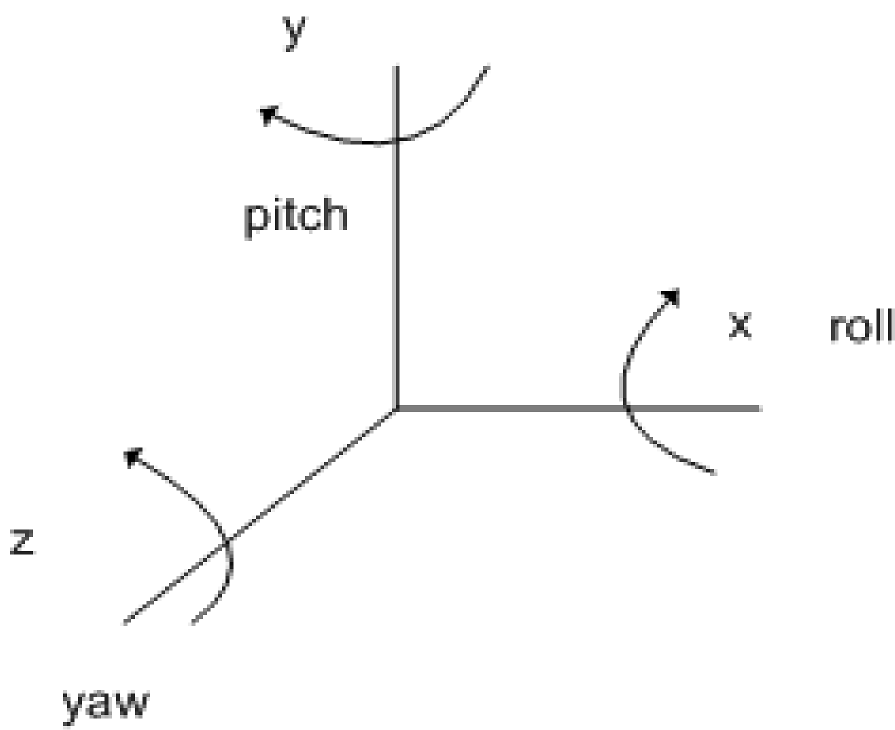

Figure 8 -The fixed coordinate system of Euler Angles

Rotation Matrix

The rotation matrix is also known as the 'Direction Cosine Matrix' (DCM). The rotation matrix can be interpreted as the unit vector components of the sensor coordinate system, s, expressed in G shown in Figure 6. The determinant of a rotation matrix, is normalized to be equal to one where R is the rotation, || R || = 1. Therefore rotation R_{GS}followed by the inverse rotation R_{GS} will yield the identity matrix I^3, $R_{GS}R_{SG}$ = I^3.

Rotation Matrix expressed as Euler-Angles

The Euler-Angles (roll, pitch, and yaw) recorded from the MTx is in respect to the fixed coordinate. This means the process of converting the devices coordinate to the fixed is eliminated. However, the three angles each possess their own independent rotation shown by the equations below.

$$R_{\Psi}^{Z} = \begin{bmatrix} cos\Psi & -sin\Psi & 0 \\ sin\Psi & cos\Psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \text{Eq. (1a)}$$

$$R_{\theta}^{Y} = \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix} \qquad \text{Eq. (1b)}$$

$$R_{\Phi}^{X} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\Phi & -sin\Phi \\ 0 & sin\Phi & cos\Phi \end{bmatrix} \qquad \text{Eq. (1c)}$$

Each roll, pitch, and yaw angle has its own independent rotation. A rotation is needed to convert the acceleration in the x, y, and z from the device's coordinate to the same Earth's fixed coordinate as the orientation angles. In order to create one independent rotation matrix that represents the rotation of each independent roll, pitch, and yaw with respect to x, y, and z correspondingly, we multiply the three matrices together to create the rotation.

$$R_{GS} = [R_{\Psi}^{Z} \quad R_{\theta}^{Y} \quad R_{\Phi}^{X}] \qquad \text{Eq. (2)}$$

The rotation matrix R_{GS} :

$$R_{GS} = \begin{bmatrix} cos\Psi & -sin\Psi & 0 \\ sin\Psi & cos\Psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cos\theta & 0 & sin\theta \\ 0 & 1 & 0 \\ -sin\theta & 0 & cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\Phi & -sin\Phi \\ 0 & sin\Phi & cos\Phi \end{bmatrix} \quad \text{Eq. (3a)}$$

$$= \begin{bmatrix} cos\theta cos\Psi & sin\Phi sin\theta cos\Psi - cos\Phi sin\Psi & cos\Phi sin\theta cos\Psi + sin\Phi sin\Psi \\ cos\theta sin\Psi & sin\Phi sin\theta sin\Psi + cos\Phi cos\Psi & cos\Phi sin\theta sin\Psi - sin\theta cos\Psi \\ -sin\theta & sin\Phi cos\theta & cos\Phi cos\theta \end{bmatrix} \quad \text{Eq. (3b)}$$

The rotation matrix is multiplied by the measured acceleration in the x, y, and z in the device's coordinate in order to have the acceleration in the x, y, and z coordinates of the fixed Earth.

If the fixed coordinate acceleration is represented by the matrix:

$$\vec{A} = \begin{bmatrix} \hat{a}_x(t) \\ \hat{a}_y(t) \\ \hat{a}_z(t) \end{bmatrix}$$

We can determine the fixed reference acceleration for measured acceleration.

$$\begin{bmatrix} \hat{a}_x(t) \\ \hat{a}_y(t) \\ \hat{a}_z(t) \end{bmatrix} = \begin{bmatrix} \cos\theta\cos\Psi & \sin\Phi\sin\theta\cos\Psi - \cos\Phi\sin\Psi & \cos\Phi\sin\theta\cos\Psi + \sin\Phi\sin\Psi \\ \cos\theta\sin\Psi & \sin\Phi\sin\theta\sin\Psi + \cos\Phi\cos\Psi & \cos\Phi\sin\theta\sin\Psi - \sin\theta\cos\Psi \\ -\sin\theta & \sin\Phi\cos\theta & \cos\Phi\cos\theta \end{bmatrix} \begin{bmatrix} a_x(t) \\ a_y(t) \\ a_z(t) \end{bmatrix}$$

Eq. (4)

The result of the acceleration is then integrated to determine the velocity and further integrated to receive the distance x, y, and z.

$$\begin{bmatrix} v_x(t) \\ v_y(t) \\ v_z(t) \end{bmatrix} = \int \begin{bmatrix} a_x(t) \\ a_y(t) \\ a_z(t) \end{bmatrix} \text{dt} \qquad \text{Eq. (5)}$$

$$\begin{bmatrix} x_x(t) \\ x_y(t) \\ x_z(t) \end{bmatrix} = \int \begin{bmatrix} v_x(t) \\ v_y(t) \\ v_z(t) \end{bmatrix} \text{dt} \qquad \text{Eq. (5)}$$

The distance of x, y z is the coordinate position

$$\overrightarrow{P(t)} = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix}$$

4. Exploration and Test of MTx Motion Tracker

MTx Motion Tracker is a complex system. In this chapter, we first reported the exploration of the characteristics of the MTx Technology. Then, we discussed the test-bed that was developed for performance evaluation to determine the precision of the MTx Motion Tracker Technology for indoor geolocation.

4.1 Exploration of the MTx Technology

The research section was divided into two parts. First, we explored the all available information about the inertial system technology. Then, we worked on to familiarize the components and functions of the miniature three-degrees-of-freedom MTx inertial orientation tracker. By completing this, we achieved an in-depth understanding of the characteristics of this technology.

4.1.1 Previous Work

Inertial system technology is in a developing stage for indoor geolocation. Previous journals, reports, and other published articles are available to read and were ready to be expanded upon. These previous work explained this new technology in depth and the experiments that were ran. We took the information and used it to grasp a better understanding for this project. These published materials can be found in our reference section.

4.1.2 Understanding of the MTx Motion Tracker

The next step was to get familiarize with the MTx Motion Tracker from Xsens Technologies. To achieve this step, multiple experiments were run from the MTx device to attain the output data and functions of the motion tracker. Along with the help of the provided MTx user manual, the experimental observations were made comprehensible.

In order to start the recording of the MTx output values for the experiments, the motion tracker must be powered through the USB connection of a computer. Then the MT Manager, a program that was provided by Xsens for recording the movements and data, must be running on the computer. Figure 9 shows the setup of the MTx motion tracker.

Figure 9 - MTx Motion Tracker Setup

As for the experiments, the MTx was placed at a fixed starting point every time when an experiment was begun. First experiment was to record the MTx while stationary. Then as for the other experiments, starting from the fixed starting point, the MTx was moved along an imaginary X/Y/Z axis according to the device coordinates. X direction was the vertical motion; Y direction was the horizontal motion, while the Z direction was an upward or downward motions. As the tracker was move in each direction, the MT manager recorded and output all the essential data provided by the tracker. The MT Manager allowed the team to view the motions of the device as well as the Euler angles, acceleration, angular velocity and magnetic field in the XYZ directions over time. Figure 10 shows a sample output view from MT Manager.

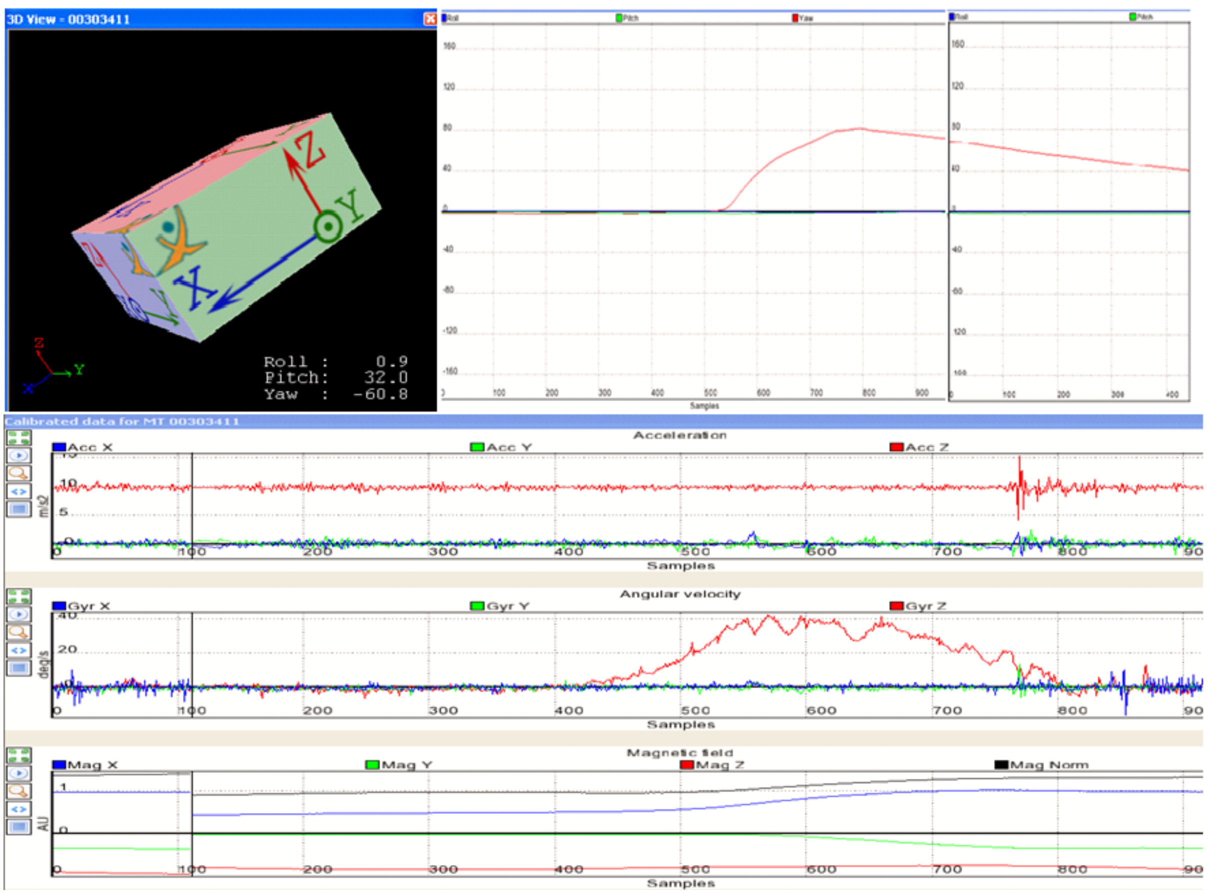

Figure 10 – MT Manager Output Sample

As seen on the last page, there is a live 3D view of the device with the roll, pitch and yaw rotational measurements in degrees. The plots also run live so that the output from the accelerometers. Gyroscopes and magnetometers can be seen. The measurement values from these three components were best viewed from Microsoft Excel where the data could be displayed in orderly fashion and further analyzed. Figure 11 shows a sample of these measurement values.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	// Start Time: 0												
2	// Sample rate: 100.0Hz												
3	// Scenario: 5.4												
4	Counter	Acc_X	Acc_Y	Acc_Z	Gyr_X	Gyr_Y	Gyr_Z	Mag_X	Mag_Y	Mag_Z	Roll	Pitch	Yaw
5	43920	0.10444	0.005234	9.875807	0.000557	-0.01042	-0.01103	0.436995	-0.02001	-0.79301	0.030367	-0.6059	2.518846
6	43921	0.023041	0.077544	9.806005	0.011273	0.007112	-0.00994	0.434481	-0.02079	-0.79338	0.036904	-0.6018	2.513154
7	43922	0.008089	0.149385	9.800741	0.001608	-0.00605	-0.00991	0.436888	-0.02027	-0.79277	0.037885	-0.60526	2.511262
8	43923	0.03933	0.20801	9.840318	-0.01521	-0.0095	0.006768	0.436153	-0.01974	-0.79317	0.112133	-0.57208	2.514277
9	43924	0.033349	0.27088	9.810905	0.007425	-0.0082	0.004448	0.436381	-0.02269	-0.79362	0.116362	-0.57678	2.556107
10	43925	0.079	0.285739	9.806005	-0.00244	-0.00938	0.000056	0.436951	-0.02143	-0.79156	0.381284	-0.51892	2.553551
11	43926	0.133997	0.247211	9.80096	-0.01265	-0.02471	-0.01985	0.435711	-0.01987	-0.79248	0.37414	-0.533	2.405042
12	43927	0.174324	0.230702	9.801779	-0.01038	0.002521	-0.00987	0.437024	-0.02004	-0.79241	0.664168	-0.54806	2.396585
13	43928	0.192646	0.210532	9.795815	0.00036	-0.00826	-0.01548	0.43669	-0.02177	-0.79206	0.664457	-0.55269	2.297661
14	43929	0.231128	0.15918	9.780179	-0.0274	-0.01073	-0.00318	0.436495	-0.02294	-0.79373	0.841842	-0.65247	2.293708
15	43930	0.26047	0.131649	9.775783	-0.00476	-0.00616	-0.0055	0.43808	-0.02129	-0.79282	0.839144	-0.65595	2.174782
16	43931	0.251618	0.112981	9.801819	0.000948	0.010268	-0.02875	0.4361	-0.01957	-0.79425	0.919126	-0.78707	2.1574
17	43932	0.240758	0.094493	9.807658	0.009172	-0.00819	-0.0111	0.436624	-0.01974	-0.79327	0.924463	-0.79166	2.031439
18	43933	0.224063	0.091027	9.780488	-0.01651	-0.01716	-0.00324	0.43602	-0.01923	-0.79342	0.917482	-0.91179	2.029388
19	43934	0.209763	0.096154	9.82135	0.022447	0.006082	0.002146	0.437675	-0.02124	-0.7938	0.93032	-0.90832	1.973954
20	43935	0.165776	0.099815	9.815127	0.059267	-0.02078	-0.00359	0.436241	-0.02058	-0.79388	0.937546	-0.98982	1.97217
21	43936	0.152711	0.125738	9.797012	0.010834	-0.0016	-0.02658	0.436723	-0.0217	-0.79385	0.944014	-0.99049	1.903373
22	43937	0.132687	0.142104	9.815913	0.007155	0.011398	-0.00108	0.437518	-0.0213	-0.79213	0.924607	-1.00959	1.903279
23	43938	0.099661	0.193501	9.827725	0.002533	0.010284	-0.01101	0.436322	-0.02052	-0.7922	0.926164	-1.0036	1.833823
24	43939	0.088158	0.230711	9.783777	0.000668	-0.00173	-0.00327	0.436235	-0.02045	-0.794	0.929991	-0.99511	1.831871
25	43940	0.080885	0.248995	9.79682	0.023317	-0.00042	-0.00559	0.43878	-0.02031	-0.79303	0.943403	-0.99529	1.771975

Figure 11 - Sample Display of Measurement Values

The MTx motion tracker outputs measurement values for the acceleration, gyroscope, and magnetic field in the XYZ directions. However, for this project, only acceleration and the Euler angles were take into consideration for observation and calculations. Acceleration is measured in m/sec^2 while the Euler angles units are in degrees. With the different experiments output data, we compared and contrasted them from each direction to the stationary sample. By doing this, the team was able to observe the following characteristics:

- The duration of the test run was discovered by using simple computation. Time was calculated by the total number of points divided by the tracker's set frequency of 100Hz. The unit for time is seconds.
- Acceleration in the Z direction was within the range of 9.78 and 9.82 m/s^2 when the motion tracker was not moved in that direction. This is around the Earth gravitational acceleration constant of 9.81 m/s^2.
- Yaw has a change of 90 degrees when the MTx device is rotate left or right. +90 for left turn and -90 for a right turn.

4.2 Test Experiments for Performance Accuracy

With the characteristics of the MTx Motion Tracker completely investigated and comprehended, we performed two fundamental experiments that included one turn. The purpose of these two experiments is to be able to get a final mapping of the route taken and view the precision of the MTx motion tracker. The route taken for each experiment was similar to an L-shaped so that this could consist of one 90 degrees left or right turn. Figure 12 shows the two routes taken during the testing.

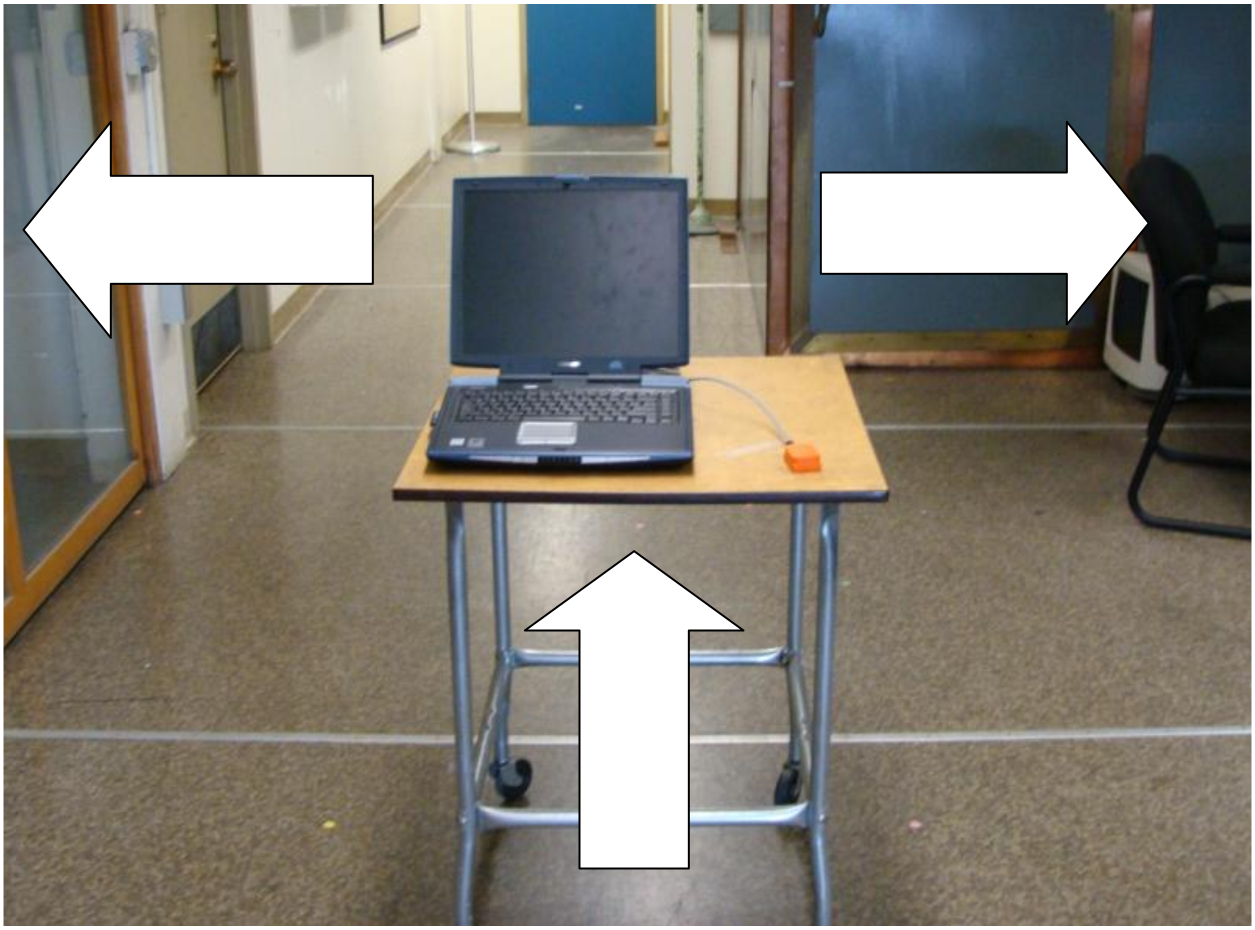

Figure 12 - Routes of Experiments

For these experiments, the team wanted to achieve a two dimensional mapping. Therefore, the MTx tracker was stationary placed on a mobile cart to not take into account of the Z direction. The MTx device was taped down to avoid any movements while the cart was pushed. The cart was moved at a constant speed to keep the two experiments consistent. From a starting position, the cart is moved in a straight heading for about 1.3 meters and then either takes a left of right turn for 1 meter. The results of the performance accuracy experiments are discussed in the next chapter.

5. Experimental Results

In this chapter, we displayed the results from the 90 degrees left and right turns test experiments described in chapter four. First, we changed the outputted data from device coordinates to fixed coordinates. Then, we integrated the fixed data and the inertial localization algorithm with MATLAB to determine the precision of the MTx device. Finally, we show the final maps of these two experiments.

5.1 Device and Fixed Coordinates

The results of the taken routes were logged by the MTx program manager. The key output data that was taken into account were the relative acceleration and the Euler angles, also known as rotation of coordinates. The relative acceleration was given according to the device coordinates. In order to attain the final mapping, the device coordinates had to be changed to Earth fixed coordinates. Eq. (4) was used here to achieve the change. The relative acceleration is multiplied by the rotational matrix to get the fixed acceleration. From there, further calculations would be in the fixed coordinates.

5.2 Plots of Acceleration, Euler Angles, Velocity and Distance

The values in the fixed coordinates obtained were programmed and manipulated in MATLAB to produce the display of data on two dimensional plots. The MATLAB code can be found in the Appendix. The acceleration, the Euler angles, the computed velocity and distance for both left and right turn experiments are shown and discussed in this section. The duration for each of these experiments was around 17 seconds.

5.2.1 Acceleration

The acceleration data was changed from the device coordinates to the fixed coordinates. The acceleration over time plots for left and right turns experiments are displayed below in Figures 13 and 14, respectively.

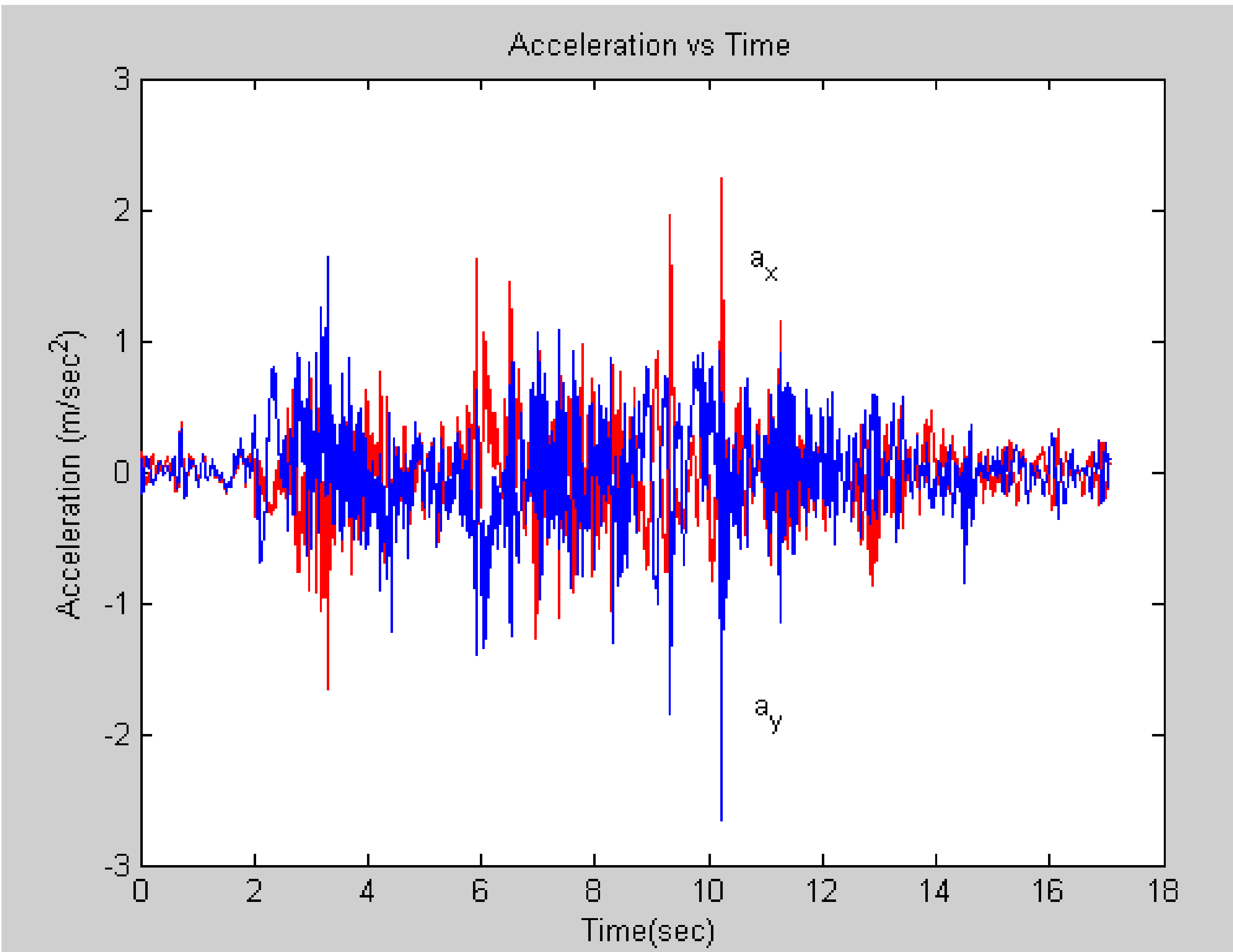

Figure 13 – Acceleration vs Time for Left Turn Experiment

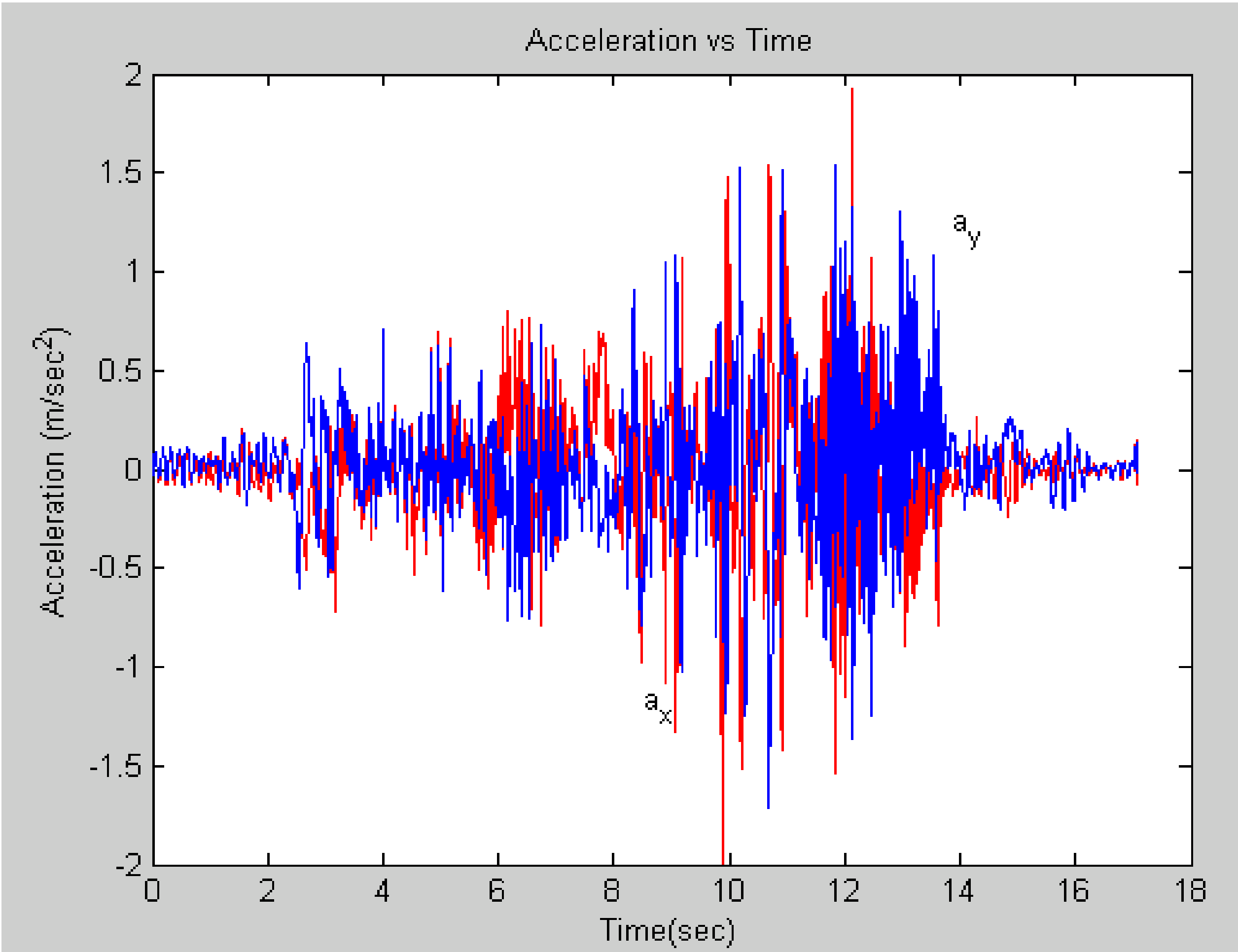

Figure 14 - Acceleration vs Time for Right Turn Experiment

These plots were obtained by taking the X and Y accelerations in the fixed coordinates and plotted versus time. As you can see from the plots above, the MTx tracker is very sensitive which causes lots of noise density to the data. The cart pushed starting around two seconds as the XY acceleration spiked. Acceleration started to decrease as it approaches ten seconds because the cart was making the turns. Around ten seconds, the spiked again as the cart started to be pushed again in the new direction. This proves the MTx tracker is accurate in outputting the acceleration data because the plots show the correct timing of the increased and decreased acceleration from beginning to end.

5.2.2 Euler Angles

The MTx tracker logs the roll, pitch, and yaw. These values are the Euler angles at which the device rotates. The MATLAB software manipulates the values in order to obtain the angles at which the user of the device is turning. Figures 15and 16, respectively, show the plots of the roll, pitch and yaw degrees over time for the left and right turn experiments.

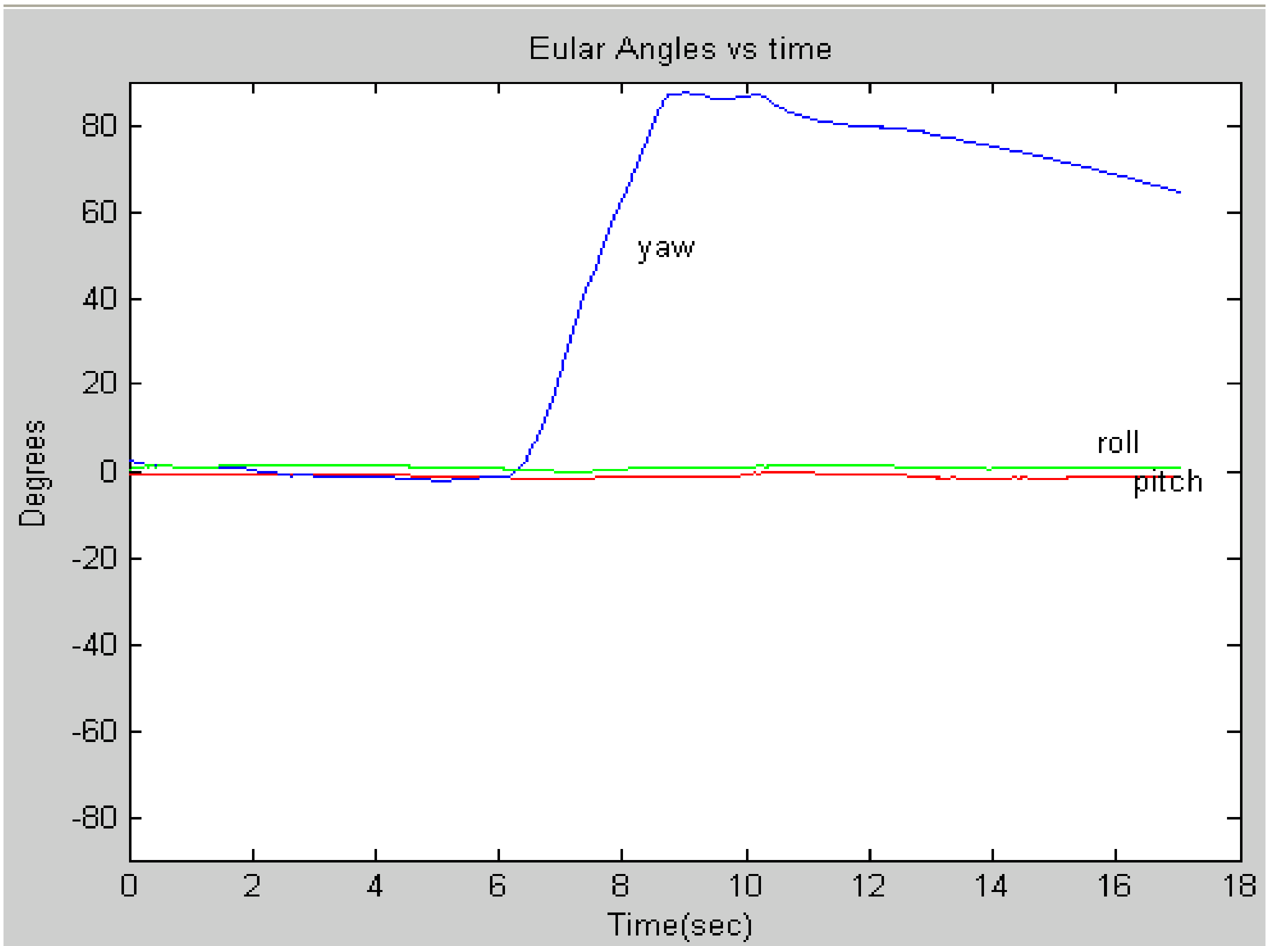

Figure 15 - Euler Angles vs Time for Left Turn Experiment

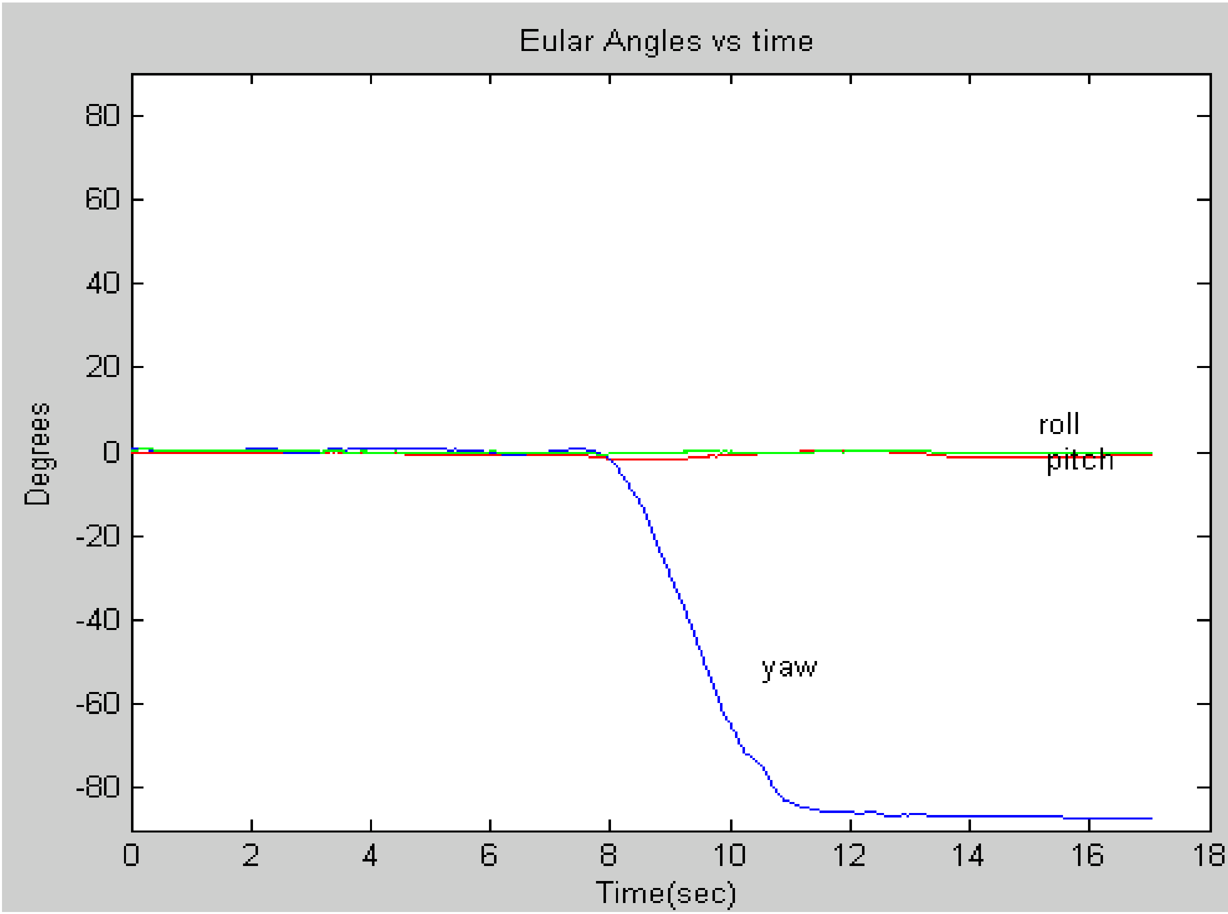

Figure 16 - Euler Angles vs Time for Right Turn Experiment

As the cart was pushed with the stationary MTx tracker on it, the roll and pitch were expected to stay around zero degree while the yaw was projected to change significantly as the cart took a turn. The plot above proved this theory as roll and pitched hovered around zero while yaw spiked in degrees as a turn was taken. A +90 degrees change is assumed when a left turn is taken, while a -90 degrees change is seen for a right. The turns for both experiments were completed around ten seconds as this match with the acceleration plots from earlier for when the cart was pushed in its new direction.

5.2.3 Velocity

To find the velocity over time, equations (6) and (7) are used:

$$\int \hat{a}_x(t)d(t) = V_x(t) \qquad \text{Eq. (6)}$$

$$\int \hat{a}_y(t)d(t) = V_y(t) \qquad \text{Eq. (7)}$$

The integral of acceleration over time calculates to velocity. In MATLAB, the function for integral of Y with respect to X is CUMTRAPZ. The left and right turn experiments' plots of velocity in the X and Y direction vs. time can be seen below in Figures 17 and 18, respectively.

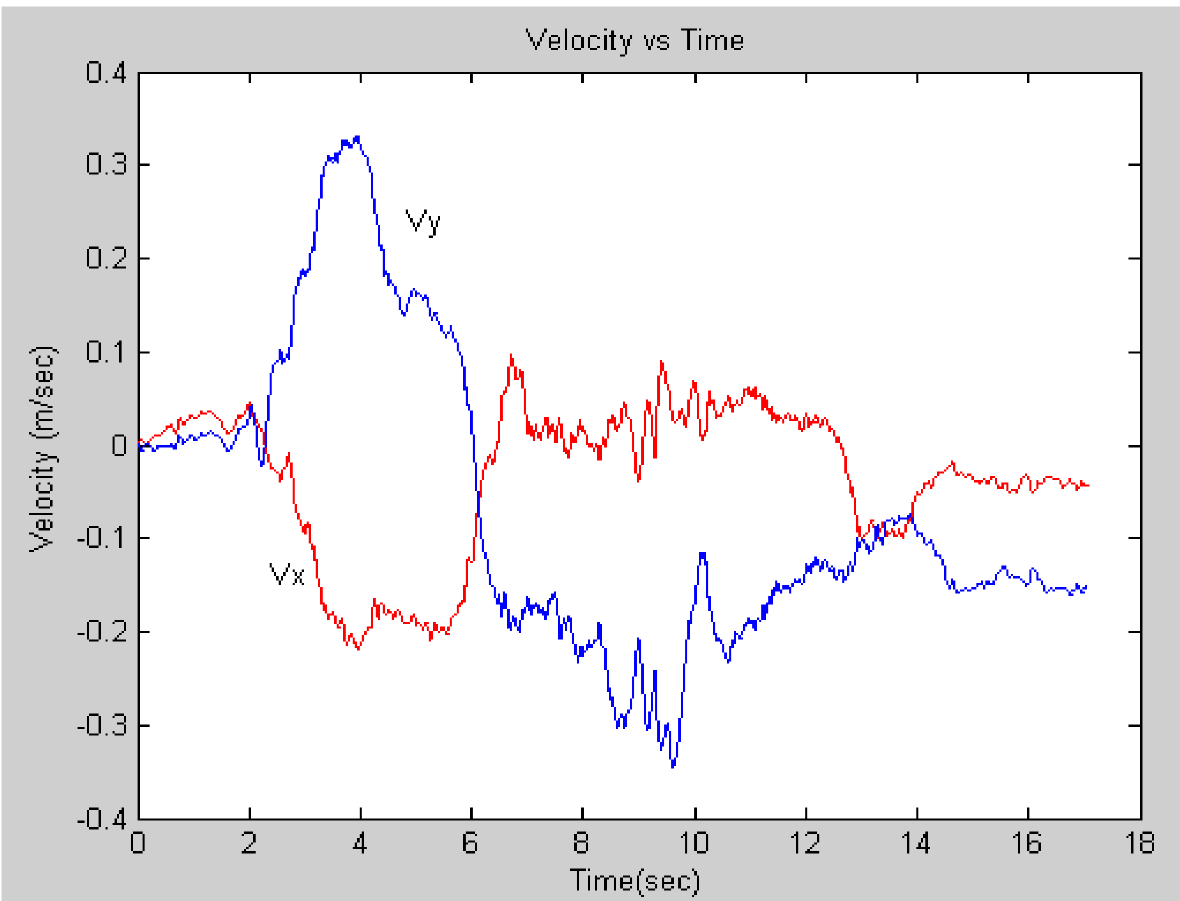

Figure 17 - Velocity vs Time for Left Turn Experiment

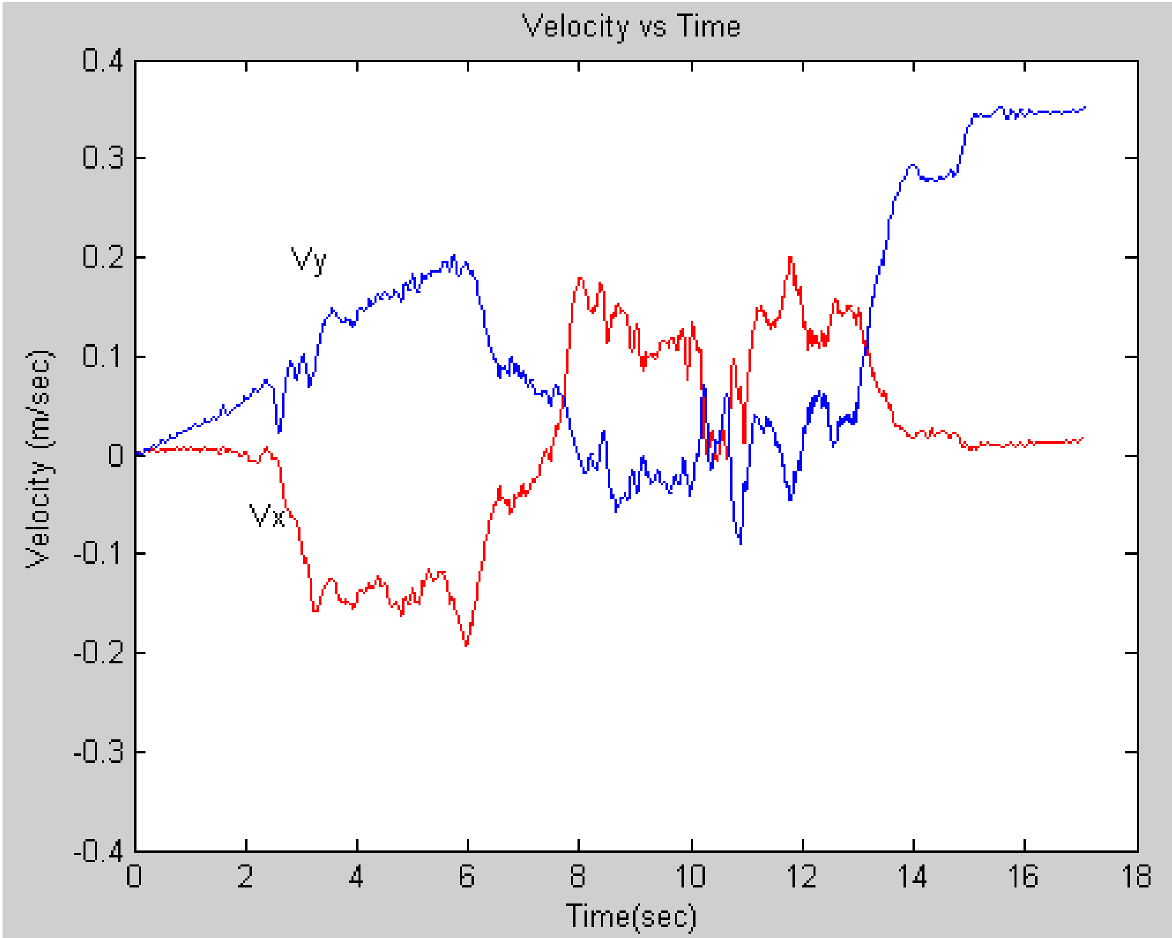

Figure 18 - Velocity vs Time for Right Turn Experiment

Viewing the velocity plots, it can be concluded that the data is effected by the noise density. However, these plots prove the theory of the inertial localization algorithm. From the algorithm, X-direction velocity, Vx, and Y-direction velocity, Vy should flip when the tracker is moving in a new direction. Around eight seconds for both of these experiments, Vx and Vy crosses each other as shown from above.

However, there is an issue that arises from these velocity plots. From the experiment, the cart was stopped around fourteen seconds. Looking at the plots, velocity in the X and Y directions after fourteen seconds shows that the device is still moving when it should not be. This is cause by the bias stability in the device.

5.2.4 Distance

To compute the distance of the experiments, the velocity data was integrated over time. Equations (8) and (9) were used to calculate the total distance in the X and Y direction.

$$\int V_x(t)d(t) = x(t) \qquad \text{Eq. (8)}$$

$$\int V_y(t)d(t) = y(t) \qquad \text{Eq. (9)}$$

From this, the distance vs time plots of the left and right turns can be seen below in Figure 19 and 20, respectively.

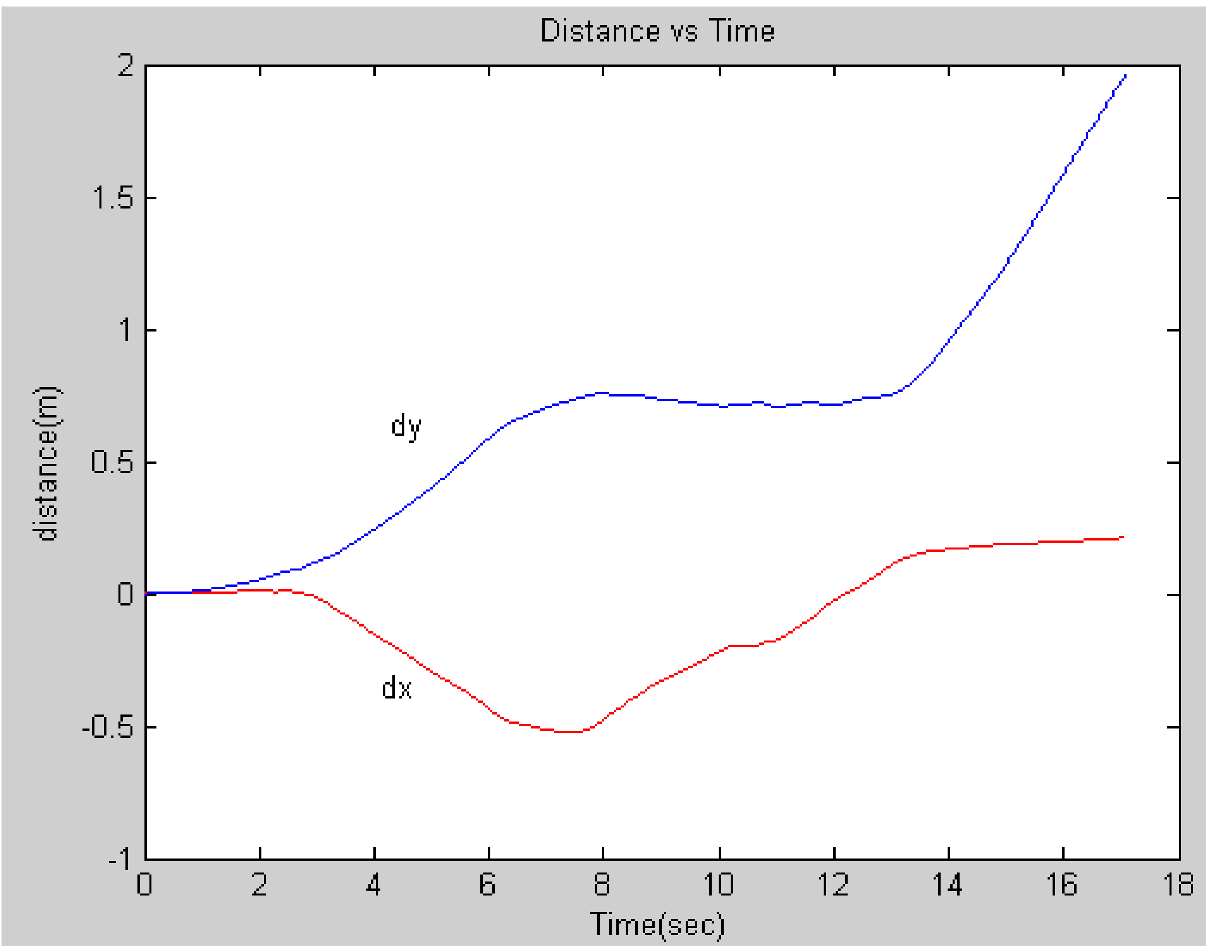

Figure 19 – Distance vs Time for Left Turn Experiment

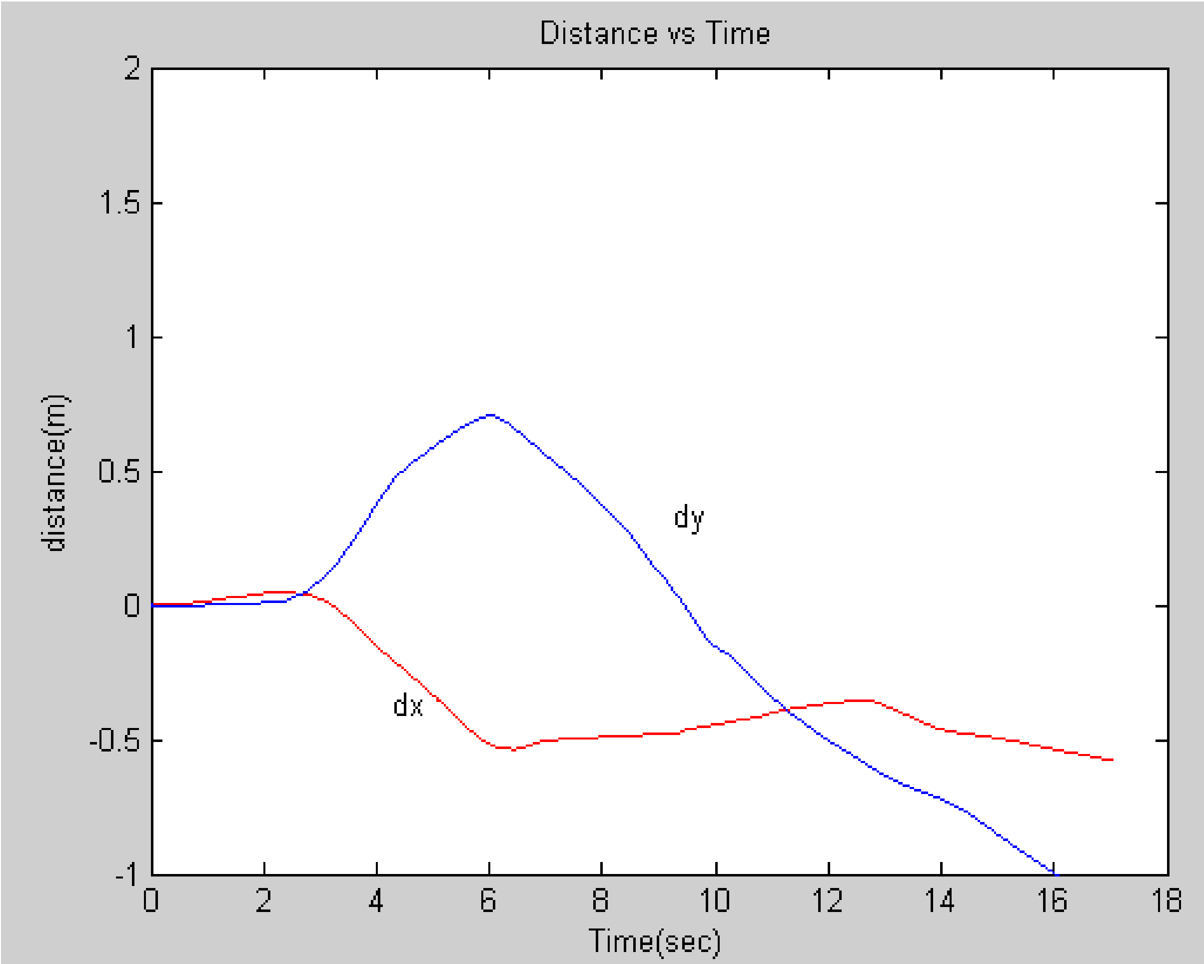

Figure 20 - Distance vs Time for Right Turn Experiment

These graphs show the distances in X and Y direction covered during the two fundamental experiments. As we start from rest, distance began to increase according to the direction of the device. When you turn, one of the distances in the X or the Y stays constant. For example, with the left turn, Y direction stays constant as X direction changes. While with the right turn, it is opposite way around X direction stays constant as Y direction changes. Both experiments ends around 14 seconds. However, the changes in distance continue. This is cause by the noise that causes the device to start drifting.

5.3 Final Mappings

Now that the distance values are known in each direction, we are able to produce the final mappings. The final maps are two dimensional plots of distance in X direction vs the distance in the Y direction. The two maps are scaled alike to show that the beginning route of both experiments were the same. Left and right turn routes are display below in Figures 21 and 22, respectively.

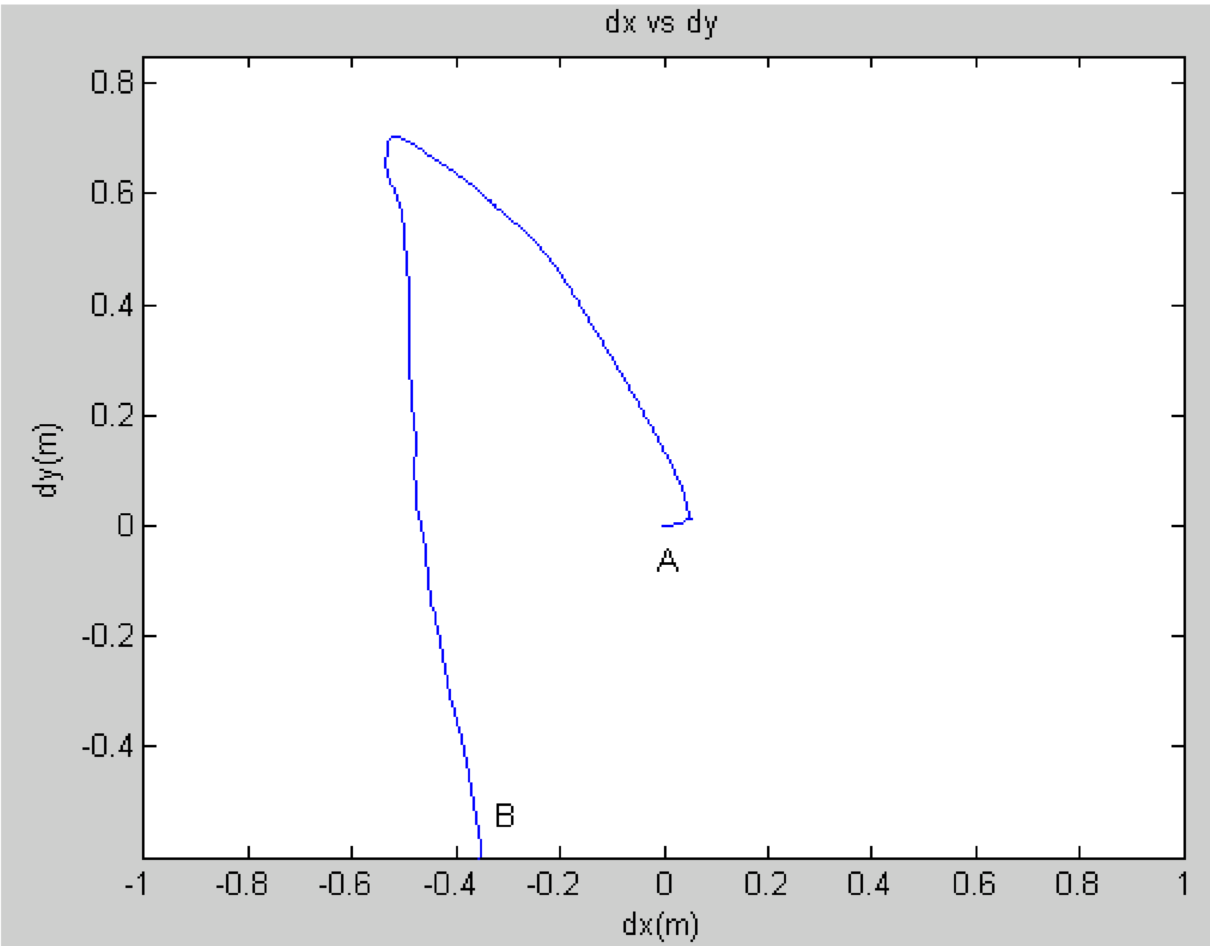

Figure 21 – Final Mapping for Left Turn Experiment

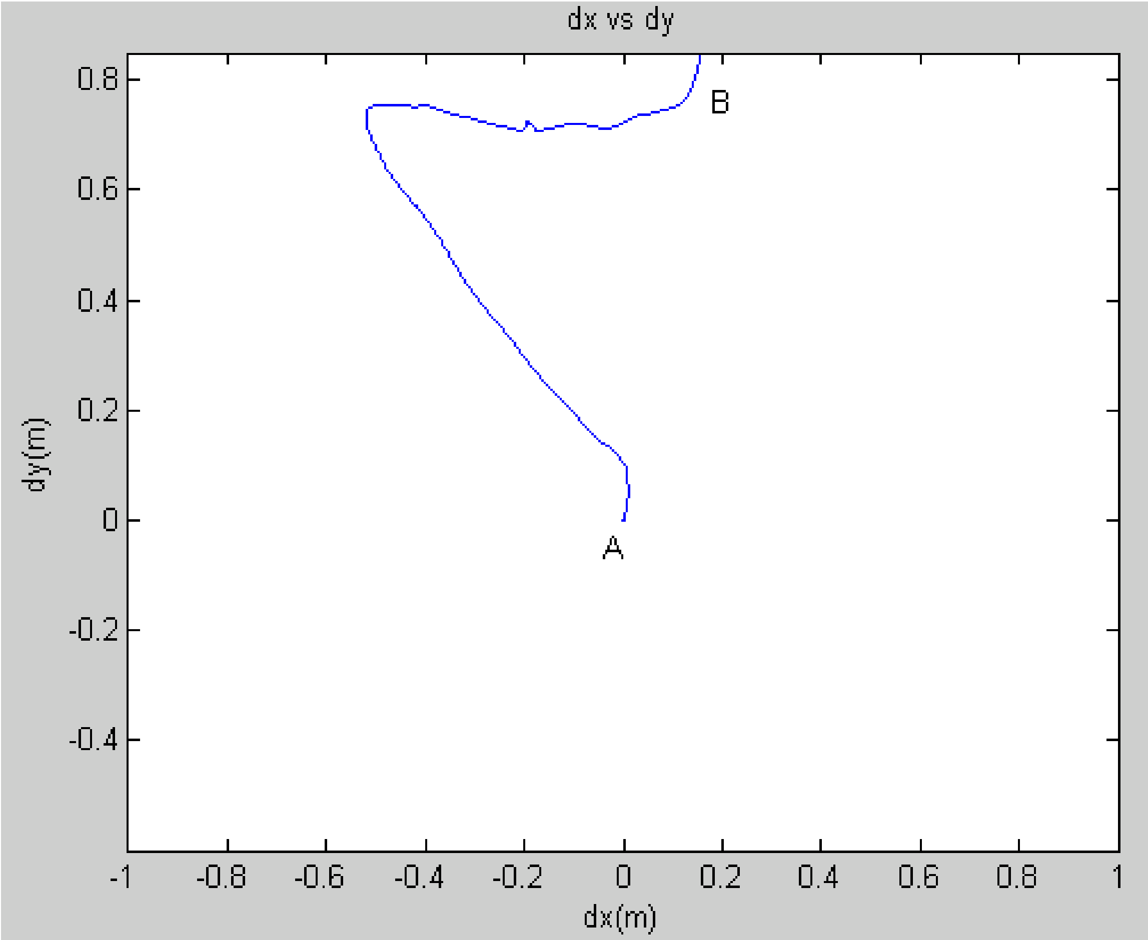

Figure 22 – Final Mapping for Right Turn Experiment

Starting from position A and ending at position B, these final mappings shows a correct left and right turns. Position A begins at point (0, 0). As the MTx motion tracker is move, the routes before their respected turn of each experiment are similar as they should be. However, the angles of these turns are not a complete 90 degrees as in the experiments. This may be caused by the noise density or the bias stability which causes the device to drift. But, the turn angles of the left and right turn routes are alike. According to the maps above, roughly 1.8 meters were covered. This was within range of the actual hand measurements of 2.3 meters.

6. Summary and Conclusion

In this project we researched and explored the characteristics of inertial systems using the Xsens Motion Tracker device for indoor geolocation and created a test-bed to evaluate the performance of the technology. The Xsens Motion Tracker attempts at providing an accurate indoor geolocation technology by using inertial systems. The MTx is used to record and store acceleration in the x, y, and z direction as well as the orientation angels, which are then used by the team in algorithms to output an indoor displacement mapping of experiments.

The parameters used from the device were divided into acceleration in the x, y, z direction and orientation angles. These two sets of information were found to be in respect to two coordinate; the device's coordinate frame and the Earth's fixed coordinate frame. The three dimensional acceleration is in respect to the device's coordinate frame system and the orientation angles in respect to the Earth's fixed coordinate system. The acceleration in respect to time is converted to the fixed coordinate by use of the rotation matrix. By multiplying the rotation matrix with acceleration in the x, y and z direction in respect to time, the three dimension acceleration vector in respect to time is produced. We then integrate the acceleration vector to get the velocity vector with respect to time. This is followed by integrating the velocity vector with respect to time to get the position vector with respect to time. This position vector is combined with the orientation angles through software programming to produce a final mapping of the test-bed.

The test-bed consisted of a fundamental experiment including a left 90 degree turn and a right 90 degree turn. In each case, after testing using the procedure explained, the final mapping showed the equivalent expected mapping of left and right turns. The angles of the two turns were not complete 90 degrees but can be shown with further algorithm development.

Based on the device's performance and the inertial localization algorithms, we were able to conclude that with further development in the algorithm to reduce noise, bias, or drifts, the Xsens Motion Tracker device is marketable and may be effective where Global Positioning Systems fail.

6.1 Future Recommendations

Outdoor localization is a well developed industry that global positioning systems is a technology of which most are familiar with and has very popular usage. Its main downfall is that it is very ineffective indoors. The indoor localization field is still in its process of development and has a lack of applications committed to orientation tracking indoors. By continuing the process of developing the inertial system for indoor localization using devices such as the Xsens Motion Tracker and comparing it with other technologies such as Wi-Fi localization, the indoor geolocation field continues to expand and may be integrated with outdoor localization applications. Other recommendations that would benefit the industry are to integrate such an application with GPS for both outdoor and indoor localization and to design hybrid localization using inertial systems.

References

1. Xsens Technologies. “MTi and MTx User Manual and Technical Documentation”.

2. Eric Foxlin. “NavShoe™ Pedestrian Inertial Navigation Technology Brief”. 8/2006 http://www.ece.wpi.edu/Research/PPL/Workshops/2006/PDF/InterSense.pdf

3. Eric Foxlin. “Pedestrian Tracking with Shoe-Mounted Inertial Sensors”. 12/2005

4. Stephane Beauregard. “Omnidirectional Pedestrian Navigation for First Responders”.

Appendix

Matlab Code for Plotting

<u>For Left turn experiment:</u>

```
A=dlmread('AVGexperiment90Leftturn(cart).txt');

%*****Declarations of Variables***********
t=[0:0.01:17.05];      % Time in seconds
a_x=(A(:,1));          % X Acceleration
a_y=(A(:,2));          % Y Acceleration
a_z=(A(:,3));          % Z Acceleration
roll=(A(:,4));         % Roll
pitch=(A(:,5));        % Pitch
yaw=(A(:,6));          % Yaw

%*****Acceleration from Device Coordinates to Fixed Coordinates****
for k=1:length(A)
%Simplified Rotational Matrix for X
xx{k}=(a_x(k)*cos(yaw(k)))+(a_y(k)*sin(yaw(k)));
%Simplified Rotational Matrix for Y
yy{k}=(a_x(k)*sin(yaw(k)))+(a_y(k)*cos(yaw(k)));
end

z=cell2mat(yy);
a_y2=z(1,:);
z1=cell2mat(xx);
a_x2=z1(1,:);

%******Velocity Computation****************
vx=cumtrapz(t,a_x2); % Velocity in X Direction
vy=cumtrapz(t,a_y2); % Velocity in Y Direction
%vz=cumtrapz(t,a_z);

%********Total Distance Computation*********
dx=cumtrapz(t,cumtrapz(t,a_x2)); % Distance in X Direction
dy=cumtrapz(t,cumtrapz(t,a_y2)); % Distance in Y Direction
%dz=cumtrapz(t,cumtrapz(t,a_z));

%******Rotational Matrix Equation***********
% for k=1:length(A)
%     G{k}=[cos(yaw(k)) -sin(yaw(k)) 0;sin(yaw(k)) cos(yaw(k)) 0;0 0 1];
% H= [dx(k);dy(k);dz(k)];
% Y{k}=G{k}*H;
% end
%
% z=cell2mat(Y);
% dx2=z(1,:);
% dy2=z(2,:);
% dz2=z(3,:);
```

```
%*********************************PLOTS*********************************

%*************ACCELERATION************
    figure
    plot(t,a_x2, 'r')
    hold on
    plot(t,a_y2, 'b')
    title('Acceleration vs Time')
    xlabel('Time(sec)')
    ylabel('Acceleration (m/sec^2)')
    gtext('a_x')
    gtext('a_y')
%**************VELOCITY************
    figure
    plot(t,vx, 'r')
    hold on
    plot(t,vy, 'b')
    title('Velocity vs Time')
    xlabel('Time(sec)')
    ylabel('Velocity (m/sec)')
    gtext('Vx')
    gtext('Vy')
%*************ROLL, PITCH, YAW*************
    figure
    plot(t,pitch, 'r')
    hold on
    plot(t,yaw, 'b')
    hold on
    plot(t,roll, 'g')
    title('Eular Angles vs time')
    xlabel('Time(sec)')
    ylabel('Degrees')
    gtext('roll')
    gtext('pitch')
    gtext('yaw')
%***********Total Distance*****************
    figure
    plot(dx,dy)
    title('dx vs dy')
    xlabel('dx(m)')
    ylabel('dy(m)')
    gtext('A')
    gtext('B')

    figure
    plot(t,dx,'r')
    hold on
    plot(t,dy,'b')
    title('Distance vs Time')
    xlabel('Time(sec)')
    ylabel('distance(m)')
    gtext('dx')
    gtext('dy')
```

For Right Turn Experiment

```
A=dlmread('AVGexperiment90Rightturn(cart).txt');

%*****Declarations of Variables***********
t=[0:0.01:17.05];      % Time in seconds
a_x=(A(:,1));          % X Acceleration
a_y=(A(:,2));          % Y Acceleration
a_z=(A(:,3));          % Z Acceleration
roll=(A(:,4));         % Roll
pitch=(A(:,5));        % Pitch
yaw=(A(:,6));          % Yaw

%*****Acceleration from Device Coordinates to Fixed Coordinates****
for k=1:length(A)
%Simplified Rotational Matrix for X
xx{k}=(a_x(k)*cos(yaw(k)))+(a_y(k)*sin(yaw(k)));
%Simplified Rotational Matrix for Y
yy{k}=(a_x(k)*sin(yaw(k)))+(a_y(k)*cos(yaw(k)));
end

z=cell2mat(yy);
a_y2=z(1,:);
z1=cell2mat(xx);
a_x2=z1(1,:);

%******Velocity Computation****************
vx=cumtrapz(t,a_x2); % Velocity in X Direction
vy=cumtrapz(t,a_y2); % Velocity in Y Direction
%vz=cumtrapz(t,a_z);

%********Total Distance Computation*********
dx=cumtrapz(t,cumtrapz(t,a_x2)); % Distance in X Direction
dy=cumtrapz(t,cumtrapz(t,a_y2)); % Distance in Y Direction
%dz=cumtrapz(t,cumtrapz(t,a_z));

%******Rotational Matrix Equation***********
% for k=1:length(A)
%     G{k}=[cos(yaw(k)) -sin(yaw(k)) 0;sin(yaw(k)) cos(yaw(k)) 0;0 0 1];
% H= [dx(k);dy(k);dz(k)];
% Y{k}=G{k}*H;
% end
%
% z=cell2mat(Y);
% dx2=z(1,:);
% dy2=z(2,:);
% dz2=z(3,:);
```

```
%***********************************PLOTS**********************************

%*************ACCELERATION************
    figure
    plot(t,a_x2, 'r')
    hold on
    plot(t,a_y2, 'b')
    title('Acceleration vs Time')
    xlabel('Time(sec)')
    ylabel('Acceleration (m/sec^2)')
    gtext('a_x')
    gtext('a_y')
%**************VELOCITY************
    figure
    plot(t,vx, 'r')
    hold on
    plot(t,vy, 'b')
    title('Velocity vs Time')
    xlabel('Time(sec)')
    ylabel('Velocity (m/sec)')
    gtext('Vx')
    gtext('Vy')
%*************ROLL, PITCH, YAW*************
    figure
    plot(t,pitch, 'r')
    hold on
    plot(t,yaw, 'b')
    hold on
    plot(t,roll, 'g')
    title('Eular Angles vs time')
    xlabel('Time(sec)')
    ylabel('Degrees')
    gtext('roll')
    gtext('pitch')
    gtext('yaw')
%***********Total Distance*****************
    figure
    plot(dx,dy)
    title('dx vs dy')
    xlabel('dx(m)')
    ylabel('dy(m)')
    gtext('A')
    gtext('B')

    figure
    plot(t,dx,'r')
    hold on
    plot(t,dy,'b')
    title('Distance vs Time')
    xlabel('Time(sec)')
    ylabel('distance(m)')
    gtext('dx')
    gtext('dy')
```