INERTIAL NAVIGATION SYSTEM (INS) DATA PROCESSING FOR LAND VEHICLE MAPPING

By

KHURRAM NIAZ SHAIKH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
in Fulfilment of the Requirements for the Degree of Master of Science

November 2004

DEDICATION

I dedicate this research to my parents especially my mother who bore the absence of her beloved son and prayed all the time for my success and accomplishment due to which it became possible for me to write this thesis.

Abstract of thesis presented to the Senate of University Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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Chairman: Associate Professor Abdul Rashid Mohammad Shariff, PhD

Faculty: Engineering

Locating the positions and mapping the spatial information is of critical significance in the field of Precision Farming. Global Positioning System (GPS) is the main tool being utilized for this purpose but it is dependent on the satellite signals, unfortunately these signals may get lost due to the blockage by canopy of the orchards. Inertial Navigation System (INS) can address this problem and support the non-availability of GPS signal for a short time. INS is capable of individually calculating the vehicle's position without any external references. However, its high cost and time dependent errors are its major drawbacks.

The research focuses on the mapping solution by INS only so that it can provide solution in the absence of GPS signal. Low cost inertial sensor (Xbow RGA300CA) was used for data collection and processing. Data Processing was done in Matlab/Simulink environment. A Simulink processing model is presented in detail to give an insight of the Strapdown INS Mechanization. Low pass filter and wavelet denoising model was used to

assess the margin of improvement for noise filtering. Accurate GPS information was used as a reference of comparison.

The model was tested in the lab as well as in the field for its validity. Before going to the field the Inertial sensor was tested in the lab for yaw rate drift and for stationary drift. For kinematic field testing, inertial sensor with GPS was mounted on the vehicle to get the positions for straight trajectories up to 100 meters. Results obtained are presented in detail. A gradual error growth was observed in the INS data and the sensor was found to be stable for short term only.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMPROSESAN DATA SISTEM NAVIGASI INERSIA BAGI PEMETAAN KENDERAAN DARAT

Oleh

KHURRAM NIAZ SHAIKH

November 2004

Pengerusi: Profesor Madya Abdul Rashid Mohammad Shariff, PhD

Fakulti: Kejuruteraan

Menentukan kedudukan dan memetakan maklumat spatial sangat kritikal dalam bidang Pertanian Tepat. Sistem Posisi Global (GPS) ialah sistem utama yang digunakan untuk tujuan ini, tetapi ia bergantung kepada isyarat daripada satelit, sedangkan isyarat-isyarat tersebut mungkin hilang akibat halangan kanopi pokok di dalam ladang. Sistem Navigasi Inersia (INS) boleh mengatasi masalah ini dan boleh menampung ketiadaan isyarat GPS bagi masa yang singkat. INS mampu mengira kedudukan kenderaan tanpa rujukan luaran. Tetapi kosnya yang tinggi dan ralatnya yang bergantung pada masa adalah kelemahan system ini.

Oleh itu penyelidikan ini tertumpu kepada penyelesaian pemetaan menggunakan INS agar ia dapat menghasilkan penyelesaian tanpa isyarat GPS. Penderiaan Inersia berkos rendah (Xbow RGA300CA) digunakan untuk pengumpulan dan pemprosesan data. Permprosesan data dibuat di dalam Matlab/Simulink. Sebuah model pemprosesan Simulink dipersembahkan dengan terperinci untuk menjelaskan Mekanisasi INS

“Strapdown model”. Tapisan laluan rendah dan “wavelet denoising” telah digunakan untuk menilai tahap pembaikan bagi “nosie filtering”. Maklumat GPS yang jitu telah digunakan sebagai rujukan bandingan.

Model ini telah diuji di dalam makmal dan juga di lapangan bagi menentukan keberkesananya. Sebelum deria inersia dibawah ke lapangan, ianya terlebih dulu diuji didalam makmal bagi menantukan kadar halaju pecutan dan kadar pemberhentian. Bagi tujuan ujian kinematik, deria inersia dan GPS diletakkan diatas kenderaan untuk mendapatkan posisi bagi projector laluan lurus sehingga 100 meter. Keputusan yang didapati daripada ujikaji ini telah diterangkan dengan lengkap. Penigkatan ralat yang biasa telah diperhatikan didalam data INS dan deria inersia itu didapati stabil dalam jangka waktu yang pendek sahaja.

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I am also grateful to Mr. Zakaria Ghazali (Technical Officer at Department of Civil Engineering) for his help and sharing of experience in the use of survey equipments.

I certify that an Examination Committee met on **date of viva** to conduct the final examination of **Khurram Niaz Shaikh** on his **Master of Science** thesis entitled "**Inertial Navigation System (INS) Data Processing For Land Vehicle Mapping**" in accordance with Universiti Putra Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Chairman, PhD
Professor
Faculty of Graduate Studies
Universiti Putra Malaysia
(Chairman)

Examiner 1, PhD
Professor
Faculty of Graduate Studies
Universiti Putra Malaysia
(Member)

Examiner 2, PhD
Professor
Faculty of Graduate Studies
Universiti Putra Malaysia
(Member)

Independent Examiner, PhD
Professor
Faculty of Graduate Studies
Universiti Putra Malaysia
(Independent Examiner)

GULAM RASOOL RAHMAT ALI, PhD
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

This thesis submitted to the Senate of University Putra Malaysia and has been accepted as fulfilment of the requirement for the Degree of Master of Science. The members of the Supervisory Committee are as follows:

Abdul Rashid bin Mohammad Shariff, PhD
Associate Professor
Department of Biological and Agricultural Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Hishamuddin Jamaluddin
Lecturer
Department. of Biological and Agricultural Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Shattri Mansoor, PhD
Associate Professor
Department. of Civil Engineering
Faculty of Engineering
Universiti Putra Malaysia
(Member)

AINI IDERIS, PhD
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

KHURRAM NIAZ SHIAKH

Date:

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LIST OF ABBREVIATIONS

DCM	Direction Cosine Matrix
DTG	Dynamically Tuned Gyro
EU	European Union
FOG	Fiber Optic Gyro
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IFOG	Interferometric Fiber Optic Gyro
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
JUPEM	Jabatan Ukur Pemetaan Malaysia (Department of Survey and Mapping Malaysia)
MEMS	Micro-Electro-Mechanical Systems
MMS	Mobile Mapping System
MPOB	Malaysian Palm Oil Board
RGA	Rate Gyro Accelerometer
RLG	Ring Laser Gyro
SINS	Strapdown Inertial Navigation System
WGS	World Geodetic System

CHAPTER 1

INTRODUCTION

1.1 Background

Humans have been trying to figure out the position on earth since stone age so that we can use that information to know where we are and where we are going. Today, the strife has brought us to the technological advancement that has made things much easier and with the help of innovative technology and computing power we have been working hard to achieve accuracy with higher precision. Today, there is a wide range of navigation sensors available that can not only pin point the location on earth but also can keep track of the navigation information with velocity. In geomatics engineering sense, navigation is understood as quasi-continuous positioning of a moving object. Thus, we often encounter expressions such as "GPS-navigation". In fact, the task of navigation is much more complex than just positioning as it includes the decision making as well as steering of the moving vehicle. (OmarBashich, 1998)

Global Positioning System (GPS) is the most popular navigation system in use today. But its limitations open doors for an autonomous navigation system such as Inertial Navigation System (INS). A decade ago Inertial sensors were only limited to aerospace and military applications due to their high cost and restrictions by the government but now due to the reducing cost they are finding their way in civil applications such as, mobile tracking, precision surveying, and precision farming.

1.2 Problem Statement

No one denies the accuracy of GPS with the increased constellation of satellites and improved methods of data processing but GPS is still dependent on the satellite signal. Today, the surveyors are having problems of accuracy in places where the signal gets lost due to blockage by buildings, canopy, and other obstructions. Many of the studies are being carried out to address the issue of signal loss. Inertial Navigation System (INS) is one the most popular navigation system that can provide an autonomous solution in case of signal loss. The output given by inertial sensors is in terms of accelerations and angles only that need to be processed to get position information. Not much work has been done in the field of Inertial Navigation System (INS) in Malaysia and no proper guidelines are available to do the processing of INS data to get the position information. The manuals accompanying the Inertial equipments only specify the technical details of the equipment and do not provide much information on data processing. Thus there is a need for the formulation of methods and procedures for the processing of INS data. The resulting information need to be verified for its accuracy and reliability.

1.3 Goals and Objectives

The major goal of this research is to get accurate coordinate trajectory information from low-cost strapdown inertial systems so that it can be used as a standalone navigation system to support the short GPS outages during land vehicle mapping.

The specific objectives to achieve this goal are:

- Create INS data processing model in Matlab/Simulink to get output in terms of positions.
- Remove the Noise from the output by testing and comparing two filtering techniques Low Pass Filtering and Wavelet Denoising.
- Investigate the navigation accuracy of the RGA Inertial Sensor with accurate GPS information.

1.4 Summary of Methodology

Inertial sensors output accelerations and angles but the mapping information needs positions. Therefore, the output given by inertial sensors need to be processed to get the information in terms of positions. A low cost inertial sensor (RGA300CA) from Xbow Inc. USA was used to collect the data and process. To attain the objective of INS data processing Matlab/Simulink software was used because of its strong computing capabilities and ease of use due to built in blocks in the Simulink library. The output given by the RGA inertial sensor contains substantial noise that needs to be filtered. The software used to log the accelerations from RGA inertial sensor is Gyroview version 2.4 that comes with the RGA Inertial Sensor. The data is saved in text format that was later loaded in Matlab workspace as individual variables of three accelerations and three axis angular information. By integrating the accelerations once gives velocities and integrating again gives positions.

These accelerations multiplied by the angular information give attitude corrections. However, the noise in the RGA inertial sensor data makes output inaccurate and requires a proper noise filtering technique. Two noise filtering techniques: Low pass filtering and Wavelet denoising were testing and compared for accuracy.

The simulink processing model was tested for validity by conducting tests in the lab as well as in the field. Stationary lab testing and yaw rate lab testing was conducted to check the error growth with respect to time. Kinematic testing was conducted by mounting the inertial sensor over the vehicle and taking the measurements over the distances up to 100 meters. These measurement once processed were compared with accurate DGPS information. Chapter three of methodology discusses the research approach in detail comprising the data processing method and testing setup.

1.5 Scope of Study

The research focuses on the processing of INS data using RGA300CA inertial sensor (Figure 3.3) from Xbow Inc. USA. It does not go into the details of hardware design and configuration. It also does not deal with the details of GPS/INS integration. Field surveys were limited to the distances of up to 100 meters because of the sub meter accuracy requirement.

1.6 Summary of Results Obtained

The results obtained from INS after processing gives error growth and accuracy. A gradual error growth was found in the INS during a static lab testing of up to 100 seconds. These errors accumulate due to the integration of the input data. Errors in degree were also measured during a yaw rate lab testing. Multiple data samples were taken to avoid data ambiguity. Data obtained from kinematic surveys showed different results depending upon the type of filter used whereby wavelet denoising technique showed better result over short distances up to 40 meters while Low pass filtering found to be better at longer distances.

1.7 Previous Work

In Malaysia, there is no published work in the field of inertial navigation except the two papers. (Shariff, 2003 and Shaikh, 2004) However, it is gaining popularity as the time progresses. Most of the work in the field of navigation is being carried out at Dept. Of Geomatics engineering, University Of Calgary Canada (El-Sheimy 1996, Skaloud 1999, Mohammad 1999, Shin 2001, Zhang 2003, Petovello 2003, Nassar 2003, Park 2004)

1.8 Thesis Outline

Chapter 1 gives an overview of the research defining the problem statement and objectives and scope of this study. It also gives a brief summary of the methodology and results obtained. Chapter 2 begins with the introduction of the navigation systems like Global Positioning System (GPS) and Inertial Navigation System (INS) and goes in to the details of INS by defining different types of Inertial sensors and error sources of INS and main navigation equation. In the end it gives a brief introduction of Mobile Mapping and Integration of GPS and INS. Chapter 3 defines the research approach defining the methodology of the research experiments along with the details of hardware and software configuration and testing setup of data collection. It also gives an insight of the data processing method and INS mechanization model developed in Matlab/Simulink. Chapter 4 starts with the discussion on noise filtering techniques used and their results and analysis and discusses the processed results obtained from the static and kinematic testing. The complete data sets as well as mean results of the tests are provided in this chapter. Chapter 5 concludes the research with some recommendations for improvement and future work. The soft copy of all the Simulink models and the references are made available on the CD accompanying this thesis.

CHAPTER 2

LITERATURE REVIEW

This chapter is devoted to the background literature study fundamental to this research. It gives a brief introduction of the systems related to the research of Inertial Navigation System. Following is the brief overview of the two common navigation systems in use today.

2.1 Global Positioning System (GPS)

Global Positioning System (GPS) is the most commonly used navigation system today. Presently it has a network of 29 satellites, (Figure 2.1) about 20,200 km away from the earth that continuously transmit coded information, which makes it possible for a receiver to precisely identify locations on earth by measuring distance from the satellites. It is an American satellite navigation system operated by US department of defence. (Farrel and Barth, 1999, Grewal et al, 2001)

European Union (EU) would be launching another constellation of 30 navigation satellites known as Galileo that is planned to be operated by 2008. The term GPS (Global Positioning System) would most probably be replaced by GNSS (Global Navigation Satellite System). The launching of Galileo would tremendously increase the market of satellite navigation system.

Figure 2.1: GPS Constellation
Source: http://www.garmin.com/graphics/24satellite.jpg

2.1.1 Differential GPS (DGPS):

Differential GPS is a method of making data more accurate by observing the same satellites from a static known reference at the same time of kinematic survey by a rover. The data collected from the two receivers is post processed and hence improves the accuracy of the positions. Figure 2.2 gives the conceptual view of the differential GPS method.

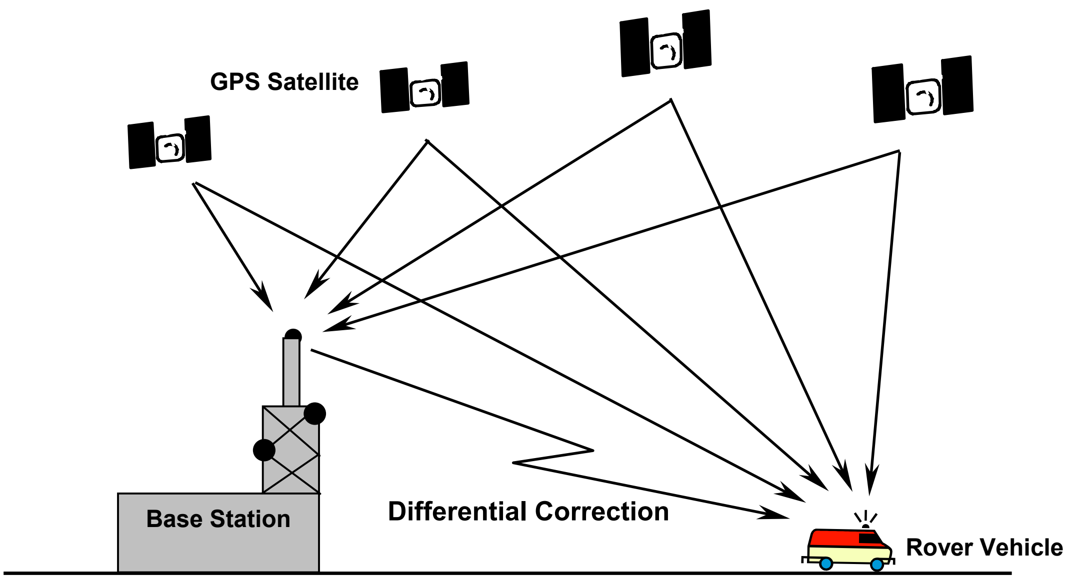

Figure 2.2: Differential GPS (DGPS)

2.1.2 GPS Error Sources:

Factors that can degrade the GPS signal and thus affect the accuracy include the following: (Garmin)

a. **Ionosphere and troposphere delays** — The satellite signal slows as it passes through the atmosphere. The GPS system uses a built-in model that calculates an average amount of delay to partially correct for this type of error.

b. **Signal multipath** — This occurs when the GPS signal is reflected off objects such as tall buildings or large rock surfaces before it reaches the receiver. This increases the travel time of the signal, thereby causing errors.

c. **Receiver clock errors** — A receiver's built-in clock is not as accurate as the atomic clocks onboard the GPS satellites. Therefore, it may have very slight timing errors.

d. **Orbital errors** — Also known as ephemeris errors, these are inaccuracies of the satellite's reported location.

e. **Number of satellites visible** — The more satellites a GPS receiver can "see" the better the accuracy. Buildings, terrain, electronic interference, or sometimes even dense foliage can block signal reception, causing position errors or possibly no position reading at all. GPS units typically will not work indoors, underwater or underground.

f. **Satellite geometry/shading** — This refers to the relative position of the satellites at any given time. Ideal satellite geometry exists when the satellites are located at wide angles relative to each other. Poor geometry results when the satellites are located in a line or in a tight grouping.

g. **Intentional degradation of the satellite signal** — Selective Availability (SA) is an intentional degradation of the signal once imposed by the U.S. Department of Defense. SA was intended to prevent military adversaries from using the highly accurate GPS signals. The government turned off SA in May 2000, which significantly improved the accuracy of civilian GPS receivers.

2.2 Inertial Navigation System (INS)

Inertial navigation system (INS) has been around since the mid of twentieth century and now gaining popularity due to technological advancements in micro machined sensors that are reducing in size as well as cost with the passage of time. The good thing about it is its autonomous availability and high bandwidth. An Inertial Navigation System (INS) is the combination of sensors (Accelerometers and Gyros) grouped together as one equipment. Accelerometer, as the name suggests, senses the acceleration along a single axis and Gyro senses the angular movements also along the single axis. Both, Accelerometers and Gyros operate on the inertial principles (Newton's Laws of Motion) providing navigation solution and for this reason it is named as Inertial Navigation System.

An INS contains three accelerometers (measure accelerations) and three gyros (measure angles). These Inertial sensors are mounted as three orthogonal axes in an Inertial Measurement Unit (IMU) {A black box that houses the inertial sensors} and output the accelerations (velocity changes over time) that can be integrated twice to get positions and Angles (Angular rates in case of rate sensors) along the same axes. Angular rate sensors are used to measure the rate that a vehicle rotates around a given axis. The rotations around x, y and z-axis are termed as Roll, Pitch and Yaw respectively, as shown in Figure 2.3.

Velocity $v = \int_{t_0}^{t} a \, dt$

Position $s = \int_{t_0}^{t} v \, dt$

These rotations can be integrated once to get the angles as a function of time and velocity changes are converted to navigation data by numerically integrating twice and transformed from Body to Navigation Coordinate system to give us positions in navigation frame that is relatively fixed. The good thing about INS is its independent and jamproof navigation data, as compared to GPS that is dependent on satellite signal, however, INS accuracy degrades with respect to time making it a major drawback.

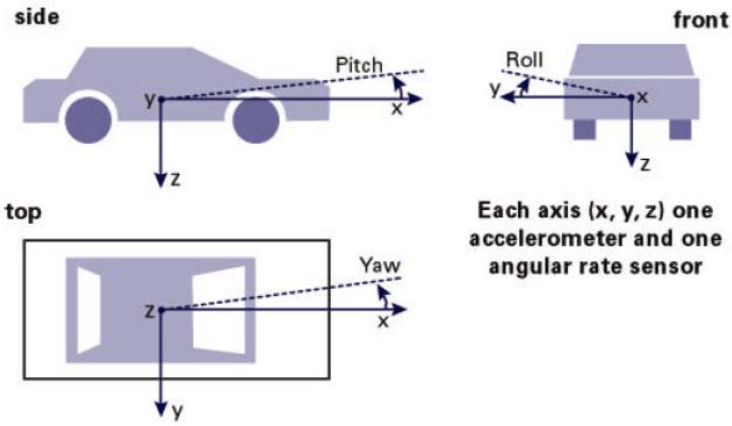

Figure 2.3: Sensor Axis on Vehicle
Source: IMU Application Note (Xbow)

Most of the errors in the INS are caused by sensor imperfections (instrumental errors), therefore, accuracy mostly depends on the type of sensors available. However, the cost of the INS is directly proportional to the accuracy, that's high performance accurate sensors are still very expensive and limited to certain applications.

Figure 2.4 gives an overview of the accuracy and cost of the gyros used in Modern INS. It can be seen that the cost of tactical and navigation grade sensors is still very high and beyond the reach for certain civil applications. The use of accurate sensors is limited to commercial and military applications.

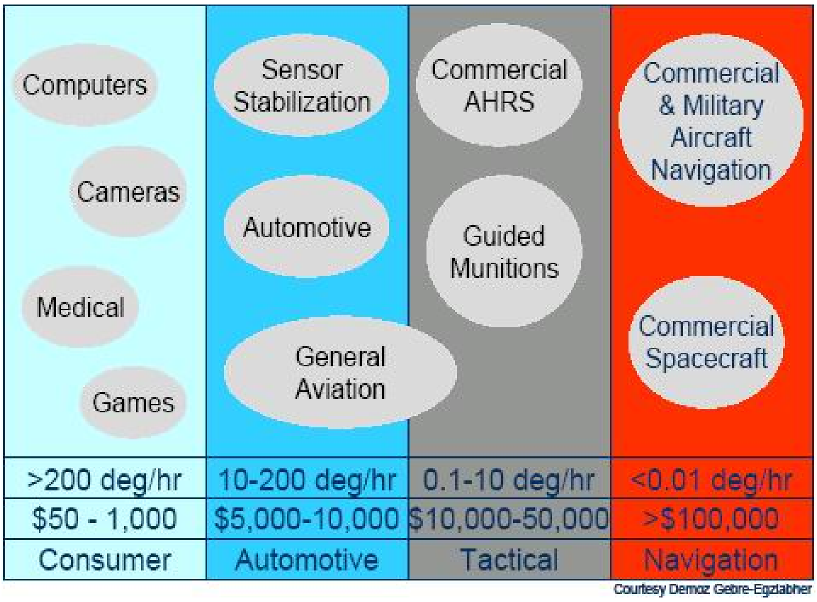

Figure 2.4: Chart of Accuracy and Cost
(Source: Gautier, 2003)

The first Inertial Navigation Systems were built based on mechanical gyros with very complex and power consuming architecture. Later on strapdown solutions have been realized by using modern integrated electro-mechanical or electro-optical sensors (Luethi, 2000). These strap down systems are mostly based on the MEMS (Micro Electro-Mechanical System) technology that is relatively inexpensive and compact. These cost effective sensors, because of its short-term sustainability and complementary characteristics, are being widely used in Integrated Navigation Systems especially with GPS (Global Positioning System).

2.2.1 Strapdown Inertial Navigation Systems (SINS)

A strapdown system is a major hardware simplification of the old mechanical systems. The accelerometers and gyros are mounted in body coordinates and are not mechanically moved. Instead, a software solution is used to keep track of the orientation of the IMU (and vehicle) and rotate the measurement from the body frame to the navigation frame. This method overcomes the problems encountered with the old mechanical (gimbaled) system, and most importantly reduces the size, cost, power consumption, and complexity of the system. (Walchko, 2002) Figure 2.5 shows the diagram of the internal structure of an strapdown INS fixed with the body of the vehicle while Figure 2.6 is a functional block diagram of a strapdown INS mechanization, which describes the process flow of the accelerations to the position, velocity and attitude.

The angles (Angular rates in case of rate sensor) given by the INS need to be converted to Euler angles to be used in Direction Cosine Matrix (Transformation Matrix) (check section 2.2.4). Quaternion, also known as Euler symmetric parameters, are more mathematically efficient ways to compute rotations of rigid and non-rigid body systems than traditional methods involving standard rotational matrices or Euler angles. Quaternions have the advantage of few trigonometric functions needed to compute attitude. Also, there exists a product rule for successive rotations that greatly simplifies the math, thus reducing processor computation time. (Walchko, 2002) Scary mathematical equations are avoided over here but for details of quaternions and Euler angles can be found in the references. (Walchko 2002 and Farrel, 1999)

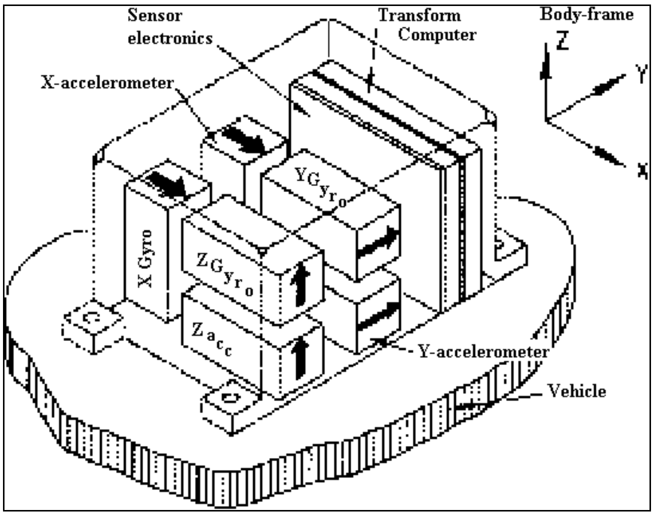

Figure 2.5: Strapdown Inertial Navigation System
(Source: Karlsson, 2003)

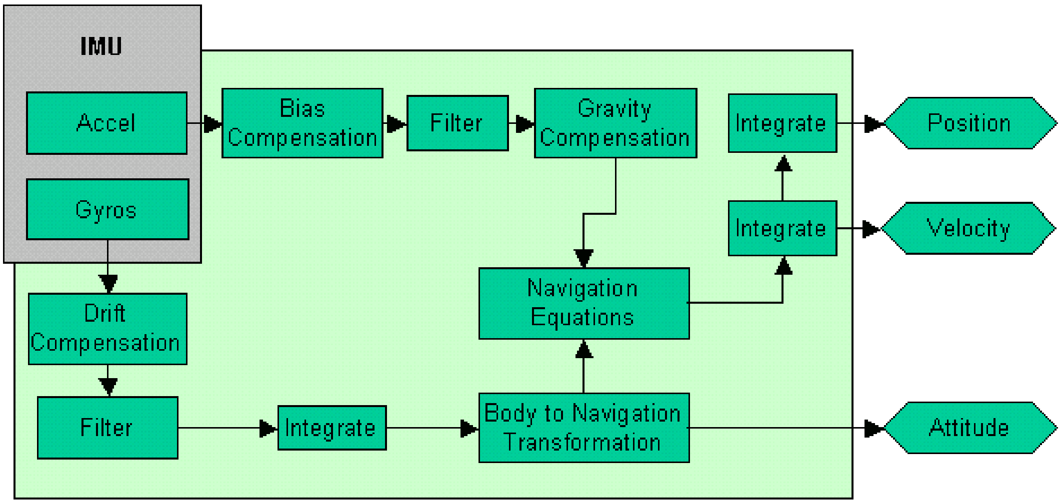

Figure 2.6: Flow chart of Strapdown INS

2.2.2 Strapdown INS Errors

Most of the error sources that corrupt the navigation solution are sensor errors or random disturbances (Stovall, 2000). Most common errors in Strapdown INS are:

a. **Bias Errors** —A constant signal on the output of a sensor, independent of the input. A bias will not change during a run, but may vary from turn-on to turn-on. A bias is modeled as a random constant. For navigation grade sensors, bias is usually specified in deg/hr.

b. **Scale Factor Errors** —A linear error that is proportional to the input signal. Scale Factor is usually specified in parts per million (ppm).

c. **Alignment Errors** —Roll, Pitch and Yaw angle errors caused by the misalignment with the body of the navigation frame.

The rate of error growth is associated with the bias quality of the inertial sensor, especially, gyroscopes. Ideally there should be no bias (or very low at least) and behave in a simple linear fashion. Unfortunately in real life, noise, disturbances, drifts, misalignments, and manufacturing complications enter into the equation and make developing an INS difficult. (Walchko, 2002) A large alignment error with high quality gyroscopes might actually be better than small alignment errors with low quality gyroscopes. These systems also require lengthy alignment time. If both of these requirements are not met, even the most accurate INS can be or become worthless (Geibner, 2000). There are many problems with noise and unbounded error that must be handled to get any meaningful result out of INS. (Walchko, 2002)

During the field test, the dynamic motions and angles of the vehicle are measured relative to the road. Accelerometers let us measure the forces caused by turning, accelerating or braking, but the measurements won't be accurate unless the vehicle is level relative to the Earth during these maneuvers (IMU Application Note). If the vehicle tilts forward, gives gravity components measured by the accelerometer and caused by the tilt angle.

Angular rate sensors can help correct the effect of the forward tilt by measuring rotations around the center of gravity of the vehicle. Unfortunately, angular rate sensors have their own drawbacks. Angular rate sensors measure rotation rate, not rotation angle; the rotation angle is found by integrating the measured rotation rate over time. Error in the rotation rate will integrate in larger error over time (IMU Application Note). However, these angular rate measurements can reduce the errors, which are systematic in nature, after being combined with acceleration measurements. With current high computational power and powerful simulation techniques these errors can be modeled and measurements in real-time can be performed with reasonable accuracy.

The science of guidance, navigation, and control has been under development for over 100 years. Many exciting developments have taken place in that time, especially in the area of navigation sensors. Today, to understand fully the entire range of navigation sensors, one needs to know a wide range of sciences such as mechanical engineering, electronics, electro-optics, and atomic physics. In recent years, three major technologies in inertial sensing have enabled advances in commercial capabilities. These are the Ring Laser Gyro (since ~1975), Fiber Optic Gyros (since ~1985), and Micro-Electro-Mechanical Systems (MEMS) (since ~1995). (Barbour, 2003)

2.2.3 Types of Inertial Sensors

Sensors are often compared on the basis of certain performance factors, such as bias and scale-factor stability and repeatability or noise (random walk). Sensor selection is made difficult by the fact that many different sensor technologies offer a range of advantages and disadvantages while offering similar performance. Nearly all new applications are strapdown (rather than gimbaled) and this places significant performance demands upon the gyroscope (specifically: gyro scale-factor stability, maximum angular rate capability, minimum g-sensitivity, high BW). For many applications, improved accuracy/performance is not necessarily the driving issue, but meeting performance at reduced cost and size is. (Barbour, 2003)

2.2.3.1 Ring Laser Gyros

Although the RLG was first demonstrated in a square configuration in 1963, it wasn't until the late 1970s and 1980s that RLG systems came into common use as strapdown inertial navigators. The RLG has excellent scale-factor stability and linearity, negligible sensitivity to acceleration, digital output, fast turn-on, excellent stability and repeatability across dormancy, and no moving parts. The RLG's performance is very repeatable under temperature variations so that a temperature compensation algorithm effectively eliminates temperature sensitivity errors. It is superior to spinning mass gyros in strapdown applications, and is an exceptional device for high-dynamic environments. (Barbour, 2003) Figure 2.7 shows the picture of a single axis Ring Laser Gyro.

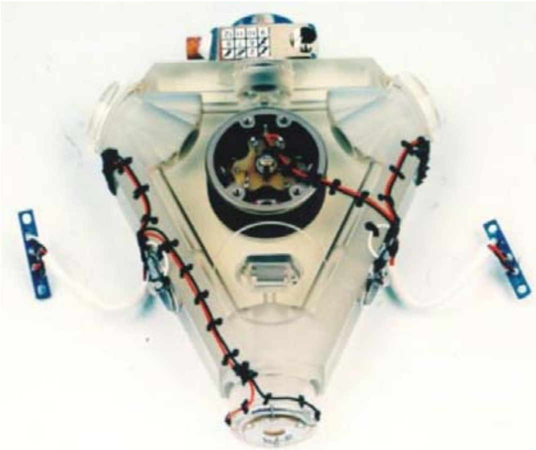

Figure 2.7: Ring Laser Gyro (RLG)
(Source: King, 98)

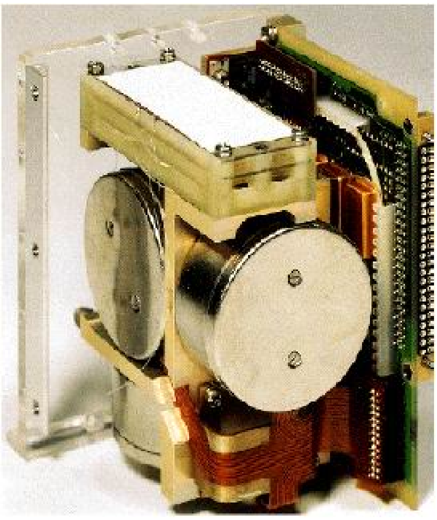

Figure 2.8: Fiber Optic Gyro (FOG)
(Source: Handrich, 2003)

2.2.3.2 Fiber Optic Gyros (FOG)

Fiber Optic Gyros (FOGs) were developed primarily as a lower-cost alternative to RLGs, with expectations of leveraging technology advances from the telecommunications industry. FOGs are now beginning to match and even beat RLGs in performance and cost, and are very competitive in many military and commercial applications. (Barbour, 2003) Figure 2.8 shows the INS based on Fiber Optic Gyros.

Fiber Optic Gyros (FOG) and MEMS Accelerometer are today used in inertial strapdown systems for medium accuracy and expanding into high performance strapdown navigation systems in competition with Ring Laser Gyros (RLG), whereas from the low accuracy side MEMS gyros are expanding to the medium accuracy ranges. (Handrich, 2003)

If we look on Fiber Optic Gyros there exists the open and the closed loop design. The major advantage of the closed loop Fiber Optic Gyro is the high linearity of the scale factor and its insensitiveness against environment, especially against vibration. (Handrich, 2003)

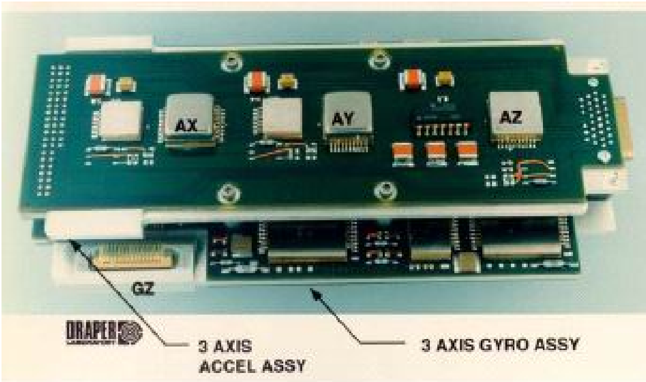

Figure 2.9: MEMS Inertial Sensors
(Source: Barbour et al, 2003)

2.2.3.3 Inertial MEMS Sensors

MEMS inertial sensors (Figure 2.9) are expected to enable so many emerging military and commercial applications that are becoming too numerous to list. Apart from size reduction, MEMS technology offers many benefits such as batch production and cost reduction, power (voltage) reduction, ruggedization, and design flexibility, within limits. However, the reduction in size of the sensing elements creates challenges for attaining good performance. In general, as size decreases, then sensitivity (scale factor) decreases, noise increases, and driving force decreases. It appears that a MEMS system with performance of around 1 deg/hr and hundreds of µg will be available by 2006. This will be a serious threat to tactical RLG and FOG systems. (Barbour, 2003)

For inertial MEMS systems, attaining suitable gyro performance is more difficult to achieve than accelerometer performance. (Barbour, 2003)

The evolution of the most important gyro technologies is shown with the plot of years against accuracies in Figure 2.10. Today the high accuracy end is still dedicated to Ring Laser Gyros (RLG). The moderate accuracy range from 0.01°/h to 30°/h is mainly covered by Fiber Optic Gyros (FOG) and MEMS gyros are coming up from the low-end accuracy. (Handrich, 2003)

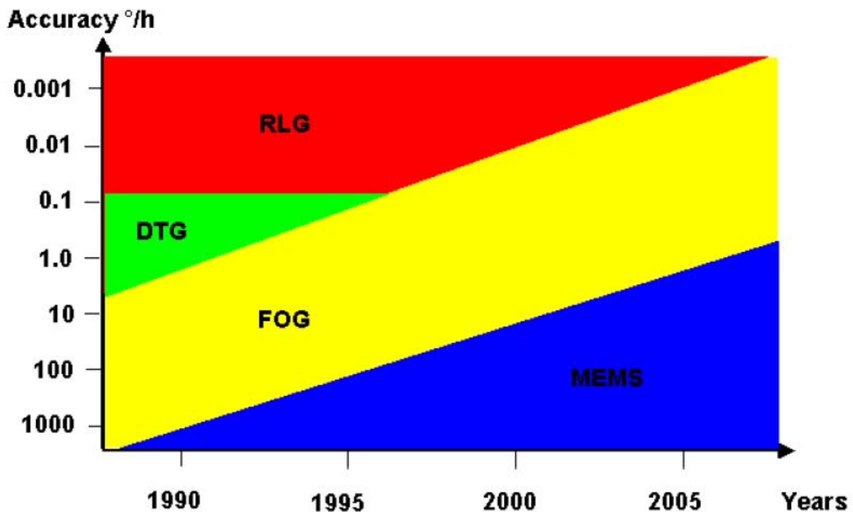

Figure 2.10: Evolution of Gyro Technologies
(Source: Handrich, 2003)

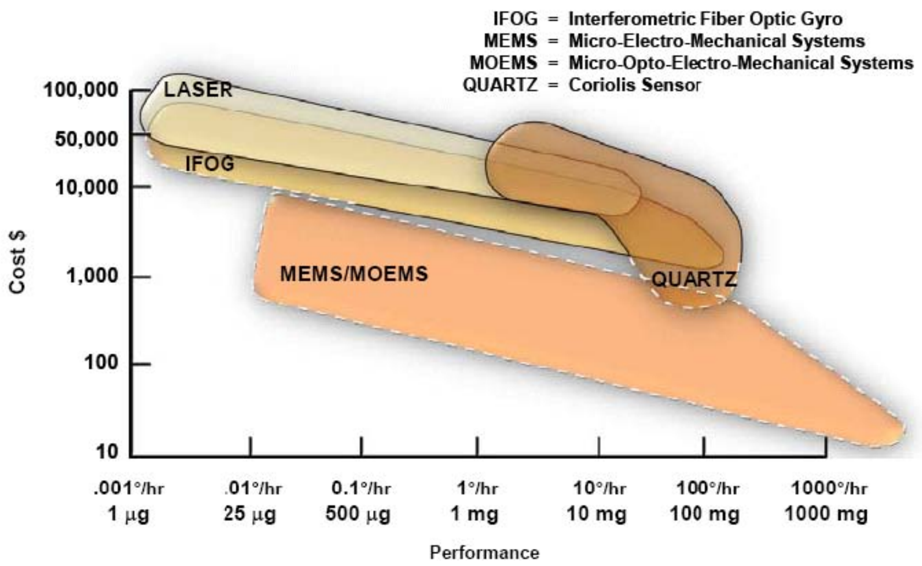

Figure 2.11: INS Cost as a function of Instrument Technology
(Source: Schmidt, 2003)

Figure 2.11 shows INS system cost as a function of inertial instrument technology and performance. The cost of a GPS receiver is likely to be so small that it will be insignificant. The systems are classified as: laser gyro or IFOG (Interferometric Fiber Optic Gyro) systems containing various types of accelerometer technologies; and MEMS/ MOEMS systems, which are all silicon. The solid line indicates the range of approximate costs expected. Clearly, the quantity of systems produced affects the cost; large production quantities would be at the lower end of the cost range. The IFOG systems have the potential for lower cost than laser gyro systems because the IFOG should be well below the cost of an RLG. However, this has not happened to date, primarily because the RLG is in relatively large volume production in well-facilitated factories and the IFOG is not yet manufactured in similar production quantities. Clearly, the MEMS/MOEMS INS/GPS systems offer the lowest cost. (Schmidt, 2003)

2.2.4 Coordinate Transformation

The inertial sensor give output with reference to the body frame that need to be transformed to navigation frame to get the trajectory information relative to the earth. Following equations are used to transform the body coordinate system to navigation reference. These equations grouped in a matrix are also termed as Rotation Matrix or Direction Cosine Matrix (DCM) C_b^n. The transformation from X-Y-Z navigation frame to the body x-y-z axes proceeds through yaw, pitch and roll rotations. This sequence of rotations produces the following transposed transformation Matrix. (Rogers 2000)

$$C_b^n = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix}$$

$$= \begin{bmatrix} \cos\theta\cos\psi & -\cos\phi\sin\psi + \sin\phi\sin\theta\cos\psi & \sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi \\ \cos\theta\sin\psi & \cos\phi\cos\psi + \cos\phi\sin\theta\sin\psi & -\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix}$$

2.3 Mobile Mapping System (MMS)

Mobile Mapping also termed as Land Vehicle Mapping is a method of collecting navigation data as well as spatial information using a vehicle on the ground. It is an automated method of data collection that not only save time but also give accurate information at a reasonable cost for large-scale application. It is the integration of the inherent intelligence of spatial information contained within a Geographical Information System (GIS) with measurements received from a navigation system. The spatial information provides additional data that can be used to constrain the navigation solution and provide a more accurate and reliable position estimate. With this approach, the solution is not dependent on the performance capabilities of the navigation sensors alone. It enables the use of lower accuracy navigation devices, thereby reducing the cost of navigation systems while still providing a viable solution. (Scott-young, 2001)

2.4 GPS/INS Integration

GPS offers quick and accurate method of gathering mapping information to meet the geographic data needs but a significant problem can be caused in the data where satellite view is obscured by foliage, buildings or other features, since GPS require line of sight to at least four satellites to achieve full precision. These problems make the data unreliable or complete loss of data, which usually require repetition of the whole process and ultimately wastes time and energy. To address the problem the integrated GPS/INS approach is utilized, which can give accurate results even in the event of temporary GPS signal loss. With GPS and INS hardware becoming ever smaller and less expensive, innovative opportunities for commercial, military, and scientific navigation systems are gaining popularity.

This integrated navigation system is used to get the continuous and reliable navigation data containing positions and heading information mounted on airborne or land vehicles. The complementary characteristics of both the systems make the integration a perfect match. Table 1 compares the characteristics of both systems.

Table 1: Benefits of GPS/INS Integration

Source: Skaloud, 1999

INS	DGPS
High position and velocity accuracy **over short term**	High position and velocity accuracy **over long term**
Accurate attitude information	Noisy attitude information
Accuracy decreasing with time	**Uniform accuracy**, independent of time
High measurement output rate	Low measurement output rate
Autonomous	Non-Autonomous
No signal outages	Cycle slip and loss of lock
Affected by gravity	Not Sensitive to gravity

INS/DGPS
High position and velocity accuracy
Precise attitude determination
High data rate
Navigational output during GPS signal outages
Cycle slip detection and correction
Gravity vector determination

Integrating GPS with INS needs an intelligent filtering and estimation procedure such as Kalman Filter that can predict the error covariance and update the data stream. Kalman Filter is widely being used to serve the purpose of GPS/INS integration. Figure 2.12 shows a generic block diagram of the GPS/INS integration architecture. There are several alternative integration techniques, which can be selected based on the specific application, performance requirements, installation constraints and cost. The last factor is often decisive, as the cost of quality INS is still much higher than GPS. However, there has been a substantial INS price drop over the past few years, which in fact allowed more widespread use of inertial navigation in mobile mapping. (Toth, 2002)

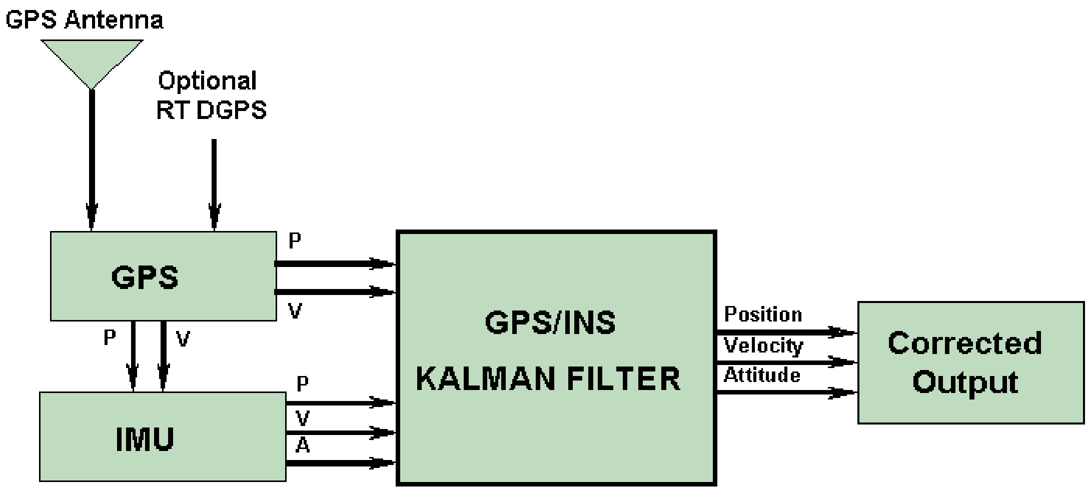

Figure 2.12: GPS/INS Block Diagram

CHAPTER 3

METHODOLOGY

This chapter defines in detail the testing setup and data collection method. Field testing in a kinematic mode was conducted to measure the accuracy of INS. Two lab tests and two field surveys were conducted. Vehicle was mounted with GPS as well as INS to collect the data for different trajectories. (as shown in Figure 3.7 & Figure 3.8)

3.1 Hardware Configuration

The Inertial Sensor used for this research is MEMS (Micro Electro-Mechanical System) strapdown Sensor RGA300CA from Crossbow (Figure 3.3). It is a combination of a Yaw Rate, Roll, and Pitch Gyros, and 3 orthogonal Accelerometers. The technical specification of the sensor is given in Table 3. For detailed specification refer Xbow.

Two kinds of GPS receivers were used, Trimble GPS Pathfinder Pro XRS (Figure 3.2) and Leica GPS System 500 SR510 (Figure 3.1) was used as precautionary backup in the first field survey. The technical specification of Xbow RGA sensor and Trimble GPS Pro XRS receiver are given in Table 2.

Figure 3.1: Leica GPS System 500
(Source: http://www.leica-geosystems.com/gps/product/images/sr530.gif)

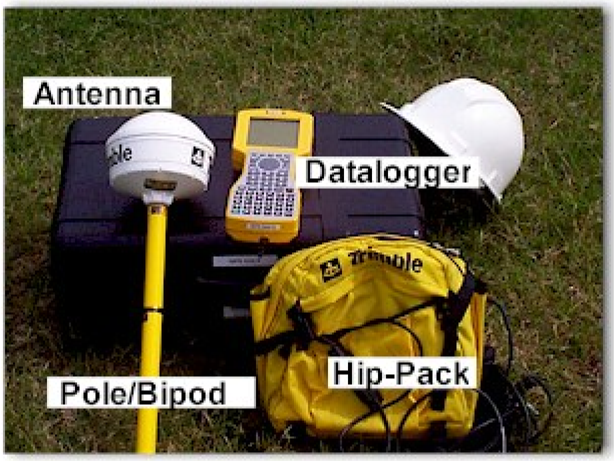

Figure 3.2: Trimble GPS Pathfinder Pro XRS
(Source: http://tsc.wes.army.mil/gps/setup1.jpg)

Figure 3.3: Xbow RGA300CA Inertial Sensor
(Source: http://www.xbow.com/Products/Product_images/Inertial_images/
RGA300CA_LG.jpg)

Table 2: System Specifications

(Source: Crossbow & Trimble)

Crossbow	RGA300CA
Update Rate (Hz)	~132
Attitude	
Range: Roll, Pitch (°)	±1.5
Resolution (°)	<±2.0
Yaw Rate	
Range: Yaw (°/sec)	±100
Bias: Yaw (°/sec)	<0.1
Scale Factor Accuracy (%)	<1
Resolution (°/sec)	<25
Random Walk (°/hr$^{1/2}$)	<2.25
Acceleration	
Range: X/Y/Z (g)	±2
Bias: X/Y/Z (mg)	<±30
Scale Factor Accuracy (%)	<1
Resolution (°/sec)	<1.0
Random Walk (m/s/hr$^{1/2}$)	<0.15
Trimble	**GPS**
Channels	12
Frequency	L1/CA code
Update Rate	1 Hz
Real time Accuracy	< 1 m
DGPS Accuracy	< 50 cm

3.2 Testing Setup and Data Collection

Before going to the field, equipment was tested in the lab in stationary mode to observe the bias and after that it was mounted over a yaw rate testing table to measure the angular drift. Details are provided in the following sections.

3.2.1 Stationary Lab Testing

The RGA sensor was tested in the Spatial Information Lab at the Faculty of Engineering with the room temperature of 25 to 30 °C. The equipment was held stationary for the time intervals of 10 to 100 seconds and data was collected for 3 times each sample to observe the stationary drift. Post processing is discussed in the next chapter while the results along with the appropriate graphs are provided in the Results and Analysis chapter four.

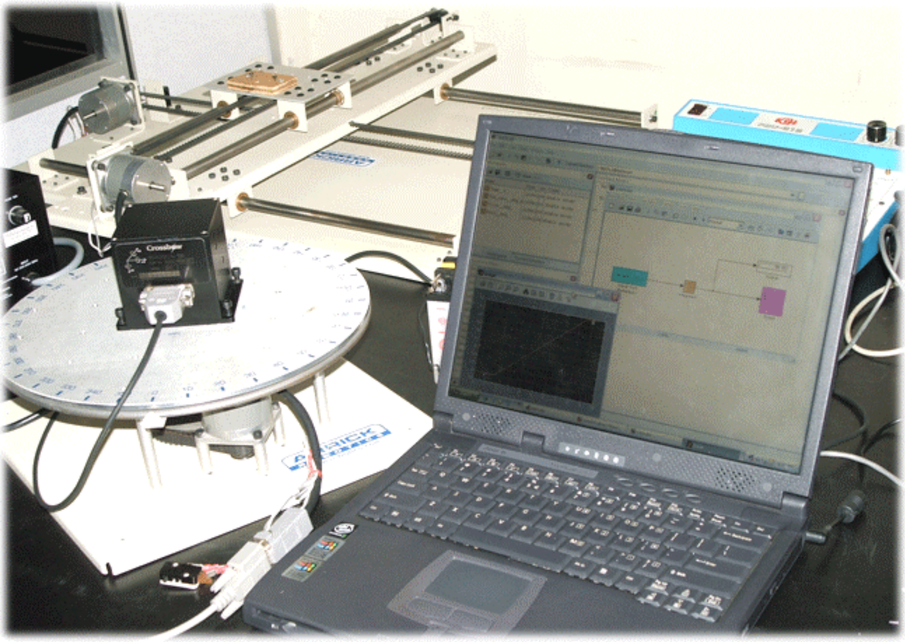

Figure 3.4: Lab Testing Setup (Yaw Rate)

3.2.2 Yaw Rate Lab Testing

The INS used in this research includes a rate gyro, which was observed in the lab before going to the field. The testing was conducted in the Control Lab of Aerospace department at Faculty of Engineering. The INS was mounted at the center of the yaw rate testing table (shown in Figure 3.4) to compare the input against the output. The yaw rate testing table was given the input of 15 to 90 degree rotation with an interval of 15 degrees and was observed against the output from INS. The simulink model used to process the yaw rate testing data is presented and discussed in the Results and Analysis chapter four.

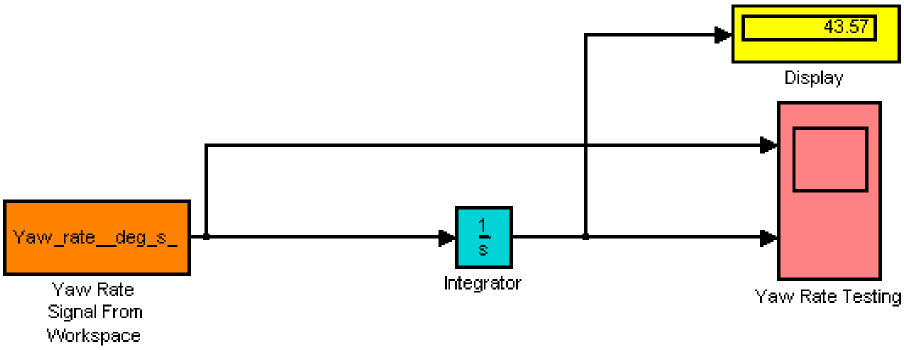

Figure 3.5: Yaw rate testing model

3.2.3 Kinematic Field Testing Setup (Survey 1)

Data was collected under the ideal conditions of clear sky at the "*Padang Kawat*' (Parade Ground) of University Putra Malaysia (UPM) on Thursday, 15th July, 2004 between 10 am to 12:30 pm. GPS antenna was mounted at the top of the vehicle, about 1.75m above the ground, exactly above the INS, which was aligned carefully as close to the center of the vehicle as possible to avoid the misalignment errors. (Figure 3.7) INS was warmed up for 1 hour before data collection and the temperature variation was between 25 - 32°C, and the maximum vehicle speed was 20 – 30km/hr. Data sampling rate of INS was set at 100 Hz, while the Trimble GPS Receiver data rate was 1 Hz. Leica GPS System 500 Receiver was also used as a precautionary backup, mounted at the top of the vehicle with the offset of 0.5m from Trimble antenna. The difference of INS and GPS vertically was measured as 0.9m. The markings on the ground were made using Total Station by measuring the distance so that the vehicle could be steered for the distance of straight trajectories of 10, 20, 30, 40, and 50m.

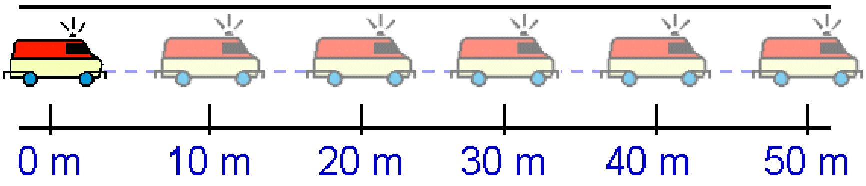

Figure 3.6: Field Data Collection Method

Data was collected for straight trajectories of 10 to 50 meters, the vehicle was started from zero mark, and stopped at different subsequent intervals. Figure 3.6 gives the concept of data collection method. The INS was reset in Gyroview at the start of each trajectory data, so that it removes the bias and initializes from zero. Obvious vibration was observed in the INS data, due to the engine of the vehicle, that was a four wheel drive car, could also be seen on the logging computer. Noise filtering topic (section 4.1) further addresses this issue. Two samples of each trajectory were taken to avoid ambiguity in the data. Appropriate marks were made on the ground so that the driver could stop the vehicle at exactly same stop point.

Figure 3.7: Field Survey 1

Figure 3.8: Field Survey 2

3.2.4 Kinematic Field Testing Setup (Survey 2)

The experiment was repeated second time for 10 to 100m trajectories with an interval of 10m each sample. A lot of vibration was observed in survey 1, therefore, this time it was decided to mount the INS over a 800cc car (Figure 3.8) that has much less vibration as compared to a four wheel drive used in survey 1. The data was collected at the same place of *"Padang K*awat", *UPM* on Sunday, 3rd October 2004 between 5:00 pm to 9:30 pm. 10 samples of each data set were collected to avoid the ambiguity by having redundant data samples. The same GPS receiver was used as in survey 1, that is Trimble GPS Pathfinder Pro XRS and was mounted at an offset of 30cm with INS in the x-axis accelerometer direction. INS data was collected this time at a sampling rate of 132 Hz, which is the maximum sampling rate of RGA300CA Sensor. For details refer to the Results and Analysis chapter four.

3.3 Data Processing and Simulation

Simulation model was created in Matlab/Simulink to analyze the processing of INS data for trajectory creation. Matlab/Simulink environment was used for processing because of its extensive numerical computing capabilities, with a variety of built-in functions, and ease of use. Simulink block library contains many blocks that saves time including the Euler transformation and quaternion blocks. Simulink treats data as signals. In our experiments the accelerations and angles are the input signals. This way the control over the signal processing tools makes the model operation and construction much easier. The simulation run time was given as the maximum value of the *Time* field of INS data so that the simulation can run for the whole data set. The data and other input variables were imported in Matlab workspace before running the simulation. The INS Mechanization section 3.3.3 briefly defines the process flow of the Simulink block diagram shown in Figure 3.10.

3.3.1 Data Post Processing

Field Survey 1 GPS data was post processed by differential correction using MPOB (Malaysian Palm Oil Board) Static GPS reference data, although Field Survey 2 GPS data was requested from JUPEM (Department of Surveying and Mapping Malaysia) since MPOB doesn’t log the static reference data on Sundays. INS data was collected through software, Gyroview version 2.4, that comes bundled with the RGA sensor from crossbow, used as a platform of INS data logging. The outputs of the RGA sensor are temperature compensated as specified in the specifications sheet and are attributed as Roll_deg, Pitch_deg, Yaw_Rate_deg_s, X_Accel_g, Y_Accel_g, Z_Accel_g.

Gyroview logs the data in ASCII (txt) format, which was later converted to excel (xls) format. Excel data of INS was imported in Matlab workspace as vector variables so that it can be accessed by the simulink model. Since Zero Command in Gyroview makes no difference for accelerations (Xbow), raw acceleration bias was compensated by subtracting accelerations from its mean value (*X_Accel* = *X_Accel –mean(X_Accel*)) assuming that the noise seen in the system is random white noise (containing all frequencies) with a zero or constant mean. A Matlab m-file is provided in the next section 3.3.2 that creates the required variables in the workspace, performs the compensation and plots the accelerations for analysis. Figure 3.9 shows the plot of raw and compensated accelerations after subtracting the mean value, for 50-meter trajectory data.

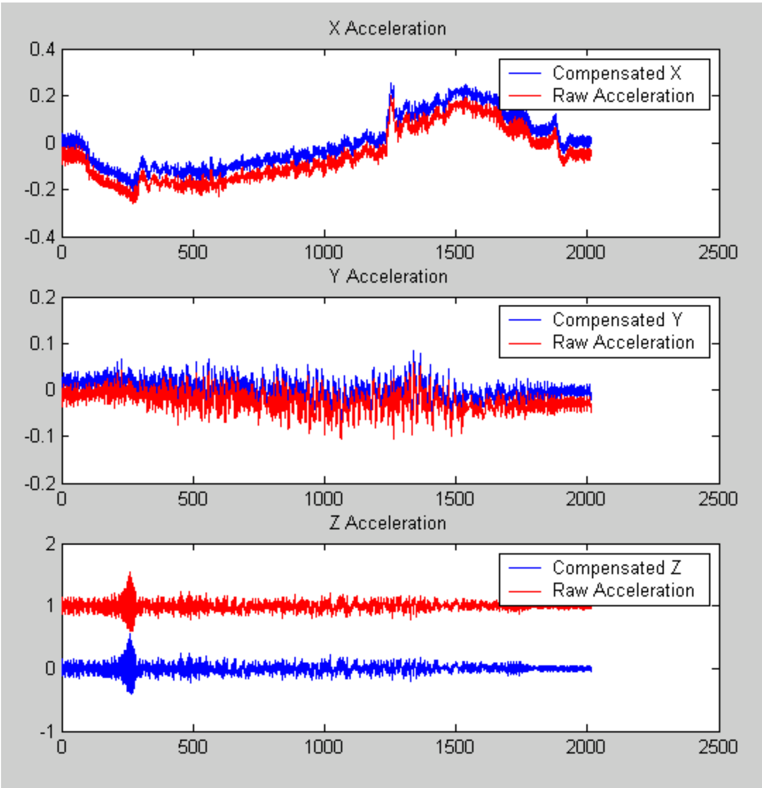

Figure 3.9: Acceleration Offset Compensation

3.3.2 Matlab m-file script for the bias compensation

```
% The accelerations are subtracted from its mean value

K = eye(3) % 3x3 Identity matrix K

xaccel = X_Accel__g_ - mean(X_Accel__g_)
yaccel = Y_Accel__g_ - mean(Y_Accel__g_)
zaccel = Z_Accel__g_ - mean(Z_Accel__g_)

% Following code plots the data

subplot(3,1,1), plot(xaccel); title('X Acceleration')
hold on
subplot(3,1,1), plot(X_Accel__g_,'r'); legend('Compensated X','Raw
Acceleration')
subplot(3,1,2), plot(yaccel); title('Y Acceleration')
hold on
subplot(3,1,2), plot(Y_Accel__g_,'r'); legend('Compensated Y','Raw
Acceleration')
subplot(3,1,3), plot(zaccel); title('Z Acceleration')
hold on
subplot(3,1,3), plot(Z_Accel__g_,'r'); legend('Compensated Z','Raw
Acceleration')

%Wavelet Denoising model variables

fs = 1;
lor = [0.2304  0.7148  0.6309  -0.0280  -0.1870  0.0308  0.0329  -0.0106];
lod = [-0.0106   0.0329   0.0308  -0.1870  -0.0280   0.6309   0.7148   0.2304];
hid = [-0.2304   0.7148  -0.6309  -0.0280   0.1870   0.0308  -0.0329  -0.0106];
hir = [-0.0106  -0.0329   0.0308   0.1870  -0.0280  -0.6309   0.7148  -0.2304];
```

Note: The K variable creates an Identity matrix of 3x3 dimension that is used in the model to see the behavior of data with angular information. X_Accel__g_, Y_Accel__g_, Z_Accel__g_ variables are logged by RGA sensor and give the raw accelerations of x, y and z axis respectively. These variables are imported in Matlab workspace. These values are subtracted from their mean and saved as xaccel, yaccel and zaccel variables.

It can be seen from the plot that after compensation the data initializes to zero levels. Although the movement of the vehicle was on x-axis only, the y-axis accelerations were recorded and the plot of y-axis even after removing the mean does not initialize to zero, the mean generated positive accelerations due to which position errors are accumulated over that axis, as will be discussed later in Results and analysis chapter four.

3.3.3 INS Mechanization and Simulation

This section explains the simulink model (Figure 3.10) constructed to get the coordinate trajectory information. The softcopy of the model is made available in the CD accompanying this thesis and detailed captures can be seen in Figure 3.10, Figure 3.11, Figure 3.12 and Figure 3.13 (Matlab & Simulink files). The model loads the data from Matlab workspace. Variable names were matched with the simulink model blocks to avoid the conflict. Before running the simulation the raw accelerations were compensated for bias by removing the mean as mentioned in the previous section 3.3.1, an m-file (Section 3.3.2) does it all and creates the variables xaccel, yaccel, and zaccel and other simulation parameters. The selector block was used so that the difference can be visualized quickly between raw and compensated accelerations. Selector and switch blocks are used in the simulation to switch between the different available options to analyze the behavior. It can be seen in the capture of the simulink model (Figure 3.10) a switch is used to switch between the two filtering options of Wavelets and Low pass filtering. Scope blocks in the simulink model are used to visualize the data at a particular instant. A lot of noise was observed due to the vibration of the vehicle that need to be removed or reduced by appropriate filtering procedures. Two techniques were used for noise filtering, Low Pass Filtering by Filter Design Toolbox and Wavelet denoising. The Low Pass Filter Design Toolbox parameters are shown in the Figure 3.14 while the Wavelet Denoising Simulink model can be seen in Figure 3.13. The wavelet-denoising model is taken from the Simulink library and used in the developed INS model. The Noise Filtering is further discussed in the section 4.1 of Chapter four. The accelerations pass through a gain of 9.8071 m/s^2 (gravity) and is multiplied with Direction Cosine Matrix (DCM) described in section 2.2.4.

The sensor used in the research is RGA300CA from crossbow (see specifications in Table 2), which is a yaw rate sensor and gives only yaw rate that need to be integrated once to get the yaw angles. These yaw angles(ψ) along with the angles of Roll ($\varnothing$) and Pitch (θ) are input as Euler angles to the Direction Cosine Matrix, transposed, multiplies with the accelerations. The process of transformation and Direction Cosine Matrix can be seen in the Subsystems shown in Figure 3.11and Figure 3.12.

It is worth noting here that quaternions, four parameter representation of transformation matrix, can be used in the model to eliminate the possible singularities but our kinematics does not include much of the roll and pitch dynamics, suffices the usual Euler transformation. As discussed in section 2.2.1 that quaternions are compact and computationally efficient representation of the rotations. Simulink contains quaternion conversion blocks to Euler angles or Direction Cosine Matrix (DCM) and can be used whenever necessary but we avoided use of quaternions for the sake of simplicity and besides it was focused only to the yaw axis due to land applications. Coriolis corrections were avoided because of a small trajectory and land application. For the details of Coriolis and centrifugal correction readers can refer to Rogers, 2000.

After multiplication the accelerations are converted to velocity by integrating once, and integrating again gives position. The xy graph plots of the positions, and the display blocks shows the final value after integration that gives the idea of the distance covered. Scopes were used at appropriate places to visualize the data behavior graphically.

Model was created in a simple and easy to understand manner so that the research could spread for further progress. Anyone familiar with Simulink environment can easily grasp the flow of the INS processing. This model is designed to work with RGA sensor from crossbow, therefore, requires minor modifications for other strapdown sensors depending upon the hardware specification. Simulink is capable of converting model to C programming code through Real-time Workshop toolbox and after incorporating GPS through the use of Kalman Filtering it can be converted to a full fledge processing software.

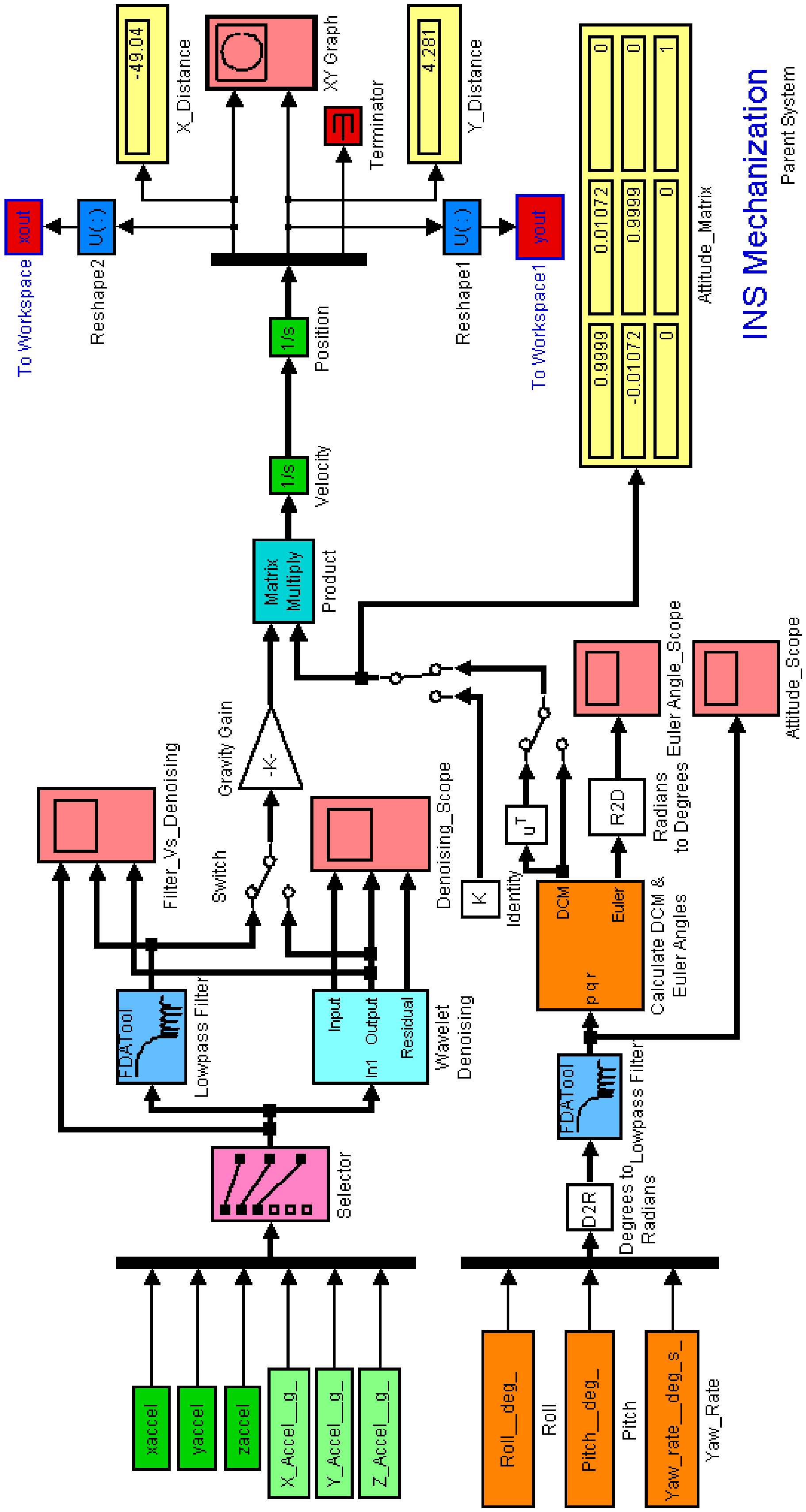

Figure 3.10: Simulink INS Mechanization Model

Figure 3.10

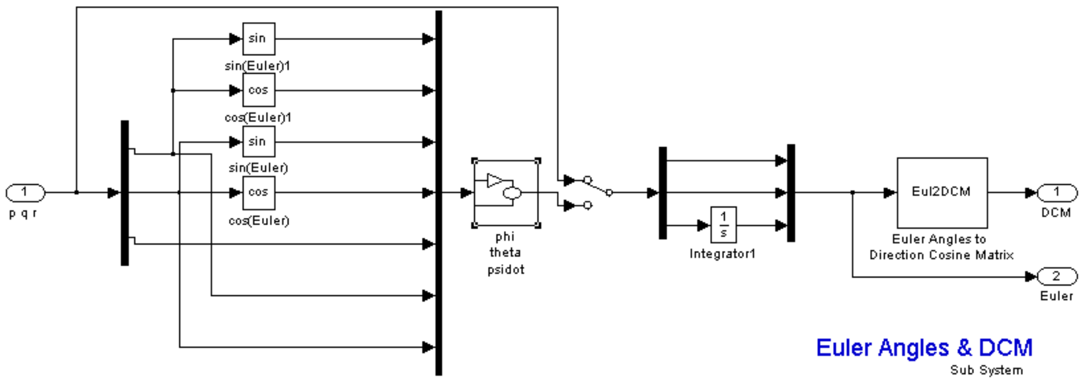

Figure 3.11: Simulink subsystem of Euler Angles and DCM

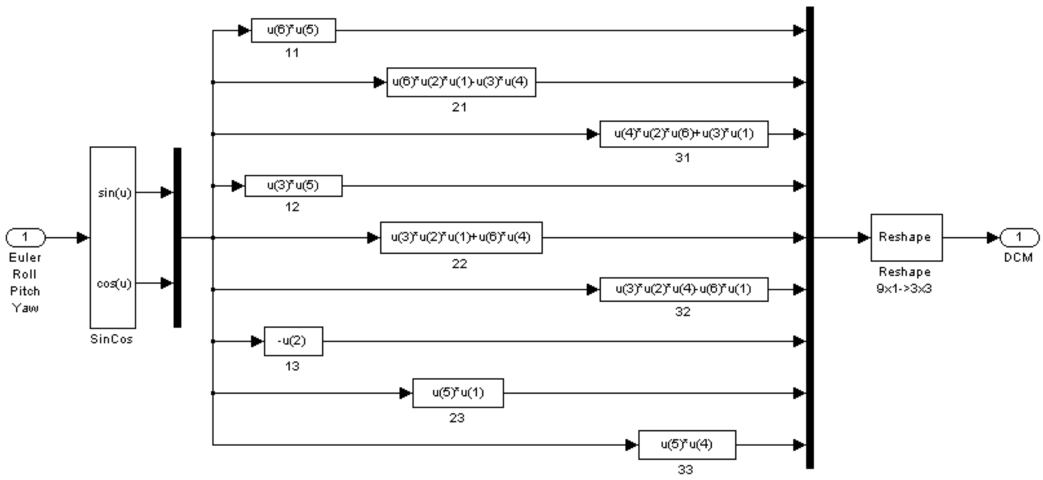

Figure 3.12: Simulink subsystem of Euler Angle to Direction Cosine Matrix transformation

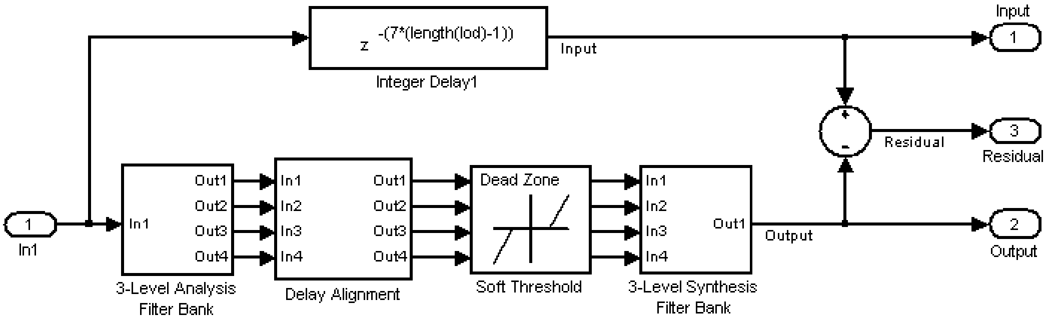

Figure 3.13: Wavelet Denoising Model

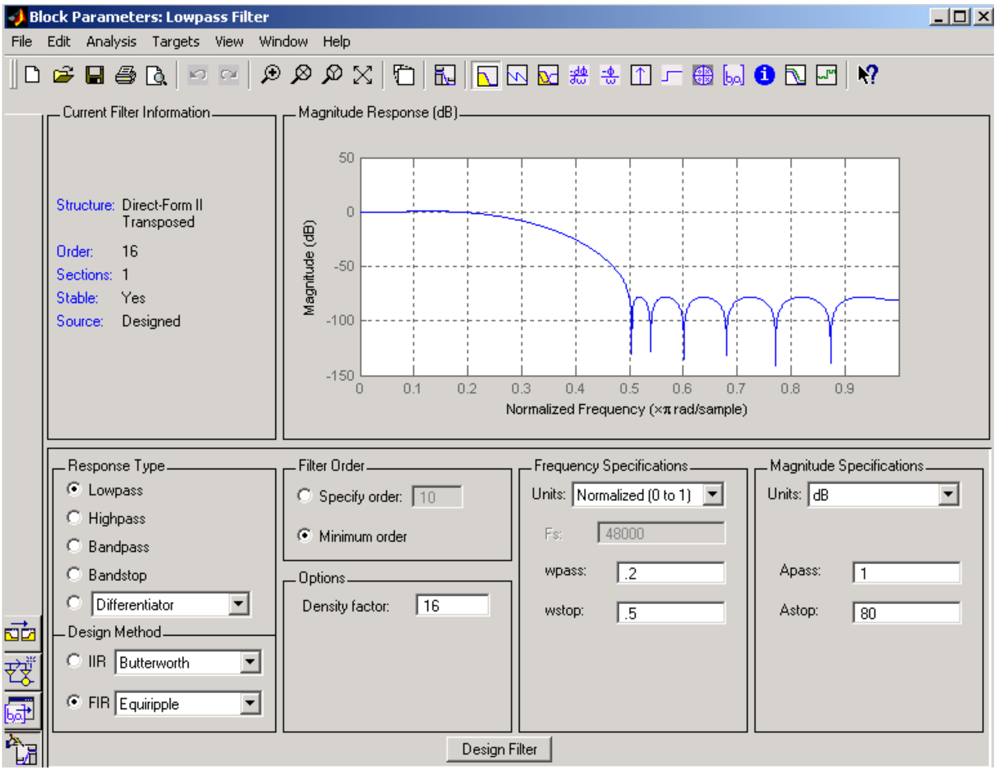

Figure 3.14: Low Pass Filter Design

The wavelet-denoising model was taken from the simulink demos of Matlab and incorporated into RGA sensor processing model (Figure 3.10). Model captures can be seen in Figure 3.13. Matlab also provides a separate wavelet toolbox that can be used to analyze further improvement by this filtering method. Manipulating the threshold values and parameters of the filter further decreases the reliability of the result. Filter design and analysis toolbox was used as the low pass filtering block in the model. Going into the further details of the filtering is beyond the scope of this thesis and a lot of literature is available on signal processing and filtering. (Skaloud, 1999) It is mentioned here to give the idea of the behavior and margin of improvement.

Scopes are used in Matlab/Simulink to visualize the behavior of the signal (Acceleration, Velocity and Position in our case). Scopes are used at many places in the Simulink INS model to get an idea of how the signal progresses to spot the error and make appropriate changes. Figure 3.15 shows the scope of Acceleration, Velocity and Attitude.

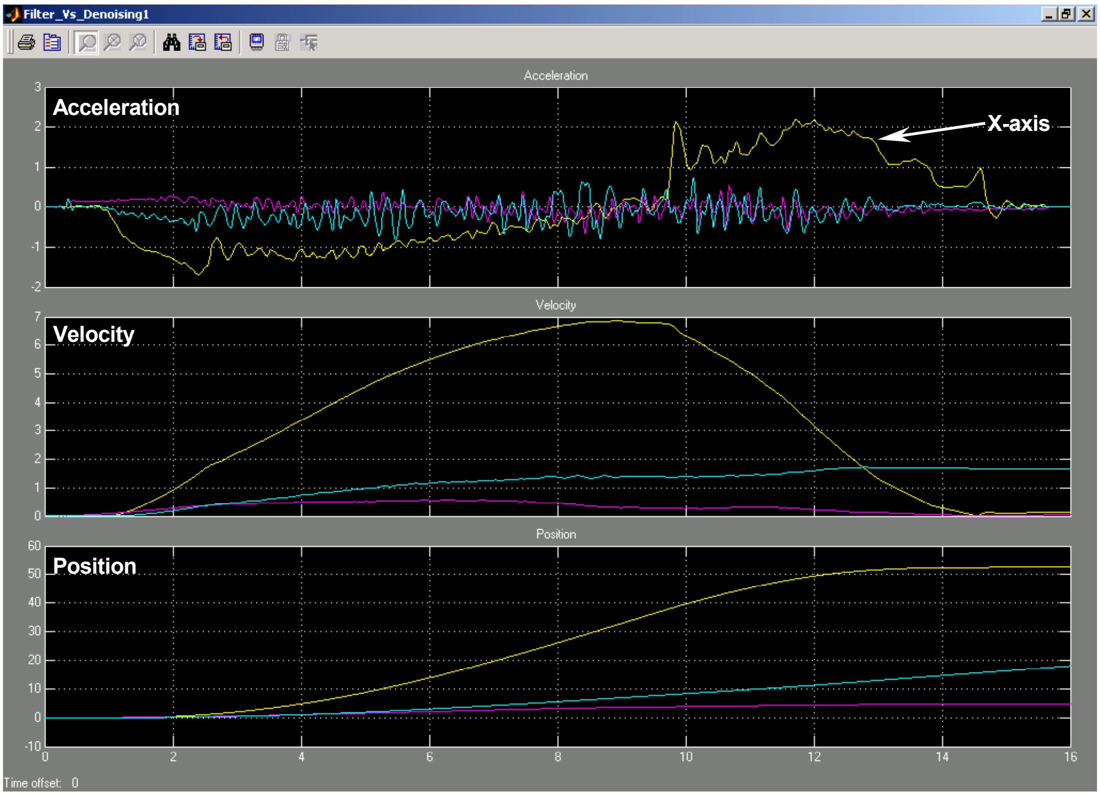

Figure 3.15: Acceleration , Velocity and Postion

CHAPTER 4

RESULTS AND ANALYSIS

This chapter deals with the results and analysis of the tests obtained in static as well as kinematic mode using RGA inertial sensor. As discussed in Data Processing section 3.3.1 bias correction was done on all the data before running the simulation which initialized all the data values to zero by subtracting from the mean of each data set. The details of the hardware and testing setup is provided in Chapter three. The processed data and graphical results of the testing are provided in the following sections to give an overview of the INS processing and comparison of filtering techniques. Although the movement was only on x axis, but it can be seen from the data that it gives accelerations over y axis due to which position errors are generated. These errors are caused by the misalignment of INS with the body of the vehicle and due to the vibration, therefore, care should be taken while aligning the INS with the body of the vehicle and proper filtering technique is inevitable. The following section of Noise Filtering discusses the filtering techniques used and their outcome.

4.1 INS Noise Filtering

Vibration in the INS data can cause a lot of problems if not well taken care of. Vibration of the vehicle contributes to the noise in the data making it inaccurate, therefore, proper filtering techniques should be devised to get accurate and worthwhile results. As mentioned before, two techniques were used to filter the noise of INS data, Low pass filter by Filter Design Tool and

Wavelet denoising, both are widely used filtering techniques in the field of signal processing. The difference of both methods was analyzed, as shown in the Figure 4.1. It can be seen from the plot that wavelet-denoising result is quite smooth as compared to Low pass filtering but it is not always the case.

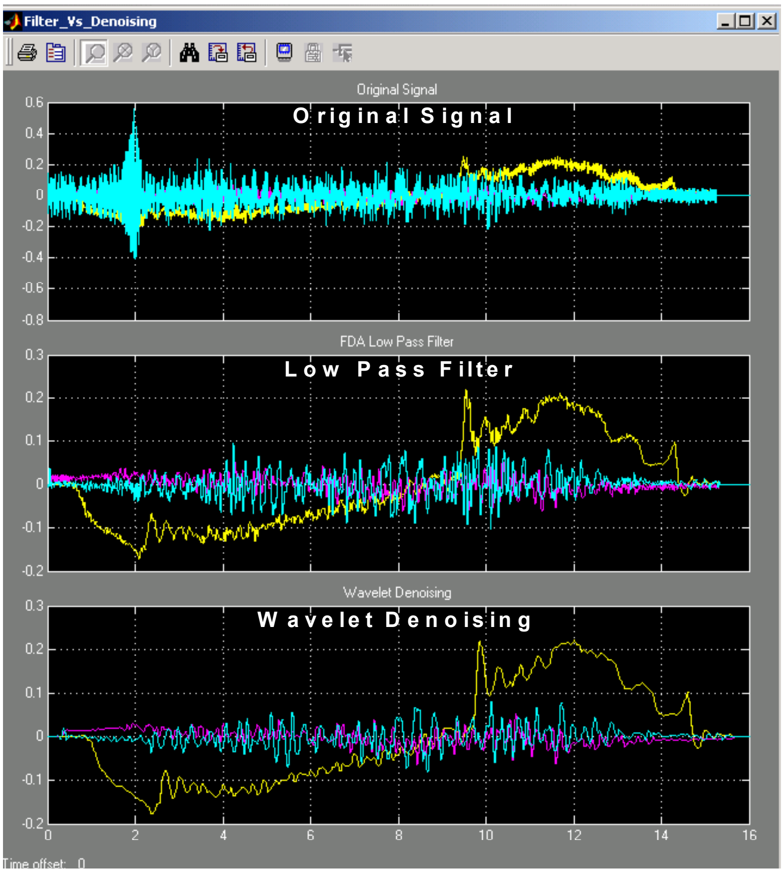

Figure 4.1: INS Data Filtering Approaches

Noise was also observed in the INS data during static mode. Since the equipment is sensitive and logs data with a sampling rate of 132 Hz, even the minor variation in the environment affects the data. Figure 4.2 shows the original data with the noise in static mode. It is obvious that equipment is sensing the movement even if it is not moving. These readings when integrated accumulate to errors as will be discussed in static testing section 4.2.

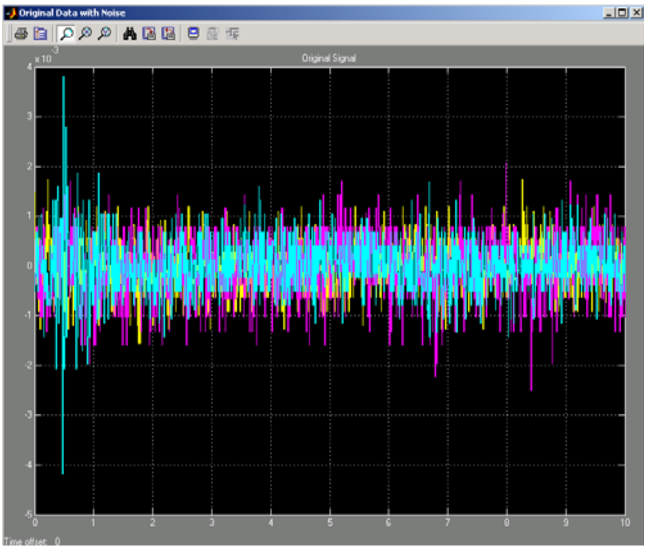

Figure 4.2: INS Noise Observed in Static Mode

Following graph (Figure 4.3) is the plot of 100m trajectory data (survey 2 sample # 2). It is zoomed in on the data to give a close look of the filtering and it is quite obvious that denoising result is quite smooth as compared to low pass filtering but the readings gave a complete different story. In this data sample (Table 10) of 100m trajectory the wavelet approach gave an error of 5.315m and Low pass filtering that looks more noisy gave an error reading of 2.045m.

Modeling the inertial errors to study their behavior is not an easy task and one should have a thorough understanding of the signal processing and filtering principles to reduce the errors. It is beyond the scope of this research to go into the details of inertial errors. A combination of multiple filtering techniques can remove the INS noise to quite some extent. (Figure 4.4)

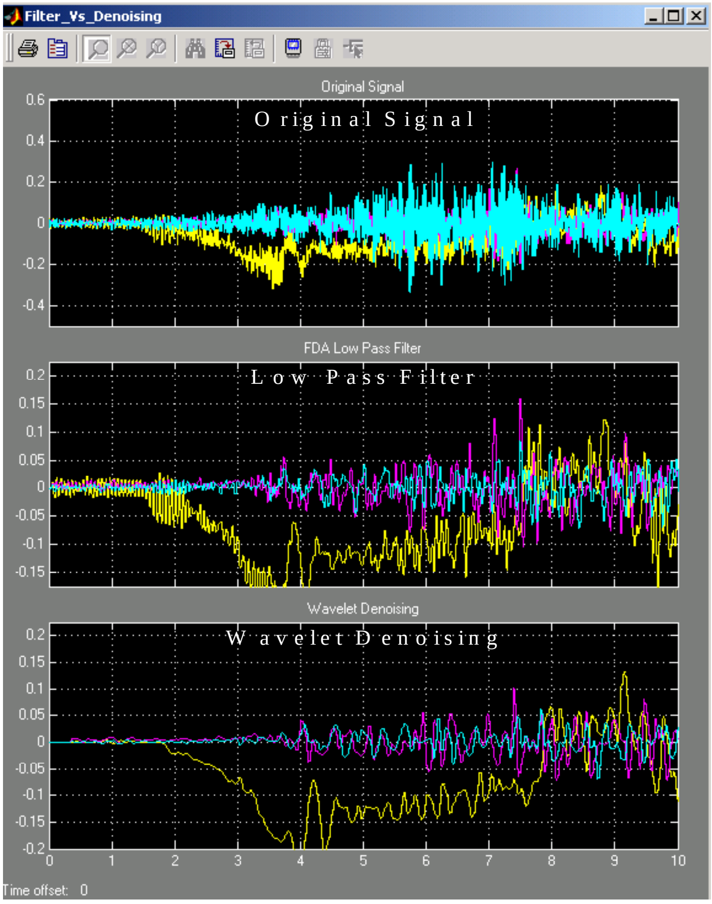

Figure 4.3: Low Pass Filtering Vs Wavelet Denoising

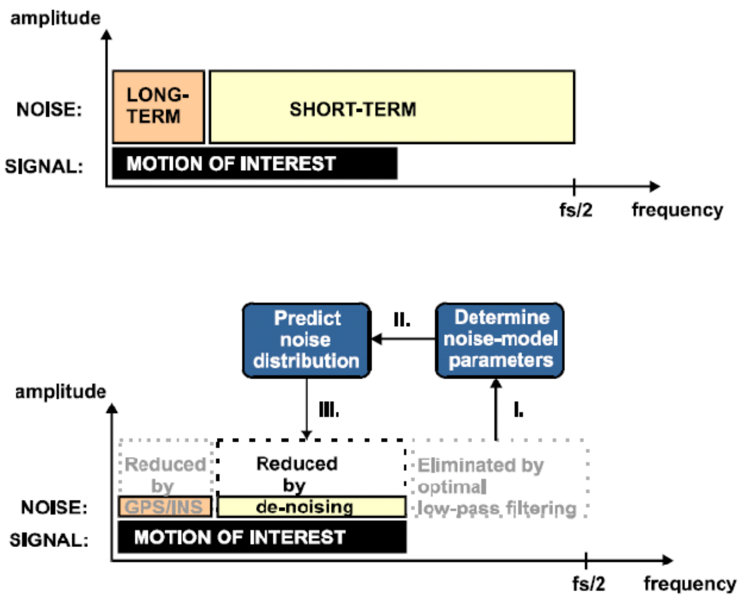

Figure 4.4: The Concept of Filtering Short Term Noise
(Source: Skaloud, 1999)

As shown in Figure 4.5 wavelet-denoising approach removes a lot of noise from INS data but still there seems to be a margin of improvement. Kalman filter also another approach that can be utilized to estimate the errors and update the output with correction. Skaloud, 1999 has discussed the use of Kalman Filter to estimate the error growth and make appropriate adjustment.

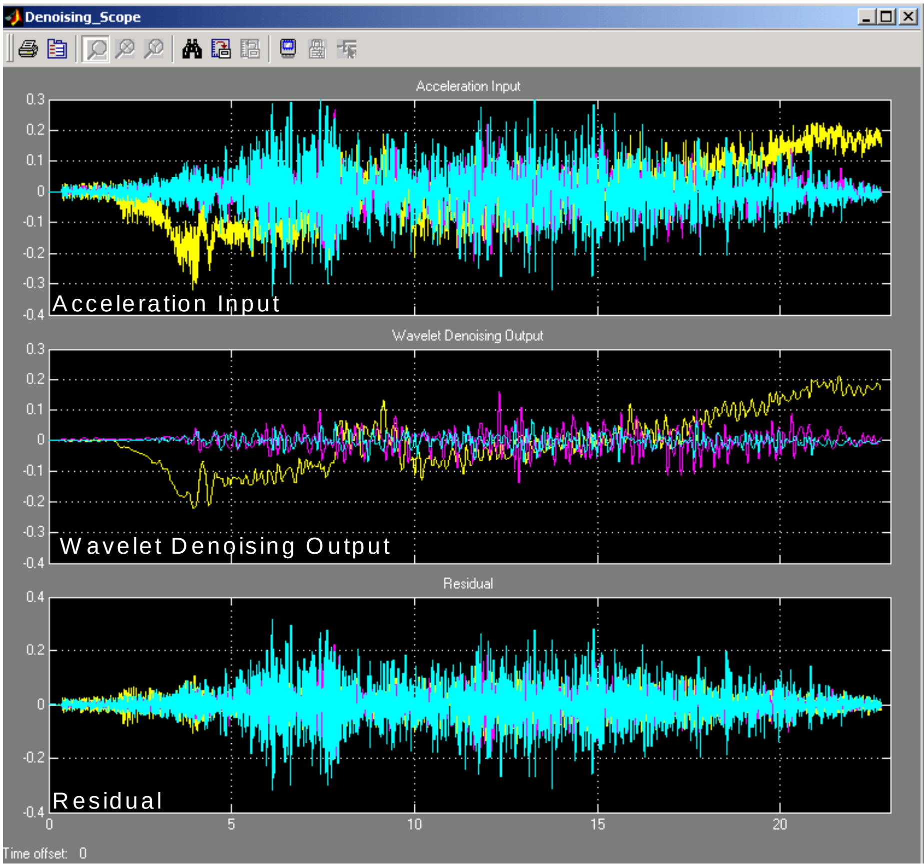

Figure 4.5: Wavelet Denoising

4.2 Static Testing Result

Before going to the field the RGA sensor was tested in the lab. The inertial sensor was held stationary for certain time intervals and the data was logged to observe the errors in static mode. Details of the testing setup are provided in section 3.2.1 of Chapter three and the complete results are provided in the following Table 4. Figure 4.6 gives the error plot of INS in static mode at different time intervals. Not much difference was found between the filtering approaches of wavelets and Low pass. Even being stationary the equipment gave readings that accumulated to error growth, as can be seen from the graph of static error plot (Figure 4.6). The static error was found to be less than the error in kinematic mode with same time interval. The error reached to 1 meter at the time interval of 90 seconds but these errors are not standard and varied each time the INS was switched on.

Table 3: Static Testing Result (Mean)

Time	Error	
	Wavelet denoising	Low Pass Filter
10	0.01205	0.011048
20	0.038804	0.036167
30	0.100635	0.093525
40	0.179317	0.166684
50	0.393834	0.366084
60	0.2746	0.255267
70	1.2294	1.1541
80	1.012584	0.941033
90	1.0774	1.001033
100	1.215717	1.12935

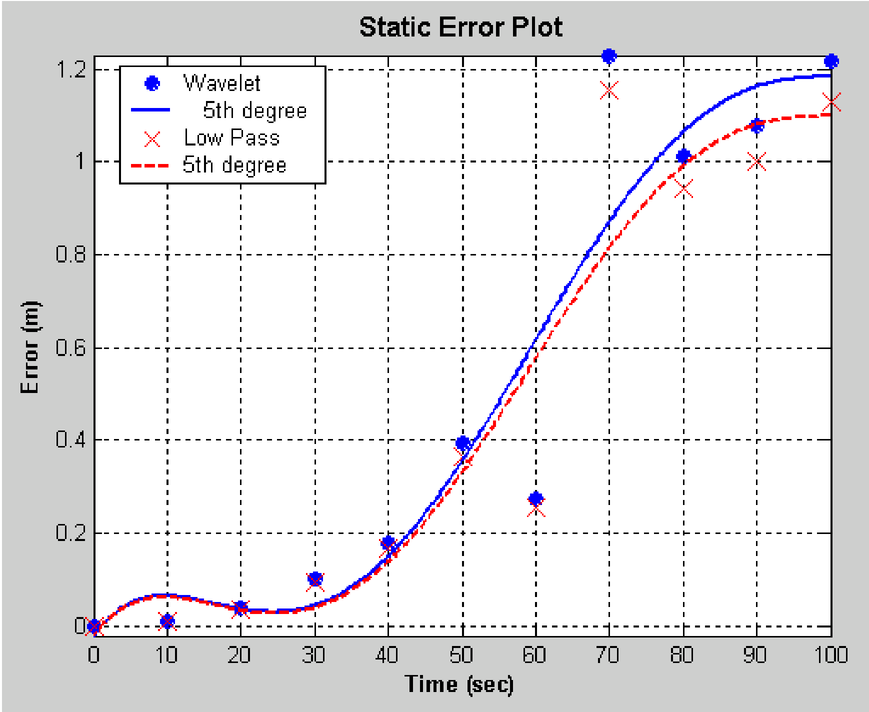

Figure 4.6: Static Error Plot

Table 4: Static Testing Data (Complete)

10 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	11.18794	0.01267	0.01522	0.01185	0.01426
2	10.49681	0.01725	0.0118	0.01613	0.01117
3	10.80002	0.00719	0.006499	0.00675	0.006123
Average		**0.01237**	**0.011173**	**0.011577**	**0.010518**
Standard Deviation		0.005037	0.004394	0.004696	0.004108

20 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	20.66524	0.01857	0.02344	0.01733	0.02198
2	20.89391	0.05379	0.08709	0.04999	0.08114
3	20.89346	0.03159	0.01834	0.02936	0.0172
Average		**0.03465**	**0.042957**	**0.032227**	**0.040107**
Standard Deviation		0.017808	0.038306	0.016518	0.035616

30 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	32.2728	0.2079	0.1616	0.1934	0.15
2	30.91114	0.05051	0.04251	0.04697	0.03955
3	31.06246	0.08348	0.05781	0.07749	0.05374
Average		**0.113963**	**0.087307**	**0.105953**	**0.081097**
Standard Deviation		0.083005	0.064793	0.077253	0.060092

40 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	40.17266	0.1301	0.1266	0.1209	0.1178
2	40.86278	0.1763	0.3773	0.1643	0.3503
3	41.00581	0.1428	0.1228	0.1326	0.1142
Average		**0.149733**	**0.2089**	**0.139267**	**0.1941**
Standard Deviation		0.023868	0.145851	0.022455	0.135285

50 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	50.96584	0.6159	0.2773	0.5718	0.2588
2	51.03151	0.3615	0.1394	0.3356	0.13
3	52.33471	0.2408	0.7281	0.2239	0.6764
Average		**0.406067**	**0.3816**	**0.3771**	**0.355067**
Standard Deviation		0.19148	0.307897	0.177624	0.285637

1 minute (60s)		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	61.8837	0.114	0.5094	0.106	0.4735
2	60.88826	0.1892	0.1115	0.1761	0.1038
3	60.79355	0.2824	0.4411	0.2623	0.4099
Average		**0.1952**	**0.354**	**0.181467**	**0.329067**
Standard Deviation		0.08436	0.21277	0.078288	0.197661

70 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	70.66327	0.6209	1.964	0.649	1.824
2	69.90154	1.455	1.356	1.353	1.259
3	70.68024	0.7295	1.251	0.6786	1.161
Average		**0.935133**	**1.523667**	**0.893533**	**1.414667**
Standard Deviation		0.45348	0.384937	0.398185	0.357864

80 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	80.92927	1.333	0.3463	1.238	0.3223
2	80.64438	1.348	1.085	1.252	1.01
3	80.71268	1.435	0.5282	1.333	0.4909
Average		**1.372**	**0.653167**	**1.274333**	**0.607733**
Standard Deviation		0.055073	0.384879	0.051287	0.358428

90 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	90.72849	1.242	0.6063	1.153	0.5632
2	90.81716	1.233	0.6849	1.145	0.6372
3	90.86511	2.369	0.3292	2.2	0.3078
Average		**1.614667**	**0.540133**	**1.499333**	**0.502733**
Standard Deviation		0.653287	0.186853	0.606808	0.172824

100 seconds		Wavelet		Low Pass	
Sample No.	Time	X	Y	X	Y
1	100.3699	0.5148	0.8025	0.4778	0.7457
2	100.5813	1.084	1.05	1.007	0.9756
3	100.8771	2.355	1.488	2.189	1.381
Average		**1.317933**	**1.1135**	**1.2246**	**1.0341**
Standard Deviation		0.94214	0.347134	0.876107	0.321665

4.3 Yaw Rate Testing Result

RGA sensor was also tested for the behavior of rate gyro. The equipment was mounted over the yaw rate testing table to observe the angles from the INS. For the details of the testing setup refer to section 3.2.2. Figure 4.7 gives the plot of raw Angular yaw rate and after the integration. The model used to process the data can be seen in Figure 3.5. Error growth was again observed which reached 1.6 degrees error at the rotation of 90 degree. This error is not much considering a turn of 90 degree but case is completely different when the equipment is mounted on a vehicle that creates a centrifugal effect making angle inaccurate. Figure 4.8 shows a gradual error growth in degrees.

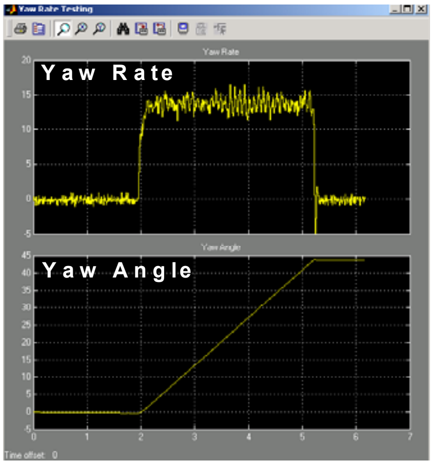

Figure 4.7: Angular Yaw Rate

Table 5: Yaw Rate Lab Testing Result (Mean)

Result (Degrees)	
Angle	**Error**
15	0.905
30	1.135
45	1.262
60	1.4
75	1.483
90	1.6

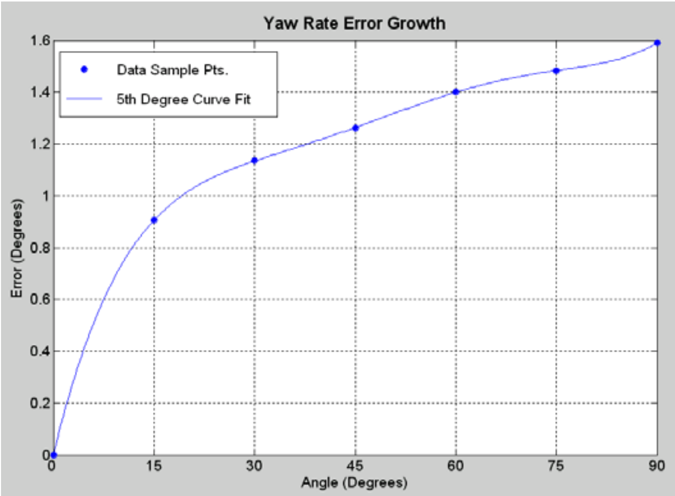

Figure 4.8: Yaw Rate Error Plot

Table 6: Yaw Rate Lab Tesing Data (complete)

15 Degree	
Distance 100	
Sample	
1	14.55
2	14.25
3	13.84
4	14.34
5	13.99
6	14.4
7	13.81
8	13.93
9	14.07
10	13.77
Average	**14.095**
St Dev	0.273831

30 Degree	
Distance 200	
Sample	
1	28.99
2	28.56
3	28.8
4	28.64
5	28.97
6	28.83
7	28.98
8	29.03
9	29.06
10	28.79
Average	**28.865**
St Dev	0.169918

45 Degrees	
Distance 300	
Sample	
1	43.57
2	43.57
3	43.76
4	43.69
5	43.67
6	43.88
7	43.92
8	43.85
9	43.77
10	43.7
Average	**43.738**
St Dev	0.121179

60 Degree	
Distance 400	
Sample	
1	58.65
2	58.52
3	58.43
4	58.42
5	58.61
6	58.6
7	58.64
8	58.72
9	58.65
10	58.76
Average	**58.6**
St Dev	0.112744

75 Degree	
Distance 500	
Sample	
1	73.88
2	73.57
3	73.63
4	73.38
5	73.5
6	73.46
7	73.33
8	73.53
9	73.51
10	73.38
Average	**73.517**
St Dev	0.157625

90 Degree	
Distance 600	
Sample	
1	88.35
2	88.22
3	88.84
4	88.33
5	88.31
6	88.83
7	88.3
8	88.4
9	88.33
10	88.19
Average	**88.41**
St Dev	0.231996

4.4 Kinematic Field Testing Result

After lab testing the RGA sensor was mounted on a vehicle for the data collection in kinematic mode. Another reason of conducting the survey was to validate the processing model and measure the accuracy of RGA sensor. The details of the testing setup are provided in section 3.2.3 and section 3.2.4, this section is only devoted to the results and analysis of the data collected. One channel (X-axis accelerometer) will be demonstrated and analyzed to give the comparable results with GPS. Two field surveys were conducted, survey 1 was conducted in a four-wheel drive vehicle (Figure 3.7) while survey 2 was collected in an 800cc car (Figure 3.8). Survey 2 was considered more reliable because of more data samples. Following topics discuss the results of each survey.

4.4.1 Field Survey 1

Obvious difference in the result was found by choosing filtering techniques, Figure 4.9 shows an error plot of the two data samples, given in Table 7, against distance by low pass filtering for the straight trajectories of up to 50 meters. The plot shows a cubic curve fit of the error growth but at the middle of the curve the error reduces a bit due to which the growth does not seem to be linear. The bulge in the curve gives the idea that error does not have a logical pattern. On the other hand if we look at the wavelet denoising error plot (Figure 4.10), it showed improved results as compared to low pass filtering but still it is not clear which filter should be preferred. This provoked the thought of conducting more data samples with longer distance trajectories and field survey 2 was conducted.

Figure 4.11 shows the plot of 50 meter GPS as well as INS straight trajectory result, the GPS data was plot over WGS 84 coordinate system and INS data over Navigation Frame, although both the data sets can be transformed to make an overlap but it was kept as separate for visualization. The position error on y-axis reached up to 4 meters, as can be seen in the plot of INS trajectory.

Table 7: Field Survey 1 Result

Distance (m)	[redacted]						Average X-Axis Error	
	Sample 1			Sample 2				
	Time (sec)	Wavelet	Low Pass	Time	Wavelet	Low Pass	Wavelet	Low Pass
		X-Axis			X-Axis			
10	10.113	1.006	1.699	10.795	0.755	1.457	0.885	1.578
20	14.523	1	2.41	11.332	1.97	3.31	1.485	2.86
30	14.151	0.06	2.36	15.629	0.49	2.69	0.275	2.525
40	16.645	1.23	1.89	15.053	1.14	2.0	1.185	1.945
50	17.726	2.16	1.65	17.691	1.51	2.41	1.835	2.03

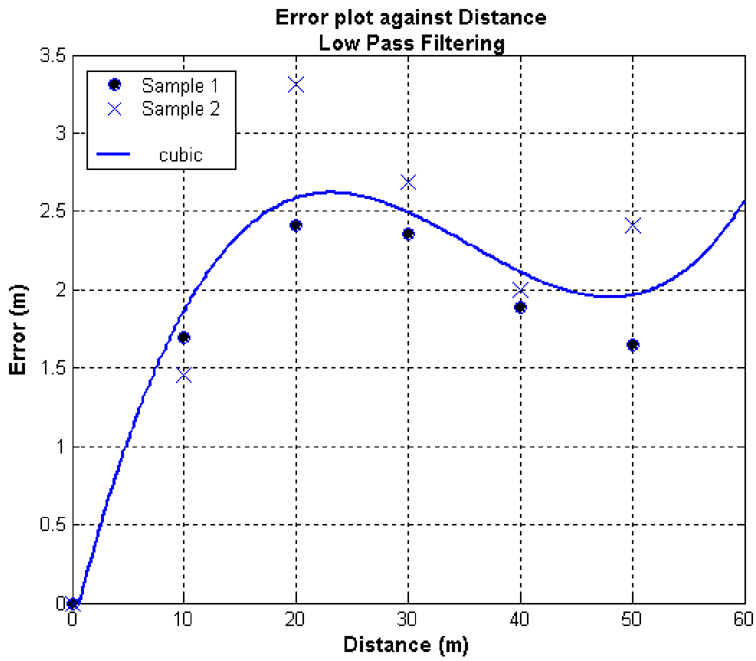

Figure 4.9: Error plot against distance by Low Pass Filtering technique

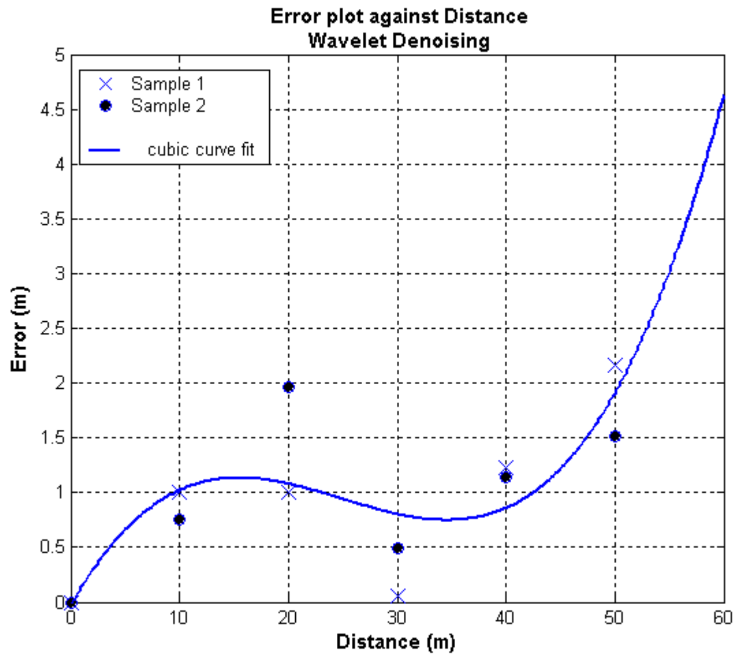

Figure 4.10: Error plot against distance by Wavelet denoising technique

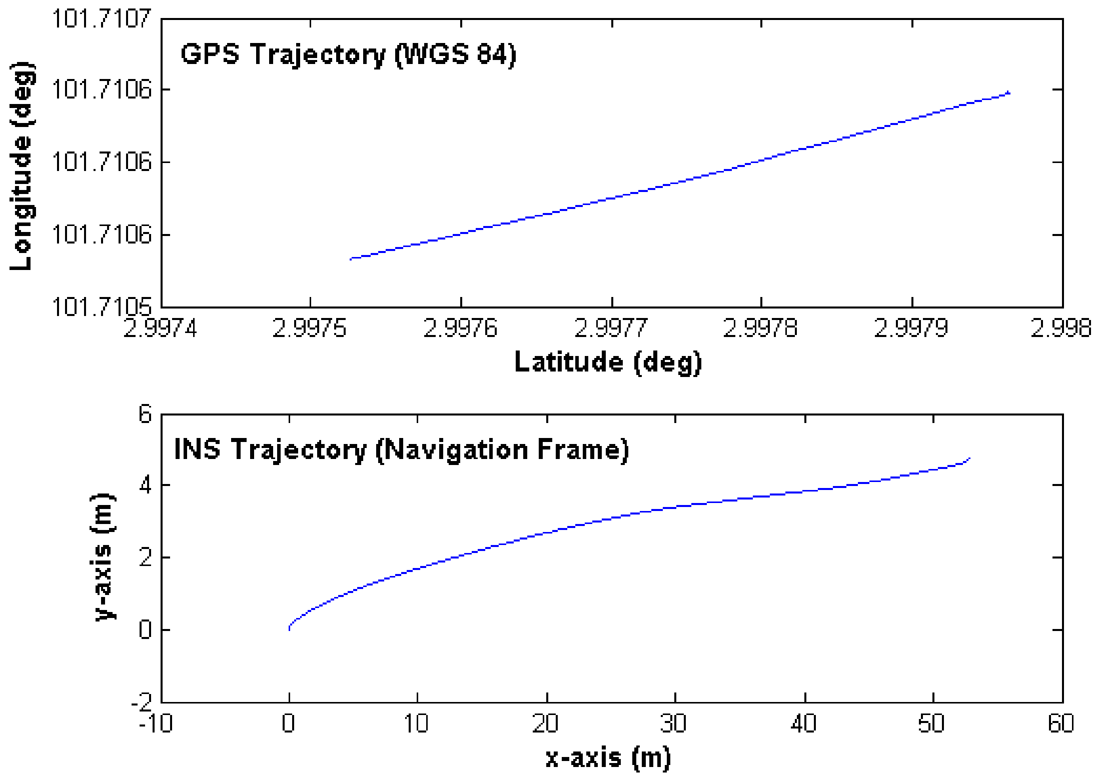

Figure 4.11: GPS and INS Trajectory (50m)

4.4.2 Field Survey 2

Due to indistinct result of survey 1 another field survey (survey 2) was conducted to collect the data until 100-meter trajectories and this time each data sample was collected 10 times. Complete data samples are provided in Table 9. The result of survey 2 gave us some of the answers that were not clear from survey 1. Table 8 is the averaged result of 10 samples collected for each trajectory. The distance calculated from INS was subtracted from the GPS distances collected for same trajectory. It was discovered from the result that wavelet denoising is better on short-term errors while low pass gave better result over longer distances of more than 40 meters.

Figure 4.12 is the error plot of field survey 2 with the 5^{th} degree curve of wavelets denoising as well as low pass filtering. The bulge in the curve of low pass filtering at 20 meter tells us that the error is starting to reduce after 20 meter. On the other hand wavelet-denoising curve gave comparatively better result until the distance of 40 meter after which low pass filtering showed improvement.

Table 8: Field Survey 2 Result (Mean)

Distance (meter)	Error (m)	
	Wavelet	Low Pass
10	1.4461	2.0537
20	1.4777	2.7937
30	0.9593	1.6148
40	1.1156	1.7914
50	3.1504	0.5766
60	4.0254	0.3776
70	4.4624	0.7226
80	4.1582	1.7128
90	5.9089	0.7441
100	5.683	1.583

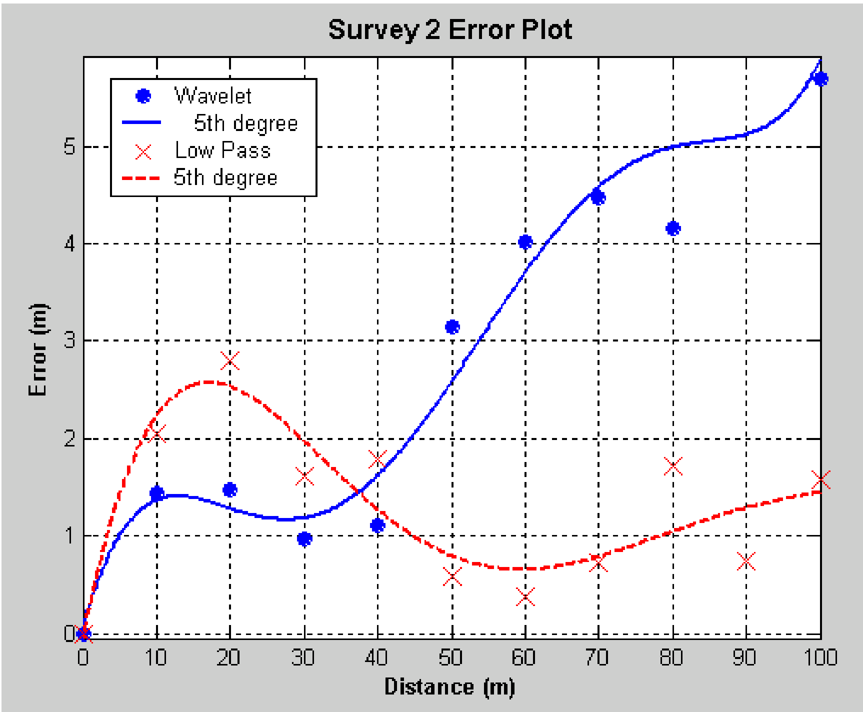

Figure 4.12: Field Survey 2 Error Plot

Table 9: Field Survey 2 Data (complete)

10 meter			Wavelet			Low Pass		
Sample No.	**Time**	**GPS**	**X**	**ΔX**	**Y**	**X**	**ΔX**	**Y**
1	17.17813	9.996	9.252	0.744	2.076	8.6	1.396	1.964
2	14.15497	9.975	9.483	0.492	1.778	8.78	1.195	1.668
3	14.64026	10.241	7.712	2.529	1.629	7.146	3.095	1.564
4	16.70911	9.873	9.029	0.844	3.28	8.386	1.487	3.082
5	14.42098	9.818	7.688	2.13	1.534	7.155	2.663	1.431
6	14.95751	10.08	9.833	0.247	1.861	9.133	0.947	1.67
7	12.61215	9.878	7.853	2.025	1.398	7.298	2.58	1.351
8	12.81679	10.312	9.689	0.623	1.698	9.001	1.311	1.583
9	12.85499	10.127	7.295	2.832	1.882	6.808	3.319	1.785
10	11.63566	10	8.005	1.995	1.076	7.456	2.544	1.02
Average			**8.5839**	**1.4461**		**7.9763**	**2.0537**	
Standard Deviation				0.947431			0.871869	

20 meter			Wavelet			Low Pass		
Sample No.	**Time**	**GPS**	**X**	**ΔX**	**Y**	**X**	**ΔX**	**Y**
1	16.33208	20	16.86	3.14	3.802	15.66	4.34	3.624
2	18.5891	19.838	18.28	1.558	5.219	17.01	2.828	4.901
3	18.52864	20.3	18.55	1.75	4.238	17.23	3.07	4.073
4	18.61999	20.066	18.36	1.706	5.087	17.06	3.006	4.83
5	17.31484	20.273	19.06	1.213	2.951	17.73	2.543	2.821
6	17.9816	19.888	18.22	1.668	4.401	16.91	2.978	4.188
7	15.64048	20.188	19.05	1.138	3.358	17.74	2.448	3.192
8	15.50398	20.254	19.39	0.864	2.772	17.99	2.264	2.602
9	17.92907	20.146	19.48	0.666	2.816	18.1	2.046	2.685
10	14.95754	20.324	19.25	1.074	2.607	17.91	2.414	2.468
Average			**18.65**	**1.4777**		**17.334**	**2.7937**	
Standard Deviation				0.692507			0.642371	

30 meter			Wavelet			Low Pass		
Sample No.	**Time**	**GPS**	**X**	**ΔX**	**Y**	**X**	**ΔX**	**Y**
1	20.35431	30.139	31.17	-1.031	6.603	28.89	1.249	6.21
2	16.23829	30.014	29.02	0.994	6.743	27	3.014	6.373
3	17.86739	30.165	30.88	-0.715	5.53	28.67	1.495	5.316
4	17.26093	30.048	31.37	-1.322	5.482	29.16	0.888	5.19
5	17.11736	30.199	28.86	1.339	5.596	26.84	3.359	5.265
6	19.92271	30.129	31.43	-1.301	6.026	29.15	0.979	5.692
7	16.71685	30.355	21.91	8.445	5.391	20.42	9.935	5.076
8	20.29509	30.026	31.07	-1.044	5.564	28.78	1.246	5.219
9	19.21019	30.166	31.29	-1.124	5.345	29.05	1.116	5.074
10	17.71606	29.957	31.06	-1.103	6.478	28.77	1.187	6.151
Average			**29.806**	**0.9593**		**27.673**	**1.6148**	
Standard Deviation				3.012911			2.76791	

40 meter			Wavelet			Low Pass		
Sample No.	Time	GPS	X	ΔX	Y	X	ΔX	Y
1	22.31257	40.374	42.31	-1.936	7.704	39.2	1.174	7.308
2	21.41658	39.846	41.06	-1.214	4.613	38.14	1.706	4.352
3	22.03859	40.297	36.64	3.657	7.829	33.97	6.327	7.455
4	21.42453	39.904	41.59	-1.686	4.658	38.67	1.234	4.591
5	18.7471	40.359	40.84	-0.481	4.274	37.99	2.369	4.074
6	18.33055	40.406	40.95	-0.544	4.72	38.07	2.336	4.588
7	21.43092	40.262	43.18	-2.918	4.307	40.28	-0.018	4.296
8	18.92196	40.487	40.15	0.337	3.715	37.35	3.137	3.518
9	18.89023	40.025	42.97	-2.945	3.574	40	0.025	3.417
10	20.86378	39.594	43.02	-3.426	4.156	39.97	-0.376	4.079
Average			**41.271**	**-1.1156**		**38.364**	**1.7914**	
Standard Deviation				2.069852			1.96648	

50 meter			Wavelet			Low Pass		
Sample No.	Time	GPS	X	ΔX	Y	X	ΔX	Y
1	21.14975	50.302	54.35	-4.048	7.023	50.53	-0.228	6.757
2	20.95987	50.091	52.95	-2.859	6.641	49.3	0.791	6.453
3	22.08102	50.274	53.66	-3.386	9.294	49.94	0.334	8.84
4	17.10178	50.749	51.99	-1.241	5.608	48.53	2.219	5.312
5	19.92193	50.946	53.41	-2.464	8.679	49.65	1.296	8.406
6	21.3688	50.071	53.88	-3.809	9.853	50.05	0.021	9.302
7	19.14862	50	53.24	-3.24	6.893	49.49	0.51	6.559
8	18.37508	50	53.63	-3.63	6.551	49.82	0.18	6.331
9	19.81466	50.035	53.28	-3.245	7.59	49.53	0.505	7.375
10	19.81713	50.028	53.61	-3.582	6.61	49.89	0.138	6.514
Average			**53.4**	**-3.1504**		**49.673**	**0.5766**	
Standard Deviation				0.811726			0.717645	

60 meter			Wavelet			Low Pass		
Sample No.	Time	GPS	X	ΔX	Y	X	ΔX	Y
1	21.42897	60.025	64.48	-4.455	6.519	60.12	-0.095	6.399
2	20.51157	59.828	64.09	-4.262	7.129	59.75	0.078	6.859
3	21.55844	60.041	64.65	-4.609	7.707	60.34	-0.299	7.605
4	20.58016	60.092	64.45	-4.358	7.159	59.94	0.152	6.856
5	22.64947	60.15	64.51	-4.36	9.921	60.04	0.11	9.443
6	20.7403	60.7	64.31	-3.61	7.851	59.87	0.83	7.454
7	19.73113	60.206	63.92	-3.714	5.947	59.47	0.736	5.836
8	17.88842	60.169	64.03	-3.861	4.867	59.68	0.489	4.898
9	19.79114	60.249	64.01	-3.761	8.447	59.66	0.589	8.163
10	20.06516	60.736	64	-3.264	8.168	59.55	1.186	7.862
Average			**64.245**	**-4.0254**		**59.842**	**0.3776**	
Standard Deviation				0.440945			0.463936	

70 meter			Wavelet			Low Pass		
Sample No.	Time	GPS	X	ΔX	Y	X	ΔX	Y
1	24.09116	70.75	75.06	-4.31	4.958	69.79	0.96	4.569
2	21.64186	70.096	74.47	-4.374	4.085	69.39	0.706	3.943
3	19.56679	70.835	74.76	-3.925	3.596	69.66	1.175	3.478
4	20.05759	70.125	74.53	-4.405	3.455	69.34	0.785	3.327
5	20.65588	69.858	74.87	-5.012	3.175	69.67	0.188	2.981
6	21.43035	70.458	74.26	-3.802	4.73	69.08	1.378	4.529
7	20.05129	69.927	74.14	-4.213	3.862	68.93	0.997	3.716
8	22.11395	69.701	74.99	-5.289	4.549	69.81	-0.109	4.365
9	22.37857	69.679	74.93	-5.251	3.651	69.71	-0.031	3.505
10	21.72728	70.577	74.62	-4.043	4.278	69.4	1.177	4.042
Average			**74.663**	**-4.4624**		**69.478**	**0.7226**	
Standard Deviation				0.537957			0.529338	

80 meter			Wavelet			Low Pass		
Sample No.	Time	GPS	X	ΔX	Y	X	ΔX	Y
1	22.94494	80.438	85.79	-5.352	3.436	79.9	0.538	3.294
2	22.42286	80.419	85.41	-4.991	5.545	79.44	0.979	5.556
3	23.14418	80.77	81.23	-0.46	4.965	75.64	5.13	4.789
4	20.82248	80.56	82.09	-1.53	4.026	76.45	4.11	3.993
5	23.7801	81.937	85.18	-3.243	4.603	79.32	2.617	4.38
6	22.69698	79.506	85.54	-6.034	3.763	79.59	-0.084	3.585
7	23.55379	80.6	84.93	-4.33	3.784	79.02	1.58	3.534
8	23.00643	79.863	84.48	-4.617	4.25	78.55	1.313	4.178
9	24.79461	80.147	86.03	-5.883	5.825	80.18	-0.033	5.418
10	22.4604	80.038	85.18	-5.142	5.392	79.06	0.978	5.074
Average			**84.586**	**-4.1582**		**78.715**	**1.7128**	
Standard Deviation				1.863147			1.736975	

90 meter			Wavelet			Low Pass		
Sample No.	Time	GPS	X	ΔX	Y	X	ΔX	Y
1	23.16521	89.926	95.45	-5.524	3.956	88.97	0.956	3.845
2	24.43036	90.829	96.82	-5.991	4.194	89.81	1.019	3.835
3	25.3619	90.28	96.26	-5.98	5.907	89.41	0.87	5.564
4	22.77092	91.435	96.41	-4.975	3.724	89.81	1.625	3.372
5	22.29361	89.949	95.89	-5.941	4.835	89.34	0.609	4.432
6	23.46283	89.678	95.23	-5.552	6.503	88.59	1.088	6.142
7	24.97669	89.988	96.4	-6.412	6	89.61	0.378	5.433
8	23.33846	89.761	96.44	-6.679	3.085	89.99	-0.229	2.95
9	23.5059	90.511	96.21	-5.699	4.363	89.69	0.821	4.108
10	25.51376	90.104	96.44	-6.336	4.947	89.8	0.304	4.712
Average			**96.155**	**-5.9089**		**89.502**	**0.7441**	
Standard Deviation				0.498125			0.508744	

100 meter			Wavelet			Low Pass		
Sample No.	Time	GPS	X	ΔX	Y	X	ΔX	Y
1	23.85492	99.949	104.4	-4.451	6.196	97.31	2.639	5.648
2	22.77063	100.685	106	-5.315	2.358	98.64	2.045	2.323
3	25.14456	99.775	106	-6.225	6.309	98.64	1.135	5.738
4	25.18205	100.064	107.2	-7.136	4.639	99.96	0.104	4.244
5	23.39271	99.878	104.9	-5.022	8.815	97.57	2.308	7.827
6	23.27906	99.824	105.2	-5.376	5.876	97.86	1.964	5.354
7	24.99946	99.794	105.4	-5.606	5.728	98.21	1.584	5.273
8	24.37067	100	106.1	-6.1	4.488	98.8	1.2	4.187
9	23.03635	99.843	105.8	-5.957	4.85	98.53	1.313	4.315
10	24.44646	99.758	105.4	-5.642	3.191	98.22	1.538	3.042
Average			**105.64**	**-5.683**		**98.374**	**1.583**	
Standard Deviation				0.733785			0.715629	

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The major objectives of the research were to develop an INS data processing model and test the filtering methods to improve the navigation accuracy of low cost RGA inertial sensor.

The model developed was tested for its validity and found to be satisfactory over short distances.

The following conclusion was drawn from the tests conducted in this thesis:

5.1 Conclusion

The results showed the gradual error growth in the INS data. Two different filtering techniques showed different results. Low pass filtering showed better performance over longer distances up to 100 meters while denoising was found to be better over short distances up to 40 meters.

To get the most out of low cost inertial sensor requires focused research work on proper error modeling (filtering and estimation) techniques to study the behavior of error growth. Single filtering technique is not enough for a sensor like RGA300CA although multiple filtering techniques with a proper switching algorithm should give a better result.

Strapdown MEMS sensors are still considered relatively poor devices in accuracy for land surveying applications despite its popular growth and low cost (Park, 2004) but can give reasonable support if used integrated with an aiding system such as GPS that can support the INS drift by giving update of accurate measurement.

It was also observed from the data that the performance of accelerometers in the RGA sensor was much better than the yaw rate gyro, which is needed for attitude information during turns and maneuvers as in case of angular trajectories.

The inertial sensor used in this study is a low cost yaw rate sensor that is not only low in cost but also low in performance and that can only support the outage of GPS for only seconds, therefore, for a better accuracy performance a better sensor is suggested such as a Ring Laser Gyro (RLG) for land applications. The study can be further progressed to improve the performance of the model created, which is possible due to Kalman filtering techniques and the inclusion of GPS data as an aiding system for INS.

5.2 Recommendation

a. An elaborate frame should be designed to mount the INS, along with a place for GPS antenna, over the testing vehicle. This will help to minimize the alignment errors and will save time to position the inertial sensor over the vehicle.

b. High bandwidth of INS data makes the processing time consuming especially if an iterative filtering model such as Kalman filter is being used, therefore high computing power should be used to do data processing.

c. Inertial sensors based on Ring Laser Gyros are recommended for use in land vehicle mapping especially if the outages are longer than 10 seconds and turns are taken during terrain mapping.

5.3 Future Work

The model developed can be further improved for performance by incorporating error-modeling techniques. By including the GPS as an aiding system the navigation solution can be converted to a mobile mapping system that could be used for land mapping of longer distances without any position outages. The possibility of GPS as an aiding system can be further studied by the use of Kalman Filter. References provided can be very helpful and contain detailed literature on GPS/INS Integration and Kalman filtering. (Grewal 2001, Farrel 1999, Fjellstad 2004) Almost all the references except hard copy books are made available on the CD accompanying this thesis.

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BIODATA OF THE AUTHOR

Khurram Niaz Shaikh was born in Karachi and raised in Hyderabad, Pakistan where he finished his high school in 1993. He completed his bachelor's degree in Civil Engineering in year 2000 from Mehran University of Engineering and Technology (MUET), Jamshoro, Pakistan. After finishing his first degree he worked as a CAD Engineer in a private firm for two years where during a project his interest in the field of Geographic Information System (GIS) and Geomatics grew and made him go for masters in GIS and Geomatic Engineering.