Implementation of GNSS in Real-Time Positioning for an Outdoor Construction Machine Simulator

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Abstract
The Institute of Engineering Geodesy (IIGS) at University Stuttgart has been involved in field of research for machine guidance and it has developed a hardware-in-the-loop simulator that allows guiding the model construction machines along a reference trajectory. The control quality is evaluated using the Root Mean Square (RMS) of the lateral deviations between the vehicle position and the reference trajectory during the test drive.

This paper focuses to implement the GNSS PPP technique for the control and guidance of the model truck along the reference trajectory. The PPP solutions are computed using the BKG Ntrip Client (BNC) at 1 Hertz data rate. The International GNSS Services (IGS) organization provides various clock products and hence the evaluation of these products is performed in this paper. The paper also focuses to perform an initial study of the integration of various sensors, like the PPP and the IMU sensor using the Kalman Filter algorithm.

In order to compare the control quality using the PPP and RTK techniques, the test drives were performed at a data rate of 1 Hertz for both techniques. The experimental results show the RMS of the RTK solution is 1 centimeter, whereas the RMS of the BNC-PPP solution in real-time is 35.4 centimeters. Simulated test drives were performed to analyze the PPP results using various settings and the RMS of the control deviation can be improved to 20.8 centimeters. Various factors affect the quality of the BNC-PPP solutions, like the quality of the clock and orbit products, number of satellites that are viewed, the error correction models, the data-rate of observations and so on. The IMU heading angles were studied in comparison with the heading angles computed using the control program. The heading angles from the IMU sensor are affected by presence of magnetic substances and compensation of the hard and soft iron interferences should be performed. The IMU heading angles were then simulated to study the performance of integration of sensors and the RMS of the lateral deviation of the integrated test drives are 21.8 centimeters. More real-time analysis can investigate the results further.

Key words: Construction Machine Guidance, Kalman Filter, Real Time Kinematic (RTK) solution, Precise Point Positioning (PPP) solution, Inertial Measurement Unit (IMU), Simulation
1. Introduction

1.1 General Introduction
Machine Control and Guidance is a rapidly advancing filed of research in Engineering Geodesy, mainly due to the reason that it is a research area where the other engineering fields like mechanics, electronics, informatics, construction are all collaborating with engineering geodesy. Machine Guidance is a terminology to describe the various techniques that are used to improve the productivity of construction, mining and agricultural equipment, by incorporating GPS and other motion measuring units to provide information about movement of the machine.

1.2 Simulator at IIGS
With the development of precise positioning technologies and sensors, there is tremendous amount of research work that is being done in the field of geodesy related to navigation, control and guidance of vehicles. The Institute of Engineering Geodesy (IIGS) at Stuttgart University also focuses on this type of research work and has been successful in accomplishing a modular closed loop system for geometric guidance and control of construction machines. An outdoor construction machine simulator for experimental purposes has been set-up on which different control algorithms and vehicle models can be implemented. The simulator can be used for testing and solving problems that might be encountered in the real field during control and guidance of the construction machine. More details can be found regarding this in Beetz (2012).

1.3 Thesis Objective
The construction machine simulator at IIGS is developed for indoor as well as outdoor applications. The Real Time Kinematic (RTK) positioning has been already implemented on the construction machine simulator and RMS of the lateral deviation of 5-8 millimeter has been achieved using the PID controller and Kalman Filter algorithm at a velocity of 7-14 cm/s at a high data rate of 20 Hertz (Lin et al., 2014).

The main objective of this thesis focuses on the implementation of real-time PPP (Precise Point Positioning) solutions from BNC (BKG Ntrip Client) software for the control and guidance of the truck. The main reason to use of this software is that it is the only open-source software currently available to compute the real-time PPP solutions. The thesis also compares the different clock products from different IGS centers in order to evaluate their performances. The control quality of the PPP solution is compared with that of the RTK solution at the same data rate of 1 Hertz.

Another focus of the thesis was to study the performance of the IMU (Inertial Measurement Unit) sensor in order to integrate the data from various sensors for the control of the construction machine. An initial analysis was performed for the IMU 3DM-GX2 sensor from MicroStrain Inc. Simulated test drive of the PPP solutions from the BNC software and the heading angle from the IMU sensor was performed in order to study the integration of both sensors.
2. GNSS Techniques

2.1 General Introduction
GNSS (Global Navigation Satellite System) is a system of satellites providing the accurate position, navigation and time information in a continuous way by transmitting signals. Due to wide range of applications and availability, GNSS technologies are now being used in many fields of engineering like civil, surveying, communication, agriculture and navigation.

2.2 Real Time Kinematic (RTK) Technique
RTK positioning approach is a differential GNSS technique that requires at least two stations to compute the accurate position of the user’s receiver. The DGPS (Differential GPS) technology requires a reference station with precisely known positions to send the correction files to the user receiver, which enables the users to use this information to compute its position with high precision. The distance range of the RTK approach is usually 10 - 20 kilometers, which provides positioning accuracy in the range of few centimeters. This technique is widely applied in surveying applications, due to its higher performance.

2.3 Precise Point Positioning (PPP) Technique
In the late 1990s, the NASA’s Jet Propulsion Laboratory introduced a new technique to compute the precise positions and named it as Precise Point Positioning (PPP). The PPP solution provided around 1 centimeter accuracy with a single receiver and without any ground control.

Precise Point Positioning (PPP) is a technology that integrates the un-differenced dual frequency pseudorange and carrier phase measurements obtained from one dual-frequency GPS receiver with precise orbit and clock information. The PPP technique is an alternative to the RTK technique and is advantageous as compared with the traditional Nowadays, there are several organizations that provide the precise GNSS orbit and clock information via the internet, like the International GNSS Service (IGS), JET Propulsion Laboratory (JPL), Natural Resources Canada (NRCan).

The concept of Precise Point Positioning (PPP) is that with the availability of precise orbits and clock information, the user station can be positioned very accurately, along with receiver clock and tropospheric bias. However, the common mode errors (clock and orbit errors) are not cancelled in PPP solution. Hence, the station for which the PPP solution is to be computed contains errors that have to be considered. These include the satellite dependent errors (like clock and orbit errors), medium dependent errors (like ionospheric and tropospheric errors, multipath errors) and receiver dependent errors (like receiver clock error, antenna phase center changes and uncertainty in measurement) (Nistor and Buda, 2012). With the success of the PPP systems, there is improvement in the flexibility of operation and reduction in cost of applications.
3. BNC (BKG NTrip Client) Software

3.1 BNC Software – PPP module

The BNC is a program that has been developed within the framework of the EUREF (IAG sub-commission for Europe) and IGS (International GNSS Service), which can retrieve, decode, convert and process the real-time GNSS data streams at the same time. The BNC software can compute the coordinates for a user receiver station using the PPP approach, using the code or code and phase data that are ionospheric free combinations P3 or L3. The output of the PPP solutions are in the NMEA format and it can be written to a local IP port of the computer. In the PPP module of BNC software, some error effects like Solid Earth Tides, Phase Windup and Receiver Antenna offset are corrected, whereas some effects like satellite and receiver antenna phase center offsets, ocean loading as well as polar effects are not corrected.

3.1.1 Selection of Clock Product

The first step for analyzing the BNC software is to analyze the different real time clock products from IGS analysis centers, in order to analyze which clock product would produce the best results. There are various kinds of clock products that are produced by different organizations using various software and GNSS products. In order to do the same, the different clock files were selected to provide corrections for the PPP solution and the data was recorded for each clock file for about 2 hours’ time. Then the bias of the North, East and Up components of the PPP solution were derived by comparing the positioning results of BNC-PPP solution with the reference to the coordinates obtained for the Frankfurt station. Table 3.1 presents the RMS and standard deviation of the N, E and U components using the BNC-PPP approach.

<table>
<thead>
<tr>
<th>Clock Product</th>
<th>Statistical Parameter</th>
<th>North (cm)</th>
<th>East (cm)</th>
<th>Up (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLK00</td>
<td>RMS</td>
<td>13.1</td>
<td>19.7</td>
<td>15.4</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>2.9</td>
<td>19.0</td>
<td>8.1</td>
</tr>
<tr>
<td>CLK01</td>
<td>RMS</td>
<td>8.8</td>
<td>8.1</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>1.9</td>
<td>8.1</td>
<td>3.6</td>
</tr>
<tr>
<td>CLK11</td>
<td>RMS</td>
<td>7.6</td>
<td>4.9</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>4.5</td>
<td>4.9</td>
<td>10.1</td>
</tr>
<tr>
<td>CLK20</td>
<td>RMS</td>
<td>7.6</td>
<td>38.8</td>
<td>38.6</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>7.6</td>
<td>10.3</td>
<td>19.4</td>
</tr>
<tr>
<td>CLK30</td>
<td>RMS</td>
<td>34.9</td>
<td>33.2</td>
<td>13.7</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>9.2</td>
<td>11.8</td>
<td>12.2</td>
</tr>
<tr>
<td>CLK31</td>
<td>RMS</td>
<td>10.9</td>
<td>70.8</td>
<td>70.9</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>4.9</td>
<td>57.9</td>
<td>41.6</td>
</tr>
<tr>
<td>CLK90</td>
<td>RMS</td>
<td>9.9</td>
<td>3.7</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>7.4</td>
<td>3.2</td>
<td>9.9</td>
</tr>
<tr>
<td>CLK91</td>
<td>RMS</td>
<td>7.7</td>
<td>3.6</td>
<td>8.8</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>1.5</td>
<td>2.8</td>
<td>4.5</td>
</tr>
</tbody>
</table>
It can be seen from the table that the positioning results are varying, when different clock products are used. For some of the clock products (CLK01, CLK11, CLK90, CLK91), the accuracy reaches in the range of 4-10 centimeters in North, East and Up direction. Hence, these clocks have been selected for the PPP positioning. On the other hand, the results obtaining using some clock products (CLK20, CLK30, and CLK31) are much higher than these values. The results achieved are similar to the results obtained for the tests conducted in Lin (2014), which was performed during the period 01.06.2013 and 01.07.2013. It can be seen from table 3.2 that the different clock products are computed by different IGS Analysis Centers and obtained using different software with data from different stations. Since the estimations of these clock products are different from each other, the results obtained will vary as well.

3.1.2 Interface program to obtain PPP solutions

The BNC-PPP solutions are obtained as NMEA messages and these messages are written to a local port that is specified by the user. An interface program developed in Labview environment is used to read these messages from the IP port. These NMEA messages are in the ITRF08 coordinate frame and are transformed to horizontal UTM (Universal Transverse Mercator) coordinates, which is transferred to the control program to guide the truck.

3.2 Inertial Measurement Unit (IMU)

3.2.1 General Introduction

The IMU is a device that is used to measure the state like the orientation, velocity and position of a stationary or dynamic object with respect to the inertial reference frame. The main advantage of the low cost IMU is that they are small in size as well as weightless and at the same time very powerful. But the main issue with these systems is big measurement errors and noise as compared with the navigation or tactical grade IMUs. The orientation is computed from a set of measurements like angular rates from the gyroscopes, linear accelerations from the accelerometers and the magnetic fields from the magnetometers. Hence, the accuracy of the IMU sensor depends on the algorithm that is used to combine the various sensor units.

3.2.2 MicroStrain (3DM-GX2) IMU Sensor

The IMU sensor (3DM-GX2) is a high performance gyro enhanced orientation sensor that uses the MEMS sensor technology. The various sensors like 3-axis accelerometer, 3-axis gyroscope, 3-axis magnetometer, temperature sensor and on-board processors are combined in a sensor fusion algorithm. 3DM-GX2 sensor can provide outputs like acceleration, angular rate, magnetic field as well as orientation matrices. The IMU (3DM-GX2) sensor frame is oriented in such a way that the unit vectors are as follows: X is parallel and outward from the connector; Z is normal to the top and running from top through the bottom; the Y axis completes the frame using the right hand rule. These axes are selected as follows so that when the connector on the device is pointed true north and the device is upright and leveled, the sensor frame will match the NED frame exactly, giving zero rotation (when represented by Euler angles).
4. Integration of Sensors

4.1 Kalman Filter algorithm

4.1.1 Existing Implementation
Kalman Filter is an algorithm developed by Rudolf. E. Kalman in 1960. It is a very common algorithm that is used to estimate the state of dynamic systems. It uses the measurements that are observed over time, containing noise (random variations) and other inaccuracies and computes the estimate of the unknown variables in the best optimal way. More details about the implemented Kalman filter algorithm (variant 1 and variant 2) can be found in Beetz (2012).

4.1.2 Integration of IMU and PPP
The accuracy of the positioning results using the BNC-PPP algorithm is not very accurate (nearly 40 centimeters accuracy only) and the current data rate of the BNC-PPP algorithm is only 1 Hertz (1 data per second). Thus, it was decided to study about the integration of other sensors, like the IMU, which can provide precise heading angle information at a higher data rate of 100 Hertz, along with the coordinates computed using BNC-PPP algorithm. In order to integrate the sensors, the coordinates of the current truck position are obtained using the PPP solution computed from the BNC software and the orientation angle is obtained from the IMU sensor, which is fixed on the truck. Figure 4.6 shows a simplified flowchart for integration of the sensors.

Figure 4.1 : Flowchart for integration of sensors

5. Results and Analysis

5.1 Test Field
In order to perform the test drives for evaluating the performance of GNSS solutions, a smooth surface concrete area was set-up in Stuttgart University campus at Vaihingen. Several test drives were conducted on 14th, 15th and 20th of May, 2014 (before noon) using GNSS (RTK and PPP) solutions along the oval shaped reference trajectory and the results were analyzed. The quality of measurements is determined using the Root Mean Square (RMS) of the lateral deviations of the position of the truck with respect to the reference trajectory.
5.2 RTK Solutions

5.2.1 Test Scenario 1
The RTK (Real Time Kinematics) solution obtained using SAPOS (German NRTK provider) was used to compute the current position of the truck to the control program, in order to drive the truck in the desired trajectory. More details about the RTK algorithm can be obtained in Lin (2014). For the purpose of comparison with the BNC-PPP solution, the RTK solutions were generated at a data rate of 1 Hertz. Different settings of the control program were used to analyze the best possible setting for driving the truck in the reference trajectory. During the test drives, the truck was made to drive at a constant speed along the reference trajectory. The orientation angles in the control program are computed using three different options to compute the orientation angle, namely, ‘Position’, ’Trajectory’ and ‘Average’.

5.2.2 Analysis of test scenario 1
Table 4.1 presents an analysis of the test drives that was performed with various settings of the control program.

<table>
<thead>
<tr>
<th>Case</th>
<th>Velocity (cm/s)</th>
<th>Controller</th>
<th>Kalman Filter</th>
<th>Orientation Angle Chosen</th>
<th>RMS Straight Line [cm]</th>
<th>RMS Clothoid [cm]</th>
<th>RMS Circle [cm]</th>
<th>RMS Mean [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.1</td>
<td>12.3</td>
<td>--</td>
<td>--</td>
<td>1.3</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>6.2</td>
<td>25</td>
<td>0.5</td>
<td>0.001</td>
<td>1.3</td>
<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>5.4</td>
<td>12.3</td>
<td>--</td>
<td>--</td>
<td>5.6</td>
<td>5.4</td>
<td>5.1</td>
<td>5.4</td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>12.3</td>
<td>--</td>
<td>--</td>
<td>2.6</td>
<td>2.6</td>
<td>4.3</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>5.9</td>
<td>12.3</td>
<td>--</td>
<td>--</td>
<td>1.6</td>
<td>1.2</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>6</td>
<td>6.4</td>
<td>25</td>
<td>0.5</td>
<td>0.001</td>
<td>2.8</td>
<td>2.1</td>
<td>2.1</td>
<td>2.3</td>
</tr>
<tr>
<td>7</td>
<td>5.4</td>
<td>25</td>
<td>0.5</td>
<td>0.001</td>
<td>2.0</td>
<td>1.4</td>
<td>2.3</td>
<td>1.9</td>
</tr>
<tr>
<td>8</td>
<td>8.0</td>
<td>25</td>
<td>0.5</td>
<td>0.001</td>
<td>1.8</td>
<td>0.5</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

The results in table 4.1 show that:

1. The test drives 1 and 2 indicate the RMS of the lateral deviation of the drives using the P and PID controller and without the Kalman Filter. It can be seen that when the PID controller is implemented, the RMS of the lateral deviation is 1.1 centimeters as compared with the P controller, which has a RMS value of 1.2 centimeters.

2. The test drives 3-5 shows the RMS of the lateral deviation using the Kalman Filter option and the P controller. The RMS of the lateral deviation is best acquired when the orientation angle is computed using the ‘Average’ option (deviation is 1.3 centimeters). This is due to the fact that in the ‘Average’ option both the orientation angles from the measurements as well as the reference trajectory are considered. The test drives 6-8 illustrates the implementation of PID controller and the Kalman Filter. The results are
improved by using the Kalman Filter option and the Kalman filter smoothens the measured values.

3. The test drives 3-7 indicate that the RMS of the lateral deviation using Kalman Filter is increased than that without using the Kalman Filter. Further investigation has to be done in this regard in order to analyze the cause of this behavior.

4. In figure 4.1, the orientation angles are computed using the measured coordinates (‘Position’ option) and the orientation angles computed using the reference trajectory (‘Trajectory’ option) are plotted for two drives. It can be seen that both orientation angles are almost similar, whereas along the clothoids, the orientation angle computed from the measurements show a fluctuating behavior. This is due to the oscillating movement of the truck along the clothoid paths, which is due to the fact that the clothoid is an approximation of the circle path.

![Comparison of Orientation Angles](image.png)

**Figure 5.1 : Comparison of Orientation Angles**

### 5.3 BNC – PPP solution

#### 5.3.1 Test Scenario 2

The Precise Point Positioning (PPP) solution was obtained from the BNC-PPP module for performing the test drives on 14.05.2014 and 20.05.2014. The real-time kinematic PPP solutions that were obtained from the BNC software were compared with the post-processed results using CSRS (Canadian Spatial Reference System) provided by NRCan (Natural Resources Canada). The post-processing was performed after almost two weeks’ time, in order to ensure that the most accurate PPP solutions were computed by CSRS. The biases in X, Y and Z values of the BNC-PPP solutions and the CSRS solutions were compared to study the performance of the BNC software. The analysis is presented in the next section.

#### 5.3.2 Analysis of test scenario 2

A comparison of the real-time PPP solution obtained using the BNC software on 14.05.2014 and the post-processed PPP solution from CSRS tool were made in order to analyze the accuracy of the real-time BNC-PPP solution. Figure 4.2 shows the accuracy of the real-time PPP solutions.
It can be seen in the figure that the BNC software takes a long time to converge to a solution of accuracy of 40 centimeters (nearly 30 minutes). Hence, it can be considered that when the BNC software can compute the PPP solutions with an accuracy of at least 40 centimeters, the truck can be guided to follow the desired reference trajectory.

It has been noted with several experimental test drives that when this accuracy level are not reached, the truck cannot follow the reference trajectory. For example, figure 4.3 shows the bias of the BNC-PPP solution that was obtained on 20.05.2014. It can be seen in the figure that the X, Y values have a bias of 80 centimeters and the bias of Z values are less than 60 centimeters, after a long convergence time of more than 50 minutes. Various factors affect the accuracy of the BNC-PPP solutions, like the quality of the clock and orbit products, the number of satellites that in view as well as the geometry of the satellites, the error correction models, the data rate of the solution and so on. One main issue that was faced using the BNC software was that the software always crashes after 2 hours of running. More investigations have to be done in this regard in the future.
5.3.3 Test Scenario 3
The GNSS receiver was fixed on the truck and the BNC-PPP solutions were used to compute the current position of the truck. The obtained results are analyzed in the following section.

5.3.4 Analysis of test scenario 3
Table 4.2 presents the RMS of the lateral deviation that was obtained during the test drives using the P controller at a data rate of 1 Hertz.

Table 5.2: PPP Solutions

<table>
<thead>
<tr>
<th>Case</th>
<th>Velocity (cm/s)</th>
<th>Controller</th>
<th>RMS Straight Line [cm]</th>
<th>RMS Clothoid [cm]</th>
<th>RMS Circle [cm]</th>
<th>RMS Mean [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2.7</td>
<td>32.7</td>
<td>36.4</td>
<td>37.3</td>
<td>35.4</td>
</tr>
</tbody>
</table>

Only a few test drives could be successfully conducted using the real-time BNC-PPP module, as on the other days the PPP solutions from the BNC software was not precise enough (required less than 40 cm) to make the truck drive along the desired trajectory. The results in table 4.2 show that:

1. The table shows that using P controller without Kalman Filter, the RMS of the lateral deviation obtained is 35.4 centimeters at a velocity of 2.7 cm/sec. It can be seen from the results that the RMS of the lateral deviation using the RTK solution is better than that of the BNC-PPP solution.

2. Figure 4.4 shows the plot of the reference trajectory and the BNC-PPP computed coordinates. It can be noted from the figure that there is a large deviation of the BNC-PPP solutions from the reference trajectory (approximately ±35 centimeters). The oscillation is caused due to the P controller, since in the P controller, the control deviation is always present, (that is, there always exists a steady state error in case of P controllers). The simulated results using PID controller (next section) shows better results compared to the P controller. Further studies should be done to evaluate the performance of the P controller. Another solution could be to change the value of the controller parameter of the P-controller. The algorithm that is used to compute the control deviation might be also one of the reasons for the large deviation. The distance between the points along the reference trajectory is set to be 10 cm and the positioning accuracy of the BNC-PPP solution is about 30 – 40 cm sometimes. When the lateral deviation is computed, the algorithm considers the shortest distance between the current position of the truck and the points along the reference trajectory.
5.4 Simulated PPP Drives

5.4.1 Test Scenario 4
In order to investigate the performance of the BNC-PPP solutions with the various settings of the control program, a simulation of the test drives were performed using the Software Simulator Module (SSM). The various settings of implementing the P and PID controller as well as the Kalman filter and the various methods to compute the orientation angles were chosen for analysis.

5.4.2 Analysis of test scenario 4
Table 4.3 shows the results of the RMS of the lateral deviations that were obtained during the simulated test drives for various settings. The data rate was chosen as 1 Hertz for all the simulated drives.

Table 5.3: Simulated PPP Drives

<table>
<thead>
<tr>
<th>Case</th>
<th>Controller</th>
<th>Kalman Filter</th>
<th>Orientation Angle Chosen</th>
<th>RMS Straight Line [cm]</th>
<th>RMS Clothoid [cm]</th>
<th>RMS Circle [cm]</th>
<th>RMS Mean [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.3</td>
<td>--</td>
<td>No</td>
<td>32.7</td>
<td>36.3</td>
<td>37.2</td>
<td>35.4</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>0.5</td>
<td>Yes Position</td>
<td>31.1</td>
<td>34.5</td>
<td>33.4</td>
<td>33.0</td>
</tr>
<tr>
<td>3</td>
<td>12.3</td>
<td>--</td>
<td>Yes Trajectory</td>
<td>28.9</td>
<td>29.1</td>
<td>31.1</td>
<td>29.7</td>
</tr>
<tr>
<td>4</td>
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<td>Yes Average</td>
<td>30.3</td>
<td>17.8</td>
<td>20.9</td>
<td>23.0</td>
</tr>
<tr>
<td>5</td>
<td>12.3</td>
<td>--</td>
<td>Yes Position</td>
<td>34.6</td>
<td>30.9</td>
<td>37.9</td>
<td>34.5</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>0.5</td>
<td>Yes Trajectory</td>
<td>27.0</td>
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<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>0.5</td>
<td>Yes Average</td>
<td>20.6</td>
<td>16.9</td>
<td>24.9</td>
<td>20.8</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>0.5</td>
<td>Yes Average</td>
<td>32.7</td>
<td>36.3</td>
<td>37.2</td>
<td>35.4</td>
</tr>
</tbody>
</table>
The following results in table 4.3 indicate that:

1. Case 1 and 2 presents the RMS of the lateral deviation of the whole drives using the P and PID controllers and without the implementation of the Kalman filter algorithm. It can be seen that the PID controller (RMS of lateral deviation is 35.4 centimeters) works a little better than the P controller (RMS of lateral deviation is 33.5 centimeters).

2. The cases 3-5 shows the analysis of the test drives using the P controller and the Kalman filter using different methods to compute the orientation angles. It can be seen that the orientation angle computed using the ‘Average’ option presents slightly better results than the other options. In the cases 6-8, the PID controller is used along with the Kalman filter and different variations of the orientation angles are used. The least lateral deviation is obtained using the PID controller along with the Kalman filter algorithm and the using the orientation angle computed by the ‘Average’ option (RMS of lateral deviation is 20.8 centimeters).

5.5 IMU Sensor

5.5.1 Test Scenario 6
In order to do a comparison of the heading angles that were obtained from the IMU Sensor (3DM-GX2), and the orientation angles that was obtained from the control program, the following test drive was performed. The IMU sensor was mounted on the truck, so that the X-direction points in the driving direction of the truck and the readings were recorded using the Inertial Link software from MicroStrain at a frequency of 10Hz. The orientation angle computed from the RTK solution at a frequency of 1Hz using the control program was also recorded at the same time using the Labview program.

5.5.2 Analysis of test scenario 6
A comparison of the orientation angles obtained from the IMU sensor and the orientation angles computed by the control program are shown in figure 4.5.

![Figure 5.5: Comparison of Orientation Angles](image-url)
The orientation angles from the IMU sensor show the same trend as the orientation angles computed by the control program. The values of both the orientation angles are close to each other, but there is a shift along the curves and the clothoid parts. Upon close verification of the orientation angles obtained from the IMU Sensor, it can be seen that there are gaps in the orientation angles recorded.

One of the reasons for the missing values is that it is due to the effect of the magnetometer sensors onboard of the IMU sensor. The magnetometers are the main components to compute the yaw angle. If the magnetometer is affected by the presence of magnetic substances, then the yaw angles show the missing values. It can be seen that there is a lot of magnetic substances on the truck as well as the presence of other magnetic substances near the vicinity of the truck could also affect the magnetometer readings. Other reasons for this could be due to the fact that the IMU sensor is connected to the laptop using wireless connection and there is a possibility of loss of data over the wireless transfer or the data could be missed due to the fact that the power supply of the IMU sensor is not sufficient enough. Many other reasons could be present for this behavior of the IMU sensor and more analysis has to be done in the future to study the causes.

Figure 4.6 shows a zoomed-in plot of the change in the orientation angles for the IMU sensor and change in orientation angle of the control program. It can be seen that the change in the orientation angles from the control program show a periodic behavior whereas the change in the orientation angle obtained from the IMU sensor does not have a periodic behavior.

The RMS of the difference between the change in orientation angles from the IMU sensor and the change in orientation angle of the control program is around 0.29 radians (approximately 16 degrees). This indicates that there is a significant difference of the orientation angles that are computed from the control program and the orientation angles that are obtained from the IMU.
sensor. Also, from the orientation angles obtained using the control program, it can be seen that the accuracy requirement of the orientation angles that are required for the Kalman filter integration is approximately 0.3 degrees. More tests have to be conducted in future in order to study the performance of the IMU sensor.

5.6 Simulated PPP-IMU results

5.6.1 Test Scenario 7
During the term of this master thesis, it was not possible to integrate the IMU sensor and the control program in real time. This was due to the fact that the interface program that was developed in Labview environment in order to integrate the output from the IMU sensor with the control program could not function well on the laptop in which the control program was installed. The technical issues needs to be resolved for further integration tests in real-time mode.

In order to study the performance of the integration of the position coordinates of the truck from the BNC-PPP solution and the orientation angle from the IMU sensor, the simulation of the test drives were performed using the SSM module. The current algorithms that are used to compute the PPP solution in the BNC software can provide solutions only in the rate of 1 Hertz (that is 1 data every second) and hence the orientation angle from the IMU sensor was also assumed at the same data rate, in order to perform the simulation.

5.6.2 Analysis of test scenario 7
Table 4.4 presents the RMS of the lateral deviation for different settings of the simulated drives.

<table>
<thead>
<tr>
<th>Case</th>
<th>Velocity (cm/s)</th>
<th>Controller (P I D)</th>
<th>Kalman Filter</th>
<th>Orientation Angle Chosen</th>
<th>RMS Straight Line [cm]</th>
<th>RMS Clothoid [cm]</th>
<th>RMS Circle [cm]</th>
<th>RMS Mean [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4</td>
<td>12.3 - -</td>
<td>Yes</td>
<td>IMU</td>
<td>31.7</td>
<td>35.1</td>
<td>36.3</td>
<td>34.9</td>
</tr>
<tr>
<td>2</td>
<td>2.4</td>
<td>12.3 - -</td>
<td>Yes</td>
<td>average</td>
<td>34.4</td>
<td>31.7</td>
<td>32.7</td>
<td>32.9</td>
</tr>
<tr>
<td>3</td>
<td>2.4</td>
<td>25 0.5 0.001</td>
<td>Yes</td>
<td>IMU</td>
<td>32.1</td>
<td>35.2</td>
<td>36.5</td>
<td>34.6</td>
</tr>
<tr>
<td>4</td>
<td>2.4</td>
<td>25 0.5 0.001</td>
<td>Yes</td>
<td>average</td>
<td>24.5</td>
<td>23.9</td>
<td>17.1</td>
<td>21.8</td>
</tr>
</tbody>
</table>

The results obtained in table 4.4 show that:

1. Case 1 and 3 present the RMS of the lateral deviations obtained by the integration of the BNC-PPP coordinates and the IMU heading angles using P and PID controllers respectively.
2. Case 2 and 4 present the RMS of the lateral deviations using the P and PID controllers. The orientation angle is computed as a weighted average of the orientation angle from the IMU sensor and the orientation angle using the ‘Trajectory’ option. It can be seen from the table that the least deviation is obtained using the PID controller (RMS of lateral deviation
is 21.8 centimeters), but there is no significant improvement for the lateral deviation values when the Kalman filter is implemented. One of the main reasons for the same could be due to the fact that the orientation angles were simulated using the results of the RTK solution and not from the actual IMU sensor. Also, the data rate of the simulated readings was set to only 1 Hertz and hence all the changes in the orientation angles were not considered. Another reason for this behavior is the Kalman Filter algorithm that is used to integrate the sensors. The weights to be given to the sensors have to be analyzed further. More investigations using the real-test drives have to be made further in order to study the integration of sensors.

6. Conclusion and Outlook

The main aim of the thesis project was to implement the GNSS PPP (Precise Point Positioning) for the control and guidance of the IIGS out-door construction machine simulator. The control quality of the PPP solutions computed using the BNC software is compared with the control quality using the RTK solutions. The RMS of the lateral deviation for the RTK at 1 Hertz data rate is 1 cm at a velocity of 6.5 cm/sec, using the PID controller along with the Kalman filter and the orientation angle computed as a weighted average of the orientation angle computed from the measurements and the reference trajectory.

The BNC-PPP solutions were successfully implemented for the control and guidance of the construction machine simulator and the RMS of the lateral deviation is 35.4 centimeters. The RMS of the lateral deviation was improved to 20.8 centimeters using the PID controller and the Kalman filter algorithm, where the orientation angle is chosen as a weighted average of the orientations from the measurements and the reference trajectory. The analysis of the same has been presented in the earlier section.

The IMU (3DM-GX2) sensor from MicroStrain Inc was studied and test drives were made by mounting the IMU sensor on the truck and taking simultaneous readings of the orientation angles of both the IMU sensor and the control program. The analysis of the results shows that both the orientation angles show the same trend, whereas there are some jumps in the IMU sensor readings. A few reasons for this behavior have been presented earlier and the reasons have to be investigated in the future by performing more tests.

Some simulations were performed to study the integration of sensors. The RMS of the lateral deviation was obtained to 21.8 centimeters using the PID controller and computing the orientation angle as a weighted average of the orientation angle from the IMU sensor and the orientation angle computed from the reference trajectory. It is expected that the integration of sensors show an improvement of the lateral deviation values, but the test results show that there is no significant improvement, which can be mainly due to the fact that the orientation angles from the IMU sensor were simulated using the RTK measurements and the data rate was set as 1 Hertz. Another reason for the same could be due to the Kalman Filter algorithm that is used to integrate the sensors.
More analysis and test drives have to be done in the future in order to investigate this behavior further.

This thesis thus provides a lot of possibilities for further research work for the implementation of real-time Precise Point Positioning solutions for the control and guidance of the construction machine. Also, implementation of various sensors can provide more precise results, and more test drives in real-time can help to investigate the results obtained in this thesis work further. Another possibility that can be considered for the positioning using GNSS would be PPP-RTK, but it presents difficulties due to the data rate of the PPP solutions currently.

7. Bibliography


