EECE 5554 Robotics Sensing and Navigation

Lab 4 Navigation with IMU and Magnetometer

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Abstract

This lab is designed to perform a navigation with IMU and Magnetometer. The navigation process was performed by using a vehicle with IMU and GPS sensor mounted in the proper location. Two routes where data had been recorded are Ruggles station roundabout and a mini tour of Back Bay. This report will perform data plotting and analyzing.

Magnetometer Calibration

The data used for this section is when drove at Ruggles station roundabout. By plotting the raw magnetometer data for magnetic field x and magnetic field y the result is showed below.

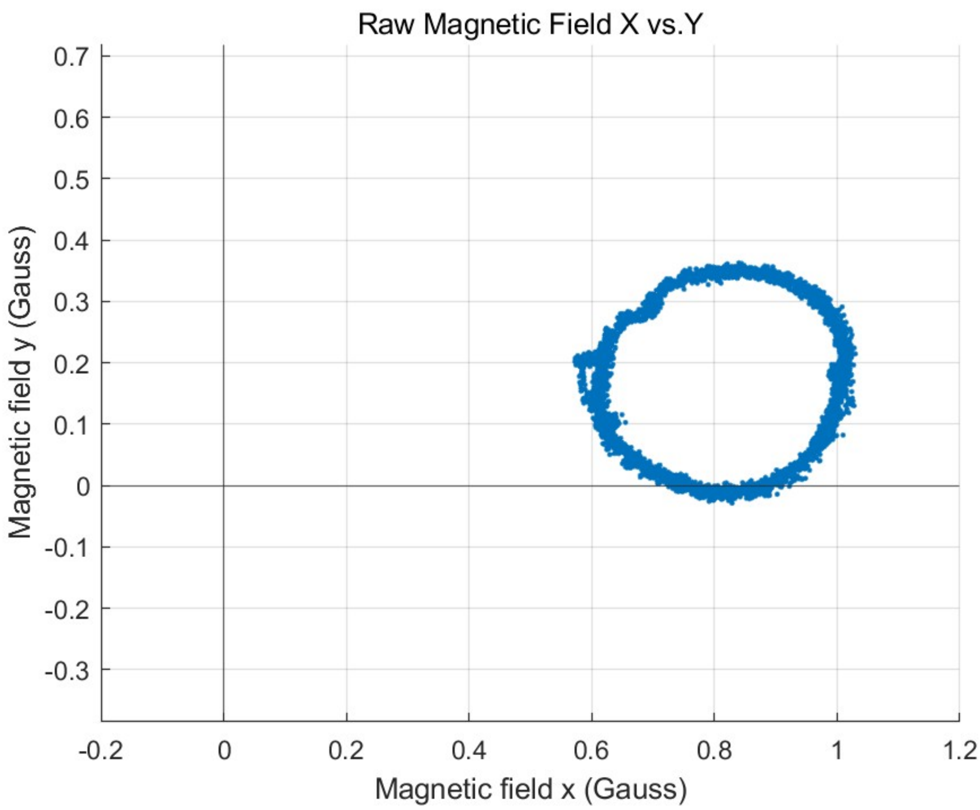

Figure 1. Raw Magnetic Field 2D Plot Before Calibration

From the background research of magnetometer hard-iron and soft-iron. If there was **no distortion** presented. The plot should **form a circle centered at the origin** $(\mathbf{0},\mathbf{0})$. **The radius of the circle equals the magnitude of the magnetic field.** [1] As for **hard-iron distortion.** The circle will **shift from the origin**, but the circle will stay perfect. The perfect here means the circle will not become an ellipse nor an oval. That is the case the hard-iron distortion present. [1] As for **hard-iron and soft-iron distortion**. The **circle will shift from the origin. Also, the circle will become an ellipse or an oval**. [1]

From the Figure 1. It is not hard to see that, the circle is not at the origin $(0,0)$. Also, by looking at figure 1, the circle left most point is close to 0.6 on x-axis, and right most point is close to 1 on x-axis. The span is around 0.4. However, the down most point is at 0 on the y-axis, the up most point is not reaching the 0.4. Therefore, the shape is more likely an ellipse. Therefore, **both hard-iron and soft-iron distortion presented**.

Method to Calibrate Magnetometer

The method to eliminate internal hard and soft iron distortion can be performed by the compensation model below:

$$m_c = S_I(\widetilde{m} - b_{HI})$$

Where m_c is compensated measurement, S_I is soft iron distortion matrix, $\widetilde{m}$ is measurement vector, and b_{HI} is hard iron bias. Expand model in matrix form is:

$$\begin{bmatrix} m_{c_x} \\ m_{c_y} \\ m_{c_z} \end{bmatrix} = \begin{bmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{bmatrix} \begin{bmatrix} \widetilde{m_x} - b_{H_0} \\ \widetilde{m_y} - b_{H_1} \\ \widetilde{m_z} - b_{H_2} \end{bmatrix}$$

Using `fit_ellipse` add-on library in MATLAB, this function takes magnetic field in x axis and y axis and generates a best-fit ellipse. From the calculated ellipse, the tilt angle $\theta = 0.2584\, rads$, hard iron distortion coefficients are `X0_in` and `Y0_in`, where $b_{H_0} = 0.8119, b_{H_1} = 0.1703$. After that, the compensation model becomes:

$$\begin{bmatrix} m_{c_x} \\ m_{c_y} \\ m_{c_z} \end{bmatrix} = \begin{bmatrix} \cos(0.2584) & \sin(0.2584) & 0 \\ -\sin(0.2584) & \cos(0.2584) & 0 \\ 0 & 0 & 1.0 \end{bmatrix} \begin{bmatrix} \widetilde{m_x} - 0.8119 \\ \widetilde{m_y} - 0.1703 \\ \widetilde{m_z} - 0 \end{bmatrix}$$

After calibration, the result is showed below:

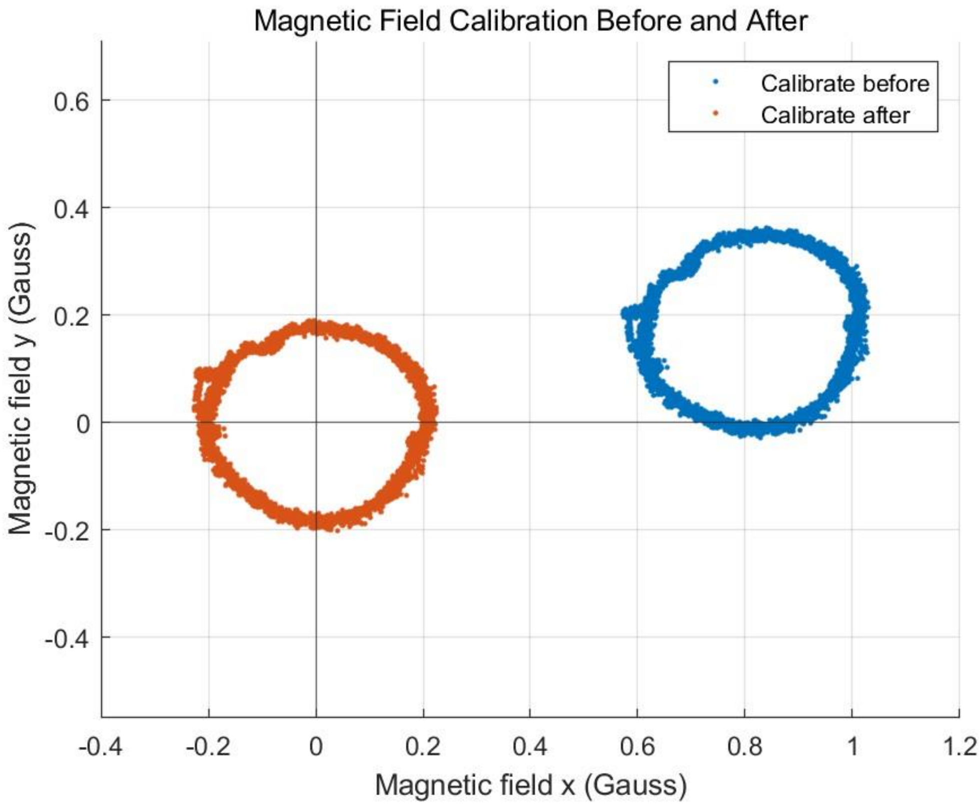

Figure 2. Magnetic Field Calibration Before and After

After calibration the result is showed in figure 2, the circle is centered at origin and looks more like a perfect circle. Which means, the hard iron and soft iron distortion have been eliminated.

Sensor Fusion

For this part, the data is from mini tour of Back Bay. The first plot in this section shows the raw magnetic field yaw and calibrated magnetic field yaw.

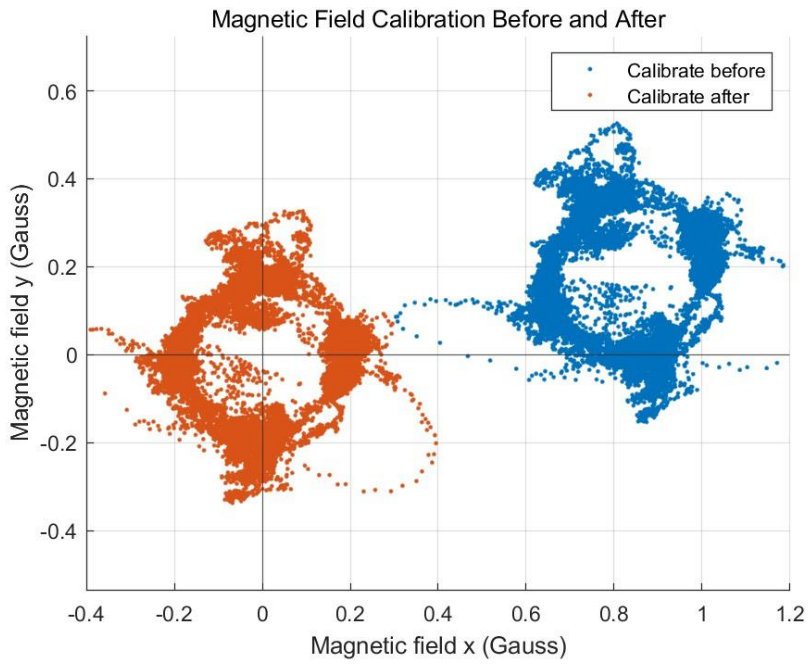

Figure 3. Driving Data Magnetic Field Calibration Before and After

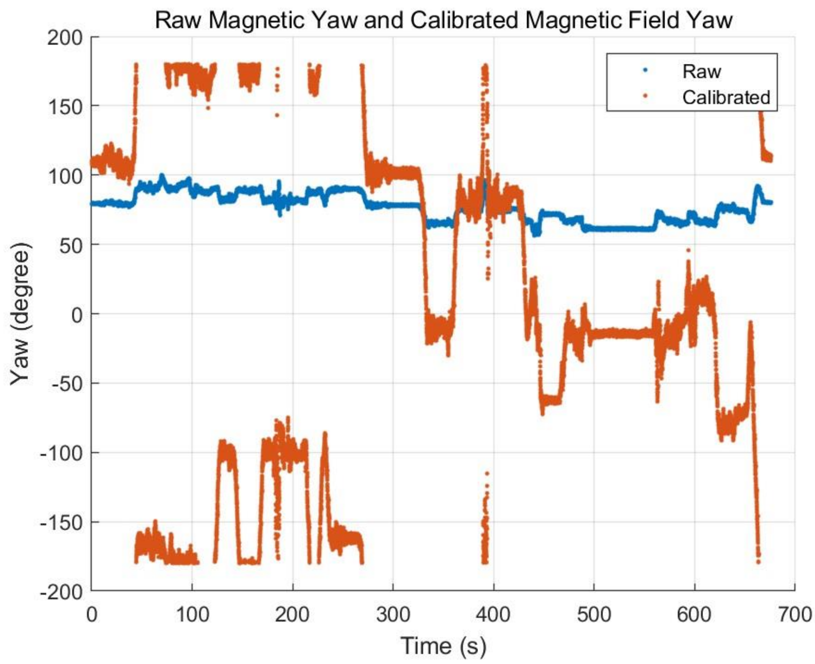

Figure 4. Driving Data Magnetic Field Calibration Before and After with Time

From now on, only calibrated magnetic field yaw will be used for further analysis. From previous process, the magnetic field distortion hard iron and soft iron have been eliminated. The further external magnetic influence could be resolved by applying a low pass filter. The disadvantage of this method is that this will delay the measurements. An alternative method is to use magnetometer and the gyro scope. Although, the gyro scope will also have internal noise. By using gyro scope and magnetometer together, these two sensors can calibrate each other. Consider a situation where magnetometer picks up a turning signal in magnetic field, the gyro scope can use to determine whether this is an actual physical phenomenon happened or it is a sensor noise. By doing the integration of the angular velocity reading from the gyro scope this will provide another estimation of the yaw result. The integration process is doing the job as a high pass filter. And the inverse tangent process is like a low pass filter. Combining two filter together, a complementary filter formed. The alpha value also known as cut-off frequency has been selected to 0.03. After doing the complementary filter II. The result is showed below. [2]

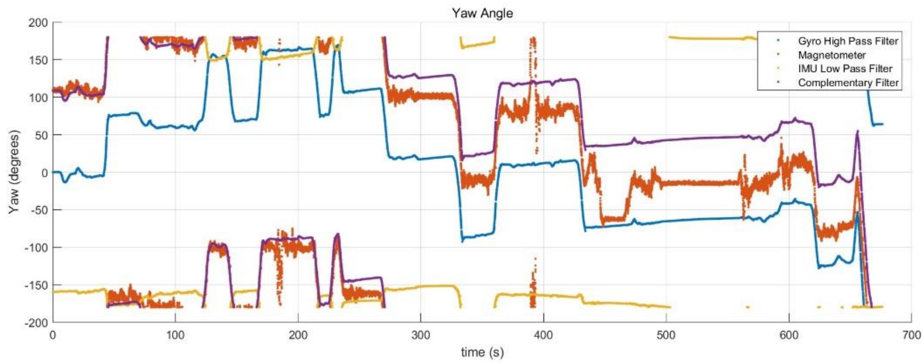

Figure 5. Yaw Angle Estimation

By observing the figure 5. It can tell that an IMU navigation is using complementary filter and sensors are calibrating with each other to eliminate some noise and give a better outcome. In fact, by doing the research, the IMU is using Kalman Filter commonly to eliminate distortions. It works similarly as complementary filter proceeded in this lab. [3]

Estimate the Forward Velocity

In this lab, the IMU is mounted on the vehicle with x direction facing forward. Therefore, the linear acceleration in x direction has been analyzed. Here is the raw forward acceleration plot from IMU.

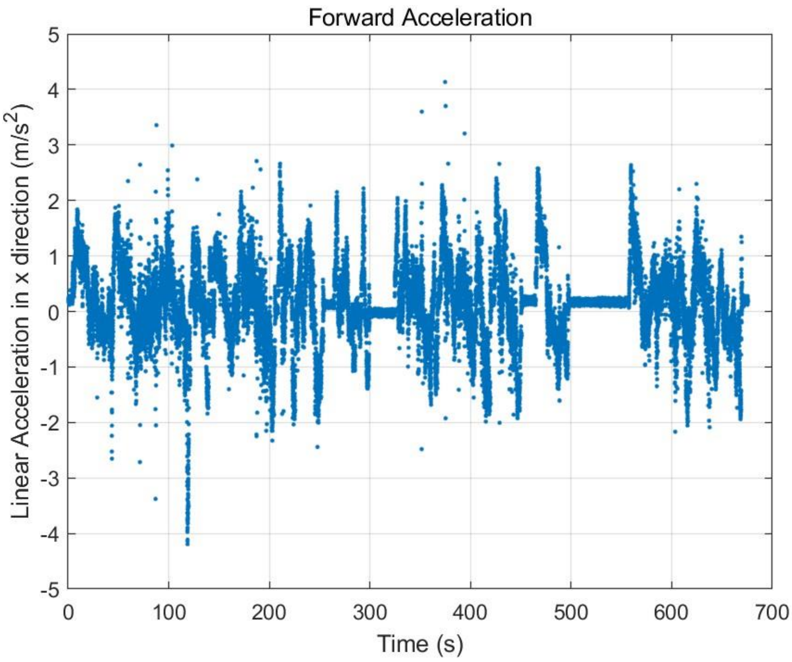

Figure 6. Forward Acceleration

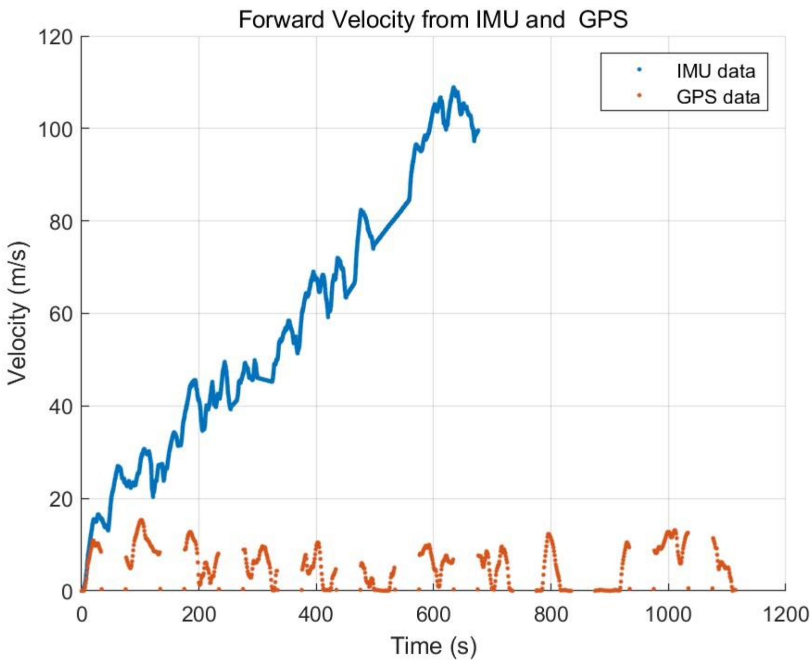

Figure 7. Raw Forward Velocity from IMU and GPS

Before calibration, the raw IMU velocity and GPS velocity are very hard to match with each other. Here because of the unit conversion issue with GPS header timestamp, there exist a mismatch between IMU time and GPS time.

Two calibrate IMU velocity, the vehicle is not accelerated at all time. At some point, the vehicle is stopped at red light, the vehicle is stopped for crossing, these data should all be subtracted from the raw data. Therefore, if the vehicle is not made an actual physical move, these data points will be set to zero. Besides, some noises are caused by unwanted bumping can also be smoothed out. After calibration, the forward velocity plot is displayed below. IMU plot is more reasonable.

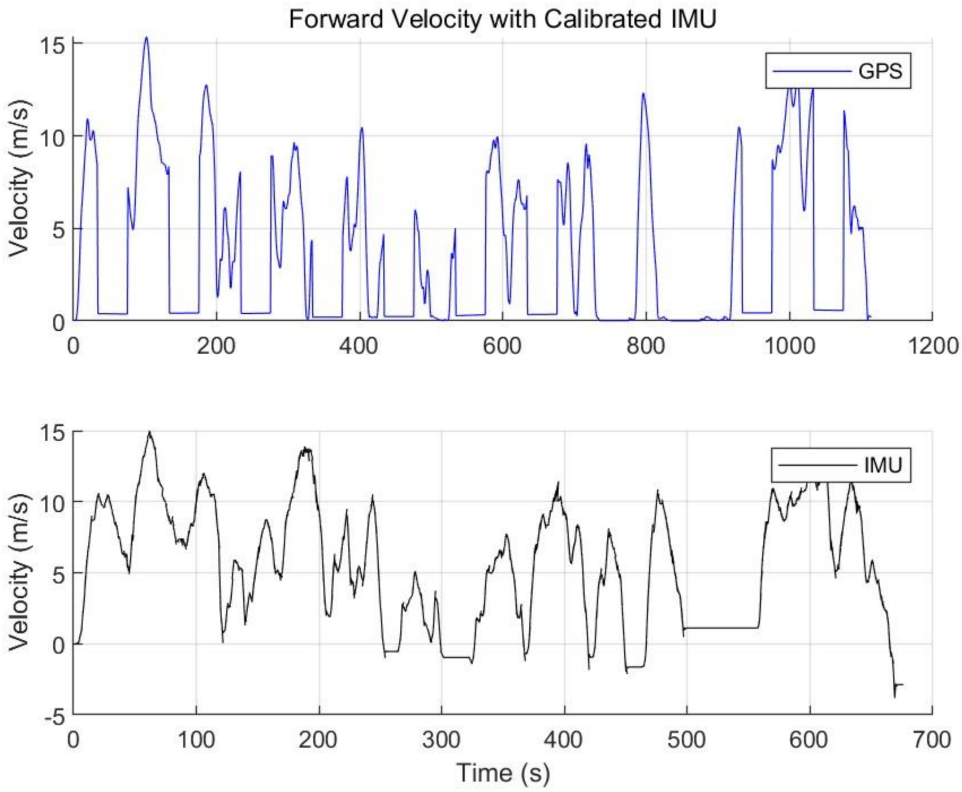

Figure 8. Calibrated Forward Velocity with IMU and GPS

Dead Reckoning with IMU

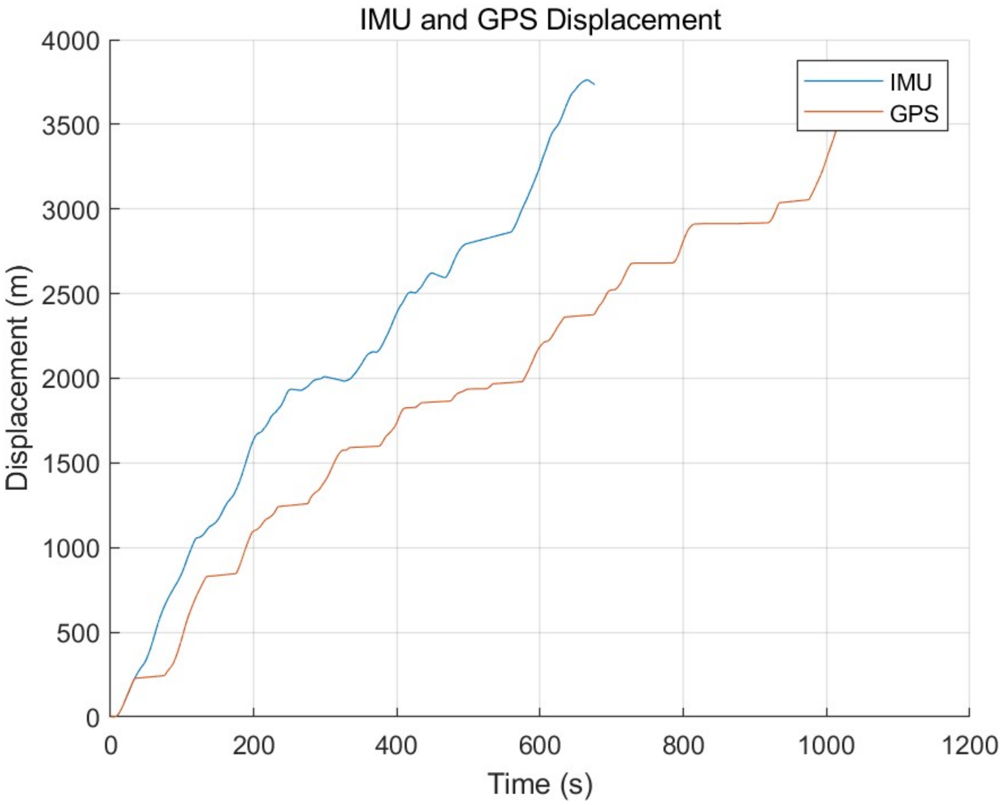

Figure 9. Calculated IMU and GPS Displacement along Time

The result here is calculated by taking integration further on the velocity. There are some issues with the timestamp header due to the unit conversion, but the total displacement is the same. The IMU plot is going up quickly compared to the GPS line. Because by doing the integration have a chance to make the bias larger.

The assumption is that the vehicle is driving in a 2-dimensional plane. The equation used for this part is mentioned in the lab instruction.

$$\ddot{x}_{obs} = \ddot{X} - \omega\dot{Y} - \omega^2 x_c$$
$$\ddot{y}_{obs} = \ddot{Y} - \omega\dot{X} - \dot{\omega} x_c$$

With assume the vehicle did not drift and without any other external influences. The observation through forward acceleration from IMU is similar to the actual forward acceleration of vehicle. Here is the plot for the forward velocity which calculated before and multiply the yaw angle from gyro sensor compared to the acceleration measured from the IMU.

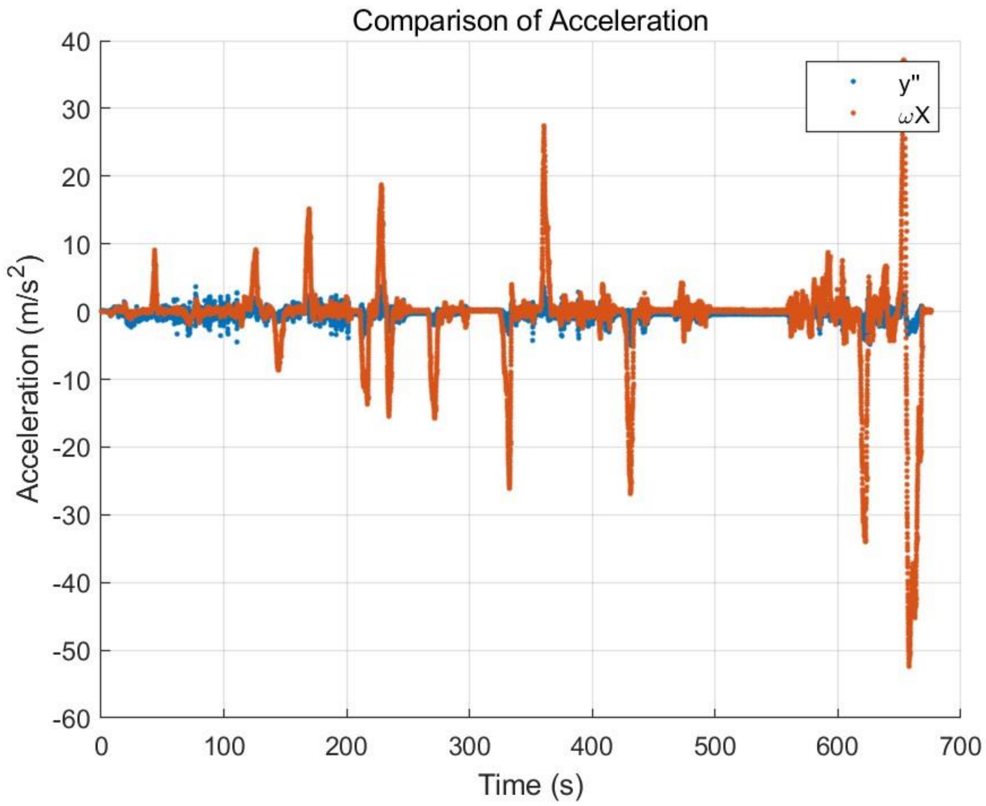

Figure 10. Acceleration Comparison

From the figure 10, it is not hard to see they fit with each other at edge cases. The difference between them is the gyro scope measures bias in the lateral acceleration. By using the magnetometer, the forward velocity can be divided into northing and easting. By taking the integration, this can provide a global position that can use to compare with the GPS.

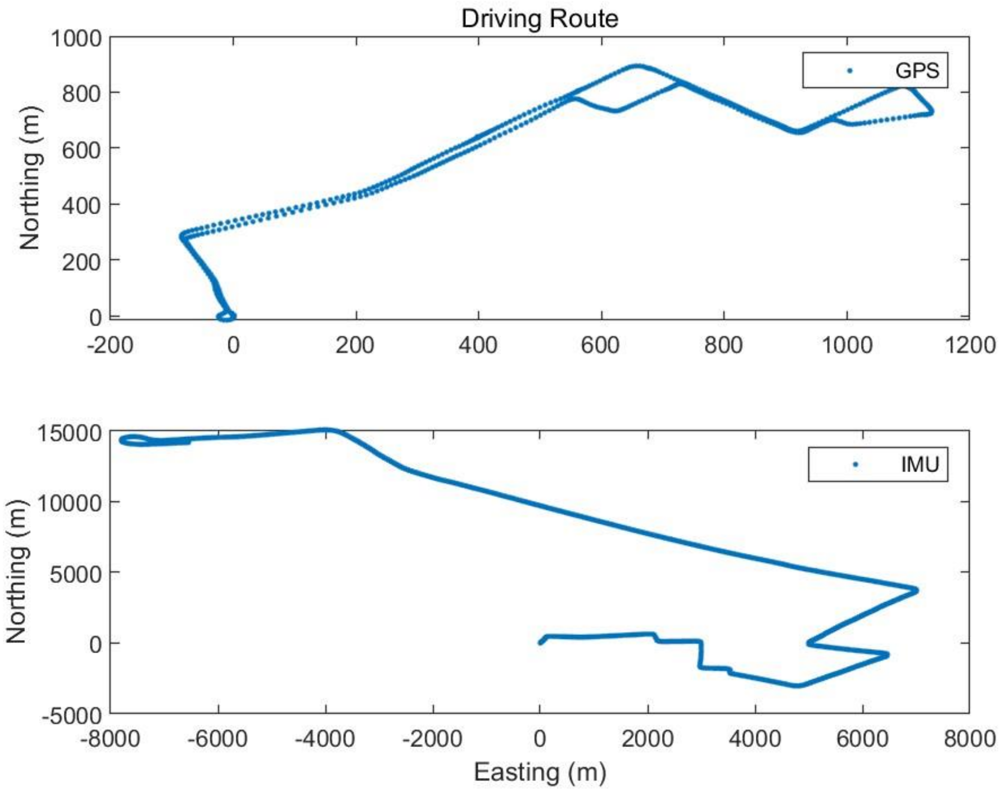

Figure 11. Driving Route IMU and GPS

Two routes seem inversed, but the route have some similarities. It is not hard to see that IMU have some different route than GPS. Where GPS is always updating its global position. Due to the slow motion, the IMU is not necessarily needed to do with accuracy. Because the GPS is updating every second. And it contains information more dynamic. The IMU however, can fill up the blank between second to second.

Estimation of IMU Offset

From previous equations,

$$\ddot{x}_{obs} = \ddot{X} - \omega\dot{Y} - \omega^2 x_c$$
$$\ddot{y}_{obs} = \ddot{Y} - \omega\dot{X} - \dot{\omega} x_c$$

Where x_c is the offset from the center mass of the vehicle. The $\ddot{Y}$ is 0 based on the assumption there is no lateral sliding occurred during the experiment. Using the result that calculated in the previous section, yaw, forward velocity, and yaw acceleration, it is possible to estimate the IMU offset. The calculated sensor offset from MATLAB using the `linsolve` function, the result is -0.9312.

Reference

[1] VECTORNAV, 3.6 Magnetometer Hard & Soft Iron Calibration
https://www.vectornav.com/resources/inertial-navigation-primer/specifications--and--error-budgets/specs-hsicalibration
[2] Lecture PowerPoint, Dead Reckoning & IMU Sensors
[3] Analog Dialogue, Kalman or FIR Filter for my IMU
https://www.analog.com/en/analog-dialogue/raqs/raq-issue-127.html