ECE 167 Sensing and Sensor Technologies

Lab #3: 3D Sensor Calibration

February 28, 2024

Final Check-off: 2/27/24

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I. Overview

This lab aims to familiarize us with a 9-DOF IMU sensor, specifically the BNO055 module, emphasizing calibration techniques to mitigate scale factor and bias errors. We used linear algebra methods to calibrate the accelerometer, magnetometer, and gyroscope, addressing imperfections such as biases, scale factors, and noise. The focus includes a 2D ellipsoid calibration using simulated data, followed by naive 3D calibration for accelerometer and magnetometer. We also analyzed gyroscope bias and drift, and calibrated scale factors through manual simulation. The last portion involved a real tumble test, collecting data for training and validation sets, and applying iterative calibration methods. The lab offers practical insights into overcoming challenges in low-cost IMU sensors, enhancing our understanding of calibration procedures for accurate motion and orientation measurements.

II. Wiring and Diagrams

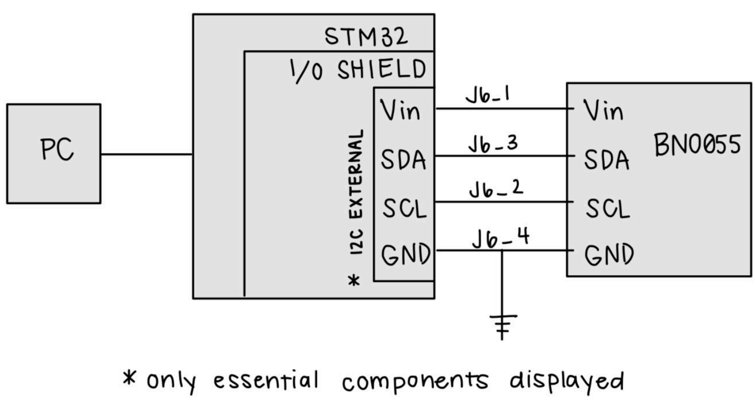


Figure 1. BNO055 Wiring to System

III. Project Design

Part 1: 2D Ellipsoid Calibration using Simulated Data

The estimate of the parameters, x_0, y_0, a, and b, is obtained from least squares. The least squares for $Az = b$ where

$$A = \begin{bmatrix} & \vdots & \vdots & \\ x_i & y_i^2 & y_i & 1 \\ & \vdots & \vdots & \end{bmatrix} \qquad b = \begin{bmatrix} -x_i^2 \\ \vdots \\ -x_n^2 \end{bmatrix} \tag{1}$$

The resulting matrix is

$$Z = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} = \begin{bmatrix} -2x_0 \\ a^2/b^2 \\ (-2a^2/b^2)y_0 \\ x_0^2 + (a^2/b^2)y_0^2 - a^2R^2 \end{bmatrix} \tag{2}$$

Once I obtained the resulting Z matrix and solved for an estimate of the parameters, I could use these to determine the calibrated $\hat{x}$ and $\hat{y}$ values. The calibrated values were derived from the relationships in Eq. 3, 4.

$$\hat{x} = \frac{1}{a}(x - x_0) \qquad (3) \qquad\qquad \hat{y} = \frac{1}{b}(y - y_0) \qquad (4)$$

Once I obtained the calibrated values, I plotted them against the original data to see how the data was calibrated from an ellipse to a circle with an apparent origin at (0, 0).

Part 2: Naive 3D Calibration of Accelerometer and Magnetometer

To start calibrating the accelerometer, first I started measuring raw data of each axis in their orientation. To minimize the effect of noise, I sampled for 60 seconds which resulted in about 500 samples. Using least squares I was able to extract both scale factor and bias for each axis.

I used the same method to calibrate the magnetometer with a few modifications. Since the magnetic field is not perfectly aligned, I rotated the sensor until the axis' that was not being measured read close to 0. In my case, the origin value I chose was 200 so that I could obtain a more varied reading since the values for some of the axis' never went close to 0. To reduce the noise I measured for the same amount of time as before. To calibrate the magnetometer, I used the average of the minimum and maximum readings of each axis and using least squares I calculated the scale factor and bias values.

Part 3: Gyroscope

The gyroscope in the BN0555 measures the body-fixed rotation rate, but the bias and drift rate in our gyroscopes is larger and faster.

3.1 Bias and Bias Drift

First I took a 10 second reading of the gyroscope laying flat and averaged the reading to obtain an initial estimate of the bias for each axis. Next, came a 10 minute reading. The hour reading was not possible due to complications with CoolTerms platform but 10 minutes was deemed sufficient. To get an initial estimate of the biases for the 10 minute reading I used least squares. The next part was plotting the bias over time. This involved creating an array for the time axis which consisted in determining how often it sampled and how many samples there were. The bias was calculated using cumulative trapezoidal numerical integration on the axis with biases subtracted from them with respect to time. From the plot we can visualize how the drift values increased with time.

3.2 Gyroscope Scale Factor via Angle Integration

For this portion I used the same biases obtained from the initial 10 second reading. The bias was subtracted from the gyroscope readings. The initial scale estimate obtained using least squares on the 10 minute reading from part 3.1, was used as a scale factor for each axis. After testing how the scale and bias performed, I adjusted the scale factor until the angles printed coincided with the angle the sensor was turned. The calibration changes depending on where and when it's measured so it had to be adjusted accordingly.

Part 4: Tumble Test

4.1 Simulation

For this first portion of the tumble test, the data to be processed would be randomly generated. This was done with the help of CreateTumbleData function using the command $[A, M, Ad, Bd] \ = \ CreateTumbleData(1000);$. Once I had obtained the fake tumble data, I converted it into engineering units by creating two scale factors. The first one for the accelerometer converted from g’s to bits by and the other scale factor was for the magnetometer and was to scale μT/bits since earth's magnetic field is measured in micro Teslas according to the data sheet.

Once the data was scaled, it was split up into each x, y, and z component for both the accelerometer and magnetometer readings. The first step was to calibrate the 3D elliptical data from sensors using the iterated least squares matrix method using the provided function CalibrateEllipsoidData3D. After the calibration, I corrected data using the CorrectEllipsoidData3D with the parameters of the scale and bias obtained from the calibration.

Lastly I was able to plot the newly calibrated and corrected data along with the previously scaled data. The results of these are in the Testing & Results section.

4.2 Real Tumble Test for Accelerometer and Magnetometer

Now that I had practiced calibrating and correcting the data I could move on to the real tumble test. From previous data collections, I knew that one minute of data gathering was equivalent to an average of 500 data points. To collect about 1000, I tumbled the sensor for about two minutes. I used this data and passed it through the same algorithm as the one used for the simulated data. First was the scaling of the data then correcting it. Once that was done I could plot the data to compare the pre-calibrated and post-calibrated data.

IV. Testing & Results

Part 1: 2D Ellipsoid Calibration using Simulated Data

After using least squares and deriving the parameters from the resulting matrix, I could use those to calibrate the measured x and y values. This calibration resulted in the original data that formed an ellipse now forming a circle centered about (0, 0) as can be observed in Fig. 2. The radius now corresponds to R=1.

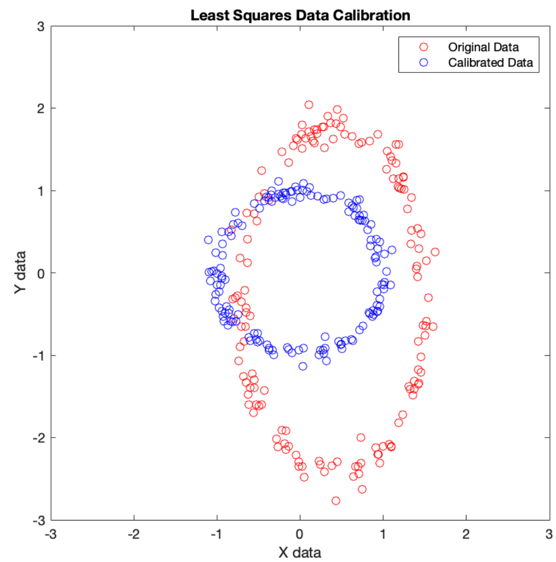


Figure 2. The 2-norm of the Pre-Calibrated and Post-Calibrated Simulated Data

Part 2: Naive 3D Calibration of Accelerometer and Magnetometer

After measuring the specific force on each axis, I was able to obtain the scale and bias using least squares. The results of this are in Table 1 where the scale factor remained the same but the bias changed for each axis.

Table 1. Scale and Bias of Accelerometer Reading

	X-axis	Y-axis	Z-axis
Scale	0.0010	0.0010	0.0010
Bias	-0.0134	0.0879	0.0091

The calibration of the Magnetometer was done in a similar fashion. The data at the maximal value at each axis while keeping the others at a set low value was taken for one minute which resulted in an average of 500 samples for each axis. After taking the average of each maximal and minimal reading, least squares were used to determine the scale and bias shown in Table 2.

Table 2. Scale and Bias of Magnetometer Reading

	X-axis	Y-axis	Z-axis
Scale	0.0018	0.0017	0.0017
Bias	-0.8823	-0.4828	-0.8729

Part 3: Gyroscope

3.1 Bias and Bias Drift

This portion involved taking two samples of the gyroscope readings. The first reading took 10 seconds of samples. From this I obtained the bias values from the average of the reading for each axis. This resulted in a bias of -17.5784 for the x-axis, -3.3431 for the y-axis, and 5.8725 as the bias for the z-axis.

The next reading took 10 minutes of samples and using least squares on the average of the readings I obtained the scale factor and bias for each axis. This was important since the bias changes over time. The scale and bias for all three axes was 0.0039 and 0.0020 respectively.

After subtracting each bias obtained from the 10 second reading from the 10 minute reading, the values along with a time array could be used to plot the gyroscope bias over time as can be seen in Fig. 3. This shows how much the bias drifted with respect to time.

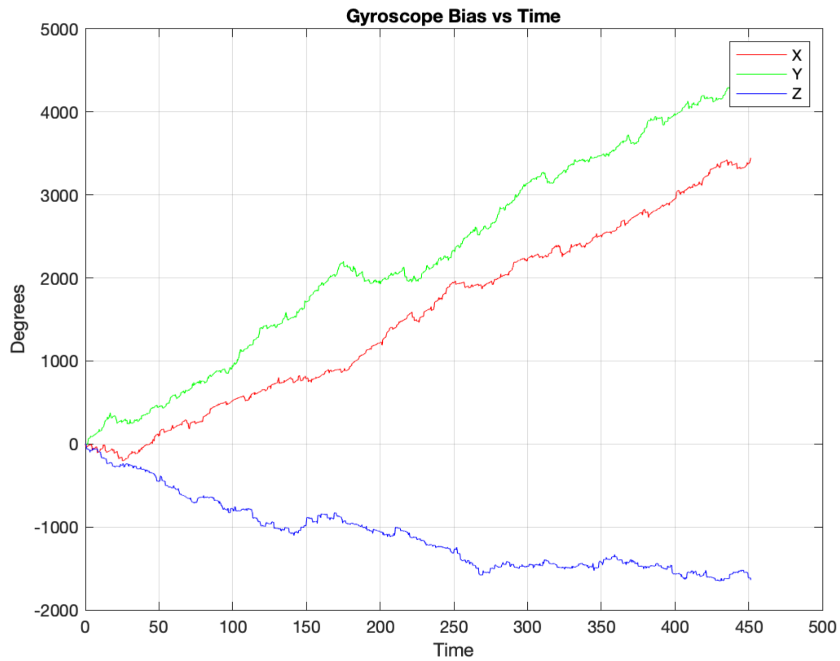


Figure 3. Gyroscope Bias over Time

3.2 Gyroscope Scale Factor via Angle Integration

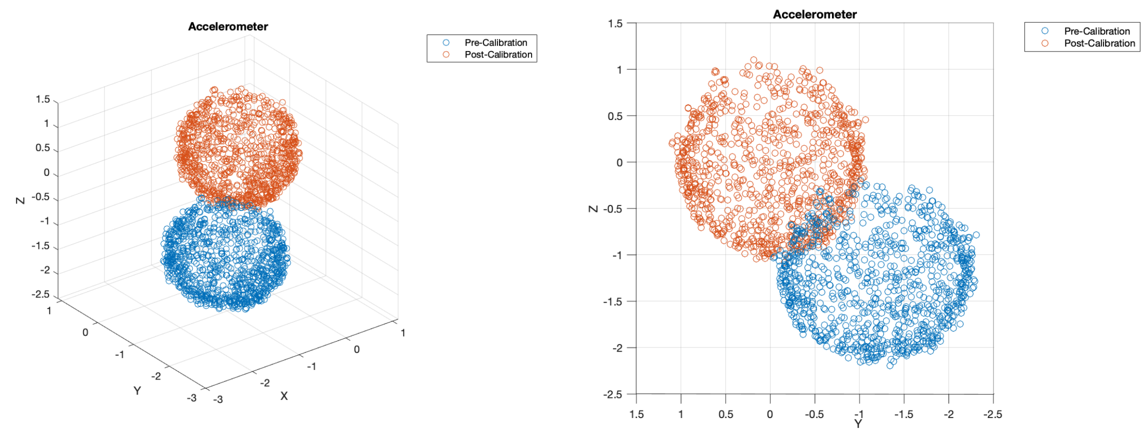
Instead of using a rate table, I used the 10 second reading I had previously taken and used the biases previously calculated. The new calibrated axis readings will be based on y = mx+b where y is the calibrated reading, m is the scale factor, x is the measured reading and b is the bias value. The scale factor was modified using the raw reading at 90 degrees to scale the reading even further. Each calibrated value was then scaled by 0.01 to more legible reading.

Part 4: Tumble Test

4.1 Simulation

Once I had calibrated and corrected the randomly generated fake data, I could plot both the scaled data and the newly calibrated and corrected data to compare. Fig. 4 corresponds to the data generated for the accelerometer. We can observe that the pre-calibrated data is not centered around the origin (0, 0, 0). From Fig. 4(b) which is a centered view of the clouds on the a Z and

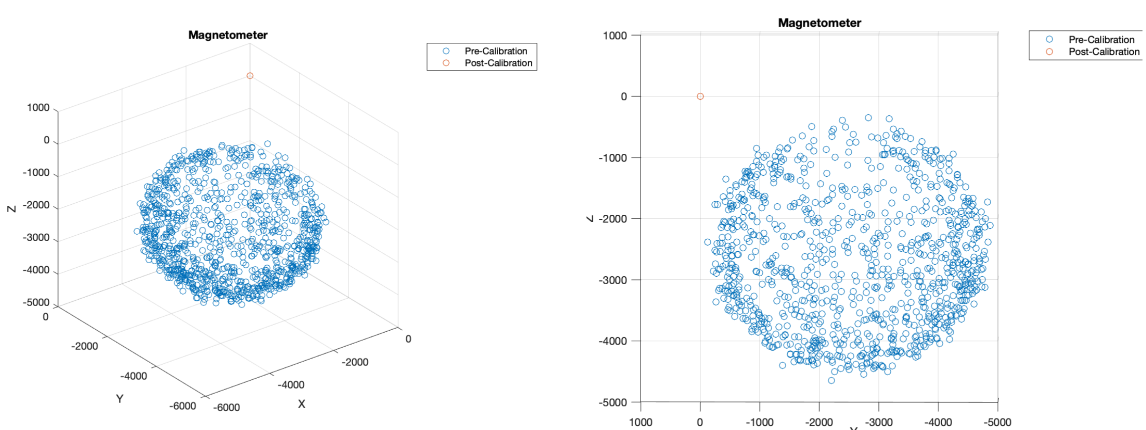
X axis, we can observe that the post-calibrated data is centered around the origin. The data centered around the origin means that the data was corrected and calibrated correctly.



(a) Data clouds showing three axis (b) Data showing two axis

Figure 4. Accelerometer Data Clouds

The same calibration and correction was applied to the magnetometer data which generated the clouds in Fig. 5. The pre-calibration cloud becomes a point at (0, 0, 0) once it is calibrated and corrected.



(b) Data clouds showing three axis (b) Data showing two axis

Figure 4. Accelerometer Data Clouds

4.2 Real Tumble Test for Accelerometer and Magnetometer

Once I had collected all the data I was able to calibrate the sensor readings. This was done using the same method as for the simulation using the same algorithm of calibrating and correcting the data. This generated the calibrated data clouds for magnetometer in Fig. 5 and accelerometer in Fig. 6.

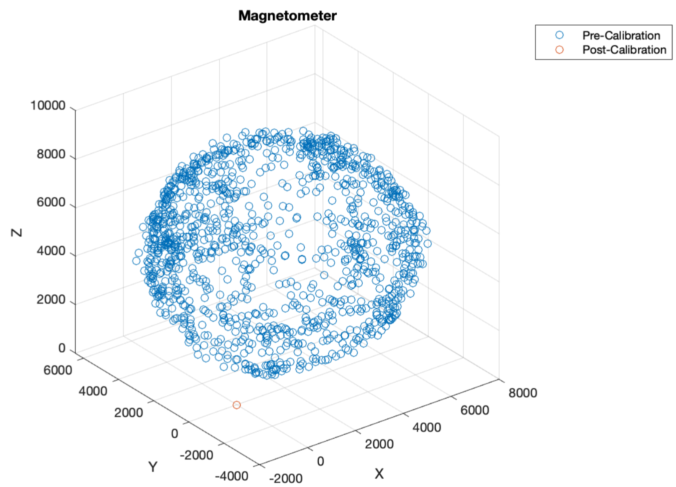


Figure 5. Magnetometer Data Clouds from Tumble Test

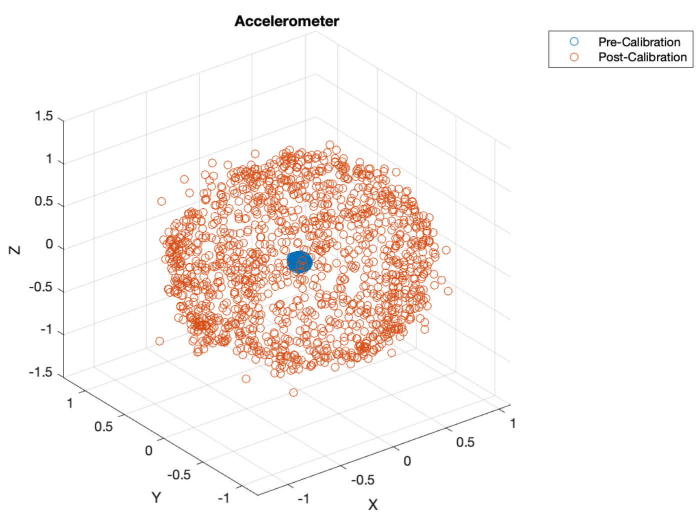


Figure 5. Accelerometer Data Clouds from Tumble Test

V. Conclusion

In conclusion, the 3D Sensor Calibration lab provided valuable hands-on experience in understanding and mitigating errors associated with a 9-DOF IMU sensor, specifically the BNO055 module. Through some calibration techniques employing linear algebra methods, I addressed biases, scale factors, and noise in the accelerometer, magnetometer, and gyroscope. The 2D ellipsoid calibration using simulated data demonstrated successful transformation from an imperfect ellipse to a calibrated circle. Naive 3D calibration for the accelerometer and magnetometer involved least squares to obtain scale factors and biases, to increase the precision of measurements. The gyroscope analysis revealed the impact of biases and drift over time, necessitating careful calibration for accurate readings. The tumble test, both in simulation and real-world scenarios, proved the effectiveness of iterative calibration methods in correcting sensor data, ensuring accurate and reliable motion and orientation measurements. Overall, the lab offered practical insights into the complexities of IMU sensor calibration, enriching our understanding of sensor technologies and their applications.