Digital Compass Accuracy

Lindsey Hines, University of St. Thomas
Mentor: Dr. James Bellingham
Summer 2007

Keywords: digital compass, Microstrain, tilt measurement error

ABSTRACT

The overall goal of the ongoing project is to assess the accuracy of three digital compasses: the Sparton SP3003D, Microstrain 3DM-GX1, and OceanServer OS5500-S. Compasses can be affected by many different factors, but the scope of work during the summer of 2007 was to initiate the project and to begin an evaluation of pitch errors for the Microstrain compass. A testing rig was built in which the compass was rotated through 360 degrees at various pitch angles. Heading was calculated from magnetic field strength, roll, and pitch compass outputs and compared to actual heading as determined by an encoder. While problems were encountered during the testing process, including environmental noise and some repeatability issues, the rig and testing procedure was shown to be adequate in displaying compass pitch errors.

INTRODUCTION

Digital compasses play a vital role in autonomous vehicles. They can not only determine bearing, but when used as an element for dead reckoning, can determine location. Placement in a vehicle, however, exposes compasses to a variety of hard to quantify influences. Digital compasses are subject to hard and soft iron errors, acceleration errors, and severe inclinations, which can affect a heading calculation and increase error. In the field, if something goes wrong, it can be difficult to determine what has happened; by testing compass accuracy in a lab one can better understand the limitations of a given device.

The goal of this project is to asses the accuracy of three digital compasses, the Sparton SP3003D, Microstrain 3DM-GX1, and OceanServer OS5500-S. The Microstrain compass is presently in use in MBARI vehicles today. Of the three compasses to test and compare it is the most expensive and consumes the most power. However, it has certain additional features, like gyroscopic stabilization, that give it the potential to be most accurate overall. This needs to be verified; perhaps a cheaper and less power hungry compass will do the same job adequately.

Compass errors due to tilt measurement, even without considering any other factors, can be quite significant. Depending upon geographical location and inclination of the compass, a tilt measurement can have a varying effect on heading accuracy. In California, where the earth's magnetic field has an inclination of around 60 degrees downward, even if compass is level, if pitch is measured with an error of one degree, a maximum heading error of 1.8 degrees is possible. Figure 1 below demonstrates heading error with various pitch measurement errors.

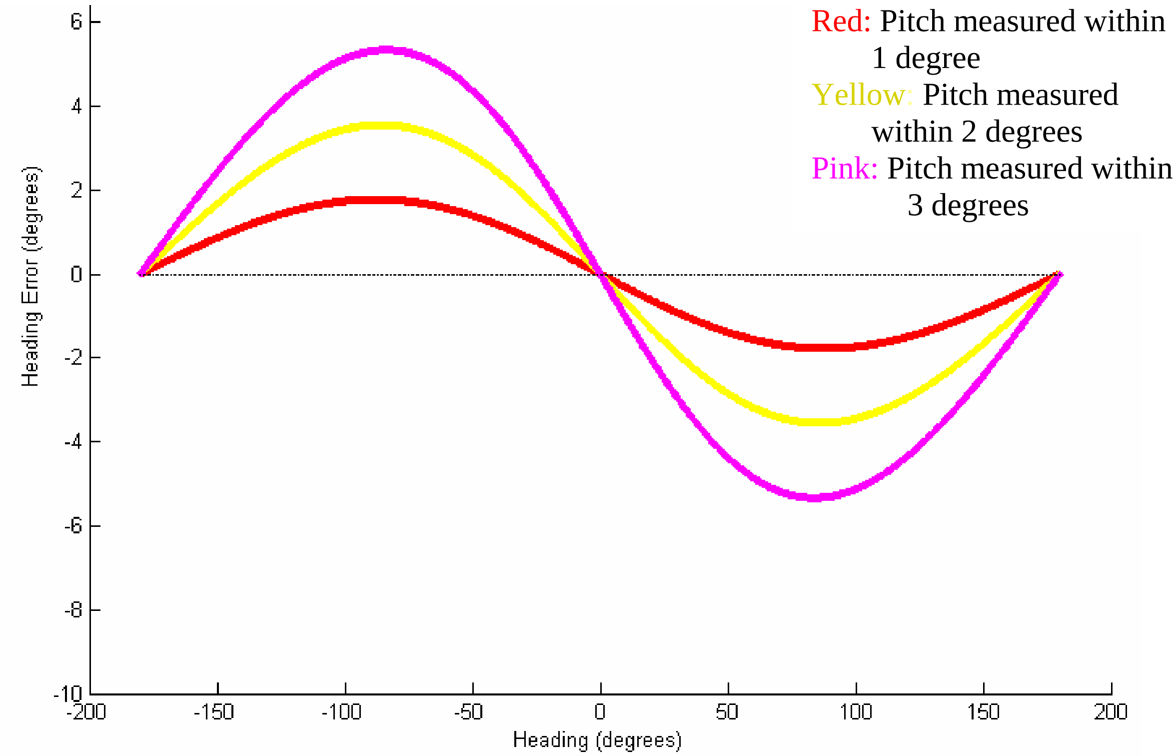


Figure 1: This plot demonstrates heading error due to three different pitch measurement accuracies. This assumes the compass is horizontal and the earth's magnetic field has a inclination of 60 degrees downward. Heading error varies with both orientation and tilt measurement accuracy.

While there are many different elements that can affect compass accuracy, work during the summer of 2007 focused on heading error related to pitch and roll measurement. A testing rig was designed and constructed for the purpose of rotating the compass around 360 degrees at various pitch angles while collecting and recording data. Heading error was calculated from magnetic field, roll, and pitch compass outputs. Testing could not be completed due to time constraints and noise issues in the testing space, but the data gathered demonstrated the ability of the rig and testing procedure to show compass heading errors due to errors in tilt measurement.

MATERIALS AND METHODS

EQUIPMENT / TESTING SETUP

The equipment used is as follows:

- H5D US Digital Incremental Encoder
- PCI-3E US Digital PC Interface card
- IoTech DaqBook 2005
- Bartington *Mag*-03MC Magnetometer
- Bartington MAG-03PSU Power Supply
- Microstrain 3DM-GX1 Digital Compass
- Computer with XP OS
- 12 Volt Battery

The software used is as follows:

- LabVIEW 6.1
- MATLAB 7.0.4

The equipment was connected as displayed below in Figure 2.

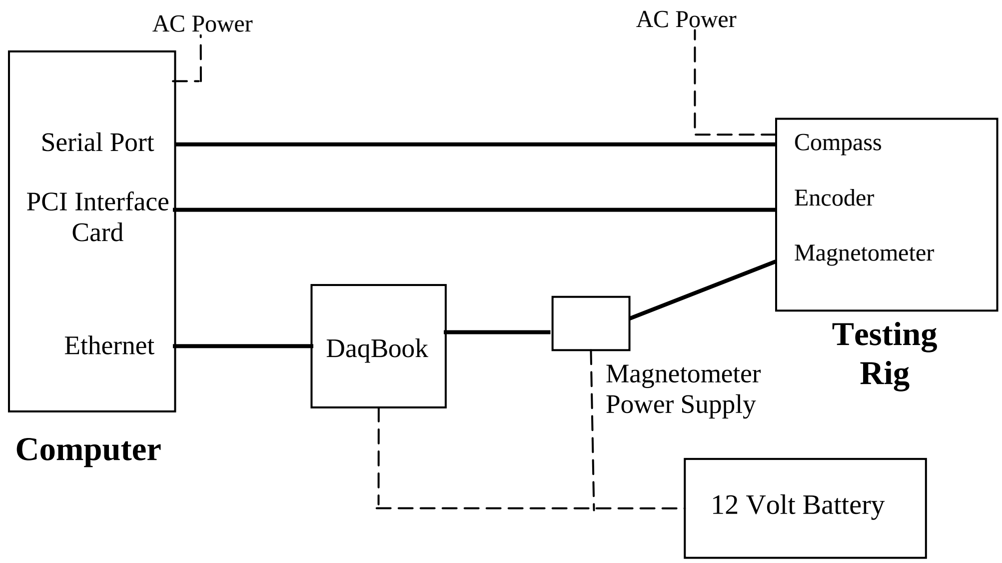


Figure 2: The equipment was connected to both the computer and various power supplies.

While the diagram above shows both the compass and magnetometer on the rig, they were not attached to the rig and tested at the same time because of interference issues.

The equipment mentioned includes an incremental encoder; the presence of an index, and the ability to reset count number to the index, allowed determination of position even between runs or power disconnects. An absolute encoder was not necessary. The encoder had 1250 CPR and the option of x4 quadrature, which was used. This allowed a resolution of 0.72 degrees.

TESTING RIG

A simple and inexpensive design was implemented in order to perform compass testing. The testing rig was constructed of nonferrous materials gathered from the machine shop scrap pile. Parts were cut with the water jet and fastened together with brass bolts. The fully constructed rig involved a rotating platform fastened to a lifted base, an adapter plate for consistent compass and magnetometer mounting, and eight different inclined blocks to induce a range of pitch and roll values for the compass. Figure 3 below shows the constructed rig during testing.

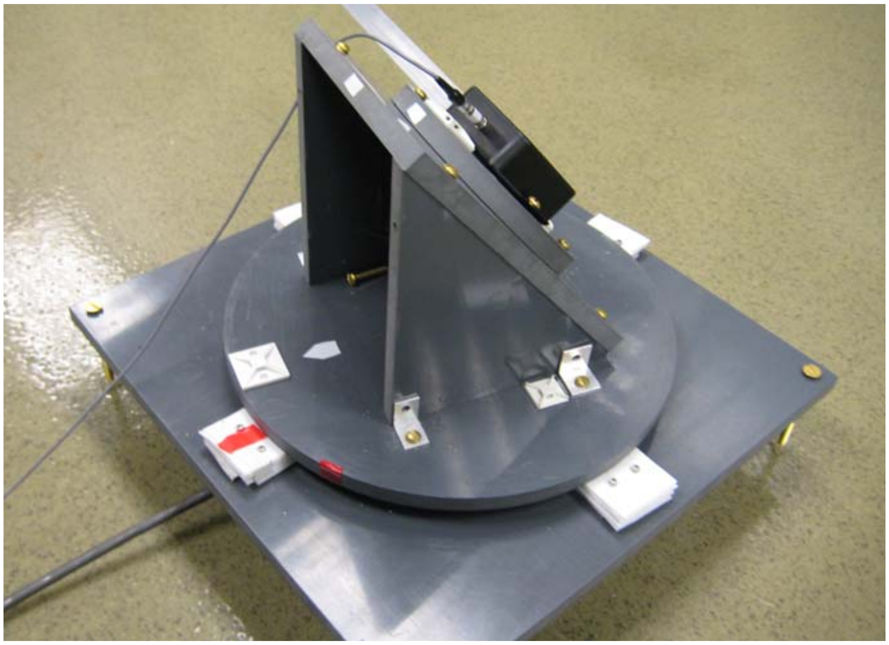


Figure 3: Constructed testing rig during experimental run.

DATA COLLECTION

LabVIEW programs, modified from code provided with the DaqBook, encoder, and Microstrain compass, were used to sample and write data collected during testing to separate files. Writing sampled data to single file would have been preferable, but time stamping the data served to allow syncing encoder data to magnetometer and compass data later. A desktop computer was required to collect the data because a PCI interface card was required for the encoder. Data from the Microstrain was read through a serial port while the DaqBook, the acquisition system for the magnetometer, was connected through Ethernet.

EXPERIMENTAL PROCEDURE

An extended experimental procedure is attached as number 1 in the Appendix. A short overview of the testing procedure is as follows:

1. Verify environment and rig with by testing for noise and slip in rotating joint.
2. Attach compass to inclined block and collect magnetic field, roll, pitch, and yaw data over three revolutions.

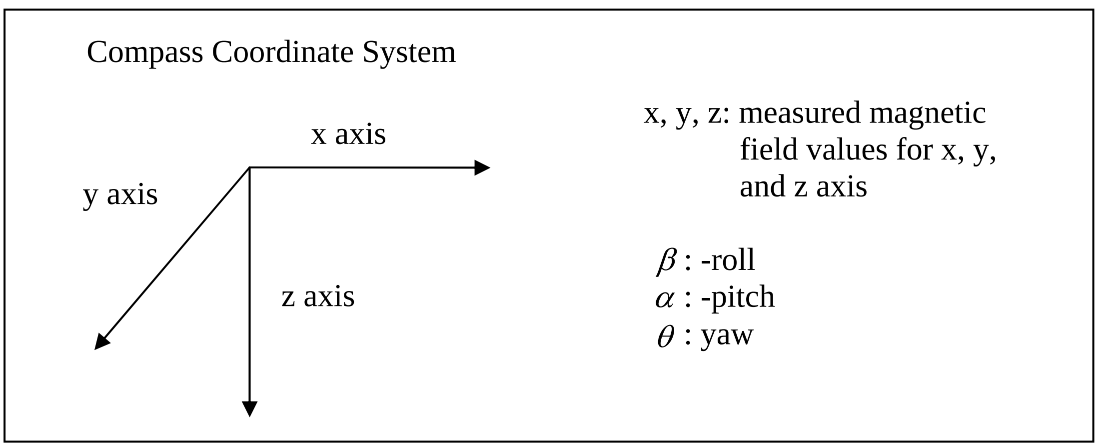
3. Remove compass and attach magnetometer to block and collect magnetic field data over three revolutions.
4. Repeat data collecting with compass and magnetometer attached to different blocks to induce different pitch and roll angles.
5. Verify environment and rig again before completing testing.

The magnetometer was intended to be used as a magnetic field reference to determine the direction of magnetic north.

DATA ANALYSIS

Using MATLAB, compass and magnetometer data that was collected in experimental runs was interpolated and synced to encoder position data. This allowed magnetic field readings and heading values to be examined over position, or orientation of the compass.

To better understand the compass data, yaw was calculated from the magnetic field, roll, and pitch outputs of the compass. The method of yaw calculation by the compass is not disclosed by the company, so it can be difficult to determine what drives that value. The following equations, (1), (2), and (3) depict how the calculated yaw was determined from the compass outputs. Before the actual magnetic field values are used to calculate heading, they are transformed by rotation matrices for both roll and pitch compensation.



Roll Compensation:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\beta) & \sin(\beta) \\ 0 & -\sin(\beta) & \cos(\beta) \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} \qquad (1)$$

Pitch Compensation:

$$\begin{bmatrix} \cos(\alpha) & 0 & -\sin(\alpha) \\ 0 & 1 & 0 \\ \sin(\alpha) & 0 & \cos(\alpha) \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} \qquad (2)$$

Calculate Yaw:

$$\arctan(y_3 / x_3) = \theta \qquad (3)$$

RESULTS

TESTING ISSUES

There were several challenges encountered during testing involving both the testing environment and the rig.

Noise

One problem encountered was noise in the testing lab space. Figure 4 below displays the magnitude of the magnetic field for one axis over time. The second part of the plot shows a large increase in the magnetic field value in response to the operation of the crane over the tank room next-door.

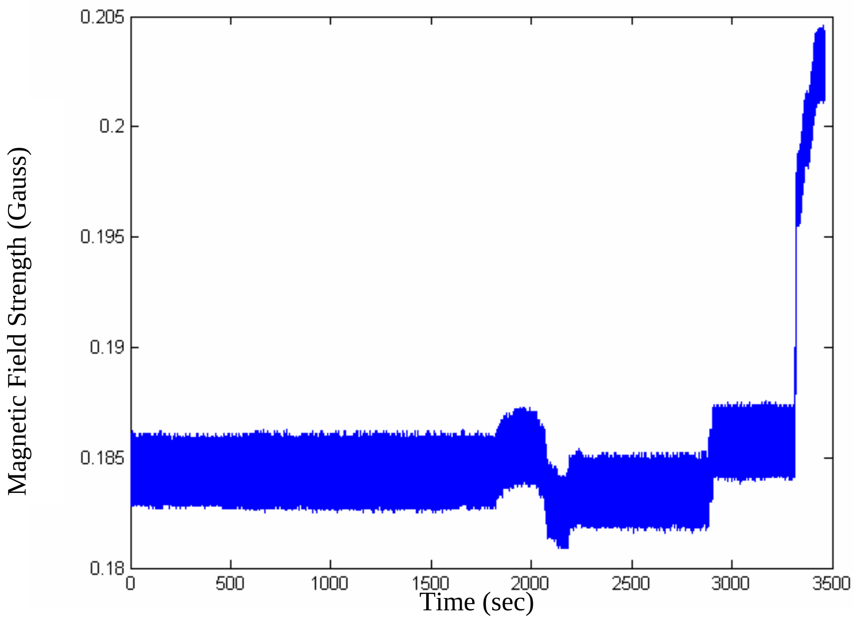


Figure 4: Magnetic field strength shows an increase with operation of crane.

In addition, there was constant background noise in the testing space, as shown in Figure 5. An analysis with a discrete Fourier Transform showed a strong signal spike at 60 Hz.

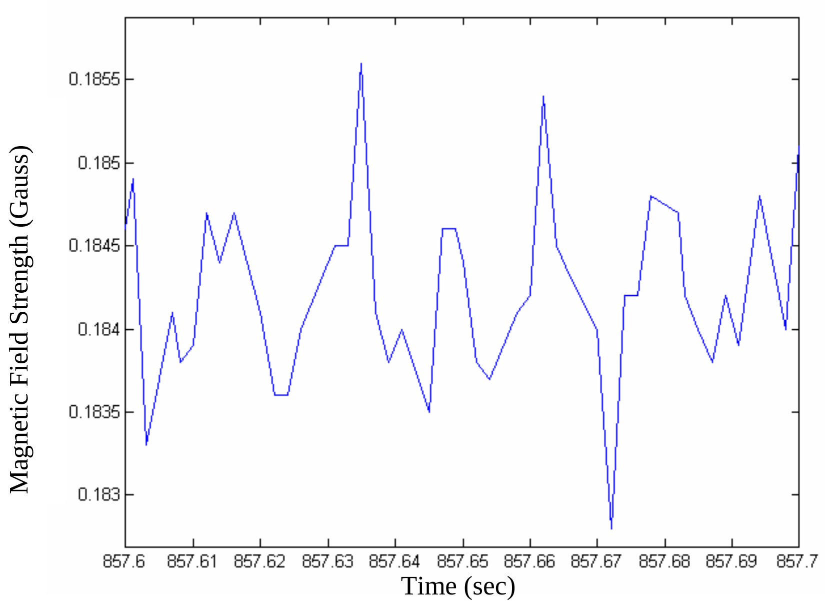


Figure 5: Close-up view of signal noise shows about six spikes for a tenth of a second.

Magnetic Field Gradient

Another issue encountered was a lack of uniformity in the magnetic field. With a uniform magnetic field the magnitude of the magnetic field vector would remain the same at any point on the circle (Figure 6) below. This translates to the same magnitude vector at any compass orientation. A gradient in the magnetic field, however, produces a magnetic field vector with varying magnitude depending on position (Figure 7).

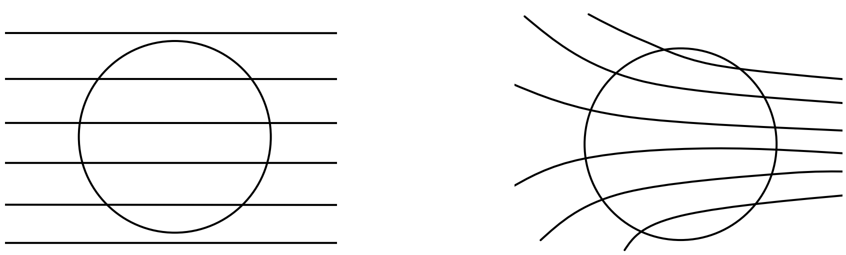


Figure 6 and 7: The diagrams above depict examples of a uniform magnetic field and a magnetic field with a gradient.

The calculated magnitude of the magnetic field vector for the compass rotated through several revolutions is depicted in Figure 8. The varying magnitude is indicative of a magnetic field gradient. The testing rig was constructed to minimize this by centering the compass over the axis of rotation, to rotate the compass through the same space. Unfortunately the placement of the actual magnetic sensors in the compass casing must not have been aligned to the exact axis of revolution.

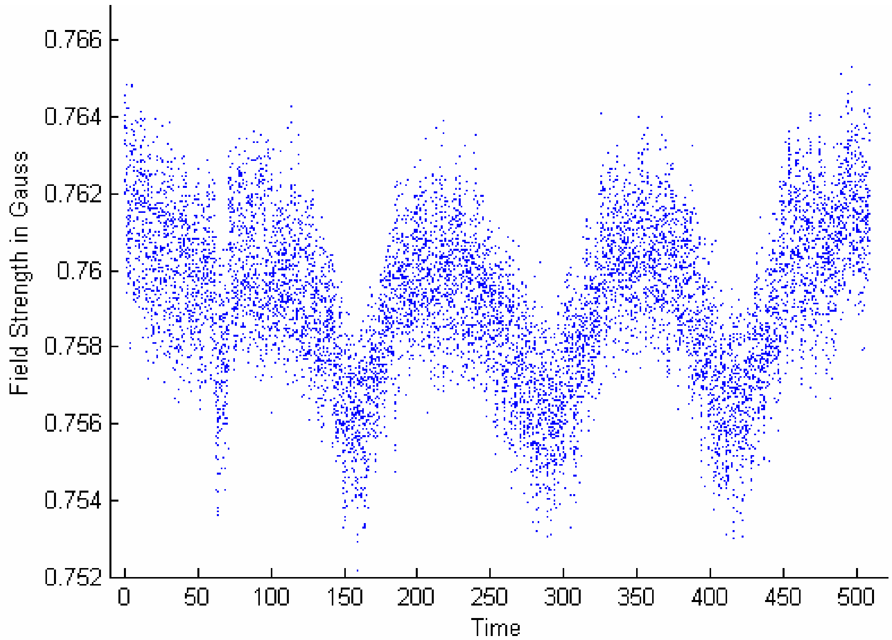


Figure 8: Magnitude of the magnetic field vector shows variation, indicative of a gradient in the magnetic field.

Magnetic field noise and magnetic field variation are both problems associated with the testing environment, and could be improved with a change in location. Do to time constraints a new testing space has not yet been found. These effects need to be minimized in order to judge compass error due to pitch measurement error and not any other factor.

Testing Station Stability

Testing was originally performed on a plastic cart which, while minimizing hard and soft iron error, twisted when revolving the rig. This resulted in the same magnetic field values read over a spread of counts, or a range of positions, for three revolutions. Figure 9 shows an example of this repeatability error, displaying a range of counts as high as 65, or 4.7 degrees. This level of repeatability is not sufficient for accuracy testing.

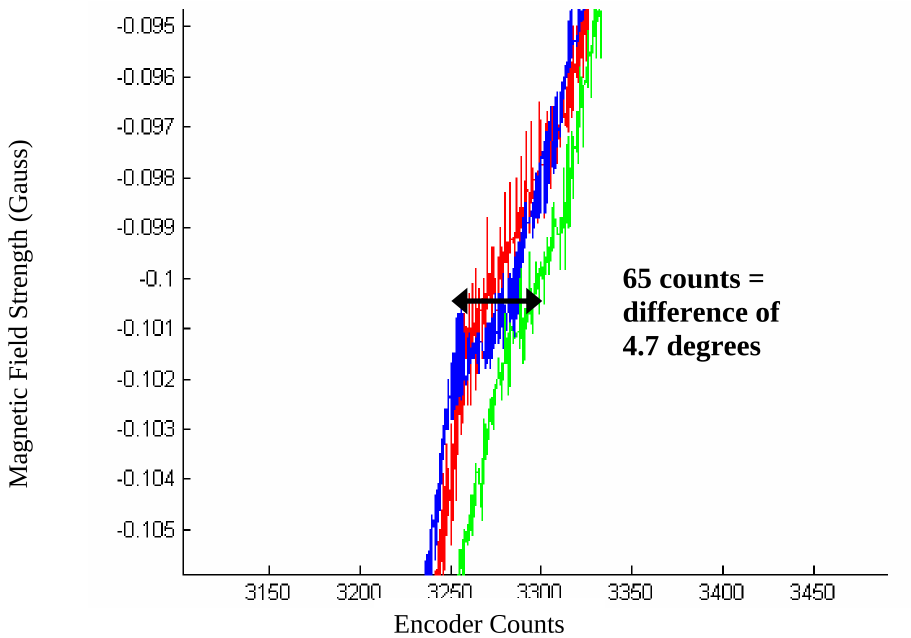


Figure 9: Magnetic field readings could not be repeated with enough accuracy, which the plot shows as a spread of the same magnetic field value over a range of counts.

The testing rig was then moved to the floor and glued to the ground. Compass readings improved dramatically, as shown in Figure 10, decreasing to a difference of 0.72 degrees. Magnetometer readings, however, still retained a significant spread, as displayed in Figure 11.

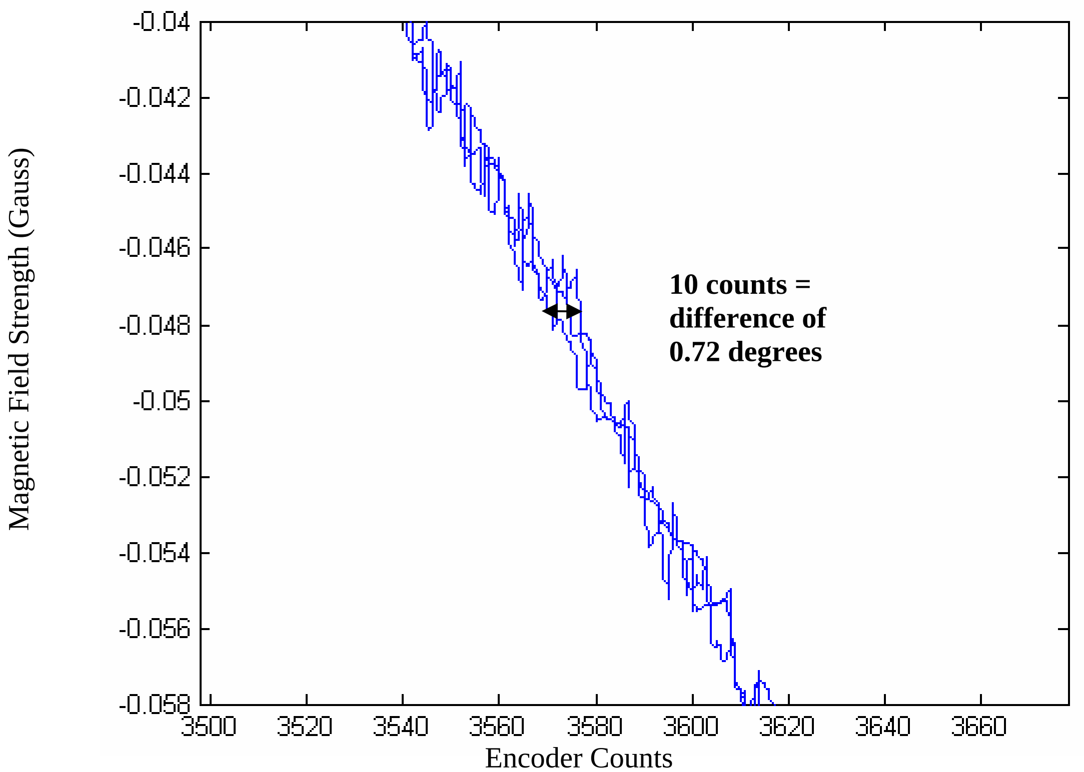


Figure 10: Compass magnetic field readings over position show improvement after moving testing rig to floor.

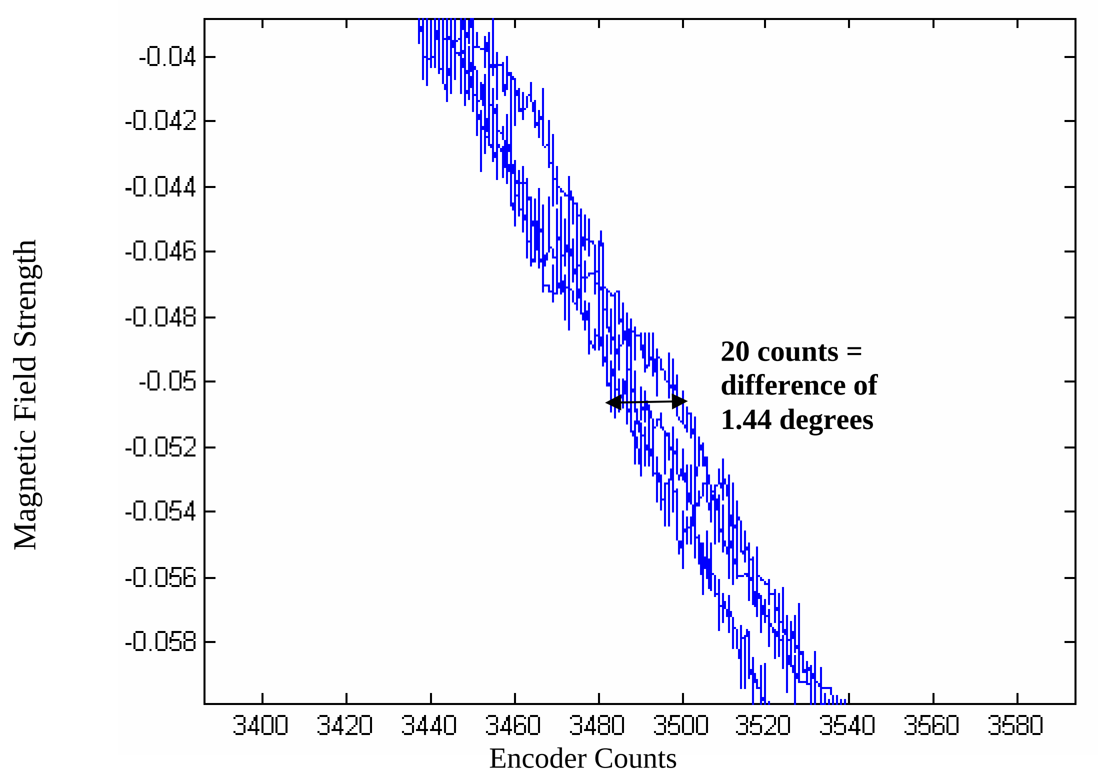


Figure 11: Magnetometer magnetic readings over position still have repeatability issue between revolutions after moving testing rig to floor.

This spread of counts remained with additional testing. The inability to collect repeatable results prevents the magnetometer from being used as a reference sensor before this problem is resolved.

TEST RUNS

Due to a lack of time, not all of the issues encountered could be resolved. Test runs were performed anyway in an attempt to see if the rig and experimental procedure were adequate in demonstrating the sought after pitch measurement errors.

Data was collected for the Microstrain compass at pitch angles of 0 and 50 degrees. Figure 12 and 13 show calculated yaw over position for both cases respectively.

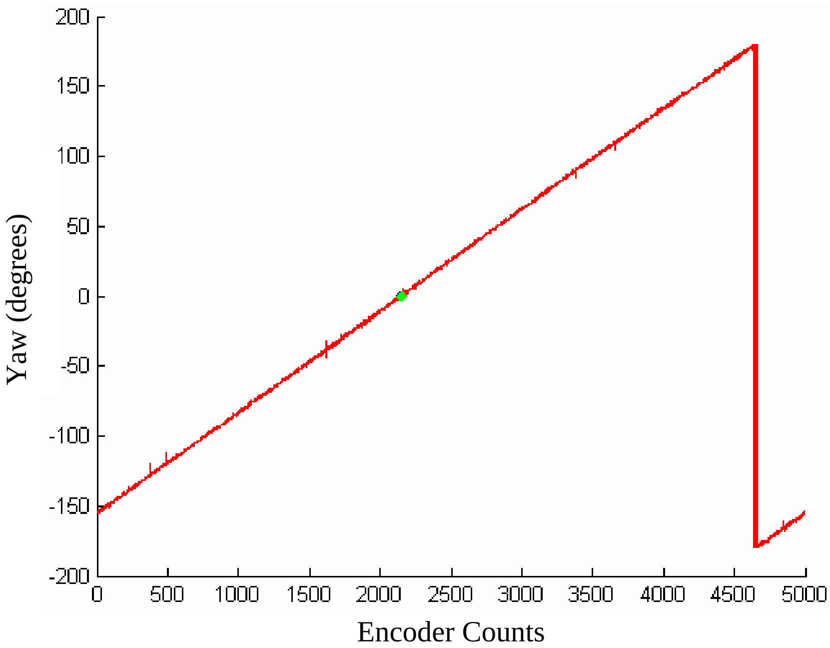


Figure 12: Calculated yaw over position (or encoder counts) for a pitch angle of 0 degrees shows a linear relationship.

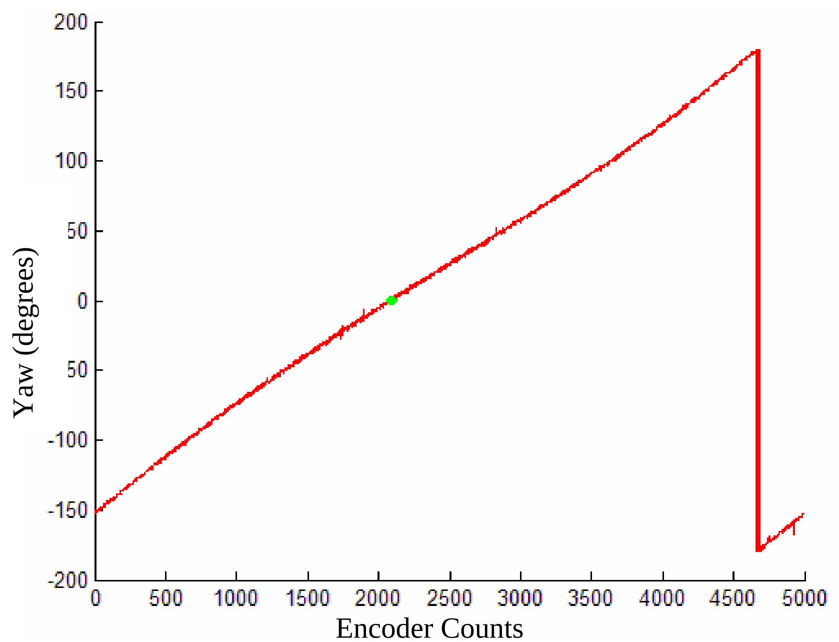


Figure 13: Calculated yaw over position (or encoder counts) for a pitch angle of 50 degrees shows a slight curvature where you would expect a straight line.

Yaw is expected to change linearly with change in compass orientation, which is demonstrated in Figure 12 for the 0 angle pitch case. The yaw calculated in the 50 degree pitch angle case begins to show a slight curvature.

Because the magnetometer was deemed unreliable, the yaw value used as a reference for heading error was the value calculated from the compass at a pitch angle of zero degrees. Figures 14 and 15 below show the heading error over actual heading for both the 0 and 50 degree pitch angle case.

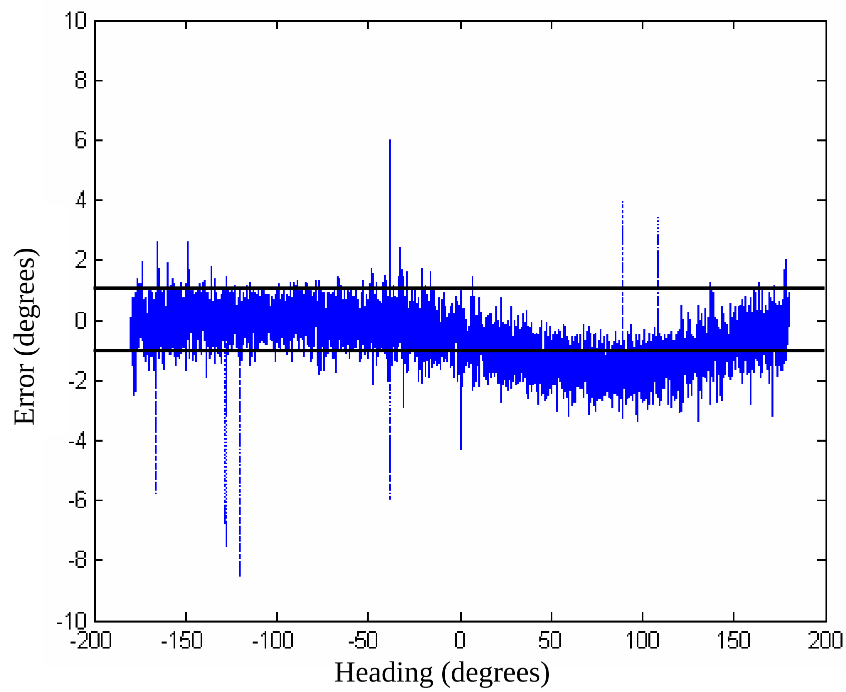


Figure 14: This plot displays the heading error versus heading for the 0 pitch angle case.

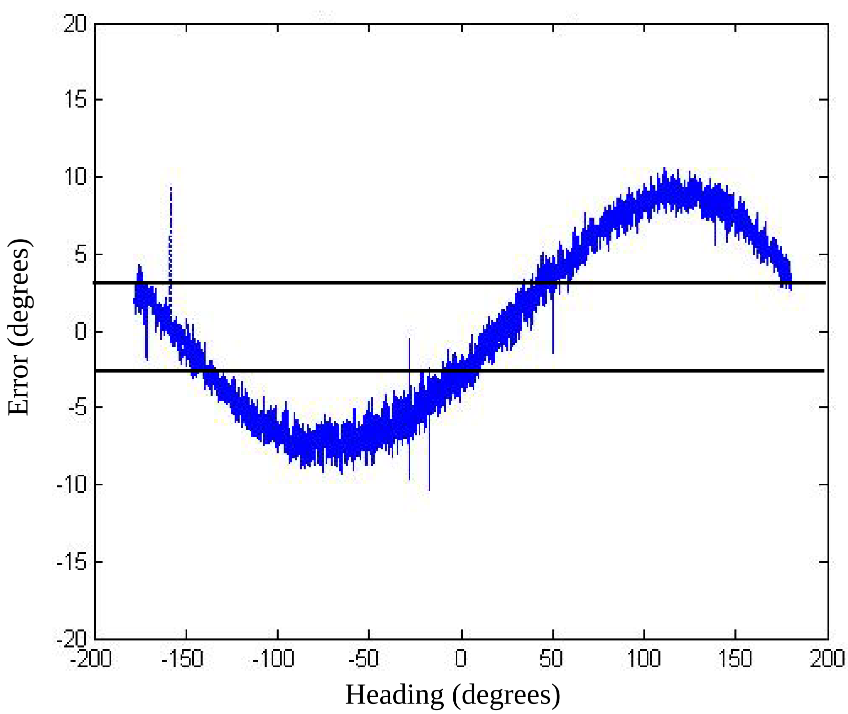


Figure 15: This plot displays the heading error versus heading for the 50 pitch angle case.

The black bars on the error plots are the range of errors that could be attributed to the gradient of the magnetic field in the lab space. The error plot for the 0 degree pitch angle case is about what can be expected with the variety of environmental issues in the testing area. The error plot for the 50 degree pitch angle case, however, shows errors that are significantly worse than what can be expected from noise or magnetic field variation. The sine wave form of the error is characteristic of a pitch measurement error.

CALCULATED AND OUTPUT YAW

While it was calculated yaw that was examined, compass output yaw was also collected. The plots below shows data collected during three revolutions of the compass at zero pitch. Figure 16 and 17 below shows both plotted over time.

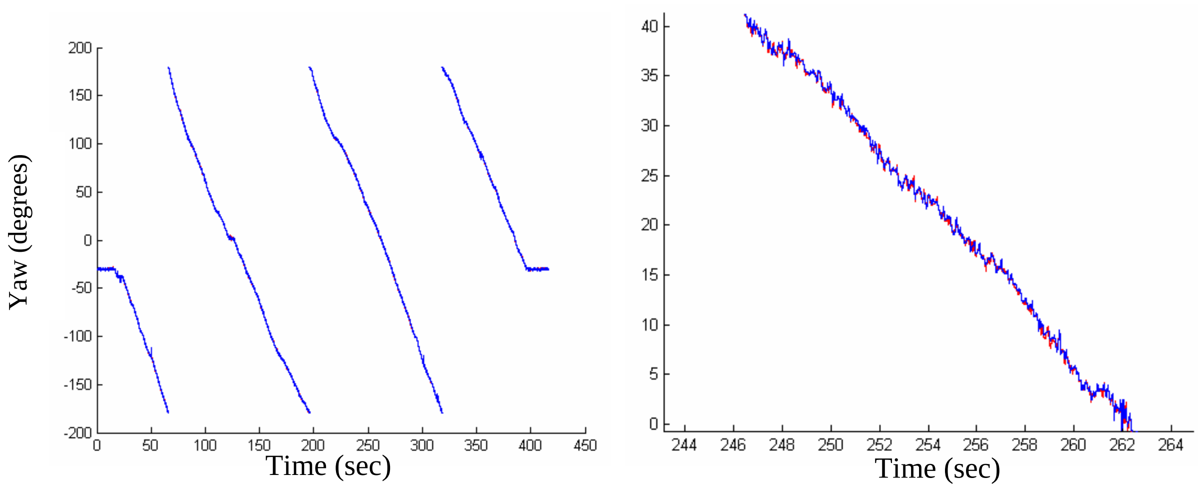


Figure 16 and 17: Output yaw (blue) and calculated yaw (red) plotted over time show that they are nearly indistinguishable.

The error between the two yaw values is shown below in Figure 18.

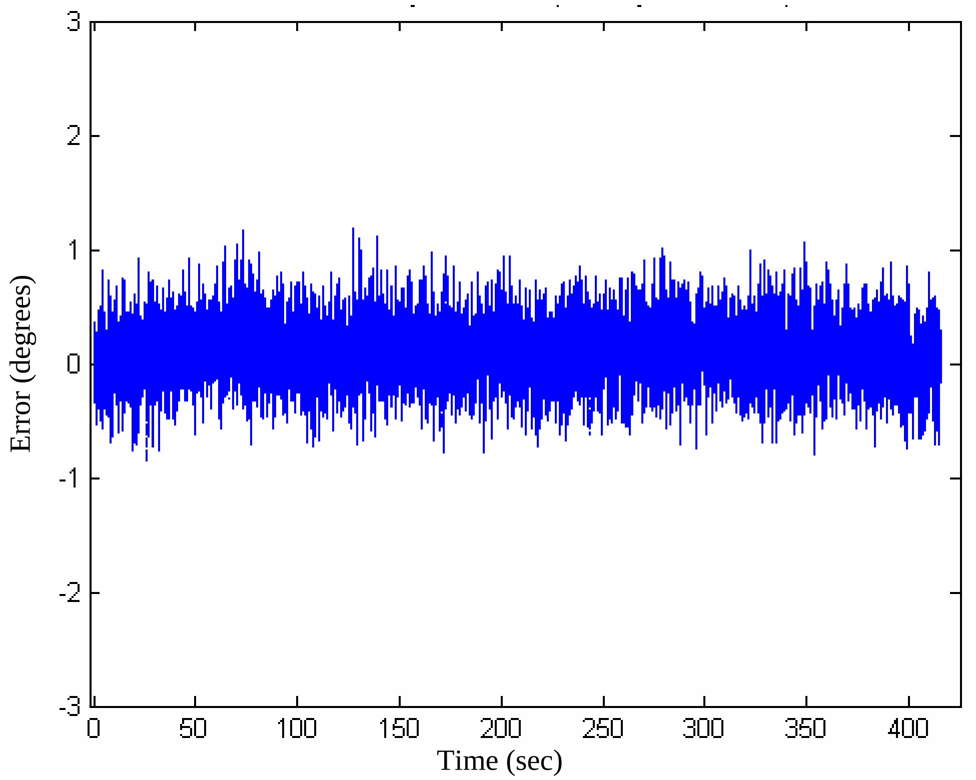


Figure 18: Error over time between outputted yaw and calculated yaw remains about zero.

The error plot shows little difference between the calculated yaw and the yaw outputted by the compass. This correlation was not limited to the 0 degree pitch angle case; a similar error range was seen during the run with the compass at 50 degrees pitch.

DISCUSSION

Data collected in the lab showed that there were couple different factors that could affect accuracy testing of a compass. The occasional crane operation, as well as the proximity of other devices running constantly in the background, produced noise that can skew compass readings. The presence of a gradient in the magnetic field can also contribute to errors. In order to evaluate compass accuracy with pitch and roll measurement errors, these issues need to be resolved, which would involve finding another testing environment.

The repeatability of measurements with the testing rig was achieved when the platform was moved and secured to the floor, but only for the compass. Magnetometer readings, which were originally intended to be use as a reference for the magnetic field strength and direction, retained a significant spread over position.

Though the issues with lab space noise were not resolved, two testing runs were completed in an attempt to see if the rig and testing procedure were adequate, even if the environment was not. The headings errors found showed a sharp increase between the 0 and 50 degree pitch angle case. The errors seen in the pitch angle case were too large to be attributed to variation in the magnetic field and showed the characteristic sign wave of error due to tilt measurement.

Yaw calculated from the compass outputs of magnetic field, roll, and yaw was shown to correlate well to the yaw outputted by the compass. The spread of error values between the two could be due to environmental noise.

CONCLUSIONS/RECOMMENDATIONS

Testing showed that while a new environment will have to be found to continue testing, the compass rig and testing procedure can demonstrate compass heading errors due to tilt measurement. Therefore one of the first steps in continuing this project would be to find a new testing location to continue accuracy tests. Once the Microstrain is completed, the Sparton and OceanServer compasses need to be run through the same tests in order to make comparisons.

One interesting issue that cropped up was the repeatability problem with the magnetometer. If it is going to be used in the future as a reference, this problem needs to be resolved.

The correlation between the calculated yaw and compass outputted yaw suggests that our method is the same or quite similar to the compass calculations. It would be worth examining, as suggested by Michael Godin, to see if creating a workable compass from separate and cheaper individual sensors and calculating yaw ourselves would be feasible.

Finally compass accuracy testing should be extended to include the effect of hard and soft iron error as well as the any improvement compass calibration can achieve.

ACKNOWLEDGEMENTS

I'd like to thank my advisor Dr. James Bellingham, Thomas Hoover, Michael Godin, and Brett Hobson for all their support, assistance, and sanity checks. I'd also like to thank Dean Martinez in machine shop whose speedy work with the water jet allowed the testing rig to be constructed. This summer was fantastic! Thank you for making it possible, Jim, George, and everyone!

References: (Heading 1, Times New Roman, 12 pt, bold)

APPENDIX

1. Expanded Experimental Procedure