

Manufacturing a Calibration Device for Orientation Sensors

Carrie M. Hall
Department of Physics and Engineering
Bob Jones University
1700 Wade Hampton Blvd.
Greenville, SC 29614

Rapid Prototyping Center
Milwaukee School of Engineering
1025 N. Broadway
Milwaukee, Wisconsin 53202

Faculty Advisor: Dr. Larry Fennigkoh

Abstract

This research involves creating a method and device to calibrate orientation sensors. Orientation sensors are a developing technology that can find the roll, pitch, and yaw of a moving object; however, unless these sensors are properly calibrated, the information they supply is not reliable. The focus of this work was calibration of the Microstrain 3DM-GX1™ gyro enhanced orientation sensor. The Microstrain 3DM-GX1™ sensor is calibrated when it is manufactured, but the common user has no tool or technique for testing the calibration of the sensor. In order to calibrate the sensor, a device has been created which moves the orientation sensor to different angles in each of the three planes. A vernier scale aids in the accuracy of these angle measurements. Using the information gathered by moving the sensor in the mechanism, a graph that shows the relationship between voltage output and the angle moved can be analyzed to find a proper calibration factor. A prototype of the device was created using the 2050 LaserGraver at the Milwaukee School of Engineering (MSOE). By using the device to test the sensor, the user can ensure that it is properly calibrated for a specific application. The device will also provide a way to do further studies about the effects of age, temperature, magnetism, and weather conditions on the calibration of orientation sensors.

Keywords: orientation sensor, calibration, laser engraving, vernier

1. Introduction

The purpose of this research is to create a device which can be used to calibrate orientation sensors. Orientation sensors use magnetometers and accelerometers to provide information about the angles that an object moves. These angles are commonly referred to as the roll, pitch, and yaw. Roll, pitch, and yaw are the angles rotated about the x-, y-, and z-axes, respectively.

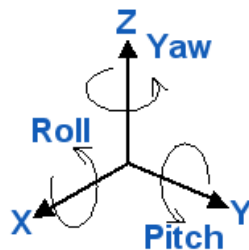


Figure 1 Roll, pitch, and yaw diagram¹

The angle measurements from orientation sensors provide information about movement and direction for a variety of applications:

- Orientation sensors provide navigational information for unmanned aircraft and underwater vehicles.
- Orientation sensors give robotic equipment information about how far it has moved and where it is.

- Orientation sensors have been used to investigate body movement in various sports and to study joint movement. For example, the Microstrain 3DM-GX1™ was used in a study of the knee joint by David Churchill in which he attached two sensors to the leg above and below the knee and used the sensor output to gather information about the angles the knee joint moved when a person walked, did jumping jacks, and rose from a sitting position.²

In all of these applications, the information supplied by orientation sensors is only valuable if the sensors are properly calibrated.

1.1. Microstrain 3DM-GX1™

This project involved the Microstrain 3DM-GX1™ gyro-enhanced orientation sensor. The 3DM-GX1™ sensor uses a gyroscope to stabilize its readings. Stabilization is needed since orientation sensors have the inherent problem of not being able to decipher linear acceleration from gravity. Therefore, unadjusted readings will show the affects of gravity. Other approaches to correcting this problem involve using an electronic low pass filter on the sensor's output to lessen the gravity readings and give more accurate results. While this method works, the results have a time delay. Microstrain's gyroscope stabilization allows their sensor to provides correct readings with a faster response time than those given by low pass filtering.³

1.2. current calibration methods

Orientation sensors are currently calibrated at the manufacturer by using a robotic arm to move the sensor. The relationship between a known angle of rotation and the voltage output of the sensor is used to create a conversion factor. The conversion factor is then used to convert the voltage output of the sensor into its angle reading.



Figure 2 Microstrain robotic arm for calibration

Figure 2 illustrates the arm which Microstrain uses to calibrate their sensors. The apparatus has “an indexing head mounted to a servo-motor controlled rotary stage” which rotates the sensor for “static and dynamic calibration.”⁴

A few other sensor calibration mechanisms have been designed and created. For example, the Department of Mechanical Engineering and the Avionics Engineering Center at Ohio University produced a device to calibrate inertial measurement units, which are a predecessor of the orientation sensor. Their device uses GPS antennas and a moveable platform on which the sensor is mounted.⁵



Figure 3 Calibration device made by Ohio University⁶

The device moves the sensor in all three directions and also moves up and down but is fairly large and complex.

1.3. sources of calibration error

Weather conditions, humidity, and temperature could introduce errors to the factory calibration of orientation sensors; however, these areas have not yet been studied extensively. Magnetic fields are known to affect sensors and can be a major source of error in measurements. Microstrain includes a hard iron calibration for the 3DM-GX1™ sensor that allows the user to recalibrate the sensor to account for any magnetic object such as metal that is near the sensor. The object accounted for must stay at the same position relative to the sensor or the calibration is again inaccurate. Therefore, the sensor could be mounted in a car and hard iron calibration would be effective in providing the correct calibration factor. Unfortunately, if that car goes over railroad tracks the calibration will be erroneous again due to the magnetic field created by the tracks.⁷

In addition, Microstrain has provided no way to account for soft iron calibration. Soft iron calibration would adjust for a ferromagnetic object that distorts the Earth's magnetic field near the sensor.⁸ Errors in calibration due to a change in magnetic field need to be explored more so that the actual effects of these changes can be quantified.

2. Designing the Calibration Device

A new calibration device is needed in order to do further studies of orientation sensors and ensure their proper calibration. This project involves creating an easily transportable calibration device composed of a sturdy, nonmagnetic material that will resist swelling and allow for reproducible measurements. The calibration device has an outer circle marked in degrees that resembles a circular protractor. This circular ring is mounted in a stand. A holder allows the outer circle and stand to be put in a vertical position. Two interchangeable center platforms are free to rotate inside the outer circle so that the sensor can be moved to different angles in the sensor's x-, y-, and z-planes. A vernier piece is attached to the center platform to increase the accuracy of measurements. Initial designs for this device were created on Solidworks 2005 and the following illustrations were taken from these designs. In the drawings, an arrow has been placed on the sensor to signify the positive x direction of the sensor and demonstrate how the sensor's orientation changes for different measurements.

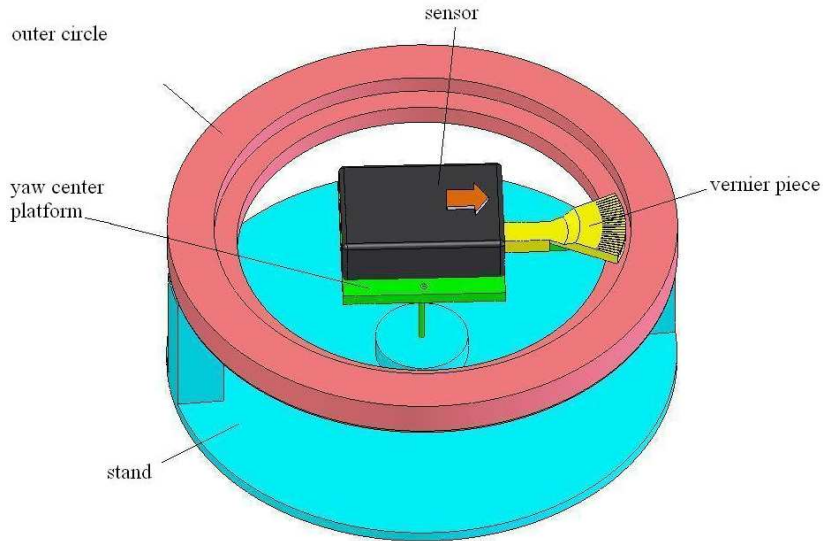


Figure 4 Position for yaw measurement.

Figure 4 illustrates the position used to measure yaw in which a center platform holds the sensor horizontally. The yaw center platform rotates inside the outer circle and can be moved accurately to different angles.

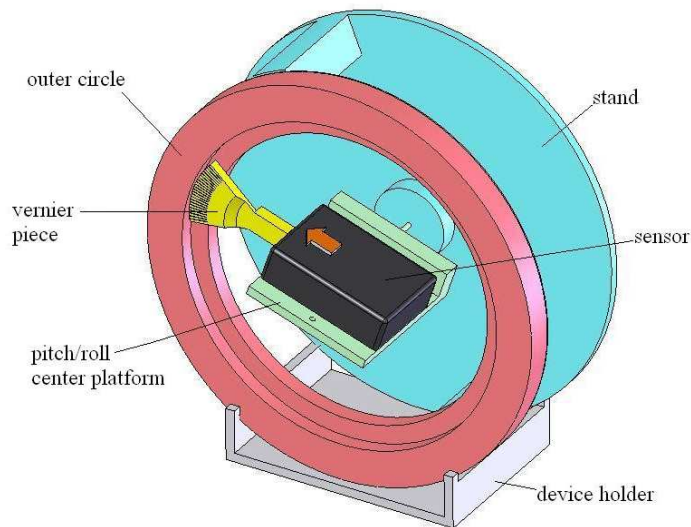


Figure 5 Position for pitch measurement.

Figure 5 shows the calibration device during pitch measurement. The holder keeps the stand and outer circle in an upright position and a second center platform holds the sensor horizontally. By changing the orientation of the sensor on this platform, the pitch and roll can both be found.

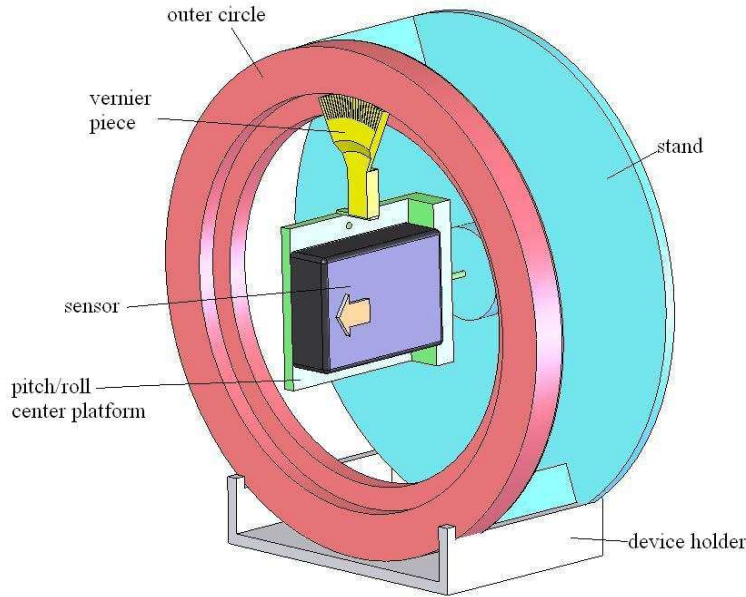


Figure 6 Position for roll measurement

Figure 6 shows how roll is measured by using the same setup used to measure pitch and moving the sensor so that the positive x direction is perpendicular to the outer circle.

2.1. outer circle with degree markings

The outer circle is marked in degrees and resembles a circular protractor. It was created in two pieces. The top layer of the outer circle has an inner diameter of nine inches and an outer diameter of eleven inches. Using AutoCAD 2006, 360 evenly spaced degree markings were created around the inner circumference of the circle using the polar array function and then labeled from 0 to 180 in both directions. The bottom layer of the outer circle has an inner diameter of eight inches and an outer diameter of eleven inches. This bottom layer provides a ledge for the vernier scale to run along.

2.2. vernier scale for center platforms

A vernier scale increases the accuracy of measurements. The scale on the vernier was designed so that 23 divisions on the vernier scale take up 22 divisions on the main scale.⁹ Two vernier pieces were made with one attached to each center platform so that the vernier scale is flush with the degree markings on the outer ring and glides along the ledge of the outer ring. The vernier scale allows angle measurements to be taken to within 5 minutes of arc which should be adequate accuracy for any measurements.

2.3. stand for outer circle

The stand holds the outer circle horizontally and provides a base on which the center platforms rotate. It consists of a base circle that is 11 inches in diameter. In the center of this base is an extruding circle with a plastic sleeve that holds the supporting rods of the center platforms. Four 3-inch long rods, which are approximately 90 degrees apart from each other, support the outer ring. In the future, plastic leveling feet could be placed on the base of the stand to allow the apparatus to be easily leveled.

2.4. center platform for yaw measurement

The yaw center platform holds the sensor parallel to the outer circle so that yaw measurements can be taken. This platform is a $3\frac{1}{2} \times 3\frac{1}{2}$ inch square with an aluminum rod extending from the bottom of the platform to the plastic sleeve in the stand base. The top of the platform has holes in which brass screws are attached so that the sensor can

be attached securely by brass thumb nuts using the holes on the sensor case. Aluminum and brass were used because of their nonmagnetic properties. A vernier piece is attached to the arm of the platform. The yaw platform is designed to be removable from the stand so that the two center platforms can be easily switched.

2.5. center platform for pitch and roll measurement

The second platform holds the sensor perpendicular to the outer circle. Screws holes in this platform allow the sensor to be mounted on a 3½ x 3½ inch square. A base extrudes from the platform and holds a rod that extends to the sleeve in the stand base and allows the platform to rotate smoothly. An arm with the vernier attachment rotates evenly around the circle and aligns with the center of the sensor. Readings for roll and pitch can be found by placing the sensor on the platform so that the positive x-axis of the sensor is horizontal and vertical, respectively.

2.6. holder for outer ring and stand

In order to obtain proper measurements for pitch and roll, the stand and outer circle are placed in a holder that keeps them vertical. This allows the pitch and roll center platform to move the sensor perpendicular to the outer circle while keeping the sensor horizontal.

3. Methods of Building

Several options were available to build the device. These included rapid prototyping, laser engraving, and metal tooling.

3.1. rapid prototyping possibilities

Initial plans were to create the device by rapid prototyping. Rapid prototyping creates an object layer by layer by using a laser to fuse or solidify thin layers of powder or liquid. However, objects made by rapid prototyping tend to settle over time and thus would not create a calibration device which would give consistent measurements. Since it is essential for a calibration device to be accurate and have repeatable results, members of the Rapid Prototyping Center at the Milwaukee School of Engineering (MSOE) advised against this building method.

3.2. building on the LaserGraver

Since rapid prototyping would probably not create a reliable device, the 2050 LaserGraver was used to create the device in layers from acrylic.

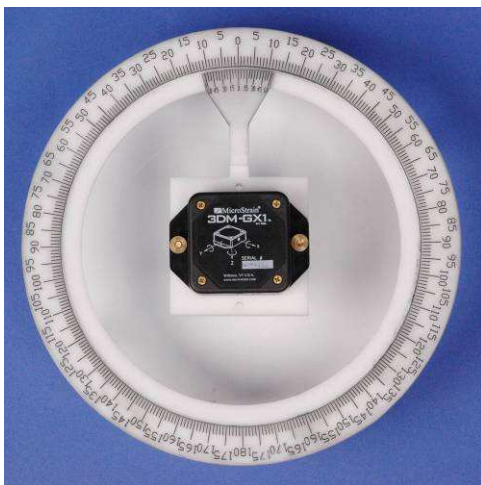


Figure 7 The device in yaw position¹⁰



Figure 8 The device in pitch/roll position¹¹

The original designs for the device had been created on Solidworks so they would be compatible with the rapid prototyping machines and thus had to be transferred into the Data eXchange Format (DXF) read by the LaserGraver at MSOE. To do this, Solidworks models were made into drawings, saved in DXF format, and imported into AutoCAD 2006.

Since Solidworks allows 3D modeling and the LaserGraver only cuts 2D objects, designs had to be modified slightly to allow the device to be made in layers. After final modifications were made in AutoCAD 2006, drawings were saved in AutoCAD Release 12 DXF format and transferred to the LaserGraver computer. The final device was built out of $\frac{1}{8}$ " and $\frac{1}{4}$ " acrylic. The layers of the device were cut on the LaserGraver and then glued together, creating the final prototype pictured in Figures 7 and 8.

3.3. possible future use of metal tooling

In the future, it would be beneficial to have the device tooled out of metal. Metal tooling would create a device that would be exact and reproducible. Since the sensor relies on the earth's magnetic field for direction, any interfering magnetic field will disrupt the sensor from giving proper measurements. Therefore, the device would have to be created out of a nonmagnetic metal such as aluminum or brass.

4. Trials and Conclusions

After final adjustments, the created prototype was tested using the Microstrain 3DM-GX1™ sensor. The first trials with the sensor involved comparing the actual angle moved with the angle indicated by the sensor in Microstrain's data acquisition software. Graphs comparing the actual angle with the indicated angle were fitted with a line of regression for the data points. While the ideal slope of the line of regression would be one, the slopes in the yaw, pitch and roll trials were 0.9965, 0.9917, and 0.9984, respectively. Microstrain only ensures the sensor to ± 0.5 degrees for static measurements so slopes close to one but not exactly one were expected.

Biopac Student Lab Pro 3.7 was used to study the relationship between voltage output of the sensor and the angle moved by the sensor.

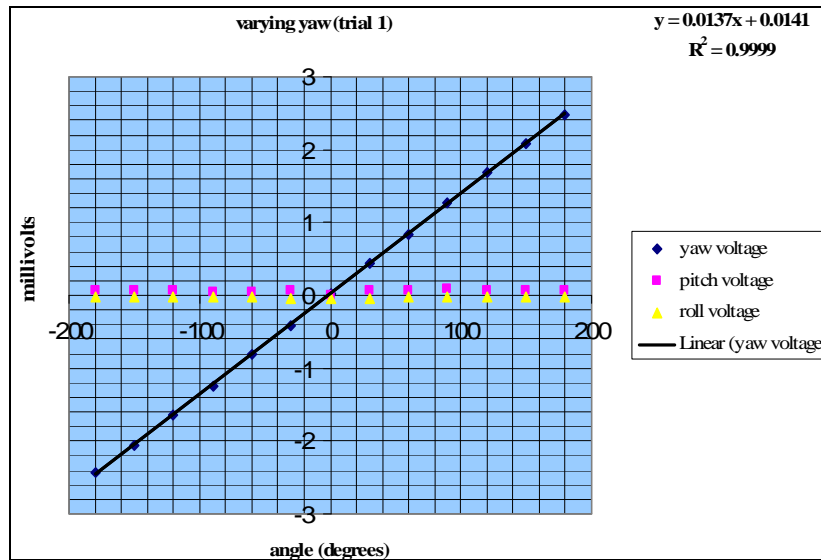


Figure 9 Angle v. voltage graph for trial varying yaw

Figure 9 shows data from trials in which the sensor was moved in increments of 30 degrees and the mean voltage output was recorded. While only one angle was varied at a time, the others were monitored as well to find any crosstalk between channels of the sensor. The results showed linear variation of voltage for the angle moved and stable voltage for the stationary angles. The only exception was in pitch testing in which roll, pitch, and yaw voltages were more random when outside the -90 to + 90 degree range of pitch motion. However, Microstrain only ensures accurate measurements for within this -90 to + 90 degree range of pitch. The lines of regression for these

graphs showed nearly the same slope in each of the three cases and each angle was tested twice with nearly identical results.

Testing has shown that a newly calibrated sensor has a linear relationship between voltage output and angle that is similar and repeatable for pitch, yaw, and roll angles. Thus, deviation from the original calibration should be easily observable.

5. Future Applications

Since this device is small and easily portable, it provides an easy way to test for calibration deviations created by different conditions. Magnetism is known to affect the sensor but if the exact effects of magnetism could be quantified, users will know if the sensor is useable for their situation. In some cases, a sensor with a range of accuracy may be acceptable, but for others exactness may be needed every time. The calibration device could also be taken outside or into different testing situations to test for changes in calibration due to rain, heat, or vibrations. By moving the sensor in only one direction at a time, any crosstalk between channels can also be found. The Microstrain 3DM-GX1™ orientation sensor is a recent development and its changes after continued use are not known. The calibration device furthermore will allow errors created from age to be identified and corrected.

6. Acknowledgements

The author wishes to thank the MSOE Rapid Prototyping Center for advice on building methods, Paul Roberts for photographing the device, and Roger Hajny and members of the MSOE machine shop for help in machining several parts of the device. Special thanks to Dr. Larry Fennigkoh for his direction and Professor Michael McGeen for his help with the LaserGraver. The author would also like to express appreciation to the National Science Foundation and the Milwaukee School of Engineering for their funding of this project, as well as to Ann Bloor and Betty Albrecht for their encouragement along the way.

This material is based upon work supported by the National Science Foundation under Grant No. EEC-0139142. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

7. References

1. The Valve Developer Community, "QAngle," <http://developer.valvesoftware.com/wiki/QAngle>, (accessed July 12, 2006).
2. David Churchill, "Quantification of Human Knee Kinematics Using the 3DM-GX1 Sensor," (Microstrain Inc., January 2004).
3. D.L. Churchill, C.P. Townsend and S.W. Arms, "A Network of Orientation Sensors for Position Feedback: Evaluation of Dynamic Sensor Performance," (paper presented to the Thirty Third Neural Prosthesis Workshop, Bethesda, MD, October 16-18, 2002).
4. Churchill, "Network of Orientation Sensors," 2002.
5. John J. Hall and Robert L. Williams II, "Cartesian Control for the Inertial Measurement Unit Calibration Platform" (paper presented to the ASME Design Engineering Technical Conference, Baltimore, September 10-13, 2000).
6. Ibid., 6.
7. Microstrain, Inc., *3DM-GX1™ HardIronCalibration* (Williston, VT: Microstrain, Inc., 2005), 6.
8. Ibid., 5.
9. Wikipedia, "Vernier Scale," http://en.wikipedia.org/wiki/Vernier_Scale, (accessed June 21, 2006).
10. Paul Roberts, photographer, (July 31, 2006).
11. Ibid.