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Importance of Industrial Grade Sensor Calibration

Sensor calibration is a method of improving sensor performance by removing structural errors in the sensor outputs. Structural errors are differences between a sensors expected output and its measured output, which show up consistently every time a new measurement is taken. Any of these errors that are repeatable can be calculated during calibration, so that during actual end-use the measurements made by the sensor can be compensated in real-time to digitally remove any errors. Calibration provides a means of providing enhanced performance by improving the overall accuracy of the underlying sensors.

Sensor Performance Categories

Most low cost MEMS sensors available on the market fall into a performance category known as *automotive* grade sensors. The use of the term *automotive* grade in this context does not necessarily imply that the sensor meets specific performance standards specific to the automotive industry. The origin of the term *automotive* grade when discussing MEMS sensor performance likely has to do with the fact that the automotive industry was one of the first to utilize MEMS inertial sensors in large volume. This performance grade is also sometimes referred to as *consumer* grade.

To meet the needs of the automotive and consumer markets, MEMS sensor manufactures provide sensors that exhibit adequate performance at the lowest possible cost. These MEMS sensors offer an attractive alternative for many industrial applications such as robotics, aviation, and platform stabilization. These applications typically have more strict performance requirements than the original automotive and consumer markets for which the MEMS sensors were originally designed. For industrial applications, overall accuracy and reliability are crucially important factors.

Options Available for Sensor Calibration

Sensor calibration provides a means of trading cost for improved performance and accuracy. There are two ways in which companies improve sensor performance by calibrating their MEMS sensors. In the first case companies can add the necessarily hardware to their design to enable sensor output correction and add in-house calibration routines into their product manufacturing process to perform individual sensor calibration. The upside to this is that it provides a company with complete control over exactly what value is added to the existing sensors. In this case sensor calibration can be tailored to match the application specific performance requirements. The downside is that it significantly increases the time to market. As we will explore later in this article, sensor calibration requires access to sophisticated test and calibration equipment. Developing the necessarily calibration algorithms and integration software can require development times of 9 to 12 months, and potentially cost hundreds of thousands of dollars in test equipment costs.

As a cost-effective alternative to in-house calibration, several companies on the market provide easy to use sensor packages that include high-quality automotive grade MEMS sensors along with a complete system level calibration. Many of these companies also provide onboard digital circuitry and signal processing algorithms loaded onto onboard processors which provide designers with additional performance and functionality. These sensor packages form a new performance grade of inertial sensors known as *industrial* grade. Due to the high precision calibration techniques utilized, industrial grade inertial sensors will provide in some cases 10X increase in accuracy and overall performance. Manufactures of industrial grade sensors typically also provide, along with the calibrated MEMS sensors, additional digital circuitry such as voltage regulation and analog signal filtering techniques which reduce product design time and component count. Also many industrial grade inertial sensor manufactures will provide an onboard processor that runs sophisticated sensor fusion algorithms which drastically improve overall system performance while at the same time providing additional functionality. These sensor fusion algorithms are very complex and require highly-skilled personnel and thousands of man-hours hours to develop in-house. Companies that offer industrial grade inertial sensors bridge the large performance gap between the low cost component level automotive grade MEMS sensors and the high-end tactical grade inertial systems. Industrial grade sensors offer a very attractive option for companies that seek improved time to market, and reduced development costs. Industrial grade sensors are especially beneficial for those with applications requiring the utmost performance possible with MEMS inertial sensors. There are many excellent manufactures of industrial grade inertial sensor modules on the market. VectorNav seeks to provide customers with a sensor module that offers true industrial grade inertial sensor performance while maintaining the form factor of component level automotive grade sensor. With a VectorNav sensor you get the best of both worlds; the absolute smallest possible design footprint; superior accuracy and performance typical of an industrial grade sensor; some of the best in-class onboard signal processing algorithms; and a full set of development tools which reduce development time, enabling faster time to market.

Purpose

The goal of this document is to provide you with the necessarily fundamental understanding of what goes into improving sensor performance from automotive to industrial grade. Hopefully it will allow you to determine whether an industrial grade sensor is right for your application. If you find that in your application you can get by with un-calibrated automotive grade sensors then hopefully this article will save you some time in making this high level decision. For those of you that find you need the additional performance provided by a system level calibration, hopefully this article will help you decide whether developing in-house calibration techniques or purchasing an industrial grade sensor is better for your application. For those of you that decide to shop around for an industrial grade sensor we hope you will consider our line of surface mounted sensor modules. If a surface mount design doesn't fit your need then I encourage you to shop around and check out many of the other quality vendors of industrial inertial sensors on the market.

Performance Comparison

Determining whether MEMS sensor calibration is required for your application isn't a straightforward task. Calculating system-level performance from the individual sensor specifications is difficult and error-prone. The remainder of this article will analyze the performance differences for the MEMS sensors used on the VectorNav VN-100. These automotive grade MEMS sensors used on the VN-100 have very similar performance to MEMS sensors used on other industrial grade inertial sensors modules. By analyzing the performance of the inertial sensors both before and after the precision system level calibration that we provide, you will begin to understand where the performance differs between automotive and industrial grades. For each calibration parameter we will discuss the required calibration process along with that components individual contribution to the overall system level performance. This should provide you with the information necessarily to determine whether industrial grade sensors are a good fit for your application.

Calibration Process

The calibration process consists of placing the DUT (device under test) into configurations where the inertial input stimuli for the sensor is known, thus allowing us to determine the actual error in each measurement. The sensors examined are the sensors that are typically found on inertial sensor packages, consisting of accelerometers, gyroscopes, and magnetometers. For more detailed information about each of these sensors take a look at our individual sensor articles.

Typical Sensor Model

For each sensor we will use a linear sensor model, which is typical for low cost MEMS sensors. This linear model consists of the following calibration parameters.

1. Sensitivity of sensor X-axis to X-axis inputs (S_{xx})
2. Sensitivity of sensor Y-axis to Y-axis inputs (S_y)
3. Sensitivity of sensor Z-axis to Z-axis inputs (S_z)
4. Sensitivity of sensor X-axis to Y-axis inputs (M_{xy})
5. Sensitivity of sensor X-axis to Z-axis inputs (M_{xz})
6. Sensitivity of sensor Y-axis to X-axis inputs (M_{yx})
7. Sensitivity of sensor Y-axis to Z-axis inputs (M_{yz})
8. Sensitivity of sensor Z-axis to X-axis inputs (M_{zx})
9. Sensitivity of sensor Z-axis to Y-axis inputs (M_{zy})
10. Sensor X-axis offset (B_x)
11. Sensor Y-axis offset (B_y)
12. Sensor Z-axis offset (B_z)

Different tests are utilized to calculate each of the above linear calibration parameters. IEEE-STD-1293-1998 offers a comprehensive sensor model approach for describing the error behaviors of a typical MEMS accelerometer. It also provides a detailed test procedure for determining each of these calibration parameters along with the recommended requirement calibration hardware.

Sensor Model Equations

Each sensor is calibrated using the linear sensor model shown below.

$$A = \begin{bmatrix} x \\ y \\ z \end{bmatrix}_I = \begin{bmatrix} 1 & M_{XY} & M_{XZ} \\ M_{YX} & 1 & M_{YZ} \\ M_{ZX} & M_{ZY} & 1 \end{bmatrix} * \begin{bmatrix} \frac{1}{S_X} & 0 & 0 \\ 0 & \frac{1}{S_Y} & 0 \\ 0 & 0 & \frac{1}{S_Y} \end{bmatrix} \left(B_D + \begin{bmatrix} B_X \\ B_X \\ B_X \end{bmatrix} - \begin{bmatrix} V_X \\ V_X \\ V_X \end{bmatrix} \right)$$

This written out as algebraic equations this gives

$$A_X = \frac{B_D + B_X - V_X}{S_X} + \frac{M_{XY}(B_D + B_Y - V_Y)}{S_Y} + \frac{M_{XZ}(B_D + B_Z - V_Z)}{S_Z}$$

$$A_Y = \frac{M_{YX}(B_D + B_X - V_X)}{S_X} + \frac{B_D + B_Y - V_Y}{S_Y} + \frac{M_{YZ}(B_D + B_Z - V_Z)}{S_Z}$$

$$A_Z = \frac{M_{ZX}(B_D + B_X - V_X)}{S_X} + \frac{M_{ZY}(B_D + B_Y - V_Y)}{S_Y} + \frac{B_D + B_Z - V_Z}{S_Z}$$

Temperature calibration

Each of the above calibration parameters will vary with changes in temperature. To account for this all VectorNav sensors utilize a third order algebraic polynomial for each calibration coefficient as a function of temperature. This is consistent with the recommended calibration procedure outlined in IEEE-STD-1293-1998. Each calibration coefficient can be calculated as follows:

$$C_n = C_{n_0} + C_{n_1}\Delta T + C_{n_2}\Delta T^2 + C_{n_3}\Delta T^3$$

$$where\ \Delta T = [Temperature - 25]\ °C$$

Accelerometer Calibration

The accelerometer is calibrated using an industry standard 6-point tumble test. Details of this tests along with the necessarily equations can be found in Ref 1. Essentially this consists of aligning each sensor axis both in the direction of and opposite to the direction of known gravity. This is typically accomplished using a device known as dividing-head. This precision device provides a means to rotate a attachment plane in extremely precise increments.

Figure 1. No Distortions

A dividing head is mounted to a work surface or slab isolated from the building floor to minimize tilt and azimuth movements. The rotation axis of the dividing head is held precisely perpendicular at all times to the known gravity vector. This allows for the DUT (device under test) to be rotated into at least four different configurations each 90 degrees apart. The test is performed at multiple times so that each sensor axis is rotated completely around the dividing block rotation axis. For each axis four measurements are collected, one with the axis in the direction of gravity, one against gravity, and the other two perpendicular to gravity. Either batch linear least-squares or a linear Kalman filter is used to estimate the optimal selection of calibration coefficients which minimize overall errors.

Thermal Calibration

As mentioned earlier each of the 12 accelerometer calibration coefficients vary with temperature. To capture these variations IEEE-STD-1293-1998 recommends performing multiple 6-point tumble test at multiple temperature inside a environmental test chamber. Environmental test chambers, also known as thermal chambers, enable test to be conducted at specified known temperatures.

Figure 2 - Environmental Test Chamber

Thermal chambers use electric heaters as a heat source and either a refrigeration cycle or liquid nitrogen (LN2) or liquid carbon dioxide (LCO2) as a means of removing heat. Refrigeration thermal chambers eliminate the need for expendable gas, however they have slow ramp rates and have difficulties reaching temperature below -20C. Liquid nitrogen and CO2 chambers provide very fast ramp rates and cold test capabilities well below -70C.

VectorNav thermally calibrates each of our VN-100T sensors using a complete 6-point tumble test at four separate temperatures of -40C, 0C, 40C, and 80C. By testing at the limits of the operational range we ensure that each sensor operates within specifications over the full temperature range.

Accelerometer Bias Calibration

The accelerometer bias has a major impact on the overall performance of an IMU or AHRS in several distinct ways. Any bias in the accelerometer output will cause a shift in the measured acceleration vector from its true direction. When integrating accelerations this will directly lead to errors in the calculated position. When determining orientation, accelerometer bias errors will have a large influence on the pitch and roll accuracy. The below plot shows the difference between the errors caused specifically by accelerometer bias after calibration for both industrial and automotive grade sensors.

Grade	Accelerometer Bias Error [mg]	Pitch/Roll Error [deg]	Horizontal Position Error 1 sec	5 sec	10 sec	20 sec
Industrial	3	0.17	15 mm	370 mm	1.5 m	5.9 m
Automotive	125	8.2	700 mm	18 m	70 m	280 m

As shown above the system level calibration reduces the bias error by nearly two orders of magnitude. The middle column titled "Pitch/Roll Error" shows the contribution the quoted accelerometer bias has on the pitch/roll angle estimate. You can see that over 8 degrees of error is possible using automotive grade MEMS accelerometers without performing a bias calibration. The two-point tumble test is all that is required to capture the accelerometer bias. If all you need is the sensor bias then you can align the sensor axis with the horizontal level plane and capture 50-200 samples. The average of these samples is the sensor axis bias. Capturing scale factor and axis misalignment require a 4-point or 6-point tumble test respectfully.

Accelerometer bias typically will vary with temperature and needs to be compensated for if you want to get good performance beyond room temperature.

Keep in mind that performing a complete thermal calibration can be a very expensive undertaking. Since the 6-point tumble test has to be performed at multiple temperatures, a thermal calibration can require several hours to perform. If a liquid nitrogen thermal chamber is used, you will need to factor in the cost of the expendable gas into your cost equations. Liquid nitrogen is typically cheaper than LCO2, but it will still run you $100-$150 per tank to refill. A bottle will typically provide 6-12 hours of cold testing.

Accelerometer Scale Factor

The accelerometer scale factor captures the sensors sensitivity to the intended acceleration excitation axis. For MEMS sensors typically a 4-point or 6-point tumble test is used to determine the these parameters. The standard gravity constant of 9.80665 m/s^2 is typically used to scale the 1g accelerometer measurements into standard engineering units.

	Accelerometer Scale Factor Error	Pitch/Roll Error	Horizontal Position Error			
Grade	[%]	[deg]	1 sec	5 sec	10 sec	20 sec
Industrial	0.1	0.057	4.9 mm	120 mm	490 mm	2 m
Automotive	5	2.9	240 mm	6.1 m	24 m	98 m

As shown in the above table the accelerometer scale factor doesn't contribute as much to the total error as the bias, however it will likely need to be calibrated to provide adequate performance of the IMU as for either position/velocity or orientation estimates. Up to 3 degrees error in pitch and roll is possible due to scale factor errors only with an un-calibrated automotive grade MEMS accelerometer. The orientation that would be most affected by scale factor would be one where the measured gravity vector sits in between two of the sensor axes. For instance if the pitch was equal to -45, then the measured gravity vector would be in the XZ sensor plane measured 45 down from the X-axis. In this orientation either a scale factor error in the X-axis or Z-axis accelerometer will result in an orientation error in the measured gravity vector. As with the bias errors this will strongly affect the performance of your orientation solution accuracy.

Accelerometer Axis Misalignment

Ideally an IMU should consist of a three axis accelerometer where each axis is exactly 90, or perpendicular to each of the other sensor axis. In this case each axis is linearly independent of the output of the other axes. A pure acceleration in the X-axis should not influence the output of the Y or Z-axis. In the real-world sensors are not perfectly aligned, and this misalignment cases the output of each sensor axis to be a slight function of the output of the other two axes. Sensor misalignment can be caused by inaccuracies inherent to MEMS sensor design and also misalignment during the placement of the MEMS sensor on the circuit board.

	Accelerometer Cross-axis Error	Pitch/Roll Error	Horizontal Position Error			
Grade	[%]	[deg]	1 sec	5 sec	10 sec	20 sec
Industrial	0.1	0.057	4.9 mm	120 mm	490 mm	2 m
Automotive	2	1.1	98 mm	2.5 m	9.8 m	39 m

Typically misalignments for MEMS sensors will be on the order of 0.5 to 1 degree. As you might suspect, a 1 degree misalignment in a sensor axis can translate directly into a 1 degree pitch and roll error. The misalignment can also result in incorrectly integrated accelerations from the accelerometer. Axis misalignment can be calculated using a 6-point tumble test.

Additional Accelerometer Calibration and Testing

Addition to the linear calibration outlined above, accelerometers can also be tested and calibrated under vibration and large accelerations using centrifuges. A centrifuge provides a means of calibrated out non-linearity's that exist beyond the +- 1g acceleration range. Under certain circumstances accelerometer bias offsets can be calibrated for if it is known that the sensor will be subjected to intense vibration during use.

Gyroscope Calibration

The gyros are calibrated using a precision device known as a rate table. A rate table has a circular platform connected to a precision brushless electric motor that is combined with a control loop capable of providing very precise angular rate outputs. A rate table will have extremely tight design tolerances which keep the rotational axis precisely perpendicular to the sensor platform plane. The rate table is also capable of very precise angular positioning which allow for dynamic testing of the accelerometer and IMU package. There are several providers of quality rate tables on the market including but not limited to the following:

Rate Table Manufactures

Ideal Aerosmith	www.ideal-aerosmith.com
Acutronic	www.acutronic.com

Figure 3 - Single Axis Rate Table

Rate tables can be purchased as either single-axis, 2-axis, or even 3-axis systems. A 3-axis rate table provides the additional benefit of being able to reconstruct known motion profiles. It provides quicker calibration times and eliminates the need for precision machine test fixtures that enable multi-axis mounting. Single-axis rate tables typically run in the $20-40k range new, and three-axis systems can costs well over $100,000.

Figure 4 - Three-axis Motion Simulator with Integrated Thermal Chamber

Gyroscope Bias

Gyro bias errors have an enormous impact on the overall performance of IMU, AHRS, and INS systems. A bias in the gyro output when integrated will cause an orientation error that grows linearly with time. For navigation and tactical grade IMU's the gyro bias has probably the largest impact on the overall system performance. The gyro bias is a deceptively simple parameter and at first glance it may not appear as if it would be difficult to compensate for, since all you have to do to measure it is take measurements while the sensor is sitting stationary and not rotating. What makes the gyro bias so important and difficult to account for is the fact that it has a random walk component that cannot be calibrated out using standard calibration methods. Even after subtracting out the stationary bias output, the gyro bias will appear to randomly walk around the initial bias value.

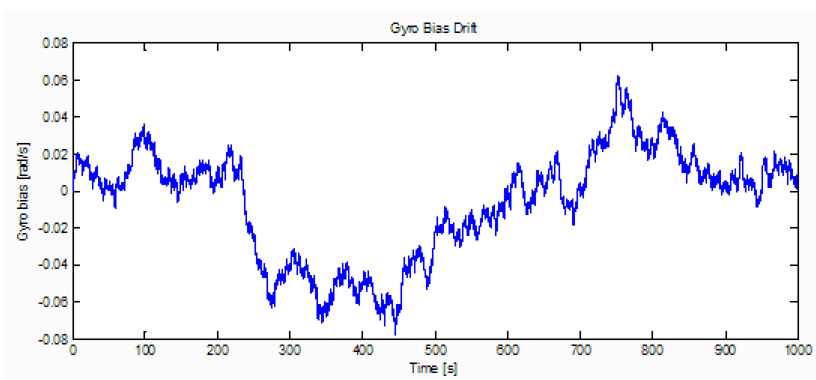

Figure 5 - Gyro Bias Drift

This walk may not be centered around the original bias, in other words the time average over a specified window will drift with time. Since this bias drift cannot be calibrated out in the laboratory directly many high-end industrial grade AHRS systems will use onboard sensor fusion algorithms to "calibrate" the gyro bias in real-time using the measurements made by the accelerometer and magnetometer. Not all industrial grade AHRS sensors on the market provide this feature. All VectorNav products utilize this real-time gyro bias capability to provide optimum performance.

Gyroscope Scale Factor

th of a degree are required. This translates into machining accuracy on the jig on better than 1 thousandth of an inch (1 mil) per linear inch. Along with our precision calibration equipment VectorNav has 3-axis CNC machining equipment which allows us to develop in-house custom calibration jigs to interface various sensor packages with our calibration equipment.

Grade	Gyro Scale Factor Error [ppm]	Angle Error [deg]
Industrial	500	0.18
Automotive	60000	22

As you can see without a gyro scale factor calibration, the MEMS gyro could be up to 22 degrees off after integrating this motion. After performing a thorough scale factor calibration, the errors can be reduced by 100X or two orders of magnitude.

Gyro scale factor is calibrated by rotating the gyro around each sensor axis at known angular rates. Linear least squares is then used to calculate the best fit linear scale factor to fit this data. A routine almost identical to the 4-point or 6-point tumble test can be performed on the rate table to calibrate both the accelerometer and gyro simultaneously.

Gyroscope Misalignment

Gyro misalignment accounts for the fact that each gyro axis may not be exactly perpendicular with the other gyro axes. As such each axis will have a slight sensitivity to rotations about the other two axes. To calibrate out the misalignments on the gyro, angular rates must be recorded in a positive and negative direction around each axes and fed into a linear least squares algorithm. For systems with very precise gyros, a second order model can be used to re-capture some of the inherent non-linearity in the gyro sensitivity. For normal MEMS gyros the 12 linear parameters will have a much stronger affect than the non-linearity.

To provide an example of how the gyro axis misalignment can result in orientation errors, consider the case given in the previous example where we rotate 360 degrees around the Z-axis. Since the X-axis and Y-axis outputs will be sensitive to Z-axis rotations, if left uncorrected the X and Y axis gyros will incorrectly measure non-zero rotation rates. This upon integration will lead to errors in the calculated orientation angles from these incorrectly measured X and Y rotations.

Grade	Magnetometer Cross-axis Error [%]	Heading Error [deg]
Industrial	0.1	0.057
Automotive	0.3	0.17

The above table shows that if left un-calibrated a automotive grade IMU could see as much as 3.6 degrees error in orientation for this simple maneuver. After performing a misalignment calibration, the estimate for the gyro axis alignment can be improved 10X, or by an order of magnitude. More precise calibrations are possible by assuming a non-linear model, although this will significantly increase the number of overall calibration parameters.

Gyroscope Sensitivity to Linear Acceleration

The output of MEMs gyros do exhibit some sensitivity to linear accelerations. This interdependence is very small and for most application that do not undergo large static accelerations larger than gravity for long periods of time, this interdependence can usually safely be ignored. For the sake of completeness VectorNav does provide the gyro sensitivity to linear acceleration calibration parameters as part of our gyro sensor model. During factory calibration we do subject the gyros to varying linear accelerations and estimate these calibration parameters using least-squares estimation. The gyro model includes the sensitivity to linear accelerations as a full 3x3 matrix located next to the bias terms.

$$\omega = \begin{bmatrix} 1 & M_{XY} & M_{XZ} \\ M_{YX} & 1 & M_{YZ} \\ M_{ZX} & M_{ZY} & 1 \end{bmatrix} * \begin{bmatrix} \frac{1}{S_X} & 0 & 0 \\ 0 & \frac{1}{S_Y} & 0 \\ 0 & 0 & \frac{1}{S_Z} \end{bmatrix} \left(\begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} - \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} - \begin{bmatrix} H_{xx} & H_{xy} & H_{xz} \\ H_{yx} & H_{yy} & H_{yz} \\ H_{zx} & H_{zy} & H_{zz} \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \right)$$

This written out as algebraic equations this gives

$$\omega_X = \frac{B_D + B_X - V_X}{S_X} + \frac{M_{XY}(B_D + B_Y - V_Y)}{S_Y} + \frac{M_{XZ}(B_D + B_Z - V_Z)}{S_Z}$$

$$\omega_Y = \frac{M_{YX}(B_D + B_X - V_X)}{S_X} + \frac{B_D + B_Y - V_Y}{S_Y} + \frac{M_{YZ}(B_D + B_Z - V_Z)}{S_Z}$$

$$\omega_Z = \frac{M_{ZX}(B_D + B_X - V_X)}{S_X} + \frac{M_{ZY}(B_D + B_Y - V_Y)}{S_Y} + \frac{B_D + B_Z - V_Z}{S_Z}$$

Magnetometer Calibration

Magnetometers are used to construct an orientation sensor known as an AHRS (Attitude Heading Reference System). To calibrate accurately a magnetometer a method is required of providing the sensor with known magnetic inputs for each sensor axis. Typically one of two methods is used to calibrate magnetometers. The first method involves the use of Helmholtz coils to produce a magnetic field in a known direction. Since the sensor will also be influenced by the earth's magnetic field, typically a 3-axis Helmholtz coil is used to produce an arbitrary magnetic field in any desired direction.

Figure 6 - 3-axis Helmholtz Coil

Helmholtz coils can be purchased either as open-loop or closed-loop systems. Closed loop systems utilize a calibrated 3-axis magnetometer sensor at the center of the coil which feeds back sensor measurements to dedicated 3-channel precision current controller which applies the necessarily current to each coil axis to maintain the desired magnetic field strength at the center of the coil. An open loop coil does not have a feedback loop and requires manual calibration. A closed loop Helmholtz coil will run you about \$60-\$100k for a full setup, while a open loop system can be obtained for about \$15k.

The second method of magnetometer calibration known as the swing method, consists of rotating the sensor around a known axis and capturing measurements at precise known heading angles. While this method may seem simpler and more cost effective than an expensive Helmholtz coil system, this method requires very tight control over magnetic disturbances due to surrounding magnetic objects. Any nearby objects which perturb the earth's magnetic field such as the electric motor in rotary stages or the parts inside the thermal chamber will create permanent errors in the magnetometer calibration process. Developing a magnetically clean calibration station can become a very daunting task and may require as much capital investment in custom rigging as would be spent on a closed-loop Helmholtz coil.

VectorNav utilizes both Helmholtz coils and a proprietary calibration algorithm along with a highly custom calibration stand to calibrate the magnetometer for scale factor, bias, and axis misalignment. Helmholtz coils are used to study the dynamic response of time-varying magnetic disturbances on the filter performance.

Magnetometer Bias

The magnetometer bias has an enormous impact upon the orientation accuracy performance of an AHRS. Small low cost AHRS sensors typically use AMR (Anisotropic Magneto Resistive) sensors to measure both magnetic field strength and direction. This type of sensor measures changes in resistance of the sensor element due to magnetic fields using a Wheatstone bridge. Due to the extremely small changes in resistance caused by the measured magnetic field, the resulting change in bridge voltage corresponds to +- 1.5mV over all possible rotations. Typically this signal is run through an op-amp to provide ~225 V/V signal amplification so that 14-16 bit ADC's can be used instead of expensive 24-bit ADCs. Since the actual voltage deflection is so small, it is entirely possible that the error in the magnetometer bias could be larger than the anticipated scale factor deflection of the magnetometer over the full orientation range. If this happens it will cause the magnetometer to not even work correctly and will lead to enormous non-linearity's in the outputs. In this case there will be orientations that are not even reachable due to the incorrectly calibrated magnetometer. This case corresponds to the 3D sensor bias existing outside the measurement sphere. For this reason is is absolutely imperative that the magnetometer bias is calibrated prior to use as an AHRS. Magnetometer sensors provided by Honeywell utilize a Set/Reset function that allows for dynamic reversal of the sensor sensitivity axis, thus providing a real-time means of nulling out the magnetometer bias. If this procedure is properly used then it will eliminate the need to calibrate the magnetometer bias. It will also drastically reduce the errors due magnetometer bias change with temperature. All VectorNav sensors utilize this Set/Reset function provided by Honeywell magnetic sensors.

	Magnetometer Bias Error	Heading Error
Grade	**[%]**	**[deg]**
Industrial	3	0.17
Automotive	125	8.2

Magnetometer Bias Sensitivity to Temperature

Both the bias and scale factor for magnetometers are strongly a function of temperature. To get high accuracy performance at temperatures beyond room temperature you will need to account for this temperature dependence in the calibration parameters. This is accomplished by performing magnetic calibrations using either the Helmholtz coil or the swing method at various temperatures. If the Helmholtz coil is used then you will likely need to have custom Helmholtz coils installed into the thermal chamber test section. These coils will either need to be closed-loop or they will need to be thermally calibrated themselves prior to operation. If the swing method is used instead then you will likely need to build a custom thermal chamber that is "magnetically clean" void of any magnetic disturbances. In practice this is very difficult to do and can be extremely difficult to implement correctly.

VectorNav utilizes highly customized calibration hardware to provide the capability to perform magnetically clean magnetometer calibrations inside a thermal chamber at set temperature of -40C, 0C, 40C, and 80C. All 12 magnetometer calibration parameters are fit to a 3rd order polynomial to account for non-linear temperature dependence.

Magnetometer Bias Change vs. Temperature								
	Temp Sensitivity	**Heading Error over Temp [deg]**						
Grade	**[mg/°C]**	**-40C**	**-20C**	**0C**	**20C**	**40C**	**60C**	**80C**
Mean	0.5	-1.86	-1.29	-0.72	-0.14	0.43	1.00	1.58
Max	1.5	-5.60	-3.87	-2.15	-0.43	1.29	3.01	4.73

The above table was constructed using actual calibration data from the VN-100T during thermal calibration. The mean and max errors represent both the mean and max errors observed on a batch of 16 VN-100T sensors. If the units were to have had only room-temperature calibration parameters loaded instead of thermally compensated parameters then on average they would have experienced 2 degrees heading error due to magnetometer bias shift over the temperature range. This small error is primarily due to the use of the Set/Reset provided by Honeywell sensors. If the Set/Reset was not utilized, then the average heading error would have likely been worse than 30 degrees. The maximum error recorded in the batch of 16 sensors was 5.6 degrees at a temperature of -40C.

Magnetometer Scale Factor

The magnetometer scale factor accounts for the sensitivity of the magnetometer sensor axis to varying magnetic fields in that same axis. In the simplest sense it can be calibrated using a procedure similar to the 4-point or 6-point tumble test described in the accelerometer calibration section. This tumble method however is difficult to perform in a thermal chamber, due to the requirement for a homogeneous magnetic field.

Magnetometer Scale Factor Change vs. Temperature								
	Temp Sensitivity	Heading Error over Temp [deg]						
Grade	[ppm/°C]	-40C	-20C	0C	20C	40C	60C	80C
Industrial	100	0.37	0.26	0.14	0.03	0.09	0.20	0.32
Automotive	3100	11.39	7.94	4.43	0.89	2.66	6.19	9.68

As shown in the above table, scale factor errors in the magnetometer can have considerable effects on the orientation accuracy for an AHRS. The data for the table was constructed considering a device oriented with a heading angle of 45 deg. In this orientation either a scale factor error in the X or Y axis will cause the measured magnetic field vector direction to shift in one direction. Worst case would correspond to a positive scale factor error in the X-axis and a negative scale factor error in the Y-axis. Scale factor errors that contribute equally to all axes cause errors in the measured magnitude of the magnetic field, however they do not cause errors in the measured direction. For this reason much of the scale factor variation with temperature which occurs equally to all three sensor axes will not affect the performance of an AHRS since it only uses the measured direction of the magnetic field and not its length to calculate orientation. Due to the high uncertainty in the scale factor errors for consumer grade magnetic sensors, performing a magnetometer scale factor calibration can reduce the uncertainty by two orders of magnitude, drastically reducing the resulting heading errors.

Magnetometer Scale Factor Temperature Sensitivity

The scale factor for the magnetometer is strongly a function of temperature. As mentioned previously since temperature variations that are in common between the three axes do not affect the vector's measured direction, much of this temperature dependence is avoided to a large extent. Each axis will have different temperature dependencies, and these will lead to errors in the calculated heading angle over temperature.

Magnetometer Scale Factor Change vs. Temperature								
	Temp Sensitivity	Heading Error over Temp [deg]						
Grade	[ppm/°C]	-40C	-20C	0C	20C	40C	60C	80C
Industrial	100	0.37	0.26	0.14	0.03	0.09	0.20	0.32
Automotive	3100	11.39	7.94	4.43	0.89	2.66	6.19	9.68

These scale factor temperature dependent errors can only be removed by performing a multiple magnetic calibrations at several different temperatures.

The VectorNav magnetometers are fully calibrated at four temperatures, -40C, 0C, 40C, and 80C inside a custom environment test chamber.

Magnetometer Misalignment

The misalignment parameters for the magnetometer account for the sensitivity of each axis to magnetic inputs in the other two sensor axis directions. The Honeywell AMR magnetic sensors provide exceptionally low cross-axis alignment errors, thus if you use a 3-axis magnetometer package such as their HMC1043 sensor, you might be able to get by without performing a axis misalignment calibration. If you use two separate sensors to measure the 3D magnetic field as done on the VN-100 with the HMC6042 and the HMC1041Z, you can get package-package misalignment which could be as high as several degrees and will definitely need to be compensated for. The HMC1041Z is very susceptible to installation axis alignment errors. While the HMC1041Z is an excellent magnetic sensor, its use necessitates a magnetometer axis alignment calibration.

	Magnetometer Cross-axis Error	Heading Error
Grade	[%]	[deg]
Industrial	0.1	0.057
Automotive	0.3	0.17

Magnetometer Misalignment Temperature Sensitivity

The magnetometer misalignment typically isn't a strong function of temperature, and in most cases can be safely ignored. The VectorNav sensors provide a 3rd order polynomial fit on all 12 magnetometer calibration parameters including magnetometer misalignment.

Conclusion

The process of performing a complete system level calibration on automotive grade MEMS inertial and magnetic sensors was described along with the benefits and maximum errors associated with each calibration term. As shown performing a complete calibration of automotive grade MEMS sensors can result in considerable performance and accuracy improvements. Hopefully this document will make it a little easier for you to determine whether industrial grade sensors are right for your application. If you need industrial grade sensors then I suggest you shop around, and find out more information from each of your potential providers as to what level of calibration they provide for their sensors. VectorNav Technologies have invested countless hours refining our calibration procedures so that we can provide the most accurate industrial grade surface mounted IMU and AHRS sensor on the market. Although there are some applications that would benefit from developing a custom calibration equipment to specifically suit their needs, the majority of projects can benefit from large NRE cost savings and quick time to market provided by the optimized system level calibration methods that VectorNav provides with each sensor.

References

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