Orthogonal perspectives

By Ian Beavers, Product Engineering Manager, Analog Devices

Question:

I am using a MEMS inertial measurement unit (IMU) in a self-balancing guidance control system for a personal transportation platform. Can I expect a consumer-targeted IMU to eliminate all misalignment errors between sensors if all the core sensor elements are on a single piece of silicon?

Answer:

No, this is generally not a safe expectation for your design. Industrial-grade IMUs, which use robust discrete sensors with optimal packaging and calibration, offer much better alignment precision than consumer-targeted IMUs residing on a single piece of silicon.

Consumer- and industrial-targeted IMUs tend to specify axis alignment behaviors differently. Consumer IMUs typically lump all misalignment errors into a single cross-axis sensitivity specification. Industrial ones, such as ADIS16490, specify alignment precision more directly using two different specifications: axis-to-axis misalignment error and axis-to-package misalignment error. The axis-to-package misalignment error describes how well the alignment in each axis relates to mechanical features within the IMU package. Axis-to-axis misalignment error describes how well the alignment of each accelerometer and gyroscope axis fits into the ideal case of mutual orthogonality. This is why the axis-to-axis misalignment error is commonly known as orthogonal error.

The mathematical relationship between cross-axis sensitivity (CAS) and axis-to-axis misalignment error (A2A_MAE) is:

$$\mathbf{CAS = \sin(A2A\_MAE)\quad A2A\_MAE = asin(CAS)} \tag{1}$$

The effect of non-orthogonality occurs between sensor axes, across sensors, or from package misalignment between sensors and their enclosure. On an industrial-targeted IMU, these specifications are fully described in the datasheet after factory calibration. For discrete components, the cross-axis sensitivity specification does not account for assembly variances for each PCB.

Ideally, multiple axes within gyroscopes and accelerometers are mutually orthogonal. However, it is a common misconception that, since a multi-axis gyroscope or accelerometer can be designed within one discrete MEMS component, each of the axes are perfectly orthogonal with the others. Although all inertial sensors in these devices are on a single piece of silicon, inherent errors introduced at fabrication and manufacturing variances can still accumulate an orthogonal error. The resulting

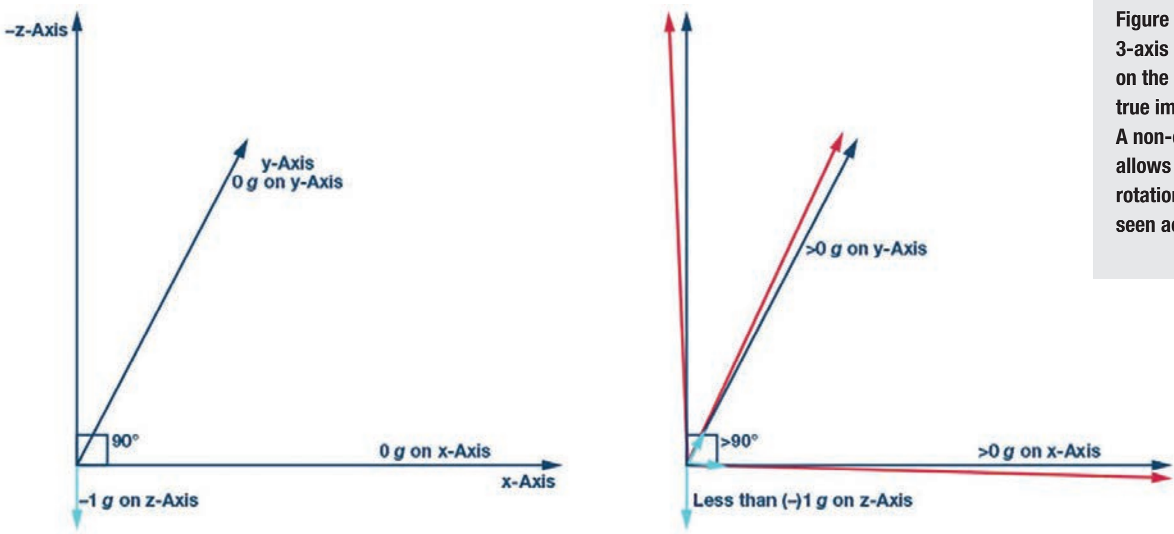

Figure 1: An ideal 3-axis orthogonal case on the left reflects the true impact of a vector. A non-orthogonal error allows leakage of rotation or force to be seen across all axes

equivalent alignment precision is actually not very impressive compared to fully-calibrated, industrial-specific IMUs.

A quick survey of consumer-targeted devices reveals that cross-axis sensitivity is often in the range of 1% to 5%. Using the relationship in Equation 1, the equivalent axis-to-axis misalignment errors are 0.57° to 2.87°. However, it could also be defined in units of milliradian, equal to 0.057°. Industrial-grade IMUs are typically much more precise.

We can also use this relationship to translate the axis-to-axis misalignment error of an industrial-targeted IMU of 0.018° into an equivalent cross-axis sensitivity of 0.031%:

$$\mathrm{CAS} = \sin(\mathrm{A2A\_MAE}) = \sin(0.018°) = 0.00031 = 0.031\%$$

Orthogonality errors

To understand the effect of non-orthogonal errors, let's assume that one accelerometer axis is pointed perfectly upward and the device is exactly level. The accelerometer on this z-axis is ideally measuring the total effect of gravity. If the other two axes were perfectly orthogonal, they would not measure any vector of gravity. However, due to non-orthogonality errors, the horizontal axis would measure some portion of the gravity vector. For example, if a device offers a cross-axis sensitivity of 1%, its equivalent response to gravity will be 10mg, which equates to an alignment error of 0.6°. Conversely, if the first axis is not orthogonal to the level frame, it will measure less than the complete gravity vector.

Orthogonality errors are especially stable components of the total error from an accelerometer. They may therefore yield to corrections based on one-time calibration.

To determine the orthogonality error of accelerometer axis pairs, the static response of each axis to gravity is measured as the accelerometer is rotated through all possible 90° orientations. This can be done using either a precision gimbal mount or on a known orthogonal surface.

It can be a challenging proposition to effectively calibrate out the orthogonal errors across the full operating conditions after mounting components onto a PCB. Inertial calibration requires observation of each sensor response, while the devices are experiencing well-controlled motion profiles. These types of profiles often require highly specialised equipment and expertise to operate effectively over time.

In contrast to an industrial-targeted IMU pre-calibrated for mounting, each mounted consumer MEMS device on a PCB would need to be calibrated against the other sensors, environmental performance and temperature.

Performance

Performance from an industrial IMU, with its three gyroscope axes and three accelerometer axes, leverages a calibration step after discrete components are mounted on a PCB in a rugged module. This single factory-calibration identifies and compensates not only for the non-orthogonality of the MEMS devices themselves, but also for any assembly related skew, minimising errors associated with variances from assembly, cross-axis and temperature. EW