Keywords: microelectromechanical inertial sensors, MEMS gyroscope, MEMS accelerometer, spacial disorientation

APPLICATION NOTE 5854

OVERCOMING DISORIENTATION: PRACTICAL WAYS TO ASSEMBLE MEMS INERTIAL SENSORS

By: Marc Smith, Principal Member of Technical Staff

Abstract: Component placement and mounting conditions can adversely affect MEMS inertial sensor performance. This application note contains practical considerations for enhancing sensor system operation where the "real-world" environment presents undesirable locomotive signals and system resonances. Topics include placement considerations on the PCB, external motion sources on the PCB (PCB resonance), and assembly mounting considerations.

A similar version of this article appears on *EDN*, June 4, 2014.

Introduction

Children and dogs effortlessly orient themselves and control gymnastic movements. Some might think that this is as easy as "child's play," until they try to make a machine or robot duplicate the feat. The human orientation system is marvelously complex and does a great job when we are on the ground. Conversely, while flying an airplane we are placed in an unfamiliar three-dimensional environment. That, combined with reduced visual orientation clues, can make spatial (dis)orientation difficult or impossible to manage. Between 5% and 10% of all general aviation accidents can be attributed to spatial disorientation, 90% of which are fatal.[1]

Microelectromechanical (MEMS) inertial sensors are sensitive to motion by design. They effectively detect and process linear acceleration, magnetic heading, altitude, and angular rate information. To fully exploit the performance potential of inertial sensors, designers must remain aware of the overall mechanical system, paying close attention to motion sources and resonances in the application.

In this article we describe how MEMS inertial sensors, e.g., gyroscopes and accelerometers, can help someone or something to overcome spatial disorientation. We explain how external forces and movement will impact system operation, and how component placement and mounting conditions—spatial relationships—directly affect the performance of a MEMS inertial sensor. Given the many different potential system configurations (e.g., board sizes, material, mounting methods), designers need to adapt unique solutions for each application. We show how to do this: to detect and mitigate erroneous inertial signals. We present practical advice for enhancing sensor system operation where, and when, the real-world environment presents undesirable locomotive signals and system resonances.

Understanding Balance, the Human Kind

We begin by discussing balance. Consider the human ear. In **Figure 1** the cochlea is the organ for hearing. The ear drum shakes the cochlea via some of the smallest bones on our body. The cochlea contains little hairs, or cilia, and it is filled with fluid. As the cochlea moves, the fluid does not move because of inertia. The cilia sense this difference of motion and transmit nerve impulses to our brain which are interpreted as

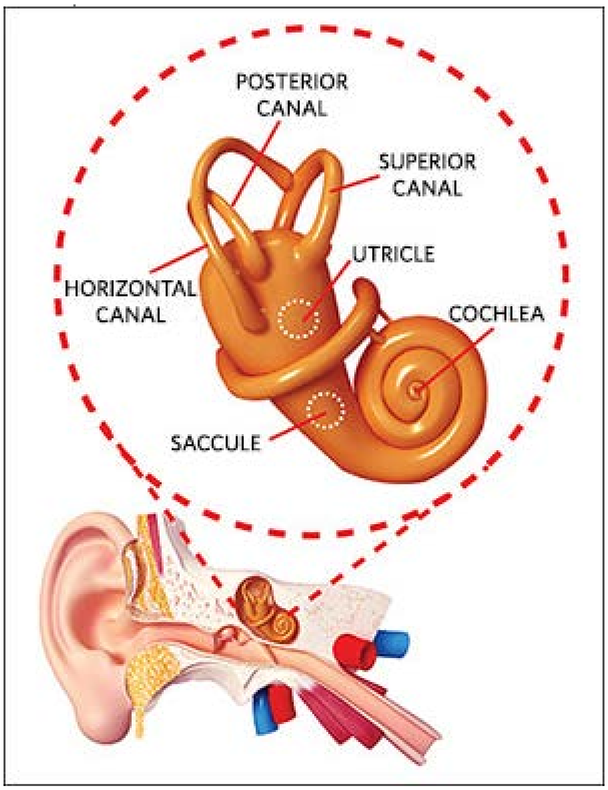

Figure 1. Human balance and hearing are part of the complex organs of equilibrium found in the inner ear.

The human ear also contains a motion detection system for equilibrium, also known as balance. Three semicircular canals, functioning similarly to perpendicular gyroscopes, detect and send impulse signals to the brain about one's state of balance. Unfortunately, there are limits to how we sense motion.

If the motion is less than about 2 degrees per second, we ignore it. If a smooth motion exists longer than 20 to 25 seconds, we stop sensing movement. These human limitations can cause confusion. There are two other sense organs in the inner ear: the utricule senses linear acceleration, and the saccule senses gravity. All five sensors in our ear help us with equilibrium or balance by informing our brain about our body's position and movement. This, along with our eyes, helps us maintain balance and keep our eyes focused on an object while our head is moving or the body rotating.

A Pilot and Spatial Orientation in Flight

Pilots need to be taught not to fly by the seat of their pants (i.e., not to rely on their internal senses). Instead, they need to rely on their flight instruments. This is a very difficult thing to learn, especially in emergency and panic situations.

According to the Federal Aviation Administration (FAA), pilots suffer from a common illusion called the Graveyard Spiral. This:

Is associated with a return to level flight following an intentional or unintentional prolonged bank turn. For example, a pilot who enters a banking turn to the left will initially have a sensation of a turn in the same direction. If the left turn continues (~20 seconds or more), the pilot will experience the sensation that the airplane is no longer turning to the left. At this point, if the pilot attempts to level the wings this action will produce a sensation that the airplane is turning and banking in the opposite direction (to the right). If the pilot believes the illusion of a right turn (which can be very compelling), he/she will reenter the original left turn in an attempt to counteract the sensation of a right turn. Unfortunately, while this is happening, the airplane is still turning to the left and losing altitude. Pulling the control yoke/stick and applying power while turning would not be a good idea–because it would only make the left turn tighter. If the pilot fails to recognize the illusion and does not level the wings, the airplane will continue turning left and losing altitude until it impacts the ground.[2]

The question is, could MEMS gyroscopes and accelerometers help a pilot to overcome spatial disorientation?

MEMS Inertial Sensors to the Rescue

The human body can be fooled and, in some cases, must rely on an external aid for good balance. With the body's susceptibility to spatial disorientation, MEMS inertial sensors offer a solution. Properly mounted inertial sensors can be used to establish an inertial frame reference, helping a user identify direction and/or movement. Using these devices can circumvent potentially flawed perception.

To ensure the operational robustness of inertial sensors, they must be mounted and oriented properly. There are good design practices for assembling inertial sensors and, when applied properly, they produce high-performance systems.

Practical Ways to Assemble MEMS Inertial Sensors

It is essential to understand a fundamental principle at the outset: in the presence of vibration, the location of an inertial sensor on a PCB *may* be a paramount consideration. Thus, how an inertial sensor is mounted, the conditions of the mount, and the location/orientation of its placement, all influence the overall mechanical system characteristics. Simply put, without appropriate design considerations, inertial signal performance will be diminished when subjected to motion.

Note that an analysis of the total mechanical system and its effects on inertial sensor performance is also highly recommended.

Placement Considerations

Let's start with orientation. Placing the inertial sensor relative to some datum (commonly done with reference to a selected PCB side), and maintaining that positioning through a surface-mount reflow process is a challenging effort. Moreover, each level of assembly (sensor to package, package to PCB, PCB to enclosure, etc.) increases alignment error. Because the sensor assembly orientation (relative to an inertial frame) sets system accuracy, any error here must be minimized. **Figure 2** illustrates the error of imperfect orientation. Software can calibrate out misalignment, but higher-order effects can diminish sensor performance if this error source is not bounded.

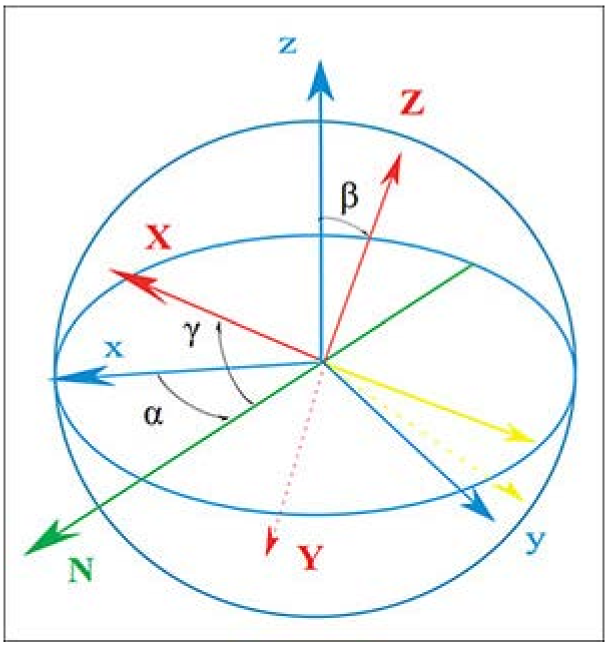

Figure 2. Illustration of inertial sensor misalignment. Graphic Attribution: Juansempere at en.wikipedia, http://en.wikipedia.org/wiki/File:Gimbaleuler2.svg. Also see http://en.wikipedia.org/wiki/Euler_angles.

Thermo-mechanical stress is an insidious source of error. It can expose itself as thermal gradients across the inertial sensor, causing package stress, and as thermal gradients in the PCB, transferring stress to the inertial sensor. These thermal effects are sometimes hard to discriminate and, in some cases, are both present. The result is package stress, which can cause bias (i.e., offset) and sensitivity performance errors. The placement of significant heat-generating devices should ideally be far from an inertial sensor, a criterion sometimes hard to meet in our world of compact PCB design. Regardless, every effort must be made to locate inertial sensors far from heat sources to minimize temperature gradients.

Assembly Considerations

Surface mounting of components requires knowledge and application of optimized temperature profiles for specific reflow jobs. While these operations typically focus on solder-joint strength, reliability, and throughput (i.e., cost), sometimes the special considerations of an inertial sensor can be overlooked. For example, a nonoptimized cool-down phase can potentially result in residual stresses to the inertial sensor's package. These stresses can degrade performance with out-of-spec bias and scale factor.

Conformal coating of PCBs is frequently used to protect electronic circuits from moisture, chemical contaminants (e.g., salts), and other disruptive effects. Conformal coating of inertial sensor devices is not recommended. It can change the sensor mechanical conditions and affect the overall mechanical system characteristic. Further, it is difficult to control conformal coat applications (i.e., viscosity, dried thickness).

Mechanical System Considerations

External motion sources (e.g., inertial signals, shocks, vibrations) can inadvertently stimulate PCB resonances. In the worse-case scenario, virtual inertial signals that are an artifact of a system resonance can occur. These erroneous signals act as noise, masking signals of interest (e.g., locomotive and/or vibratory). When a resonant condition occurs, the inertial sensor location relative to trough-node-crest wave positions on a PCB can result in degraded signal detection.

Figure 3 illustrates two possible placements for an inertial sensor on a PCB with a primary resonance mode highlighted. The lower left position displays a sensor in the (blue-green) nodal area. This is where resonant-associated angular rate signals are mitigated, compared to the sensor located in the upper right of the PCB. The second inertial sensor sits on an edge between the nodal area and an incline into a trough (shown in dark blue).This sensor is in an unbalanced-position, and more prone to acceleration and angular rate signal corruption in an excited resonance condition.

While there are many techniques available to mitigate PCB resonances (e.g., board stiffening, system damping, vibration isolation), a comprehensive analysis of the overall mechanical system should be conducted. A finite element analysis (FEA) should be performed to identify all potential resonant modes and their associated frequencies and Qs. Good design techniques can then be implemented to enhance performance.

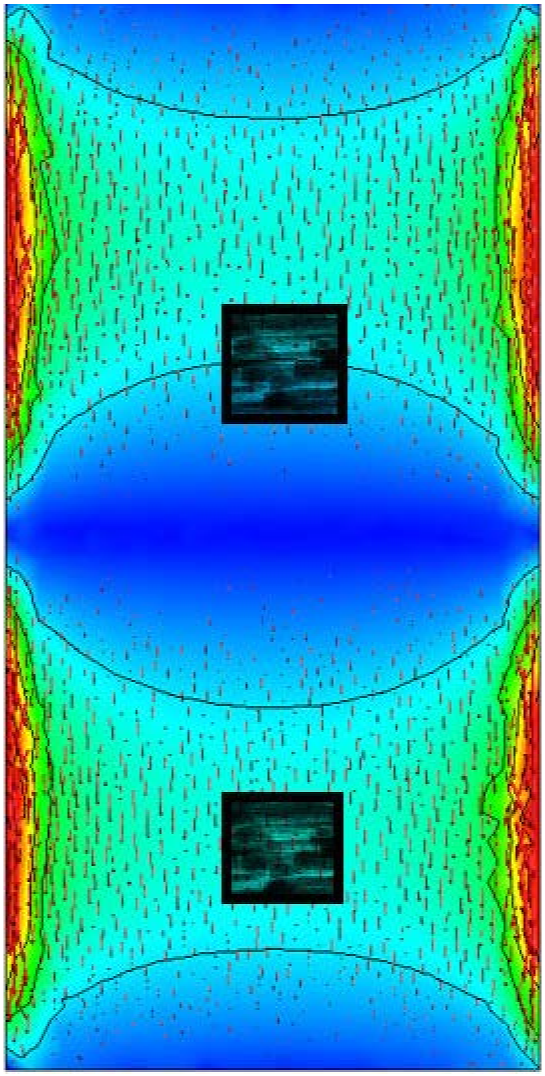

Figure 3. Simulation of PCB resonance and inertial sensor placement. The sensor in the lower nodal area is where resonant-associated angular rate signals are mitigated. The second sensor above is in an unbalanced position and more prone to acceleration and angular rate signal corruption. The PCB image is copyrighted and provided courtesy of FEKO. See www.feko.info/applications/white-papers/intelligent-design/CMA.

Conclusion

We examined motion, and understand the importance of a MEMS inertial sensor for helping to overcome spatial disorientation. We also discussed how the performance of MEMS inertial sensors can be negatively affected by poor and nonideal placement, mounting conditions, and system resonances.

Maxim Integrated offers inertial sensor products with both high accuracy and stability. For example, the MAX21100 is a monolithic 3-axis gyroscope plus 3-axis accelerometer Inertial Measurement Unit (IMU) with integrated 9-axis sensor fusion using proprietary Motion Merging Engine (MME). This device is ideal for handset and tablet applications, game controllers, motion remote controls, and other consumer devices. By following proper design considerations, you can “navigate” around these “rocky” occurrences and achieve the performance that you expect from a MEMS inertial sensor.

References

1. Antunano, Melchor J., "FAA: Medical Facts for Pilots," Federal Aviation Administration. Retrieved 8 Dec 2011, www.faa.gov/pilots/safety/pilotsafetybrochures/media/SpatialD.pdf#page=1&zoom=auto,-7,0
2. Ibid, page 5.

Related Parts		
MAX21100	Low-Power, Ultra-Accurate 6+3 DoF IMU	Free Samples

More Information
For Technical Support: http://www.maximintegrated.com/en/support
For Samples: http://www.maximintegrated.com/en/samples
Other Questions and Comments: http://www.maximintegrated.com/en/contact

Application Note 5854: http://www.maximintegrated.com/en/an5854
APPLICATION NOTE 5854, AN5854, AN 5854, APP5854, Appnote5854, Appnote 5854