Sensor data fusion: a key component for enhancing gaming, navigation and virtual reality experiences

By Kaustubh Gandhi, Product Manager Software, Bosch Sensortec, co-authored with Amithash Kankanallu Jagadish, System Engineer Sensor Data Fusion software, Bosch Sensortec

Introduction

Whether it be smartphones, wearables, virtual reality headsets or even robotic vacuum cleaners, today's users expect and demand such devices to consistently behave as commanded, to smoothly and accurately adapt to their changing surrounding environments. This requires precise sensing of pitch, roll and heading, which is formulated inside their devices by fusing data collected from accelerometers, gyroscopes and magnetometers.

As is usually the case, in the real world, things are never as simple as they seem, for example, accurately determining the heading (observation) direction is a major challenge as magnetometer measurements are negatively affected by multiple objects in their vicinity. These undesirable magnetic influences, commonly known as hard and soft iron distortions, can be caused by various elements located both within the device itself and external magnetic objects in the user's immediate environment.

This article aims to provide deeper insight and understanding into effective design techniques and software solutions required for obtaining reliable sensor data in today's electronic consumer devices, and to improve user satisfaction with the final product. This article will provide examples of powerful sensor data fusion techniques such as the utilization of estimated magnetometer offsets based on gyroscope signals obtained during standard use and the impact of this on user-relevant features such as pedestrian and head tracking.

The magnetic challenge

Have you ever taken the wrong exit from a roundabout because of wrong directions given by a smartphone navigation app? Have you ever experienced a sudden nauseating bout of motion sickness when using a virtual reality headset? Or has your 'smart' robotic vacuum cleaner been repeatedly getting stuck in corners? Most of these issues are, at least partially, the result of incorrect heading information derived from imprecise inertial sensor data fusion. So, why do highly precise state-of-the-art sensors still register inaccurate information, and with such wide deviations?

Outside the laboratory, the rigidly straight lines of the Earth's supposedly constant magnetic field are constantly being modified by various objects such as door frames, tables, chairs and other metallic items. Based on their specific magnetic characteristics, these objects alter their surrounding magnetic field through phenomena known as hard iron and soft iron distortions.

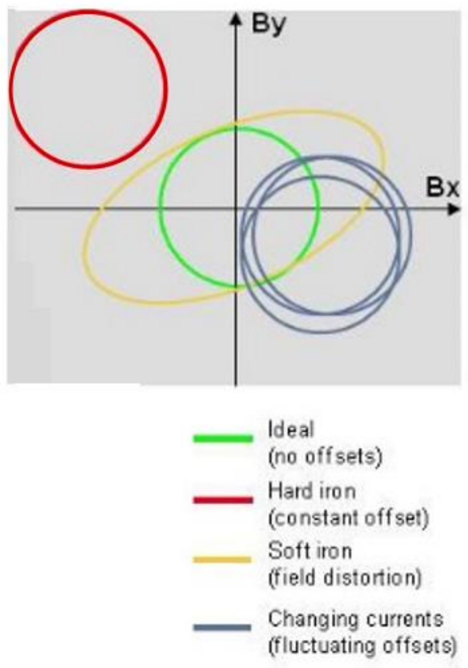

Figure 1: Sources of compass errors: external magnetic fields

Hard magnetic materials ("hard iron") such as NdFeB, AlNiCo induce a high remnant B-field or "magnetic memory", whereas soft magnetic materials ("soft iron") are typically materials such as Iron (Fe), Nickel (Ni) and their respective alloys.

When magnetometers are used in devices, hard iron distortions are created by objects that generate a magnetic field, e.g. magnets inside a speaker, resulting in a bias known as a 'constant offset' in the sensor output, which then needs to be compensated for. On the other hand, soft iron distortions are created by objects that 'passively' affect or distort their surrounding magnetic field but do not necessarily generate a magnetic field themselves, e.g. memory card slots, batteries, wireless antennae, door and window frames and various other standard objects in the ambient environment. This type of distortion alters the actual shape of the magnetic sphere and is largely dependent upon the orientation of the material relative to the sensor and the magnetic field.
As shown in figure 2, in a typical indoor area, due to magnetic field distortions caused by the presence of common objects, the compass heading varies significantly, i.e. the red 'north' needle of the compass points wildly in all directions.

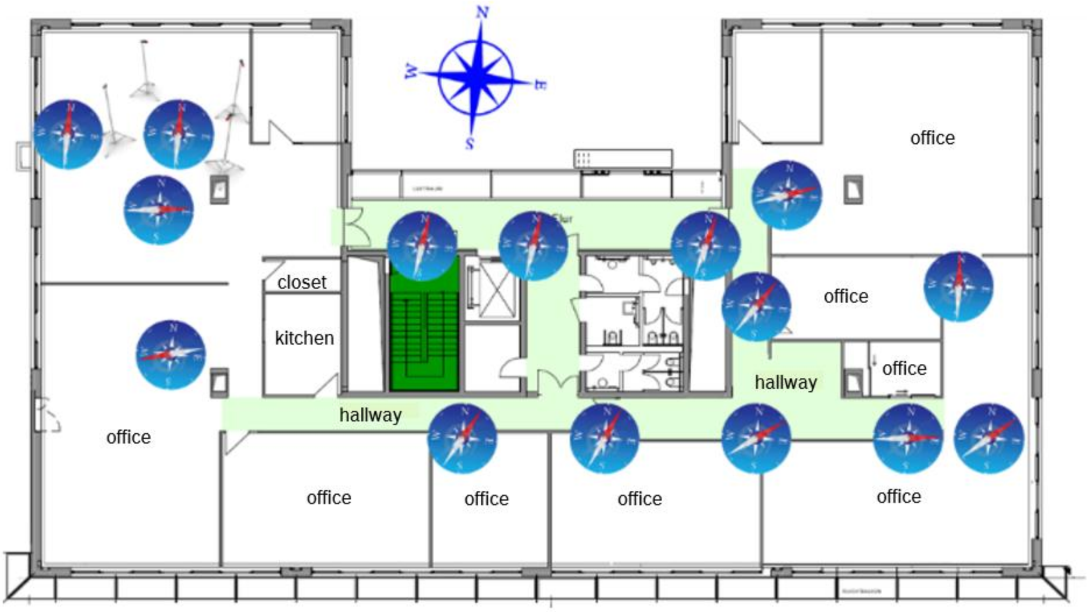

Figure 2: Variations in sensor readings (magnetometer) in a typical indoor area

Thus, compensating for both hard- and soft-iron distortions is critically important for achieving meaningful magnetometer readings. This compensation requires a sophisticated procedure during the design of the device and the incorporation of the outcome into the sensor's software during actual use, as further described in this article.

Embracing distortions

The following systematic approaches are used to compensate for distortions affecting magnetometer readings:

- In-design compensation using a soft iron matrix
- In-use calibration software with standard 'figure-of-eight movements'
- Smart calibration software with 'natural-use movements'

In-design compensation using a soft iron matrix

Soft iron distortions coming from components located inside an end-device, such as a smartphone, are constant, and hence can be compensated for by utilizing a one-off solution. Such compensation requires a so-called "Soft Iron Compensation Matrix" (SIC Matrix), where the designer has a wider range of placement options within the device. These compensated sensor readings have a substantially higher accuracy, i.e. ±2° compared to uncompensated readings where the error range can easily reach ±10°. Calibration is performed using a 3D coil system (Helmholtz coils), which consists of two solenoid electromagnets aligned on the same axis, which cancel out these undesirable external magnetic fields to provide a "clean" magnetic environment. The device with inertial sensors is placed into this clean environment and measurements are taken to create a raw data log for the magnetometer, which is then subsequently fed into a data driven tool, to generate a SIC Matrix. This SIC matrix is then incorporated into the software driver and permanently compensates for the in-device soft iron distortions affecting magnetometer data.

Since this method estimates soft iron effects under laboratory conditions, naturally, after market changes and effects of add-ons cannot be compensated for. Nevertheless, this is a very effective technique for in-device component calibration and is highly recommended during the design phase in conjunction with experts from sensor manufacturers who can accurately generate SIC matrices and apply them.

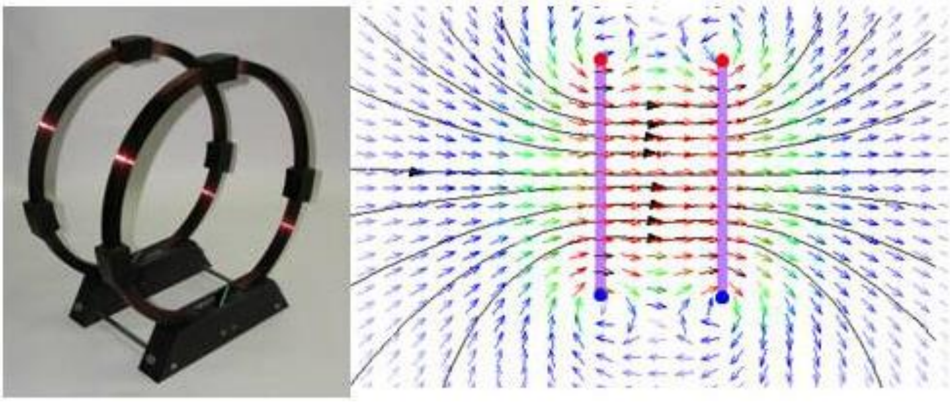

Figure 3: 3D (Helmholtz) coils for in-device magnetometer calibration

Unfortunately, it is often the case that laboratory calibration results simply do not work accurately when applied to an actual PCB, where areas known as 'forbidden zones' are created, rendering such devices so inaccurate as to make them practically unusable.

Bosch Sensortec's 3D soft iron compensation technique reduces this 'forbidden zone' substantially. For example, when distortion of sensor data was measured just 9 mm from an NFC antenna, before compensation, the maximum heading error was 8°; whereas, after compensation, the maximum error at all altitudes was just 1.5°.

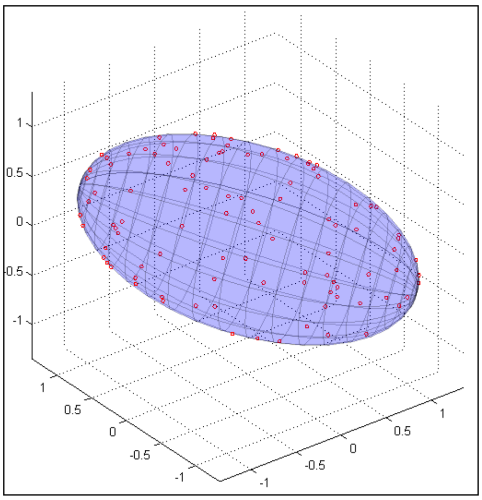

Figure 4: Magnetic sphere without soft iron compensation

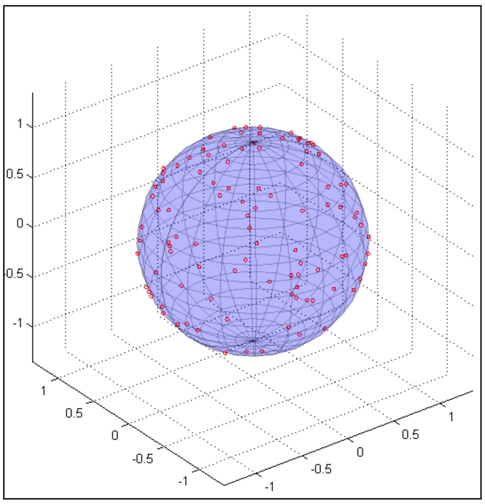

Figure 5: Magnetic sphere with soft iron compensation

In-use calibration using "figure-of-eight" movements

This method is not as laboratory-intensive but can still be used to collect a large amount of valuable data simply by moving the device (such as a smartphone) within a known magnetically clean environment. A good movement is one that measures magnetism along the largest range of orientations and can, therefore, help estimate magnetic deviations for all cases. Hence, this technique is usually performed using the figure-of-eight motion covering all three axial dimensions.

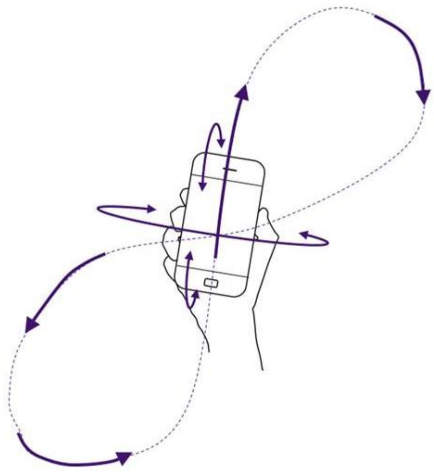

Figure 6: Following a figure-of-eight pattern in 3D space with a smartphone

This pattern traces out parts of the magnetic sphere deformed by magnetic distortions. From the obtained coordinates, the deformation of the magnetic sphere can be quite accurately estimated in order to derive the required calibration coefficients. The offset estimated using this method is used to compensate for hard iron distortions coming from the external environment.

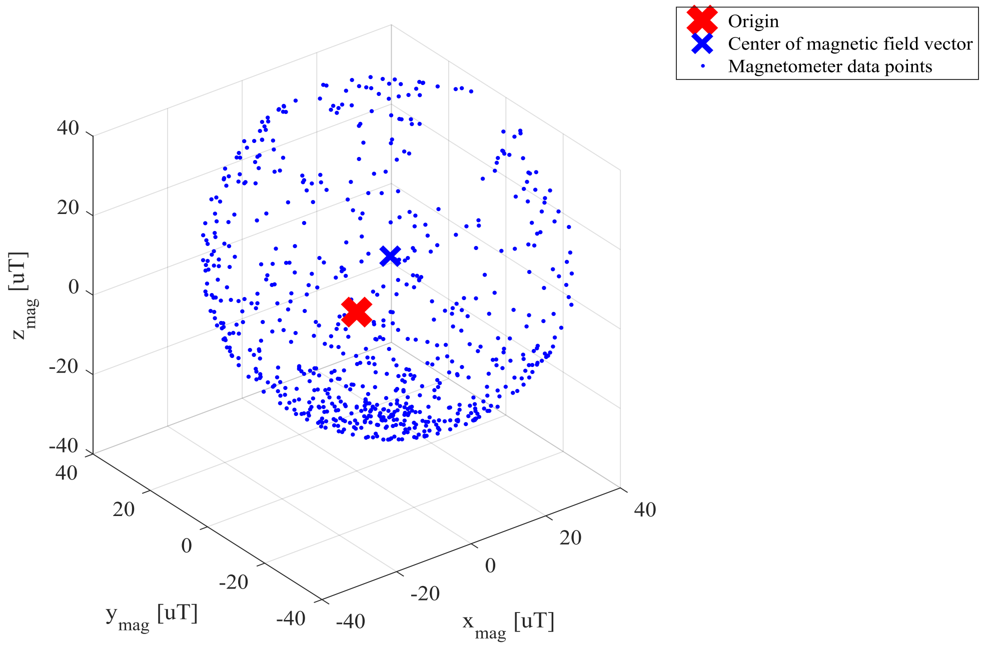

Figure: 7: Sensor data without offset-compensation

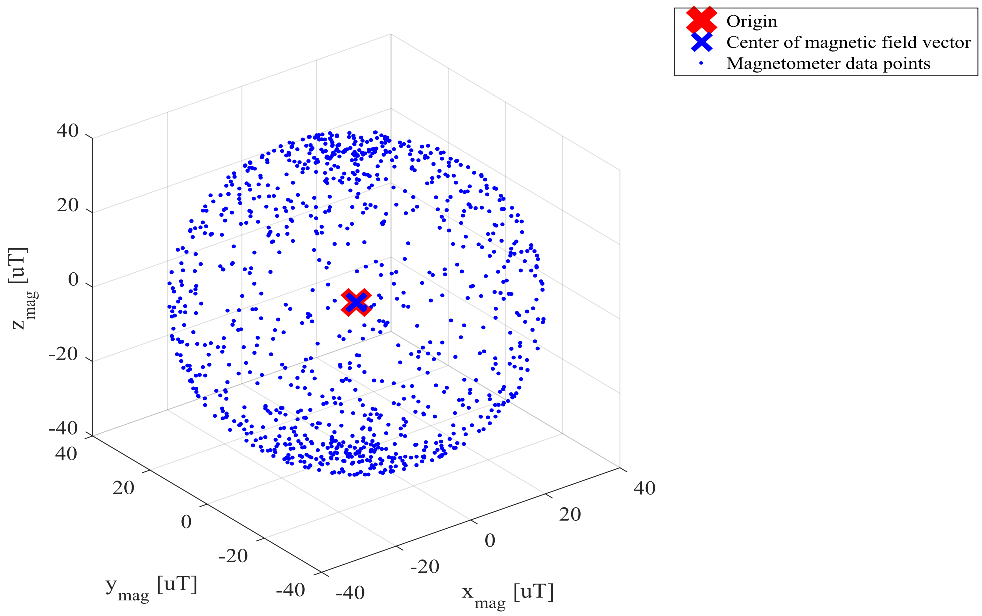

Figure 8: Sensor data with offset-compensation

A considerable number of smartphone device and operating system manufacturers still rely on this figure of eight calibration technique. For calibration purposes, today's smartphones often prompt the end-user using a map application to make figure of eight movements in the air. However, creating this pattern by moving the device in 3D space may take well over 10 seconds, and if the user is using their phone for a time critical purpose, such as playing an action game, or safety-critical task such as navigating a car with the smartphone, then it may simply be too awkward to pause the game or too risky to focus away from steering the car to recalibrate the device.

This method is, of course, commonly recommended to users since it delivers reliable results. However, it is applicable only if they can actually spend the time to recalibrate their device and if it is physically possible to move the device in such a pattern through 3D space.

Smart calibration using "natural-use" movements

Although the figure-of-eight movement may be quite suitable for smartphones, it may not be physically feasible and may feel un-natural for other types of devices such as wrist-wearables, augmented/virtual reality headsets, in-ear hearables and robot vacuum cleaners.

The basic idea behind magnetometer calibration is to estimate the offsets of the magnetometer by estimating the offset of the magnetic sphere from the Earth's magnetic field vector as a radius. In order to reduce the time required for calibration and to enable smaller more natural movements to calibrate the device, gyroscope signals are used to assist in the calibration of the magnetic field sensor.

The corrected gyroscope signal defines its rotation relative to the last magnetic field value. Once the new magnetic field value is determined, it is fed into an Extended Kalman filter (EKF). The EKF estimates the magnetometer offset and the magnitude (radius) of the magnetic field vector. Magnetometer disturbances are detected based on the Kalman Filter residual.

Since these fast traditional-type magnetometer calibrators utilize gyroscope data, the device being calibrated must be at rest during the recalibration process, i.e. the gyroscope itself is not drifting during calibration. This, however, is not feasible with newer 'body-worn' devices, as they are continuously in use and in motion, and mostly for long continuous stretches of time.

Having defined the problem, Bosch Sensortec has focused on meeting the challenge head-on by developing "natural-use" fast magnetometer calibration software that is configured to the typical uses of each of the different types of devices, even when they are in constant motion. The objective is to ensure that even without any specific, intentional action from user, the inertial sensor in a device is automatically and accurately calibrated for use across changing environments.

Several examples with wearables, controllers and headsets are explained below:

Wrist-wearables

For a person wearing a wrist watch or fitness tracker, it is quite natural to take frequent glances at their device, to check counted steps or calories burnt, or to read message notifications or to simply check the time. Since most users have no idea that they are in the vicinity of materials affecting their magnetometer or that a magnetometer is even installed in their device, calibration needs to be performed in the background, without their knowledge. Furthermore, it would look strange if users started waving their hands around in the air to calibrate their 'smartwatch'. Therefore, the Bosch Sensortec magnetometer calibrator works silently in the background, compensating magnetometer offsets whenever the user 'looks' at their wrist.

It has been statistically proven that this wearable-specific fast magnetometer calibrator can estimate the offset in as few as two or three 'looks' at the device, running at both typical and lower data rates.

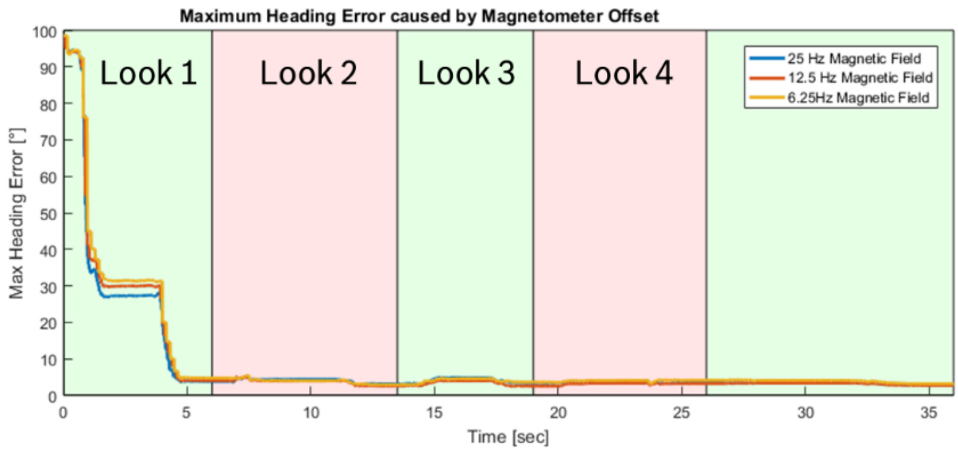

Figure 9: Systematic elimination of heading errors in wrist wearables

This calibration procedure is effective with both indoor as well as outdoor navigation applications. For example, a PDR (Pedestrian Dead Reckoning) application that estimates a user's position and a walk trajectory using 9-axis inertial sensors has a substantially higher accuracy with the calibrator activated. The example below clearly shows that while both trajectory estimates started at 0.0, a cumulative heading error on the uncalibrated device resulted in a positional error of over 43%, over a standard short walking distance of approx. 2x200m.

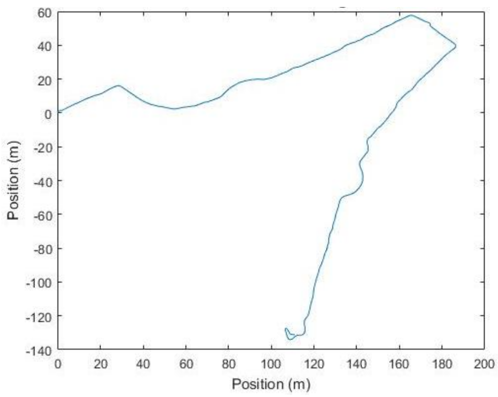

Figure 10: PDR trajectory without magnetometer recalibration

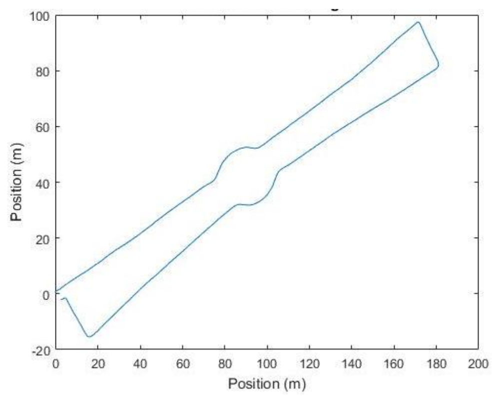

Figure 11: PDR trajectory with magnetometer recalibration

Virtual and Augmented Reality headsets

Similarly, one also cannot expect users of virtual reality headsets to regularly move their heads in a figure-of-eight motion, especially when wearing their headsets. Specifically, in the case of headsets, since the brain registers the misalignment between the user's actual motion and the visual images seen on the screen, even relatively minor heading and horizontal tilt deviations may result in very unpleasant motion sickness symptoms.

Bosch Sensortec's headset magnetometer calibrator calibrates the magnetometer while the user naturally moves their head around the axis of their neck. The positive effect of calibration has clearly been demonstrated in head tracking algorithms and key performance heading results in multiple AR/VR sub-use cases.

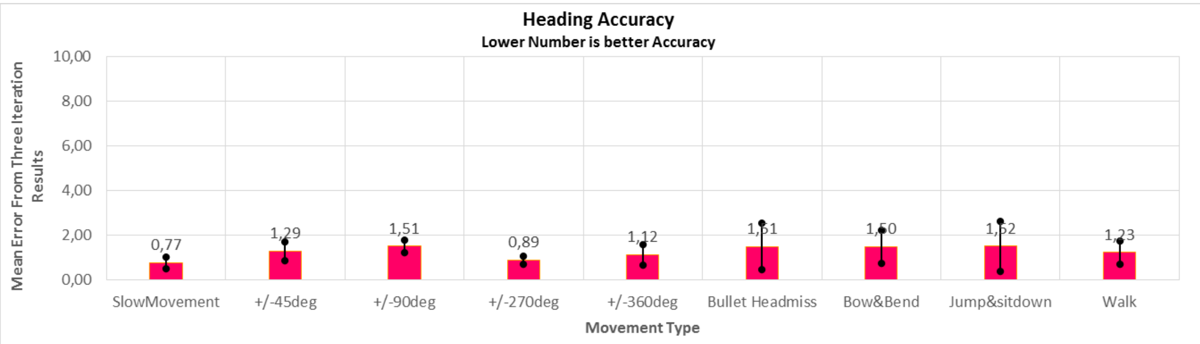

Figure 12: AR/VR Headset - dynamic movements with magnetometer calibration

Gaming control pads, VR / TV remote controls

As orientation sensors penetrated into more and more TV remote controls, and as VR remote controls and gaming control pads started offering increasingly more sophisticated services to app developers, it became crucially important to collect accurate and reliable heading data and to harmonize true north with the content display device. This problem becomes most evident when the user, holding the control device in their hand, observes a drift in the heading of the pointer despite their hand being still, or sees the cursor move in a direction differing from their actual hand motion.

Here again, Bosch Sensortec's magnetometer calibrator takes into account natural movements of the remote control or game control pad and greatly reduces the deviation in heading, as seen from the actual data presented below.

Figure 13: Gaming control pad / VR remote control accuracy with magnetometer calibration

Summary

A combination of the 3D coil and data driven tools is used to create and utilize a SIC matrix, which together with user-interfaces informing users about figure-of-eight movements and the integration of natural-use fast magnetometer calibrator software now substantially improves the reliability of 9-axis sensor data fusion. This is significant, as magnetometer accuracy and sensor data fusion are key elements deployed across a wide spectrum of devices ranging from smartphones to wearables, to AR/VR headsets and control units, and even robotic vacuum cleaners.

Bosch Sensortec’s 3D soft iron compensation reduces the 'forbidden zone' by as much as 70%, providing the designer and layout engineer far greater flexibility and assurance of accuracy and significantly reduces the need for re-prototyping of products.

Furthermore, in-use and smart calibration technologies greatly improve heading accuracy by mitigating the ubiquitous hard iron distortions present in the modern environment. While in-use calibration relies on users to make figure-of-eight movements in three-dimensional space, the smart calibrator developed by Bosch Sensortec can intelligently fuse sensor data collected during the natural use of a device to achieve the same result. For example, for wearable devices such as smartwatches, software improves pedestrian tracking reliability through sensor data fusion. On similar lines, by analyzing the various typical movements made by headset users, such as bullet head-miss, bow and bend, jump and sit-down, etc., Bosch Sensortec has achieved higher accuracy for sensor data fusion than other comparable solutions available on the market.

While improvements in heading accuracy are just one example of how sensor data fusion can improve the end-user experience, there are several other algorithms packed inside Bosch Sensortec’s sensor data fusion software that can help device makers to differentiate their devices and greatly improve the end-user experience.

Do you want to know more about sensor data fusion or give it a try?

For more information, visit the Bosch Sensortec website or contact us directly via the Bosch Sensortec contact form.