AN-5084
XKF3 - Low-Power, Optimal Estimation of 3D Orientation using Inertial and Magnetic Sensing

Summary

XKF3 is an algorithm based on Extended Kalman Filter theory, that fuses 3D inertial data (6D motion data) and 3D magnetometer data, also known as '9D' sensor fusion, to optimally estimate 3D orientation with respect to an Earth fixed coordinate frame. The input to XKF3 is provided by the AttitudeEngine™ of Fairchild's FIS1100 inertial sensor, which is a custom vector digital processor that computes the strap-down integrals to get orientation and velocity increments with high accuracy, synchronizes the optional magnetometer data, and streams the motion quantities at user selectable data rates at extremely low power consumption. XKF3 automatically calibrates for the most important sensor errors, and is able to successfully mitigate orientation errors caused by interferences such as transient accelerations or magnetic distortions. The combination of XKF3 and the AttitudeEngine enables accurate 3D motion tracking at a processor power consumption as low as 1 mA or less, offering flexibility and easy system integration. As such, this combination allows for the development of high accuracy motion tracking applications at extremely low power consumption.

Introduction

XKF3 is an algorithm that computes 3D orientation with respect to an Earth fixed frame. The computational core is based on Extended Kalman Filter theory and it fuses 3D inertial sensor data (orientation and velocity increments) and 3D magnetometer data, also known as '9D' sensor fusion. Xsens' second generation 9D sensor fusion algorithms, called XKF3, were developed in 2005 and have since then been improved using new insights from tracking theory and market feedback in real-life, demanding, applications [2]-[8].

The XKF3 algorithm has been used as part of Xsens' proprietary products or as a standalone library in a wide range of applications varying from consumer to industrial as well as military applications for over a decade (Figure 1). Examples of Xsens' products that use the XKF3 algorithm include the highly accurate IMUs, Attitude and Heading Reference Systems (AHRS) and GNSS/INS navigation systems for industrial applications [9]-[11] Figure 2, as well as the full-body wearable motion capture solution Xsens MVN [12] for real-time digitization of human motion Figure 3. In addition to Xsens' proprietary products, XKF3 is also used in combination with the FIS1100 inside Fairchild's AHRS, the FMT1000-series.

Figure 1. Left: Hocoma Valedo back pain therapy system. Middle: SAAB Unmanned Underwater Systems reconnaissance ROV. Right: SARAH UAV from Flying-Cam Inc. for film/broadcasting

Figure 2. Xsens Industrial Motion Trackers

XKF3 is not only able to compute the 3D orientation, but it also provides signals such as the acceleration in local frame (gravitational component removed), auto-calibrated angular velocity and local magnetic field.

This document gives an overview of the architecture of XKF3 in relation to the FIS1100, and the characteristics of XKF3 including performance and resources used.

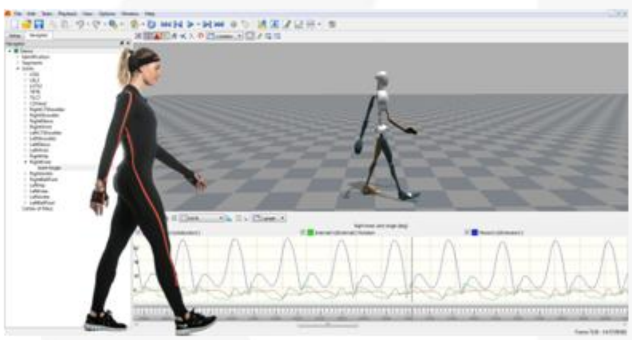

Figure 3. Xsens MVN full-body wearable motion capture solution

Architecture

XKF3 is a binary software library that accepts motion sensor data originating from the FIS1100 MEMS IMU. XKF3 will typically run on a (sensor hub) microcontroller (e.g. Cortex M class), or an Application Processor (e.g. Cortex A class or x86) as shown in Figure 4

Motion sensor data is delivered to XKF3 by the FIS1100 at a configurable rate. Inside the FIS1100, accelerometer data and gyroscope data are sampled at high frequency (1 kHz) and presented to the AttitudeEngine, where the strap-down integrals are calculated with high accuracy [1]. In addition, magnetometer data can be synchronized to the inertial data by the AttitudeEngine in order to get coning and sculling compensated orientation and velocity increments, along with optional magnetometer data at a low rate to be transferred to the XKF3 engine.

One of the advantages of the use of the AttitudeEngine, is the option to reduce its Output Data Rate (ODR) based on the application needs without the loss of accuracy [1]. Additionally, the AttitudeEngine offers an asynchronous option to acquire data from the sensor. This mechanism called Motion on Demand allows polling of the data at a time determined by the application [1].

The architecture presented in Figure 4 has a clear segmentation between the Strap-Down Integration (SDI) step, as part of the AttitudeEngine, and the state tracking step inside the XKF3 engine. The SDI calculations need to run at high rate (the AttitudeEngine performs SDI calculations at 1 kHz, see [1] for full details), whereas the actual XKF3 engine only needs to run at a much lower rate (≤10 Hz). This segmentation enables exceptionally low processor load, even when running in high accuracy 9D fusion mode and full auto-calibration.

It is important to note that the use of the magnetometer is optional. Based on just the FIS1100 without the magnetometer, XKF3 is able to estimate a 3D orientation. However, in this case the algorithm has no information to stabilize the heading which is then un-referenced and will (very slowly) drift around the vertical by design.

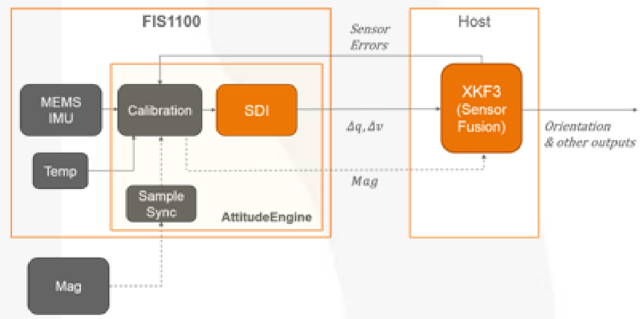

Figure 4. Overview of the architecture with a FIS1100 including the AttitudeEngine, calibration and an optional synchronized magnetometer delivering orientation and velocity increments (SDI data) to the XKF3 Engine that runs either on an Application Processor or a MCU sensor hub.

Characteristics

Coordinate Frames

XKF3 outputs 3D orientation with respect to a local Earth fixed frame based on the input data from the FIS1100 and a configuration file. The coordinate frame is defined as an orthogonal Cartesian coordinate frame which has one axes up along gravity, as shown in Figure 5.

The horizontal axes are defined using the local magnetic field, potentially corrected for declination[1]. The difference between applying and not applying the declination correction is that the latter represents the heading with respect to local (magnetic) North, whereas the first will represent the heading with respect to true North.

[1] In case the magnetometer is not present, the horizontal axes are defined orthogonal to the vertical axes, starting at zero heading.

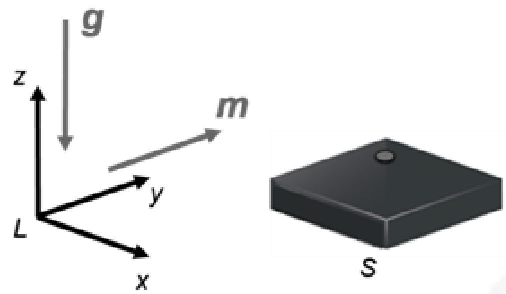

Figure 5. Local coordinate frame (L), with the vertical axis defined by gravity (g). Horizontal axes defined by the magnetic field (m). Orientation of the FIS1100 is identified by pin1, indicated by the grey dot on the FIS1100 sensor (S).

Underlying Principles

In a situation in which a well-calibrated IMU is kept still in an environment with no nearby ferromagnetic materials in the vicinity, the 3D orientation can be straightforwardly computed using the signals from an accelerometer and a magnetometer, much like using a water level and a compass needle. However, when the sensor rotates or is moved around, just the accelerometer and magnetometer are not sufficient anymore. To accurately track the 3D orientation, the use of a gyroscope is essential. The process to combine the information from these different sources of information is called sensor fusion, accomplished by XKF3, which is far from trivial as will become clear in the following.

As schematically shown in Figure 6, the signals used by XKF3 are complementary to each other by nature. The gravitational and magnetic components give stabilizing information on the long term, while the gyroscope and accelerometer, pre-processed by the AttitudeEngine, give high-bandwidth, responsive movement signals. Continuous integration of inertial sensing signals using the AttitudeEngine captures movements that are short-term accurate, high-bandwidth and high in resolution. However, inevitably the inherent integration drift grows over time. This drift is stabilized by applying some carefully chosen and precisely formulated assumptions on the dynamics and sensor characteristics providing the 3D orientation in real-time while the sensor is being calibrated.

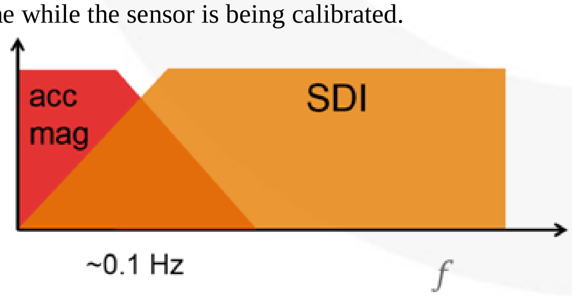

Figure 6. Complementary nature of signals used in XKF3. The horizontal axis shows the frequency for which each information source is suitable. For short periods of time, SDI data provided by the AttitudeEngine is ideal, whereas for longer periods of time, models based on gravitational and magnetic components provide stabilization.

Tracking Loop

The sensor data from the FIS1100 and the principles discussed in the previous paragraph are combined in an Extended Kalman filter (Bayesian) framework as schematically depicted in Figure 7. The AttitudeEngine provides the orientation and velocity increments which are used by XKF3 to predict the orientation as well as several variables related to the sensor and the environment. The models used in XKF3 give sufficient information not only to stabilize the orientation, but also to track back the cause of any strap-down integration errors to calibration parameters of the sensors. These calibration parameters can optionally be sent back to the FIS1100 to correct the measured sensor signals on-chip.

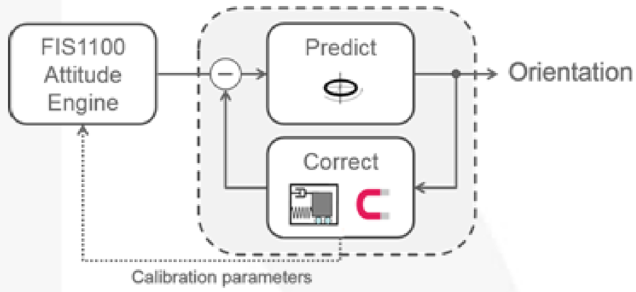

Figure 7. Two-step tracking loop of XKF3 consisting of a prediction and correction step.

Continuous Sensor Auto Calibration

Continuous sensor auto calibration is an essential feature for 9D sensor fusion since it enables a great user experience for motion sensing in terms of accuracy, consistency robustness and fluidity. Auto calibration is necessary because the sensors exhibit fundamental (stochastic) processes that change their output over time, irrespective of the actual physical stimuli. The causes are many (temperature, mechanical stress, vibration, aging, etc.) and complex, but the result is essentially minute changes in calibration parameters over time that need to be auto-calibrated for.

XKF3 calibrates for the most important sensor errors, automatically and transparently to the user without the need to interrupt the user in his task.

One of the most challenging tasks is to make full use of the 3D magnetometer data. The magnetic “environment” of the sensor continuously changes due to magnetization of the device itself, due to varying currents in nearby components or speakers and due to changes in the physical shape of the device itself (clamshell handsets, slider handsets, notebook lid open/close, robotic grippers, etc.).

For the best user experience it is important that XKF3 automatically calibrates for these effects, collectively referred to as hard and soft iron effects. XKF3 features a zero user interaction magnetometer calibration that operates continuously during normal use. The algorithm ensures that there is no need for user interruptions, ensuring a smooth user experience, high accuracy and consistent performance. An example of the performance of the magnetometer auto-calibration in XKF3 is shown in Figure 8.

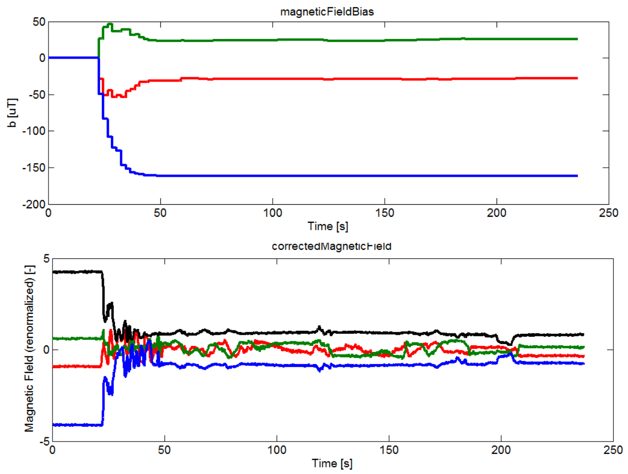

Figure 8. Output and corrected magnetic field of the magnetometer auto-calibration algorithm of XKF3. In the top graph, the estimated magnetic field bias for typical movement involving moderate rotation starting at about 25 s. The bottom graph shows the corrected magnetic field graph with the tracked bias applied.

User Scenarios

There are two main user scenarios for 3D orientation tracking:

1. NAVIGATION: tracking device 3D orientation with respect to a North referenced coordinate system for navigation, mapping, augmented reality, etc.
2. GAME_UI: tracking device 3D orientation un-referenced to North for gaming, UI, camera stabilization, etc.

The GAME_UI and NAVIGATION scenarios are similar in most aspects, but differ in the way the heading (yaw) is computed. Both use a magnetic field model describing the short-term magnetic variation as a combination of spatial and temporal disturbances on top of the earth magnetic field to compute a measure of heading. This means the magnetic field changes as a function of position (e.g. moving towards a source of magnetic distortion) and/or with time (a source of magnetic distortion moving with respect to the device). These models allow XKF3 to observe the heading under heavy magnetic distortions, as well as auto-calibrate the gyroscope bias and other parameters. The NAVIGATION scenario aims to track the true North where possible. In case of a non-initialized magnetometer auto-calibration in XKF3 at startup or varying magnetic disturbances, strap-down integration will keep the tracking solution stable as long as gyro integration allows for. However in case the magnetic field cannot be used for prolonged period of time, the tracking solution will converge to a solution based on the current local magnetic field. As soon as the magnetic North can be observed again with some accuracy, the heading estimate will converge as quickly as possible (with a jump) to true North.

The GAME_UI scenario aims to generate a 3D tracking solution with a very low heading drift, giving a smooth heading output, avoiding the fast heading adjustments that may occur in the navigation scenario. It is fully immune to magnetic disturbances. This user scenario works without magnetometer input but accuracy may improve if magnetometer data is available. The heading will exhibit slow but long term drift by design, but the drift will be much smaller than the drift obtained by simple gyroscope integration. The heading is initialized using the local magnetic field direction, if available.

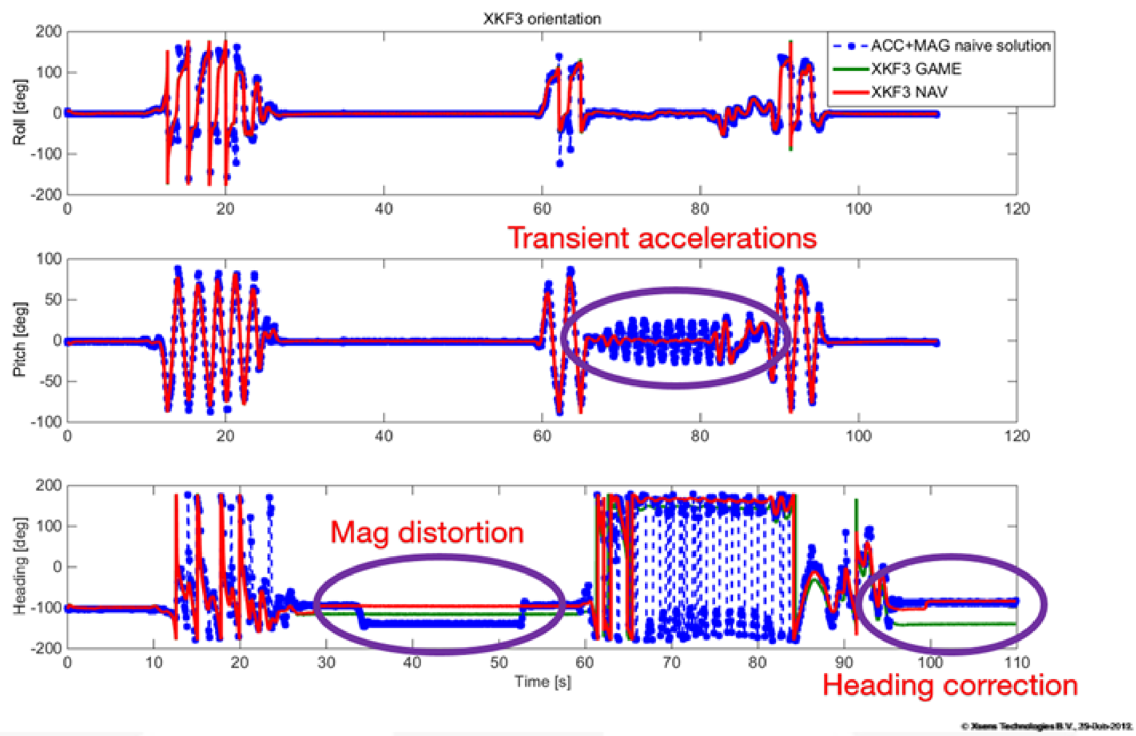

Figure 9. Example of estimated XKF3 orientation of NAVIGATION and GAME_UI scenario for a trial with transient accelerations and magnetic distortions.

Output Representation

XKF3 outputs a quaternion expressing the orientation of the sensor with respect to the Local coordinates. The orientation is given as a normalized unit quaternion q = [W X Y Z] with W the real component and X, Y, Z the imaginary parts. For easy interpretation, the quaternion is typically converted into Euler angles which are used to display the sensor 3D orientation.

Euler angles describe the rotation of a rigid body by means of three successive rotations in a particular sequence. The Euler angles used are ‘roll, pitch, and yaw’. The sequence of rotations for Euler angles follows the aerospace convention (Z-Y’-X’’ sequence) for rotation from the Local reference coordinate system L to the sensor coordinate system S.

Performance

Estimating roll and pitch to a level that “looks” accurate for the average user is relatively easy. By quickly converging to the accelerometer estimated vertical direction when there is no motion anymore, the casual user will get the feeling “it looks pretty accurate” (it is hard to look at a moving screen anyway). Hence, differences in roll and pitch accuracy between different algorithms only become evident upon closer inspection using a reference sensor under dynamic conditions. For the average user a higher accuracy on roll and pitch during dynamics will translate to a user experience that overlays “just look solid, not floating”.

The exact roll and pitch accuracy may not always be important for all applications. However it becomes critical when estimating 3D velocity and position (e.g. for PDR) or other advanced functionality such as fusion with pressure sensors (barometers) or GPS. In all cases gravity needs to be subtracted in the correct direction and the roll/pitch accuracy is then crucial. Especially when transient accelerations are present, and the low-frequent component measured by the accelerometer is not just gravity anymore, but includes significant linear or centripetal accelerations due to translation or rotations, inclination (roll/pitch) errors easily surface. XKF3 is built to handle these types of errors and is proven to handle transient accelerations and output accurate roll and pitch.

Estimating heading (a.k.a. yaw) that “looks and feels” accurate and consistent for the average user is much more challenging. To start, the Earth magnetic field that provides the reference direction is often (heavily) distorted by common materials in buildings (steel constructions, reinforced concrete), furniture, vehicles, surrounding electronic equipment and the (mobile) electronic device itself. The algorithm must deal efficiently with all these sources of error. Secondly, the user relies on the heading estimate provided when navigating through a building with all these distortions and can easily continuously monitor the output.

There are fundamental limits to the accuracy in heading that can be obtained using gyroscopes, accelerometers and magnetometers alone. XKF3 provides the most accurate heading estimate available given the input data and fundamental limitations. This is further enhanced by the use of the AttitudeEngine which enables the dead-reckoning to be extremely accurate and relied on for much longer periods of time when necessary, especially since the sensor errors are also auto-calibrated in the background. On top of this, XKF3 also implements years of practical application knowledge to present the user with a consistent heading output that matches the application, which becomes especially important in difficult situations closer to the fundamental limits of what can be computed using the input signals.

As an example, Figure 9 shows the XKF3 orientation of both the NAVIGATION and GAME_UI scenario for a trial with transient accelerations and magnetic distortions as indicated by the ellipses. From Figure 9 it becomes clear that the XKF3 orientation of both scenarios is immune to both the transient acceleration (pitch angle, middle plot), and the magnetic distortion (heading angle, bottom plot). At the end of the trial, it can be seen that the NAVIGATION scenario applies a correction to the estimated heading, whereas the GAME_UI scenario continues to dead-reckon providing a smooth output at the expense of not necessarily tracking North. It should be noted that the fact that the NAVIGATION scenario corrects using a jump in this trial is by design.

Resources

As previously mentioned, the algorithm is segmented in a high rate part (AttitudeEngine) that runs on the FIS1100 and a low rate part (XKF3 engine) that runs either on a microcontroller or an Application Processor. By running the state tracking at a very low rate, it is possible for XKF3 to track with a relatively large amount of states, enabling statistical optimal tracking of many calibration parameters without a penalty on the required system resources, as indicated by Figure 10. From Figure 10 it becomes clear that the processor load for the generic IMU case increases drastically with higher ODRs. At the same time, filter performance decreases drastically at lower ODRs (indicated in red). On the contrary, using XKF3 hardware accelerated using the AttitudeEngine in the FIS1100, the processor load does not change at higher ODR. At the same time, filter performance is identical at any ODR of XKF3 (indicated in green).

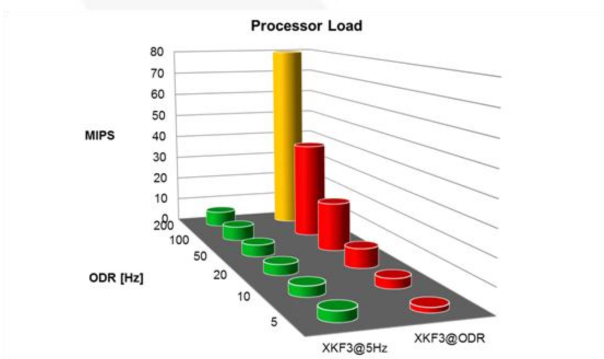

Figure 10. Estimated processor load (average MIPS) of XKF3 in combination with the FIS1100 AttitudeEngine running at 5 Hz as a function of different ODRs compared to generic IMU approach (no AttitudeEngine hardware acceleration) running XKF3 computation on calibrated data at the ODR.

Since XKF3 is based on Extended Kalman Filter theory, it is a recursive algorithm. This means that resources required for code size and memory are small and it fits in small microcontrollers (typically ARM Cortex M class).

In order to get an indication of the power savings the FIS1100 with the AttitudeEngine is able to achieve, this section shows some power calculations for the use of the FIS1100 in combination with XKF3. In case of a generic IMU that delivers calibrated data at high rate[2], Figure 11 shows the system current for the case XKF3 is implemented on a dedicated microcontroller (MCU) vs. an Application Processor for a generic IMU as well as the FIS1100 with AttitudeEngine. In all cases, XKF3 outputs quaternions at 32 Hz.

For the example shown in the bars on the left, XKF3 takes input at 1 kHz, corresponding to the sampling rate of the FIS1100 in case the AttitudeEngine is used. The power consumption on a Cortex M4F in this case is about 13 mA. The power consumption for the same case, but using a large and powerful Application Processor with a HLOS is close to 100 mA[3].

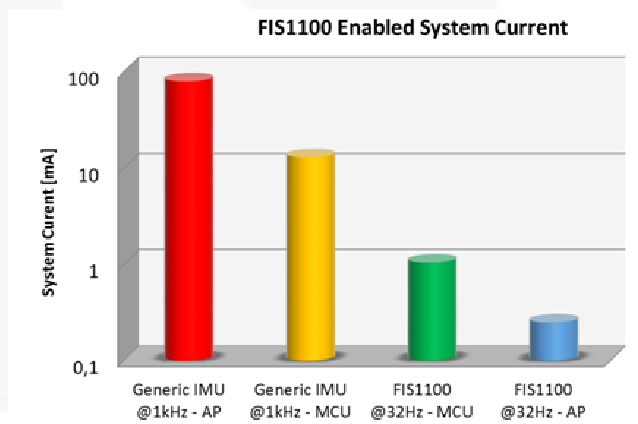

Figure 11. Overview of system current for a generic IMU (FIS1100 in Raw Mode) combined with XKF3 on an Application Processor and MCU on the left and the FIS1100 with AttitudeEngine on a MCU and Application Processor on the right.

[2] The FIS1100 does provide such a mode as well ("Typical" mode) in which accelerometer and gyroscope data are streamed directly to the processor, see the datasheet of the FIS1100 for further details [13].

[3] The power consumption for the Application Processor case is indicative and not based on actual measurements. In this case the majority of the power consumption is caused by dealing with interrupts and context switching in the HLOS, not computations.

In contrast, when using the FIS1100 in combination with the AttitudeEngine, a much lower current drain is obtained as indicated by the two bars on the right of Figure 11. When running XKF3 at 32 Hz on a Cortex M4F, power consumption is drastically reduced to only 1 mA without any compromise in accuracy. Comparing to the case of a generic IMU delivering calibrated data at 1 kHz presented above, the power saving is more than 10 times. Orientation performance is the same in both cases. In the case an Application Processor is being used, running a HLOS, together with the FIS1100, power consumption can be reduced even further as indicated by Figure 11. This assumes no change in Application Processor wake cycle, so only dynamic processor power.

Conclusion

In this paper, the XKF3 9D sensor fusion algorithm was presented. The algorithm optimally estimates 3D orientation with respect to an Earth fixed frame. The algorithm, based on Extended Kalman Filter theory, fuses 3D inertial sensor data (orientation and velocity increments) and optional 3D magnetometer data, provided by the FIS1100 AttitudeEngine.

XKF3 calibrates automatically and without any user interaction for the most important sensor errors. The algorithm successfully copes with commonly occurring distortions that may have a detrimental effect on performance if not properly taken into account, such as transient accelerations or magnetic field distortions, in-homogeneities and hard and soft iron effects.

XKF3 provides two main scenarios that are simultaneously, in parallel, available for the user. A true/local North, vertically referenced NAVIGATION scenario ideal for navigation/VR applications, and a vertically referenced GAME_UI scenario ideal for gaming/UI/OIS applications.

The total processor power consumption of XKF3 in combination with the FIS1100 AttitudeEngine is as low as 1 mA or less on a Cortex M4F. This includes acquiring the data, processing the data and generating the output. Compared to a traditional architecture based on a generic IMU, the power savings are more than an order of magnitude. This low power consumption together with the no compromises approach in accuracy of the algorithm as well as the flexibility of the architecture enabled by the FIS1100 makes it easy to integrate and develop applications demanding high accuracy 3D motion tracking.

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Index Terms — XKF3, AttitudeEngine, FIS1100, Sensor Fusion, Motion Tracking, Strap-Down Integration (SDI), Micro Electro Mechanical Systems (MEMS), Inertial Measurement Unit (IMU), Accelerometer, Gyroscope, Magnetometer, Orientation, Dead-Reckoning.

Related Datasheets

FIS1100 Product Information

FMT Product Information

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