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FIS1100 AttitudeEngine™ – Low Power Motion Co-Processor for High Accuracy Tracking Applications

Summary

The FIS1100 is an integrated 6-axis MEMS sensor which includes a 3D accelerometer, a 3D gyroscope, and a custom vector digital signal processor, the AttitudeEngine™. The device has inputs for an optional external 3D magnetometer, simplifying time alignment for 9-axis inertial measurement systems. The AttitudeEngine can process high-rate inertial data at a fraction of the power consumption needed to perform the same calculations on a generic processor core. This solution allows off-loading the host processor from high-rate and computationally intensive operations, preventing the need for high-frequency data interrupts. When the FIS1100 AttitudeEngine is used in combination with the Fairchild XKF3 '9D' sensor fusion algorithm running on an application processor or sensor-hub microcontroller, the resulting power consumption to perform accurate 3D motion tracking is as low as 1 mA or less, which is one order of magnitude lower than what a traditional architecture in which a generic IMU is used, can achieve. The FIS1100 AttitudeEngine in combination with XKF3 provides the ideal architectural partitioning in order to guarantee high level of motion tracking accuracy in combination with easy system integration and low power consumption for motion tracking applications targeting the consumer market. With the FIS1100 as main component of the FMT1000-series Motion Tracking modules, the AttitudeEngine is of vital importance for the performance of the FMT1000-series.

This application note addresses:

- Main requirements needed to enable accurate motion tracking applications.
- Introduction of the FIS1100, a smart MEMS sensor integrating a 3D accelerometer, a 3D gyroscope, with inputs for an optional external 3D magnetometer, together with a custom vector digital signal processor called the AttitudeEngine.
- Benefits for 3D motion tracking applications enabled by the use of the FIS1100 AttitudeEngine.
- Evaluation of the improvements provided by the FIS1100 AttitudeEngine used in combination with Fairchild's XKF3 sensor fusion compared to traditional architectures, both in terms of motion tracking performance and in terms of system power consumption.

Introduction

Inertial based orientation and position tracking has traditionally been used since decades for applications ranging from military, avionics or marine navigation, industrial platform stabilization, to unmanned vehicles control, etc. In the most recent years, this solution is acquiring a large interest in the consumer electronics market as well, with a broad and continuously evolving range of innovative applications: sport and fitness trackers, robotics, wearable sensors, Internet of Things (IoT), gaming and control systems, and pedestrian dead-reckoning devices are only a few examples. The enabling factor towards this revolution has been the rapid advance in Micro Electro-Mechanical Systems (MEMS) design and manufactory processes. This has made it possible to achieve high level of performance in inexpensive, small size and low power MEMS based Inertial Measurement Units (IMUs) combining 3D accelerometers and 3D gyroscopes in a single package.

However, to fully exploit the potential offered by MEMS based IMUs for consumer market applications, innovative system architectures and signal processing are required.

In fact, discussed in detail in this application note is the necessity of processing data at high sampling rates, at least several hundred of Hz or preferably more, in order to enable accurate motion tracking applications.

The traditional solution in consumer MEMS motion sensing has been to merely stream accelerometer and gyroscope samples, often not even time synchronized, from the IMU to an Application Processor (AP) or sensor hub microcontroller side (host), which then performs further processing of the inertial quantities. This approach, however, does not cope well with typical system level constraints and requirements that consumer electronics devices usually impose. This results in trade-offs and degradation in performance, causing poor user experience, unacceptably high power consumption, and problematic system integration.

To address these limitations, Fairchild introduced the FIS1100, a smart sensor module integrating a 3D accelerometer and a 3D gyroscope together with an application specific vector Digital Signal Processor (DSP), called the AttitudeEngine™. The AttitudeEngine enables

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processing of high rate inertial data at a fraction of the power consumption needed to perform the same calculations on a generic host processor. This solution off-loads the host from high rate and computationally intensive operations, reducing overall system level power consumption and preventing the need for high-frequency data interrupts to the host. At the same time, the highest level of accuracy in processing the motion data, necessary to guarantee an enjoyable user experience for the final application, is fully preserved.

The AttitudeEngine is naturally complementary and designed to work together with the Fairchild XKF3 sensor fusion [1]. XKF3 is an optimal estimation algorithm designed by Xsens, a subsidiary company of Fairchild, and brings to the consumer electronics market more than a decade of expertise of the company in human and industrial motion tracking applications. XKF3 is based on Extended Kalman Filter theory and fuses together 3D accelerometer, 3D gyroscope, and (optionally) 3D magnetometer data (‘9D’) to estimate 3D orientation and additional parameters in an Earth fixed frame of reference. When used in combination with the FIS1100 AttitudeEngine, XKF3 can be implemented on a generic host processor and run at extremely low update rates. In this way, XKF3 can accurately track a relatively large amount of states and automatically provide statistical optimal estimates of several calibration parameters including bias errors, magnetometer hard iron and soft iron effects, without resulting in any penalty in terms of power consumption on the host processor or result in any excessive requirements in terms of processing capabilities.

As discussed in this application note, the combination of the FIS1100 AttitudeEngine together with XKF3 sensor fusion algorithms running on a generic host represents the ideal architectural partitioning solution in order to provide high level of performance, easy system integration, and low power consumption for motion tracking applications targeting the consumer market.

Non-Commutativity of Rotations – Implications for Motion Tracking Applications

The core elements of any IMU are a triad of gyroscopes which sense angular velocity, and a triad of accelerometers which sense the linear accelerations of the body they are attached on. In motion tracking applications, however, the user is typically interested in integrated quantities: orientation, velocity, or position of the body the IMU is strapped on to. Strap-Down Integration (SDI), or dead-reckoning, is the mathematical procedure to integrate angular velocity and specific force (acceleration) to orientation and velocity (and optionally position) [2]-[3]. The outcome of this operation is usually combined in a statistically optimal way with additional aiding information (from e.g. magnetometers, barometers, GPS, vision, ultrasound, etc.), by sensor fusion algorithms to (auto) calibrate the sensors used and provide optimal state estimates. For example, the XKF3 [1] algorithm fuses together 3D accelerometer, 3D gyroscope, and (optionally) 3D magnetometer data, in order to provide stable orientation tracking. The sensor fusion step is necessary to correct for the otherwise constantly increasing drift fundamentally present in any strap-down integration system.

In order to achieve ideal performance, proper integration of inertial quantities therefore needs to be performed. The integration of angular velocity and acceleration into orientation and velocity, however, is not as straightforward as it might sound. The reason lies in the non-commutative nature of 3D rotations [1]; the three-dimensional integrals of motion need in fact to be calculated starting from signals which are measured in a frame which can freely rotate in space. This results in requirements for signal processing which are much more stringent compared to the case of one-dimensional signals. Specifically, large bandwidths and SDI rates much higher than what would be sufficient according to the well-known Nyquist criteria for linear dimensional signals, are needed.

It is crucial to realize that accurate orientation tracking is fundamental for velocity or position tracking applications as well. In fact, in order to obtain the specific force provided by an external excitation, the accelerometer signals need to be corrected for the acceleration due to gravity. In order to do this, first the measured acceleration (i.e. the acceleration in the sensor frame) is rotated to a global Earth referenced frame using the orientation obtained by integration of the gyroscopes output. Only at this point can the gravity be subtracted. To understand how critical proper compensation for gravity is, note that 0.1 degree attitude error determines a bias of almost 0.02 m/s^2 in the estimated specific force, which integrates to about 1 m position error (drift) after just 10 seconds.

The requirements for high rates at which SDI calculations need to be performed in order to enable accurate motion tracking, are further discussed in the next sub-sections using examples.

Performance Under Coning Motion

The well-known example of pure coning motion[1] is very useful to show the relevance of signal bandwidth and SDI rate to preserve accuracy in motion tracking applications. This motion is typically used as a reference test signal for SDI algorithm design specification and validation in tactical and navigation grade IMUs, since coning is the most demanding type of motion, and SDI algorithms that operate satisfactorily under this condition will typically meet general performance requirements under different motions as well. Therefore, coning signals allow one to evaluate a worst case scenario. Note that this scenario is however

[1] Note that in this section the specific case of coning motion only is addressed. Similarly, the case of sculling can be considered. Sculling motion occurs when one gyroscope and one orthogonal accelerometer channels sense two out of phase oscillations with same frequency [4]. If the signals are not sampled fast enough, sculling motion results in velocity integration drift on the third channel. The analysis of sculling motion demands similar design considerations to those of coning motion.

actually representative for industrial and robotics applications, where vibrations due to engines and actuators are typically present and often take the form of coning-like motion.

Under coning motion, one axis of the IMU (assumed for sake of example to be the z-axis) sweeps a cone in space, *without* any rotation around the axis itself [4]. It can be shown through the Goodman-Robinson theorem [5] that in this case, the angular velocity $\boldsymbol{\omega}(t)$ measured by an ideal triad of gyroscopes is:

$$\boldsymbol{\omega}(t) = \begin{bmatrix} \omega_x(t) \\ \omega_y(t) \\ \omega_z(t) \end{bmatrix} = \begin{bmatrix} A\cos(2\pi f_0 t) \\ -A\sin(2\pi f_0 t) \\ 2\pi f_0(1-\cos(\theta)) \end{bmatrix} \quad (1)$$
$$\theta = \mathrm{asin}\left(\frac{A}{2\pi f_0}\right)$$

where f_0 and A are defined as coning frequency and coning amplitude, respectively. Therefore the gyroscopes measure, in their *sensor frame*, two sinusoidal out of phase oscillations on the x and y channels, and a *constant offset* on the z channel. For sake of example, Figure 1 shows $\boldsymbol{\omega}(t)$ as given in eq. (1), for $A = 100$ deg/s and f_0 = 20 Hz.

From equation (1) it is immediately apparent that large bandwidth B is required in order to preserve accuracy. In fact, if $B < f_0$, the gyroscopes will only measure the constant offset term $\omega(t)_z = 2\pi f_0(1-\cos(\theta))$. Under the assumption that $2\pi f_0 \gg A$, (this assumption generally holds - note that A is expressed in rad/s for measurement units consistency), and using Taylor approximations for the asin and cos functions, results in :$\omega(t)_z \sim A^2/(4\pi f_0)$. Therefore, if $B < f_0$ the coning drift rate is directly proportional to the square of the coning amplitude A and inversely proportional to the coning frequency f_0. As example, Figure 2 shows the resulting coning drift rate vs. A and f_0, in this case.

Signal bandwidth of about 200 Hz is usually desired in order to minimize coning drift for MEMS class of sensors.

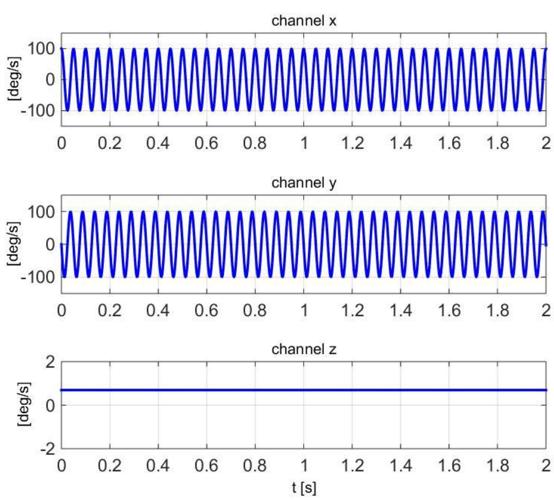

Figure 1. Signal measured by a triad of gyroscopes under pure coning motion with A=100deg/s and f_0=20 Hz.

To further understand the importance of SDI rate to preserve motion tracking accuracy, Figure 3 shows the resulting coning drift in deg/s vs. the SDI frequency f_S, for A=100 deg/s. In the plots, $f_S > 2f_0$ is considered. The strap-down integrals are calculated with a highly efficient and accurate quaternion based formulation, the same implemented in hardware by the FIS1100 AttitudeEngine. The relevance of high SDI rates in order to preserve performance becomes evident; even SDI rates of several hundred Hz can result in significant coning drift. From the figure it further becomes apparent how SDI rate requirements are much more stringent than the Nyquist criteria for linear signals, particularly for low values of f_0. For example, for $f_0 =$ 5 Hz, even sampling rates one order of magnitude larger than the coning frequency result in drift in orientation of about 5 degrees per minute.

SDI rates of about 1 kHz are therefore desired under coning motion for MEMS class of sensors.

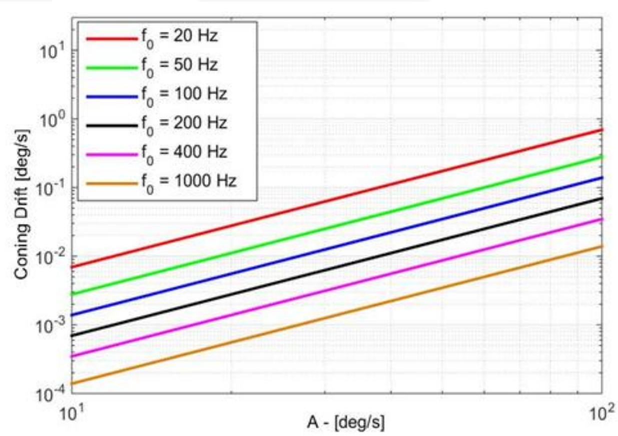

Figure 2. Coning Drift vs. Coning Amplitude A, for different coning frequencies; this drift occurs when the system bandwidth B is smaller than f_0.

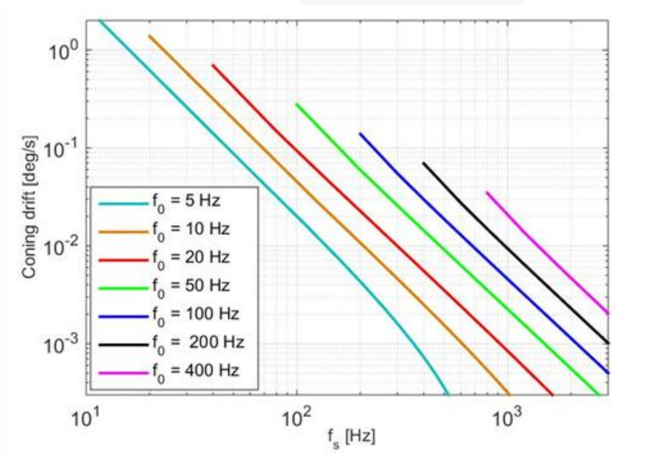

Figure 3. Coning Drift vs. SDI Rate f_S, for different coning frequencies (note that $f_S > 2f_0$ in the plots). SDI rates of about 1 kHz are desired to minimize orientation drift under coning motions.

Performance for Human Motion Tracking Applications

Human motion tracking applications can appear less demanding in terms of SDI requirements compared to the previously analyzed case of coning motions, since it is well accepted that typical human induced dynamics have frequency components within only about 10 Hz and a random like, rather than periodic and single frequency component pattern behavior. However, this is true only to some extent. In fact, similarly to the case of pure coning motion, human motion tracking applications also have multi-axes, out-of-phase excitations. Additionally, human movements can easily generate angular excitations in excess of 2000 deg/s[2]; e.g. in gaming and sport and fitness applications.

Due to the inherently random nature of human dynamics, it is more difficult to provide a systematic analysis as previously shown for the case of pure coning motion. For this reason, typical dead-reckoning orientation errors for different SDI rates are shown in the following starting from an actual recording. Figure 4 shows the accelerometer and gyroscope signals for a high dynamics, hand-held trial. It can be seen that during the portion of movement, of almost 10 seconds duration, the angular excitations exceed 1000 deg/s and the accelerations reach 4 g. This trial can be considered representative for a gaming scenario.

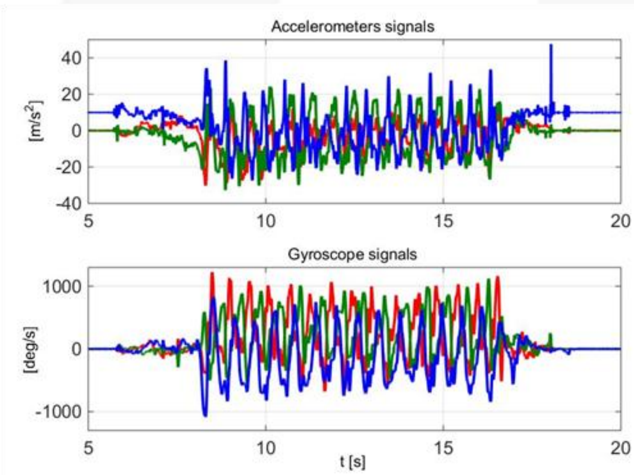

Figure 4. Accelerometers and gyroscopes signals in a high-dynamics, "gaming-like" hand-held trial.

The dead-reckoning errors for different SDI rates have been evaluated by decimating the signals to different rates: 120 Hz, 60 Hz, 40 Hz, 20 Hz. Two different processing options have been considered:

1. The signals are filtered with a low-pass filter with bandwidth B before decimation, in order to prevent aliasing.
2. The signals are always filtered with a low-pass filter with 50 Hz bandwidth. This option will potentially introduce aliasing for SDI rates other than 120 Hz.

The results of the two processing options are shown on the left and right-hand sides of Figure 5 which provides the short angle[3] orientation error obtained in the different cases. The specific values of the filter bandwidth for the first processing option are given in the legend. From Figure 5, it is clear that reduced SDI rates introduce dead-reckoning orientation drift. For the considered trial, the drift during dynamics is about 5 degrees per minute already for SDI rate = 120 Hz, and it dramatically increases for SDI rates lower than 40 Hz. It is evident that in order to preserve accuracy for human motion tracking applications, at least several hundred Hz SDI rates are necessary.

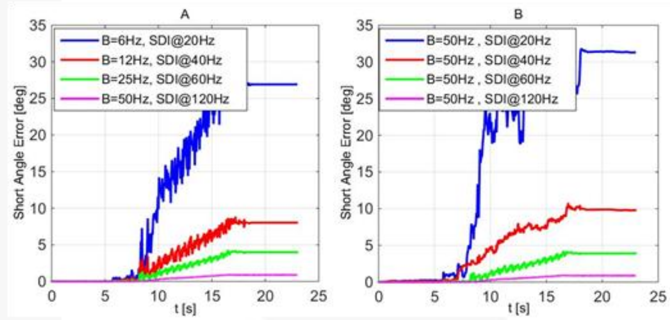

Figure 5. Short Angle Orientation Error vs. SDI Rate for High-Dynamics Hand Generated Trial. On the left-hand side (A), when filtering the original signal to prevent aliasing. On the right-hand side (B), when preserving the signal bandwidth to 50 Hz at the cost of potential aliasing. In both cases, reducing the SDI rate introduces significant dead-reckoning errors, even for f_S= 120 Hz.

Implications for System Architecture

As shown in detail in the previous section, in order to preserve accuracy in motion tracking applications, SDI of inertial quantities needs to be performed at very high rates. In fact, in order to minimize potential errors due to non-commutativity of rotations, SDI should run at least at 1 kHz rate. This requirement poses significant implications in terms of system architectural choices, especially for application of IMUs in battery powered consumer electronics applications like wearable devices, robotics, fitness trackers, mobile phones, remote game controls, etc., where integration with a general purpose host processor is needed. Typically, a host processor is already busy with many other tasks, or needs to enter low-power sleep states as much as possible to preserve power. These requirements are at odds with each other and, if not addressed, limit the use of MEMS IMUs application to less demanding uses such as screen orientation, step counting, and activity classification.

[2] Note that the coning drift on one channel is proportional to the product of the signal amplitudes on the remaining two.

[3] The short angle orientation error is defined as the norm of the angle in space between the two orientation vectors.

The solution traditionally employed has been to merely stream accelerometer and gyroscope samples from the IMU side to the host processor side, which then performs proper strap-down integration of the inertial quantities. The integrated values are then used by sensor fusion algorithms to provide the desired output. This architecture is schematically depicted in Figure 6 for the case of an orientation tracking filter.

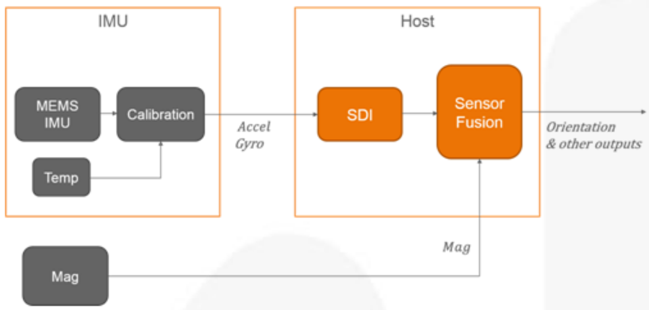

Figure 6. IMU-Host - Traditional Architectural Integration. At the left hand side the IMU streaming accelerometer and gyroscope data. At the right hand side the host with the SDI and the sensor fusion functional blocks.

When using this traditional architecture, streaming of accelerometer and gyroscope signals at very high rates from the IMU to the host processor side is necessary in order to preserve motion tracking accuracy. However, high data transmissions to the host processor are per-se unnecessary, since the actual update rate required by the final application typically ranges from some Hz (or lower) for applications like pedestrian navigation, up to few tens of Hz (30, 50, 60 Hz) for gaming, fitness tracking, robotics control, or about 100 Hz for more challenging applications such as VR/AR. Therefore, the only reason to stream the inertial data at high rates is to be able to perform accurate numerical integration of acceleration and angular velocity.

The necessity to stream data at high rates, however, poses a fundamental drawback since the host processor will need to handle very frequent data interrupts. This will prevent the main processor from entering low-power sleep mode as often as possible, dramatically increasing overall system power consumption.

Even when a FIFO buffer is used at the IMU side to mitigate the aforementioned issues, several problems are still present:

- Need for the host processor to process (much) more data, wasting computational resources and power.
- High probability of packet loss in wireless applications.
- Increased possibility of bus contention/conflict on SPI/I2C when many peripherals share the same bus.
- High speed serial bus modes such as SPI become a requirement.
- Highly efficient DMA support on the host processor always needed.
- Additional latency introduced by FIFOs and/or computations; this can be critical for highly real time applications such as increasingly popular applications in AR/VR and control of robotics.

All these drawbacks and limitations practically result in need for trade-offs, causing degradation in performance, unacceptably high power consumption, problematic system integration, high cost, and overall poor final user experience.

FIS1100 AttitudeEngine™

In order to address the aforementioned limitations suffered by the traditional architecture, the solution developed by Fairchild with the FIS1100 is to implement the strap-down integration algorithms on the IMU side.

When the FIS1100 is used in AttitudeEngine mode[4], the accelerometer and gyroscope signals are converted into the digital domain and low-pass filtered with a wide bandwidth of about 200 Hz. The AttitudeEngine then performs the SDI calculations at 1 kHz input rate in hardware. This ensures that any errors resulting from the digital calculations of the integrals of motion are practically negligible for any application.

In this mode, the FIS1100 streams motion data encoded as orientation and velocity increments (delta quantities), rather than traditional angular velocity and acceleration samples. As motivated in more detail in the following sections, the orientation and velocity increments, being calculated at high and fixed input rate, are *always* accurate, independently of the chosen output rate. Low output rates will only result in coarser time representation of the motion data, but the data itself remains accurate. In this way, the output rate can be chosen according to the specific application requirements rather than being driven by the need of performing numerical integration with high accuracy.

[4] Note that the FIS1100 additionally provides a “Typical” mode as well, in which accelerometer and gyroscope samples are directly streamed to the output. The Typical mode is not discussed further in this document; for more details about this mode, reference is made to the FIS1100 data-sheet [6].

Benefits Compared to Traditional Architecture

The use of FIS1100 in AttitudeEngine mode enables the following advantages, compared to the traditional architecture:

Low Power - SDI is a high frequency operation. Therefore, the implementation on dedicated ASIC hardware rather than on a general purpose host processor is a natural choice, since heavy customization and optimization is possible. Additional power saving is further achieved both by allowing the host processor to potentially enter much more frequently into low-power sleep mode, and by reducing the amount of transmitted data. All these points enable a low-power motion processing architecture for consumer electronics applications.

High Accuracy - In order to mitigate transmission and power requirements, in the traditional IMU-host processor architectural integration previously discussed, the Output Data Rate (ODR) at IMU side is typically chosen according to specific application demands and trade-offs. For example, for a typical MEMS consumer grade IMU the ODR can range from 32 Hz for pedestrian navigation, up to 1000 Hz for gaming and VR/AR applications. However, when choosing lower ODR any high frequent motions will cause unwanted integration drift and an overall worsening of performance. This issue is naturally solved by the FIS1100 AttitudeEngine, since the integrals are always calculated at very high rate. The motion information remains accurate no matter what is the chosen output data rate.

Easy System Integration - A key benefit coming from the FIS1100 AttitudeEngine is represented by the unique level of flexibility in system integration which is provided, since the demanding SDI functional block is implemented at the IMU side. This drastically reduces system requirements for the host processor to enable motion tracking applications. In fact, the FIS1100 can be more easily integrated with a host processor with only a limited bus speed, or when the same bus needs to be shared among a multiplicity of peripherals. The latter case is actually typical, due to the general purpose nature of host cores. Similarly, given the moderate data transmission rates needed, robustness to packet loss in case of no DMA at the host side is largely improved. The same considerations hold in terms of computational demands. All these benefits make the FIS1100 suited for integration on a large diversity of (battery powered) platforms.

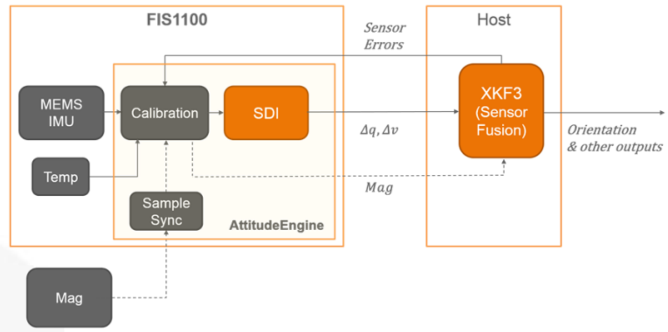

Figure 7. IMU-Host – Novel Architectural Integration; the FIS1100 AttitudeEngine performs high-rate SDI calculations and streams low-rate orientation and velocity increments to the XKF3 sensor fusion algorithm running at host side.

FIS1100 AttitudeEngine Functional Description

Figure 7 shows in detail the new architectural partitioning enabled by the use of the FIS1100 AttitudeEngine. In Figure 7 the FIS1100 works together with the sensor fusion filter XKF3 running on the host side. Since the high rate and computationally intensive SDI calculations are performed inside the FIS module, only low-rate motion data needs to be streamed to the host running XKF3, with the motion encoded in fused orientation increments Δq and velocity increments Δv.

In the following subsections, the main functional blocks and the data flows shown in Figure 7 are described in more detail. Focus is maintained to the blocks actually composing the FIS1100 AttitudeEngine. For more details on XKF3, reference is made to [1].

SDI - The SDI block converts high-rate calibrated gyroscope and accelerometer samples into low-rate orientation increments and velocity increments.

In order to understand the underlying principles of implementation, the differential equation which relates angular velocity and orientation can be considered as starting point:

$$\dot{\boldsymbol{q}}(t) = \boldsymbol{q}(t) \circledast \frac{1}{2}\boldsymbol{\omega}(t) \qquad (2)$$

where $\boldsymbol{q}(t)$ is the sensor quaternion orientation in an *external* reference frame at time t, $\circledast$ denotes the quaternion multiplication, $\{\dot{}\}$ indicates the derivative operation, and bold symbols denote vectors.

The integration of equation (2) provides the following expression to update the orientation of the sensor in the external frame at generic output rate $f_R = 1/T_R$:

$$\boldsymbol{q}(t+T_R) = \boldsymbol{q}(t) \circledast \int_{\tau=t}^{t+T_R} \delta\boldsymbol{q}(\tau) \circledast \frac{1}{2}\,\boldsymbol{\omega}(\tau) d\tau\,,$$
$$\boldsymbol{q}(0) = [1\ 0\ 0\ 0]^T$$

where $\delta\boldsymbol{q}(\tau)$ represents the elementary rotation increment around time τ.

Therefore, the orientation can be updated exactly at generic output rate f_R, if the rotation increment between the time instants t and $t+T_R$, defined as:

$$\Delta \boldsymbol{q}(t+T_R) \triangleq \int_{\tau=t}^{t+T_R} \delta \boldsymbol{q}(\tau) \circledast \frac{1}{2} \boldsymbol{\omega}(\tau) d\tau \tag{3}$$

is properly calculated.

In a similar way, the differential equation which relates at generic time t the velocity $\boldsymbol{v}(t)$ in an external reference frame and the acceleration $\boldsymbol{a}(t)$ in the sensor frame, is:

$$\dot{\boldsymbol{v}}(t) = \boldsymbol{R}_{\boldsymbol{G}(t),\boldsymbol{S}(t)} \boldsymbol{a}(t) + \boldsymbol{g} \tag{4}$$

where $\boldsymbol{R}_{\boldsymbol{G}(t),\boldsymbol{S}(t)}$ is the rotation matrix from the external frame to the sensor frame at time t and $\boldsymbol{g}$ is the Earth gravity vector in the external frame. Integrating eq. (4) results in:

$$\boldsymbol{v}(t+T_R) = \boldsymbol{v}(t) + T_R\, \boldsymbol{g} + \\ + \boldsymbol{R}_{\boldsymbol{G}(t),\boldsymbol{S}(t)} \int_{\tau=t}^{t+T_R} \boldsymbol{R}_{\boldsymbol{S}(t),\boldsymbol{S}(t+\tau)}\, \boldsymbol{a}(\tau) d\tau$$

where $\boldsymbol{R}_{\boldsymbol{S}(t),\boldsymbol{S}(t+\tau)}$ is the matrix expressing the sensor rotation between time t and time $t+\tau$. Also in this case, the velocity can be updated **exactly** at generic rate f_R, if the velocity increment between the time instants t and $t+T_R$, defined as:

$$\Delta \boldsymbol{v}(t+T_R) \triangleq \int_{\tau=t}^{t+T_R} \boldsymbol{R}_{\boldsymbol{S}(t),\boldsymbol{S}(t+\tau)}\, \boldsymbol{a}(\tau) d\tau \tag{5}$$

is properly calculated.

Fairchild has developed highly optimized numerical implementations of the integral equations in eq. (3) and (5) to specifically tailor the AttitudeEngine vector DSP architecture. This has resulted in a hardware implementation of the SDI equations, capable of preserving the full numerical accuracy required, but consuming only a small fraction of the power otherwise needed by an equivalent implementation on a generic host processor. The AttitudeEngine requires only about 30 µA in order to perform the complex SDI calculations at 1 kHz input rate; this is practically negligible within the overall '9D' motion tracking power budget.

Table 1 summarizes the AttitudeEngine main SDI performance parameters. The SDI output rates currently supported by the AttitudeEngine range from 1 Hz up to 64 Hz; this is generally sufficient to cover the applications of interest[5]. It can be further seen that the power consumption is independent of the chosen output rate.

[5] Note that the SDI ODR directly determines the XKF3 orientation output rate provided to the application. The internal rate at which XKF3 performs the core sensor fusion is instead fixed and independent of the chosen ODR. See [1] for more details in this respect.

Table 1. AttitudeEngine SDI Parameters

SDI Output Rate [Hz]	1	2	4	8	16	32	64
SDI Input Rate [Hz]	1000	1000	1000	1000	1000	1000	1000
SDI Power Cons. [µA]	30	30	30	30	30	30	30

Sample Synchronization – In order to preserve ideal motion tracking accuracy, proper timing between data from different sensors needs to be guaranteed; for this reason, the FIS1100 performs synchronous sampling of the 3D accelerometer and 3D gyroscope sensors. Six parallel Sigma Delta ADCs ensure ideal timing between the inertial data channels.

As shown in Figure 7, the FIS1100 further supports an *optional* external magnetometer connected through an I2C master. When the external magnetometer is additionally used, the AttitudeEngine guarantees that the 3D magnetometer samples are precisely aligned in time with respect to the IMU data as well. The magnetometer synchronization accuracy is kept well below 1 ms; this preserves the level of accuracy needed by XKF3 to perform optimal '9D' sensor fusion. For a list of currently supported external magnetometers, reference is made to the FIS1100 datasheet [6].

Calibration - The AttitudeEngine performs continuous calibration of the most commonly occurring sensor errors: non-linearity, bias and scale factor variations, as well as correcting for temperature dependencies of these parameters.

When an external magnetometer is further used, the AttitudeEngine additionally performs compensation of soft-iron and hard-iron effects, as well as of misalignment between the IMU and the magnetometer.

Some of the calibration parameters are constant values determined during FIS1100 calibration routines performed at factory. However, to compensate for stochastic variations of calibration parameters over time (e.g. resulting from aging of the device), as well as for any possible changes in external magnetization, most of these errors are further auto calibrated continuously over time by XKF3. As shown in Figure 7, estimates for these errors are periodically fed back by XKF3 to the FIS1100 AttitudeEngine. In this way the best performance is guaranteed without requiring any specific user input. All sensor errors are continuously monitored and tracked transparently in background enabling always-on, accurate motion tracking applications.

AttitudeEngine Output Modes

The AttitudeEngine provides two different output modes, discussed in the following in more detail.

Stand-Alone Mode – This is the AttitudeEngine output mode of most common use. In this mode, the rotation and velocity increments are streamed at a fixed, preconfigured

ODR. The ODR can be changed depending on the specific application demands; however, after setting it, the time interval between consecutive output increments will be constant. Table 1 provides the supported AttitudeEngine SDI output rates in Stand-Alone mode. Note that this mode is conceptually similar to that used in traditional IMUs, in which acceleration and angular velocity are streamed at a fixed ODR.

Motion on Demand Mode – In this mode of operation there is no pre-configured ODR. Instead, the AttitudeEngine keeps on integrating in time the orientation and velocity increments as in equations (3), (5), until the host transmits to the FIS1100 a data request. Upon reception of the data request, the AttitudeEngine streams to the host a pair of increments:

$$\Delta\boldsymbol{q}(t+T_{Req}),\ \Delta\boldsymbol{v}(t+T_{Req}) \tag{6}$$

where T_{Req} is the time interval from to the previously received request, and it is allowed to be variable among different output samples in time. It is evident that also in this case the output increments are accurate independent of the specific value of T_{Req}.

The Motion on Demand mode of operation is ideal for applications in which inertial data needs to be accurately synchronized with other sensor data which might be (slightly) a-periodic in nature. For example in robotics applications it is common to synchronize inertial and odometry data; in this application, the readings from wheel encoders typically occur at irregular time intervals. Another example could be in syncing with rendering a digital scene of varying complexity, resulting in slight variations in display frame-rate.

The output time resolution provided by the Motion on Demand mode is equal to the SDI input interval, i.e. 1 ms. This value is low enough to provide the ideal level of synchronization with other sensor data or output generation.

The Motion on Demand output mode therefore enables transmission of motion information solely at the precise time instants required by the application. In this way, very efficient use of system level resources is possible, allowing for dramatic data transmission and power consumption savings. This can provide fundamental benefits for example in wireless sensor networks, in order to minimize use of wireless resources and to allow for efficient centralized based synchronization, scheduling and medium access control.

For more details on hand-shaking mechanisms between the FIS1100 and host processor in Motion on Demand mode, reference is made to the FIS1100 datasheet [6].

Note that patents have been granted and are pending on many of the concepts here described [7]-[12].

Improvements Compared to Traditional Architecture

In this section, the benefits enabled by the FIS1100 AttitudeEngine when used in combination with XKF3 both in terms of performance, and in terms of power consumption, are further discussed.

Performance Improvements - The performance improvements resulting from the use of FIS1100 AttitudeEngine with respect to traditional architecture are evaluated in terms of dead-reckoning accuracy for the same ODR streamed to the AP. The trial considered in this section contains a hand-held high-dynamic motion of more than one minute duration. The accelerometer and gyroscope signals during the trial are given in Figure 8.

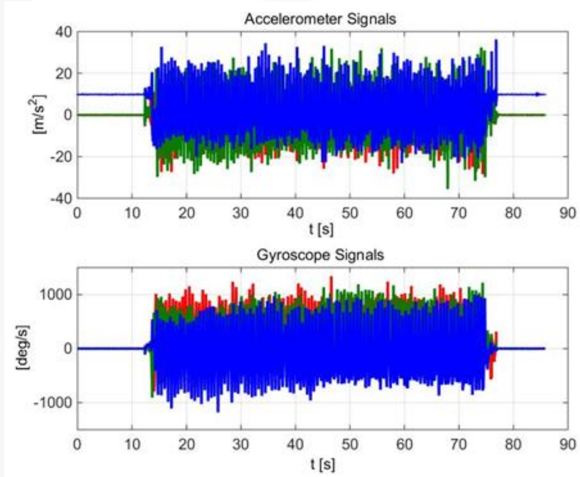

Figure 8. Accelerometers and gyroscopes signals recorded from a high-dynamics, "gaming-like" hand held recording.

Figure 9 shows the resulting orientation error after 30 seconds dead-reckoning vs. the chosen ODR, both for the FIS1100 AttitudeEngine and for the traditional architecture. The ground-truth in both cases is represented by the calculation of the orientation integrals with a very high-rate, numerically exact formulation of the SDI equations. For this reason, Figure 9 represents the errors solely introduced by the use of low data rates when calculating the integrals of motion.

When the FIS1100 AttitudeEngine is used, the resulting orientation dead-reckoning drift is only about 0.12 degrees, independent of the chosen ODR; for this reason, ODR above 64 Hz are practically un-necessary in this case. On the contrary, when using the traditional architecture, even ODR of 250 Hz introduces about a 2 degrees drift. Errors become dramatic in this case already for ODR below 64 Hz.

Figure 10 shows the same plots for the velocity dead-reckoning error[6]. Similar considerations hold in this case: the FIS1100 provides only about 0.25 m/s error, whereas the

[6] Note that for MEMS based sensors 30 seconds of velocity dead-reckoning under such dynamics is extreme for practical applications.

traditional architecture fails in providing any acceptable level of performance even for ODR = 125 Hz.

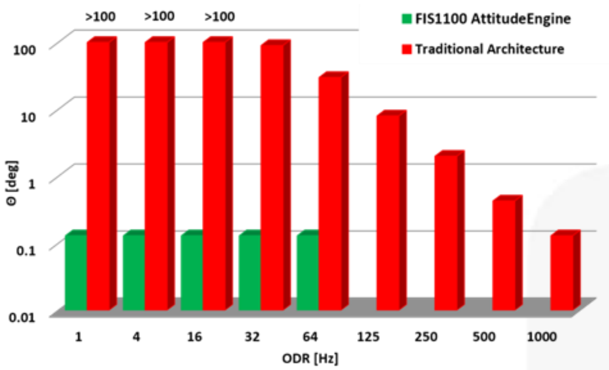

Figure 9. Short angle orientation error after 30 s dead-reckoning vs. ODR, using traditional architecture, and using the FIS1100 AttitudeEngine. Note that in the latter case the dead-reckoning error is independent of the ODR.

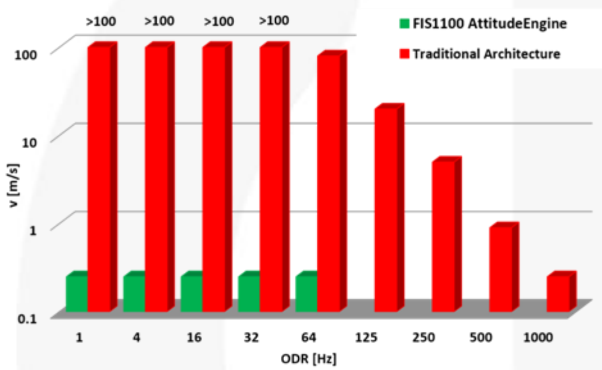

Figure 10. Velocity error norm after 30 s dead-reckoning vs. ODR, using the traditional architecture, and using the FIS1100 AttitudeEngine. Note that in the latter case the dead-reckoning error is independent of the ODR.

Power Consumption Improvements - In this section, improvements in terms of power consumption enabled by the proposed architectural partitioning in which SDI algorithms are performed at a high rate by the FIS1100 AttitudeEngine and XKF3 runs at a low rate on a general purpose processor are discussed.

It is relevant to emphasize that actual improvements are generally dependent not only on the platform used and architectural partitioning, but on specific implementation of the orientation tracking algorithms as well. For example, in a brute force implementation the orientation tracking filter could run directly at the rate at which the inertial data is streamed, resulting in a dramatic increase in power consumption; this case is discussed in more detail in [1], and for this reason it is not further addressed in the following.

In this section, instead, the comparison is limited to the case in which the same, highly optimized orientation tracking filter XKF3 runs at low rate (32 Hz) on a general purpose MCU. Both th**e** case in which the FIS1100 AttitudeEngine streams orientation and velocity increments, and the case in which a generic IMU streams accelerometer and gyroscope samples to XKF3, are analyzed; note that in the latter case the SDI calculations need to be performed by the main processor.

For the case of the FIS1100 AttitudeEngine, the orientation and velocity increments are streamed at the output at 32 Hz; note again that the motion integrals are internally calculated by the AttitudeEngine from acceleration and angular velocity samples at 1 kHz rate, guaranteeing ideal accuracy.

For the case of a traditional architecture, three different scenarios are instead considered:

- Acceleration and angular velocity are sampled at 1 kHz and directly streamed to the MCU at the same rate.
- Acceleration and angular velocity are sampled at 250 Hz and directly streamed to the MCU at the same rate.
- Acceleration and angular velocity are sampled at 250 Hz, and buffered into the IMU FIFO. The FIFO data are then streamed in bursts at 32 Hz.

Note that in the experiments made, in case of traditional architecture it has not been possible to sample inertial data at 1 kHz, then buffer the samples in the IMU FIFO and stream the data at 32 Hz burst rate, since this resulted in significant packet loss due to the use of a comparatively slow I^{2}C bus. This can certainly be considered an additional disadvantage possibly occurring in practical implementations of the traditional architecture.

Figure 11 shows the power consumption to run XKF3 at a 32 Hz input rate on a Cortex M4F, for the four different considered cases. It can be seen that when using the FIS1100 AttitudeEngine, the power consumed by the processor to perform sensor fusion is only 1.0 mA. When instead the traditional architecture is used and accelerometer and gyroscope samples are streamed at 1 kHz rate, the power consumed by the MCU is about 12.6 mA, more than one order of magnitude higher. Note again that this is the only case among the three considered ones in which the traditional architecture is capable of achieving the same level of motion tracking performance.

When in the traditional architecture the inertial data are sampled at 250 Hz, trading in accuracy for power consumption, the resulting MCU power consumption is 4.05 mA and 3.0 mA for the case in which the data are either directly streamed to the MCU, or first buffered in the IMU FIFO and then streamed in bursts at 32 Hz, respectively. In the two latter scenarios, in spite of the much higher power consumption compared to the FIS1100 AttitudeEngine based architecture, motion tracking performance is still degraded due to the lower rate at which the strap-down integrals are actually calculated.

For sake of completeness, the same analysis has been done on a Cortex M0+ processor. Results are shown in Figure 12. Note that in this case the scenario in which the traditional architecture streams data at 1 kHz rate resulted in missed samples, with detrimental effects on tracking performance.

It can be seen that although numbers are generally different, the same conclusions can be drawn. The use of FIS1100 AttitudeEngine performing high-rate SDI calculations, in combination with XKF3 running at low-rate on a generic MCU represents the optimal solution in order to drastically reduce overall power consumption, still fully preserving the highest level of accuracy in motion tracking.

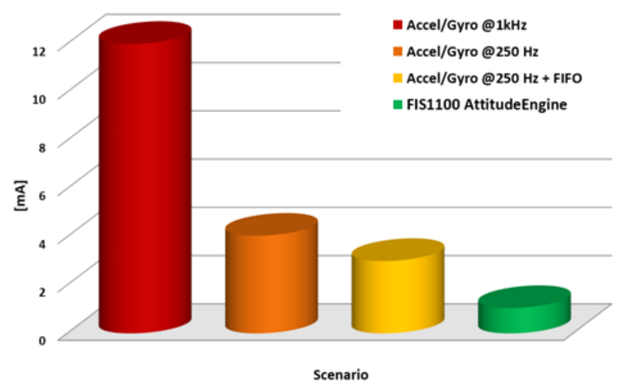

Figure 11. Power consumption to run XKF3 on Cortex M4F when the FIS1100 AttitudeEngine is used, and when a traditional architecture in which accelerometer and gyroscope data are directly streamed from a generic IMU, is used.

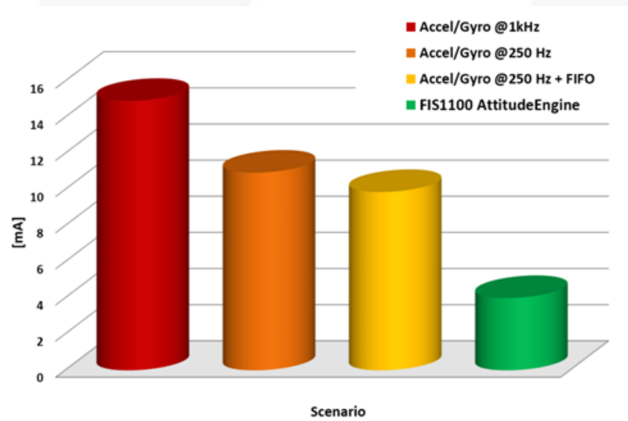

Figure 12. Power consumption to run XKF3 on Cortex M0+ when the FIS1100 AttitudeEngine is used, and when a traditional architecture in which accelerometer and gyroscope data are directly streamed from a generic IMU, is used.

Conclusion

In this paper, the FIS1100 AttitudeEngine motion co-processor has been described. The AttitudeEngine calculates the strap-down integrals of motion with high accuracy at 1 kHz input rate and streams at the output low-rate orientation and velocity increments, consuming as little as about 30 µA. This solution allows off-loading the host processor from high-rate and computationally intensive operations, preventing the need for high-frequency data interrupts. When the FIS1100 AttitudeEngine is used together with the XKF3 orientation tracking filter running on a general purpose application processor or sensor hub, the processor power consumption is drastically reduced: only about 1 mA is needed in this case to perform sensor fusion on a CortexM4F processor. In order to achieve the same level of performance in a traditional architecture where a generic IMU is used, about 13 mA would be consumed instead.

The use of the FIS1100 AttitudeEngine in combination with XKF3 and other algorithms intended to track 3D motion, therefore provides the ideal architectural partitioning in order to guarantee high level of performance, easy system integration, and low power consumption for 3D motion tracking applications targeting the consumer market.

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[11] *"Compression of IMU data for transmission of AP", US Patent: 8981904.*

[12] *"Compression of IMU data for transmission to AP", European Patent Application: EP 2645110 A1.*

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

Related Datasheets

[FIS1100 Product Folder]

[FMT Product Information]

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