IT MAKES SENSE: HOW EXTREME ANALOG AND SENSING WILL CHANGE THE WORLD

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ABSTRACT

Although only six years have passed since the adoption of motion sensors in the consumer market, the world of MEMS sensors has changed dramatically and is set to change even more in the future. If 2006 was the year of the Accelerometer's adoption by Nintendo™ in the Wii™ Controller, 2010 was the year of the Gyroscope's adoption by Smartphone manufacturers, like Apple™ and Fujitsu Mobile™. Moreover, combinations of these two inertial products, also known as Inertial Six Degree-Of-Freedom Motion Sensors (I6XDOF) are now starting to appear in the market, and most likely they will coexist with standalone accelerometers and gyroscopes, depending on customer needs in terms of compactness, performance, and final industrial design. This paper reports the details of the world smallest 3-axis Single Core and Dual Core silicon MEMS Coriolis Gyroscopes in production that fulfill the pressing market requirements for low power consumption, small size, slim form factor, high performance, and low cost. But it also addresses the recent trends of the Inertial Six Degree-Of-Freedom, Mixed Six Degree-of-Freedom M6XDOF (3X Accelerometer plus 3X Solid State Compass), Nine Degree-of-Freedom (9XDOF) systems, realized by integrating the I6XDOF with a 3-axis magneto-resistive solid state compass, and the Ten-Degree-of-Freedom (10XDOF) system, realized by adding a pressure sensor to the 9XDOF.

INTRODUCTION

Up until now, the key application driving the adoption of Motion Sensors in applications such as mobile phones and remote controllers, laptop and tablet computers, games and portable multimedia players, has been their ability to enable more intuitive user interfaces. Today, Image Stabilization, Context Awareness, Location Based Services, and Remote Monitoring are the new frontiers that will continue to drive the adoption of Motion Sensors, both in existing market segments and in many new areas, some of which are not even known today.

Linear motion detection is often required to be combined with angular velocity sensing along the pitch, yaw, and roll axes and with altitude variations in a wide range of applications where sensing three to ten degrees of freedom is required. One example is represented by Inertial Measurement Units (IMU) or Inertial Navigation Units (INU), in which accelerometers and gyroscopes are used in a complementary manner to detect linear and angular motion in many different applications: enhanced user interfaces for mobile phones, games and pointers/remote controllers, image stabilization, pedestrian and car navigation for location based services and fitness/wellness monitoring. As was the case with stand-alone accelerometers, size, performance, and price remain the driving factors for gyroscopes and for 6XDOF/9XDOF/10XDOF success in the Consumer and Industrial markets.

In Optical Image Stabilization (OIS) applications, IMUs can be used to track an object where the subject is blurred within the image due to vibrations applied to the devices. OIS systems

can be implemented using pixel tracking by intensity movement or frame tracking. Typically, the IMU is embedded in video or other systems with Pan-Tilt and Zoom capabilities or mounted on moving platforms in surveillance applications [3]. Motion activation and image stabilization are features aimed to improve picture or video quality.

Inertial Navigation Unit (INU) in pedestrian/car navigation is used for Dead Reckoning (DR) to estimate the user's current location, based on a previously determined known location, when no GPS signal is available or its quality is very poor. The information from the sensor cluster is typically processed via complex Kalman filters to estimate the current position of the user. This powerful facility opens up a wide variety of applications based on the user's actual location (the so-called LBS, Location Based Services), enabling many new innovative services that will enhance everyday life. Motion Sensors are not enough on their own, but when combined with altimeters and short range radio sniffers like WiFi, they enable an outstanding indoor navigation experience. Ten Degrees of Freedom (10XDOF) is mandatory to enable this application.

THELMA™ FABRICATION PLATFORM

All gyroscopes and accelerometers manufactured by STMicroelectronics are composed of two chips stack-assembled into one plastic Land Grid Array Package [Fig. 1]. The first chip contains the micro-machined sensing element that converts the angular rate and/or the acceleration into a capacitance variation. It is manufactured using a 1.0 μm minimum lithography proprietary fabrication process, named THELMA™ which comes in two flavors:

- THELMA™/Standard
- THELMA™/Smeraldo

The second chip is built using an advanced CMOS process (0.13 μm node) with built-in high density capacitors to amplify the small signal of the mechanical transducer and to enable an easy integration of the product in the final customer board. The motion sensor's companion CMOS chip may be analog or digital, depending on the integration of the Analog-to-Digital-Converter circuit block and on the need to have a dedicated microcontroller and memory for signal processing. The CMOS die doesn't require any additional micromachining step.

Figure 1: The micro-machined element on the left is assembled with the high performance ASIC in a single package. The package on the right measures only 3x3.5x1.0 mm³ and it's the world smallest gyro currently in high volume production.

The *THELMA*^{TM} process requires the processing of two silicon wafers and one bonding operation. It begins with a standard silicon wafer onto which a layer of oxide (~2.5µm) is first grown for electrical isolation. A thin poly-silicon layer, used for interconnections, and a second sacrificial oxide layer (~2.5µm) are then deposited. Into this layer, holes are etched at the points corresponding to the supports for fixed elements and anchors for moving elements. A thicker poly-silicon epitaxial layer (from 20 µm to 100 µm) is then grown on top of this, and into this third structural layer the structures for the moving and fixed elements of the device are etched with a single mask by means of a deep dry silicon etching process. Finally, the sacrificial oxide layer beneath the structures is removed by an isotropic wet etching operation to free the moving parts. The open space around the structures is then filled with a gas, usually dry nitrogen or argon, to tune the damping factor and the resonance frequency of the micro-mechanical structure. A second wafer, with mechanical stoppers, a getter (i.e. “gas eater”) layer and a glass frit or metal ring is then bonded to the first wafer to protect the tiny structures during an injection molding process during which high pressures are applied. The getter is fundamental to guarantee the stability over time of the product performances since any material in the world is outgassing, and thus it lowers the quality factor of the micro-machined sensing element by changing the air damping coefficient. In the *Smeraldo* process flavor, the sensor wafer has embedded Through Silicon Vias (TSV) [Fig. 2], enabling further die shrinkage and smarter 3-Dimensional stacking for future Wafer Level Chip Scale package solutions.

Figure 2: Accelerometer (top right picture) and Gyroscope (top left picture) realized in the *THELMA*^{TM} process. In case of the *THELMA*^{TM} Standard flavor the connection pads for wire bonding to ASIC are on the same side of the micro-machined structure, and the cap has some clearance window during the wafer bonding process (bottom left picture). In the *Smeraldo* flavor (bottom right picture) the connections are on the back side of the micro-machined structure, and the wafer sandwich is flat during the wafer to wafer bonding operation and at the end.

THE TRI-AXIAL SINGLE CORE AND DUAL CORE CORIOLIS GYROSCOPES

Gyroscopes enable many different applications like a more intuitive user interface, optical image stabilization, and location-based-services. User Interface and Location Based Services require the ability to measure angular rate with relatively high

full scale, from few hundred degrees/second (dps) to a few thousand dps, with a good noise density level (0.05dps/√Hz), and an output data rate of up to 1 kHz; Optical Image Stabilization requires gyroscopes with a full scale lower than 100 dps, a very low noise density level (0.01dps/√Hz), and an output data rate up to 10 kHz.

To address the different applications and to enable the roadmap of different players in the markets, from mobile phone and game console manufacturers to camera module and Digital Still Camera makers, STMicroelectronics developed two different types of gyroscopes assembled in the world smallest packages:

- *SINGLE CORE* in 3x3.5x1 mm³
- *DUAL CORE* in 4x4x1 mm³

DUAL CORE gyroscopes have two sensing cores [Fig 3] and thus enable two applications concurrently, while *SINGLE CORE* gyroscopes have only one sensing core and thus enable only one application at a time. In the first case, there are two digital outputs from which the 3 angular rates (Yaw, Pitch, and Roll) can be read simultaneously, and thus use the gyroscope to enable two applications at the same time. In the latter case instead there is only one digital output and thus only one application at a time can be enabled.

Figure 3: Each ASIC of a Gyroscope contains a driving block to resonate the tiny micro-machined mass at its resonance frequency. *DUAL CORE* gyroscopes have two sensing cores running in parallel and are able to detect small and high full scales with different data rates and resolutions.

The possibility of realizing these two classes of Gyroscopes by using the same chip architecture for both *SINGLE* and *DUAL CORE* gyroscopes with a single mechanical element is grounded on an innovative micro-machined transducer design that will be described in the next paragraph. It is known as “*The Beating Heart*”.

The innovative, compact micro-mechanical transducer, which combines a triple tuning-fork structure with a single vibrating mass, is named “*The Beating Heart*” because of its

working mode. The Beating Heart achieves excellent performance in terms of thermal stability, cross-axis error, and acoustic noise immunity by using a small die size.

Furthermore, the presence of a single primary vibration mode for the simultaneous excitation of the three tuning-forks, together with the ability to sense the pickoff modes in a multiplexing fashion, allows the design of a small area, low power companion chip. In fact, the presence of a single vibrating mass avoids the problems of mechanical frequency mixing and interference, extremely deleterious in gyroscopes based on multiple vibrating masses. The mechanical structure design is explained with the aid of Figure 4.

Figure 4: The poly-silicon micro-machined structure on the top is expanding and contracting at a frequency of 20 kHz around the suspended center of mass highlighted in the bottom left picture and thanks to the spring shown on the bottom right picture.

The structure comprises four suspended plates coupled to each other by means of four folded springs connected to their outer corners, and elastically connected to a central cross-shaped hinge by an additional set of central coupling springs. The primary mode of vibration (driving mode) consists of an in-plane inward/outward radial motion of the plates: on the whole, the structure cyclically expands and contracts, similarly to a beating heart (hence, the name). Primary actuation is provided with a set of comb-finger electrodes placed only on a pair of opposite plates; the mechanical motion is then propagated to the second pair by means of the coupling folded springs at the corners. The secondary modes of vibration (sensing modes) consist of an in-plane, opposite-phase motion of the second pair of plates (yaw mode), and two out-of-plane, opposite-phase motions of both pairs (pitch and roll modes).

The yaw mode is sensed by a set of parallel-plate electrodes located on the second pair of plates, whereas the pitch and roll motions are detected by sensing the capacitive variations between each plate and an electrode placed underneath; additional comb-finger electrodes are reserved for sensing the vibrating motion of the driving mode. The mechanical coupling between the two proof masses of each sensing pair allows the secondary vibrating motions to be read in differential mode, thereby improving rejection of external linear accelerations and

vibrations. In addition, each secondary mode has a single resonant sensing frequency instead of two independent frequencies that require accurate matching to avoid performance degradations, which is a disadvantage of designs with uncoupled proof masses. The overall mechanical structure has frequency-unmatched primary and secondary modes, with a peak-to-peak movement of the driving mass of about $20\mu\text{m}$ and a nominal primary resonant frequency of 20 kHz. Combined with a high and time-stable quality factor (Q-Factor), guaranteed by the presence of a gettering material in the wafer-level cavity, this design choice results in an excellent level of acoustic noise isolation.

The Coriolis force exciting a secondary mode, which is proportional to both the velocity of the driving mode and the input angular rate, is directed orthogonally to both the driving axis and sensor rotation axes. The angular rate measurement is obtained from the sensed Coriolis acceleration by demodulation, once the driving mode is oscillated at constant amplitude [1].

Figure 5: System Architecture Block Diagram

The primary mode is excited to oscillate at resonance by closing a feedback loop around the micro-resonator made up of the resonating masses and the drive-readout/drive-forcing comb-finger electrodes. In the feedback path, the capacitive unbalancing generated by the oscillating motion of the primary mode is converted into a voltage signal by a differential charge amplifier; then, a band-pass (BP) switching-capacitor (SC) amplifier removes the residual offset and provides the necessary phase adjustment to give a total loop phase shift of 360° at the resonant frequency, which is required to enforce a sustained oscillation in the electromechanical loop. The BP amplifier output is interpolated by a 2nd order continuous-time (CT) low-pass (LP) Chebyshev filter. The resulting signal is then amplified by a variable-gain amplifier (VGA), whose gain is automatically tuned by an outer automatic gain control (AGC) loop to regulate and verify the amplitude of the sustained oscillation at the CT-LP filter output to a constant set-point value. Finally, the VGA output, boosted by a charge-pump, is fed back to the comb-drive actuating electrodes. All internal timings are generated by a PLL synchronized with the CT-LP filter output.

A single, time-division multiplexed open-loop readout interface is used to retrieve the angular rate measurements from the Coriolis accelerations along the three sensing axes. A differential charge-amplifier front-end circuit converts the capacitive imbalance induced by the movement caused by the Coriolis forces into a voltage signal, which is then synchronously AM-demodulated using a carrier that is in-phase with the velocity of the primary mode motion. A 12-bit SAR (Successive Approximation Register) ADC performs internal A/D conversion at a rate of 6.06kHz/axis; a 100/200/400/800Hz output data rate (ODR) is selected by changing the decimation factor of the output sync-decimators. The final output is a 16-bit value. The compensation of the quadrature error, the most significant challenge in gyroscopes due to the non-uniform deep silicon etching profile, is performed passively, thanks to extremely good control of the spring cross section.

Figure 6: ZRO stability over temperature and statistical distribution of the ZRO over temperature (first 6 graphs - top). Sensitivity (So) stability over temperature and statistical distribution of So over temperature (bottom graphs).

The characterization results of 33 different samples are reported in Figure 5, with all tests performed with a Full Scale of 2,000dps.

The overall performance results are excellent: the average noise density level is less than 0.02dps/√Hz (with BW=40Hz and ODR=200Hz. and the zero-rate output (ZRO) and sensor

scale factor (So) are very stable over temperature. With FS=2000dps, the ZRO temperature sensitivity is less than $\pm 0.04\text{dps}/^\circ\text{C}$, while the scale factor change over the temperature range -40°C to 85°C is within $\pm 2\%$ of the factory trimmed value ($\text{So}=70\text{mdps}/\text{LSB}$ with FS=2000dps). The design robustness is assured by the tight statistical distributions of the ZRO and So temperature sensitivities. Thanks to the highly symmetric mechanical design, the cross-axis sensitivities, measured as a percentage of the nominal selected full scale, are always less than $\pm 2\%$ and are mainly due to mounting tolerances during the packaging phase.

Figure 7: Statistical distributions of the cross-axis sensitivities over a set of 33 samples. Tests have been performed with FS=2000dps.

High immunity to acoustic noise is evident from data reported in Figure 7 (Test conditions FS=2000dps, ODR=200Hz, output BW=50 Hz).

Figure 8: Gyroscope output response to an acoustical stimulus (sine noise at 90dB SPL, frequency sweeping in the range 500Hz ÷ 25 kHz with steps of 5Hz). The plots show the average values of the pitch/roll/yaw angular rate outputs for each frequency of the sinusoidal acoustical stimulus.

In terms of power consumption, with a supply voltage in the range 2.16 - 3.6V, the current consumption is 5mA during

normal operation, 1.5mA in sleep mode (sensing electronics switched off, but with the driving block still operative to reduce the power-on time), and 5µA in power-down mode.

Market applications will continue to require lower power consumption gyroscopes, in the range of 1 mW, and that is where different suppliers are aiming with their product and technology roadmaps.

INEMO™: THE TEN ANALOG BUILDING BLOCKS OF THE FUTURE SMART DEVICES

Depending on the application needs of the customers, on the layout constraints for the final product, and on the customer's purchasing strategy, there are cases in which Six Axis and Nine Axis Modules are preferred to discrete solutions. The ability to design and produce both tri-axis accelerometers and tri-axis gyroscopes in the same technology platform makes it easy to produce Inertial Six Degree-Of-Freedom Combos (I6XDOF). STMicroelectronics is currently in production with high performance Inertial Six Axis Motion Sensors in 3.5 x5.0 x1.0 mm3 packages and is aiming to further miniaturize the solution by exploiting the integration advantages of the *THELMA™* platform. Often customers worry about the miniaturization of the sensor itself and forget about the space required by the passives for the proper operation of the device itself. STMicroelectronics has been the first player to successfully integrate passive components, like discrete capacitors and resistors, together with micro-machined sensing elements in one package.

The Inertial Six Axis Motion Sensor is a result of the combination of volume-proven micro-mechanical structures which may be implemented on two different silicon dice or on the same die, but in either case are assembled with the companion CMOS chip in the same package by means of System-in-Package (SiP) assembly techniques [Fig. 9 and Fig. 10]. The bigger technology challenge STMicroelectronics fixed, in order to enable the integration of the Accelerometer and Gyroscope sensing element on the same chip, has been the selective realization of different vacuum levels in the two different cavities hosting the two different sets of masses.

Figure 9: Six Axis Motion Sensor in 3x5.5x1.0mm³ LGA Package seen in perspective and in cross section. The Accelerometer and Gyroscope mechanical structures are located on two different silicon dice. The discrete capacitor is embedded in the same package.

Figure 10: 3X Gyroscope and 3X Accelerometer on the same silicon die realized with the *THELMA™* micromachining platform.

Some customers, however, may not require the integration of the gyroscopes with an accelerometer, and thus they are considering the M6XDOF, i.e. the combination of a 3X Accelerometer with a 3X Compass. As an example, there are customers that having integrated the *Dual Core* gyroscope in the camera module of a smartphone or a tablet, do not require another any additional gyroscope on the main PCB of the device. In this case, the best solution for the customer is the one depicted in Figure 11.

Figure 11: A 3X Compass and a 3X Accelerometer in the same package. The Z-Axis Magnetoresistive element has been assembled at 90° on the ASIC for the realization of the M6XDOF.

There are many different technologies available to realize the compass, including Hall-effect devices and MagnetoImpedance-based sensors. STMicroelectronics uses the Anisotropic MagnetoResistance-based approach because of its

very high resolution, high temperature stability, and low current consumption.

At this point, a 9XDOF sensor can be easily realized by adding all the sensors together. The 9XDOF sensor can be offered as a discrete module or as an integrated package as in Figure 12.

Figure 12: The three basic components of the 9XDOF are each housed in three different packages (top picture). The Accelerometer package footprint is $3 \times 3 \text{ mm}^2$, the Gyroscope one measures $3 \times 3.5 \text{ mm}^2$, and the Compass is $2 \times 2 \text{ mm}^2$, totalling a footprint of 23.5 mm^2 + the passive components overhead. In the bottom picture, instead, the three basic components of the 9XDOF are packaged altogether in a single package measuring only $3.0 \times 6.5 \times 1.0 \text{ mm}^3$ or $4 \times 4 \times 1.0 \text{ mm}^3$

For some applications, like indoor navigation, the 9XDOF is not enough since the altitude may need to be known, and thus an altimeter is required [Fig. 13]. As a rule of thumb, the weight of atmosphere decreases 1 mBar every eight meters of altitude, and thus by measuring the pressure, it is easy to understand at which floor one is on in a mall, for example.

Figure 13: X-ray picture of $3 \times 3 \times 1 \text{ mm}^3$ packaged Pressure Sensor.

THE ALTIMETER FOR THE CONSUMER MARKET

Pressure Sensors have long been in service measuring pressure and flow in a variety of industrial, automotive, and medical applications. Micro-machined pressure sensors are fabricated in Silicon with the physical sensing mechanism being either a variable resistance or a variable capacitance. The fabrication is either “Bulk” or “Surface” micro-machining or a combination of the two. Standard silicon substrates or more expensive Silicon-On-Insulator substrates are equally used as a starting point.

The variable resistance type uses the piezo-resistive nature of silicon to convert stress in a small diaphragm into a very small resistance change. Bulk micro-machining technology is the preferred technique. The variable capacitance type uses two parallel plates. One is fixed and the other is a thin diaphragm moving in an orthogonal direction to the plane of the chip. A very small change in capacitance then occurs between these two plates. Surface micro-machining methods are preferred for this class of pressure sensors. The interface circuitry that converts resistance to voltage, or capacitance to voltage, can be integrated at chip level or at package level, as for motion sensors. But also in this case, the System-In-Package solution guarantees faster commercialization time and higher flexibility for the customer.

No ideal manufacturing process exists, but each company follows the micro-machining approach that best exploits its experience and its manufacturing assets. Nonetheless, because of the plethora of processes running in different semiconductor fabs, the high-volume consumer market players have had to accept compromises related to price, size, and performance of the pressure sensor. And this compromise has limited the wide adoption of this sensor in consumer devices, delaying the deployment of Location Based Services.

Only recently some companies have found a viable solution for the consumer market. In particular, STMicroelectronics developed a micro-machining technology called VENSENS^{TM} in high volume production that enabled the realization of a $3 \times 3 \times 1 \text{ mm}^3$ package. As Figure 14 shows, this proprietary technology enables the manufacturing of a “Full-Silicon” small footprint ($0.8 \times 0.8 \text{ mm}^2$), thin ($\sim 0.3 \text{ mm}$) and inexpensive pressure sensor transducer that, once combined with an extreme analog ASIC, is able to detect the altitude with extreme accuracy, i.e. within $\pm 1 \text{ mBar}$.

Figure 14: The VENSENS^{TM} piezoresistive pressure sensing element by STMicroelectronics (top picture) is packaged in a small 9 mm^3 package together with its specific ASIC (bottom pictures).

VENSENS™ FABRICATION PLATFORM

The *VENSENS™* process begins with a standard silicon wafer. A proprietary combination of wet and dry silicon etching steps enables the formation of a sacrificial layer on top of which a monocrystal silicon layer is grown (Figure 15) with a proprietary epitaxial process.

The thickness of the sacrificial layer is less than 3µm and the thickness of the structural layer can reach 20µm. The end result is very similar to what is possible to get with bulk micro-machining wafer-to-wafer bonding. But the big advantage is to have thinner, smaller, and mechanically more robust chips [Fig 16]. Moreover, the sealing of the cavity requires no any wafer-to-wafer bonding and thus the reliability of the sealing joint is definitely higher.

Figure 16. The two drawings are not to scale. On the left, a membrane manufactured with the *VENSENS™* process, on the right the same membrane realized with standard bulk micromachining process. The *VENSENS™* process requires no wafer-to-wafer bonding step to seal the cavity.

Because of the superior electrical properties of the monocrystal silicon, high-quality, stable resistors can be integrated in the structural layer through implantation or diffusion process. Then these resistors are connected with an aluminum metal layer to realize the four branches of a Wheatstone bridge. The bridge is sensitive to pressure changes due to the excellent piezoresistive properties of the monocrystal silicon layer.

The metal layer is then covered with a standard dielectric, like silicon-oxy-nitride, to provide the required protection against the external corrosive agents.

Because of the intrinsic vertical stopper, this solution is also highly mechanical shock compliant, and thus is able to withstand all the potential mechanical solicitations that the sensor could experience in a portable device such as a smartphone or a tablet.

ALGORITHMS FOR SENSOR FUSION AND MICROCONTROLLERS

When designing a system using multiple MEMS sensors, it is important to understand the advantages and disadvantages of accelerometers, gyroscopes, magnetometers, and pressure sensors. Sensor fusion solves key motion sensing performance issues of 6-axis modules consisting of a 3-axis accelerometer and a 3-axis gyroscope or a 3-axis accelerometer and a 3-axis magnetic sensor.

An I6XDOF with an accelerometer and a gyroscope loses its absolute orientation as the gyro drifts over time, requiring calibration to restore an accurate heading reference. A M6XDOF with accelerometer and magnetometer is prone to data corruption in the presence of ferrous materials in the environment. A 9XDOF with an accelerometer, a gyroscope, and a magnetometer eliminates the drift that occurs with stand-alone sensor solutions. But these can be subject to magnetic interference. Algorithms to fuse the sensor data are required to compensate for the magnetic interference. The purpose of sensor fusion is to take each sensor measurement data as input and then apply digital filtering algorithms to compensate each other and provide accurate and responsive dynamic attitude (pitch/roll/yaw) results.

The Kalman filter is a mathematical method invented by Dr. Rudolf E. Kalman. Since its introduction in 1960, the Kalman filter has been implemented in many applications. The most well-known application is the GPS receiver itself and later, on the integration of GPS with an Inertial Navigation System (INS). This recursive digital algorithm is used to integrate or fuse GPS measurement with accelerometer and gyroscope data to achieve optimal overall system performance. The Kalman filter algorithm produces estimates of the true values of sensor measurements and their associated calculated values by predicting a value, estimating the uncertainty of the predicted value, and computing a weighted average of the predicted value and the measured value. The most weight is given to the value with the least uncertainty. The estimates produced by the algorithm tend to be closer to the true values than the original measurements because the weighted average has a better estimated uncertainty than either of the values that went into the weighted average.

The Kalman filter tries to estimate the state x of a discrete-time controlled process that is governed by the linear difference equation,

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1}$$

$$z_k = Hx_k + v_k$$

Where,

A is a n by n matrix that relates the state at the previous time step $k - 1$ to the state at the current step k , in the absence of either a driving function or process noise.

B is n by l matrix that relates the optional control input u to the state x .

H is n by m matrix that relates the state to the measurement z_k .

w_k is the process noise (random variables).

v_k is the measurement noise (random variables).

w and v are assumed to be independent of each other, white, and with normal probability distributions so that,

$$p(w) \sim N(0, Q)$$

$$p(v) \sim N(0, R)$$

where, Q is the process noise covariance matrix and R is the measurement noise covariance matrix.

The Kalman filter algorithm is based on linear dynamic system which means that the matrix **A**, **B**, and **H** are constant. To keep it simple, process and measurement covariance Q and R are also assumed as constants. Then the calculated Kalman gain K_k at each time step will weigh the measurement continuously to maintain the minimum error covariance matrix P_k so that the updated states will be accurate and responsive. If the process to be estimated and/or the measurement relationship to the process is non-linear, this has resulted in some of the most interesting and successful applications of Kalman filtering situations. A Kalman filter that linearizes about the current mean and covariance is referred to as an Extended Kalman Filter or EKF. In something akin to a Taylor series, we can linearize the estimation around the current estimate using the partial derivatives of the process and measurement functions to compute estimates even in the face of non-linear relationships.

When 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer are installed in a strap-down system such as a 9-axis module for applications like human body motion tracking, 3D gaming, Unmanned Air Vehicles and air mouse, etc. quaternion method for rotation matrix calculation based on gyroscope measurements is mostly used because it doesn't have the singularity issue from the Euler angles. The EKF algorithm is implemented to fuse MEMS sensor data and then update the quaternion and gyroscope bias to output accurate attitude information for pitch, roll, and yaw. This is the so-called Attitude Heading Reference System (AHRS).

The EKF algorithm may run on a standard microcontroller external to the sensor module or on a dedicated microcontroller embedded with the sensor itself as shown in Figure 17. The speed of the microcontroller core and the memory size depend both on the application and on the accuracy the customer is looking for.

Figure 17: This picture shows a chip with the microcontroller and the memory bank required to run the EKF algorithm.

CONCLUSIONS

Accelerometers, Gyroscopes, Altimeters, Compasses and microcontrollers, whether discrete or fully integrated into single packages or single silicon dice, will continue to be an important part of all present and future smart consumer products. Enhanced User Interface, Optical Image Stabilization, Remote Monitoring, and Location Based Services have already been identified as important new applications that will benefit from these technologies...but many more will come. MEMS applications are only limited by imagination and future sensors will require more and more extreme analog chips!

REFERENCES

- [1] J. Geen et al., "Single-Chip Surface Micromachined Integrated Gyroscope with 50°/h Allan Deviation," *IEEE J. Solid-State Circuits*, pp. 1860-1866, Dec., 2002.
- [2] R. Antonello, R. Oboe, L. Prandi, F. Biganzoli, and C. Caminada. "Open A low power 3-axis digital output MEMS gyroscope with single drive and multiplexed angular rate readout", ISSCC, Feb 2011, San Francisco
- [3] B. Vigna, "STMicroelectronics Masters the Art and the Science of MEMS", Semicon Taiwan 2011, Sept.
- [4] B. Vigna, "Consumer Device go SMART with MEMS", Semicon China 9/2011.
- [5] C. Johnson, "Ten Technologies that will change Consumer Devices" EETimes, 1/23/12 (2012).
- [6] STMicroelectronics, L3G4IS – Dual Core Gyroscope DataSheet, www.st.com/mems
- [7] STMicroelectronics, L3G3200D – Single Core Gyroscope DataSheet, www.st.com/mems
- [8] Massachusetts Institute of Technology, *White paper – The Balance Filter*, June 2007, <http://web.mit.edu/scolton/www/filter.pdf>
- [9] STMicroelectronics, Inc., *White paper – Introduction to MEMS gyroscopes*, November 2010, <http://www.electroiq.com/index/display/nanotech-article-display/4659348781/articles/small-times/nanotechmems/mems/sensors/2010/11/introduction-to-mems-gyroscopes.html>
- [10] University of North Carolina, *An Introduction to the Kalman Filter*, July 2006, http://www.cs.unc.edu/~welch/media/pdf/kalman_intro.pdf
- [11] IEEE transaction on biomedical engineering, Vol. 53, No. 7, July 2006, *Quaternion-Based Extended Kalman Filter for Determining Orientation by Inertial and Magnetic Sensing* http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=1643403
- [12] J. Esfandyari, R. De Nuccio, Gan Xu., "Solutions for MEMS Sensor Fusion", *Solid State Technology*, June 2011, Vol. 54, No. 7, P. 18".
- [13] M. Ferraresi, "Tri Axial MEMS Gyroscope for Automotive Applications", *Smart Systems Integration*, March 2012