An Overview of MEMS Sensors

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1.0 Background

MEMS Sensors are used in many applications and can be found in systems ranging from automotive, medical, chemical, industrial and consumer applications. The advances in MEMS technology has enabled low cost sensing and monitoring of physical and environmental conditions. By putting more intelligence into the sensors, we can build better systems by combining embedded microprocessors and wireless communications.

Micro-electromechanical systems (MEMS) are a process technology used to create tiny integrated devices that combine both mechanical and electrical components. They are fabricated using conventional batch processing techniques and can range in size from a few micrometers to millimeters. The size of MEMS devices has been decreasing over time. Technology scaling has allowed MEMS chips to shrink from $1cm^2$ in 1990 to less than $1mm^2$ by 2014. The advantage of MEMS Technology is the paradigm shift in the miniaturization of both mechanical and electrical functions on the same die. Today, MEMS mechanical components can be a manufactured with excellent performance, high reliability and good yield. Figure 1 shows a microphotograph of a MEMS gyroscope fabricated on a batch silicon process.

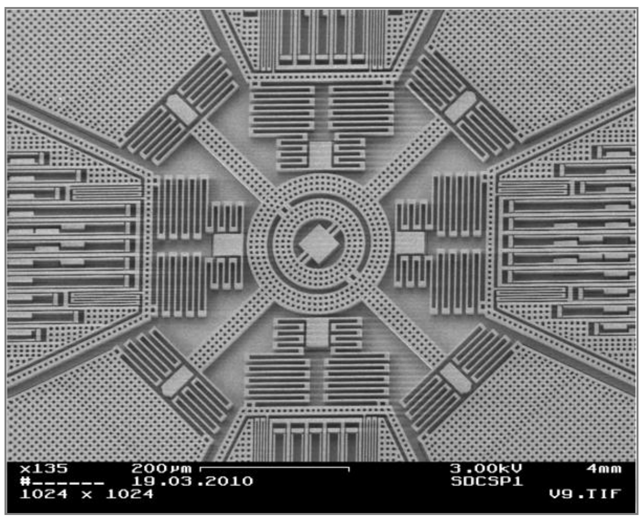

Figure 1: A MEMS gyroscope

The physical sensors which include accelerometers and gyroscopes make up the biggest MEMS sensor market. MEMS accelerometers are sensors that are capable of detecting linear acceleration, whereas a gyroscope is capable of measuring angular rates around one or more axes. A modern smart device includes a combination of accelerometers and gyroscopes, which makes it is possible to track and to capture movements in a three-dimensional space. This gives system developers the ability to deliver more immersive user experiences and accurate navigation systems.

The number of sensors used in applications is continuing to increase. For example, many cars today are using over 100 sensors and smartphones and wearable technology typical use more than 10 sensors. The market forecast for MEMS chips will top $22 billion by 2018(Figure 2: Yole Developpment, 2013).

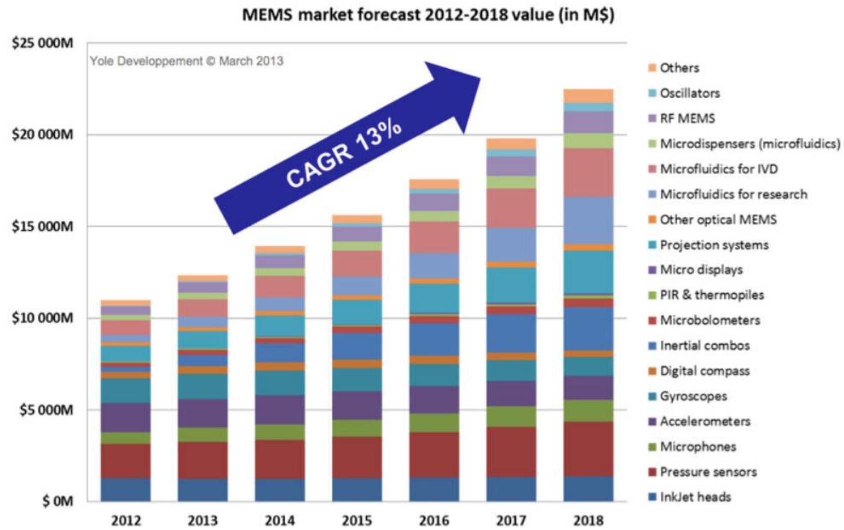

Figure 2: MEMS Sensor Market forecast
(Source: Yole Developpment, April 2015)

2.0 Sensor Design Challenges

There are many challenges in the design of smart sensors including small size, low power dissipation, high performance and robustness. Figure 3 shows a sensor based computing system. The most difficult resource to meet here is the low power consumption. This is because as the physical size of the sensing system decreases, so does energy capacity. The majority of energy consumption goes into the sensor followed by the wireless communication link. The system also includes an embedded digital microprocessor which processes and stores the sensor data. To save energy, the wireless link is normally only enabled as required to send bursts of packets at regular intervals and then put into sleep mode.

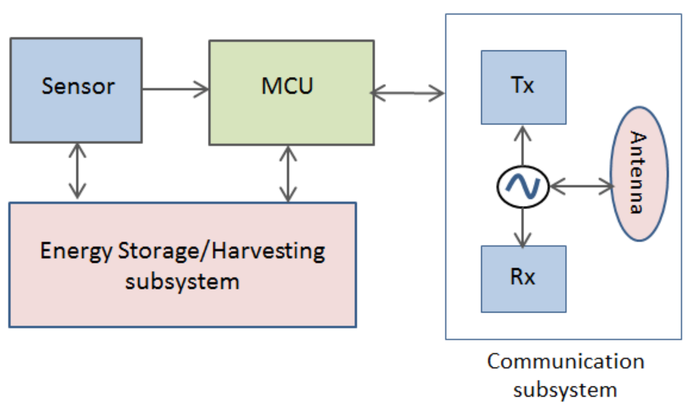

Fig. 3: Sensor based computing system

The design of the Smart Sensor system needs to consider the following key challenges:

- Low Energy Consumption: For large scale deployment, replacement of batteries would be a difficult. Energy harvesting methods need to be used to make the sensors self-sustained.

- Low Maintenance: A fault in one node should not overtly impact the operation of other sensors on the network. Fault debugging and fixing should be made easy through support from the other networked nodes. Back up control should take over to avoid losing valuable data.

- Robustness: Since these sensor nodes may be deployed under different harsh physical conditions, they need to be able to operate accurately for long periods of time without problems.

- Form Factor: The size of the sensor is determined by energy storage and type of harvester used. Scaling also affects the storage element as well as harvesting sensor size.

3.0 Applications

The growth of the IoT market is evolving rapidly and is fundamentally changing the way we interact with technology and the world around us. The IoT creates an intelligent network fabric that can be sensed, controlled and programmed. This growth of IoT market is being accelerated by Smart Sensors which are found everywhere and it is predicted by industry analyst that we will have over 50 billion connected devices by 2020.

Some of the most popular applications for Smart Sensors include automotive, smart cities, smart homes and wearable devices for health monitoring (Figure 4.0). Within the next few years, billions of cloud-connected wireless sensors and actuators will create a safer and smarter world. Furthermore, self-powered wireless sensors using harvested energy have eliminated one of the challenges for deploying WSNs, thereby avoiding the labor cost and environmental waste of replacing batteries.

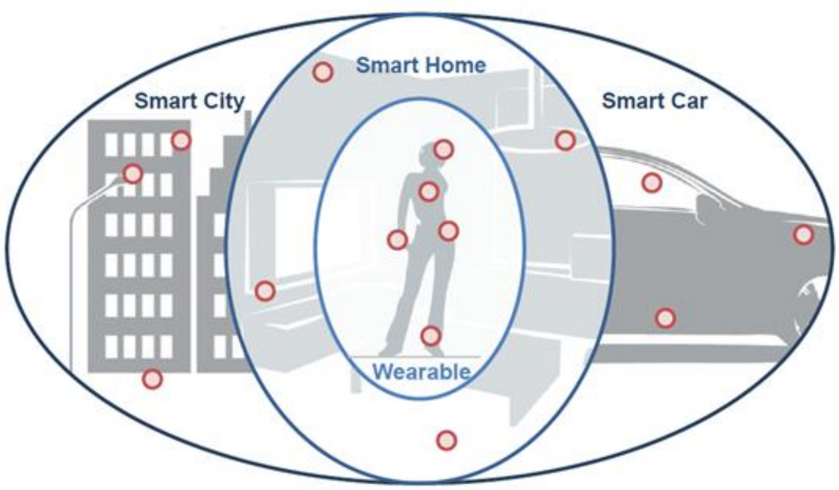

Figure 4: Sensors, Sensors everywhere

Smart Cars

Automotive airbag accelerometer sensors were one of the first commercial MEMS devices in high volume. These accelerometer chips are in widespread use today and measure the rapid deceleration of a vehicle on hitting an object. The deceleration is sensed by a change in voltage. An electronic control unit subsequently sends a signal to trigger and explosively fill the airbag.

The airbag sensor has been fundamental to the success of MEMS technology. With over 100 million devices sold and in operation over the last decade, the reliability of the technology has been proven. For example, the BMW 740i has over 100 MEMS devices including anti-lock braking systems, active suspension, navigation control systems, vibration monitoring, fuel sensors, noise reduction, rollover detection, seatbelt restraint and tensioning.

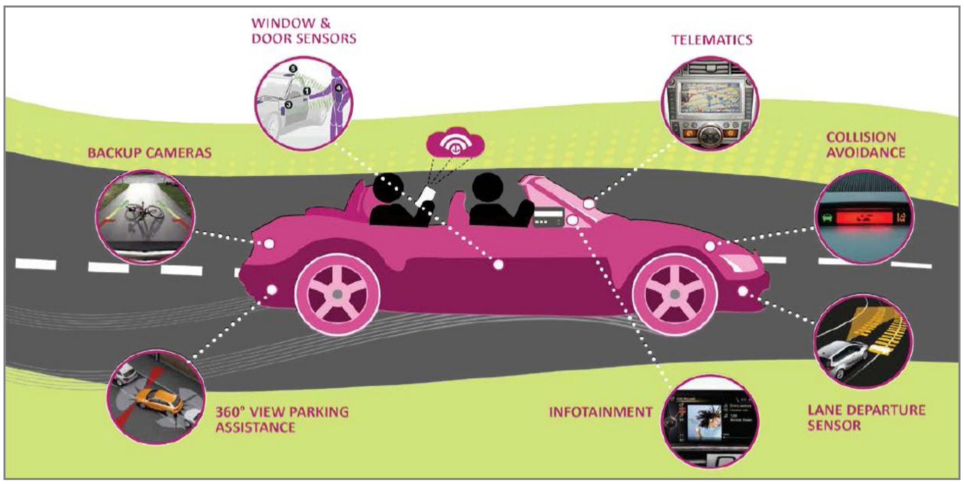

Figure 5: A modern automobile has over 100 different sensors

Smart Cities

Smart Cities use the ubiquitous communication networks, highly distributed wireless sensor technology, and intelligent management systems to create exciting new services. Smart Cities connect citizens to local government and encourage more direct participation, interaction, and collaboration. Today, there are over ten smart cities in the world including New York, Toronto and Barcelona in the Americas and London, Paris, Berlin, Copenhagen in Europe and Hong Kong and Tokyo in Asia. The number of smart cities continues to grow and is expected to be more than double by 2020.

Smart City technologies integrate and analyze massive amounts of data to anticipate, mitigate, and even prevent many problems. This data is leveraged, for example, to intelligently reroute traffic and reduce accidents, identify crime hot spots and target resources for crime reduction, and connect citizens at work or out on the town. Smart Cities proactively provide services, notifications, and information to citizens such as where to find a parking spot or a new local shop or even to monitor air pollution.

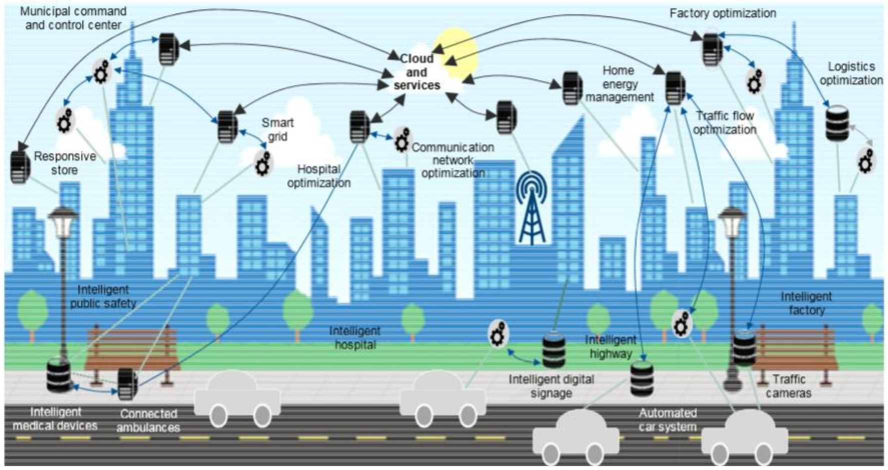

Figure 6: Smart City

Smart Homes

Smart homes will become a standard way of living by incorporating advanced automation systems to provide the occupants with intelligent monitoring and control over the building's functions. Home automation is a rapidly growing market where monitoring sensors are wirelessly connected to each other and to a central coordinator such as a set top box. This coordinator can talk to the outside world by a cable or Internet connection. The devices and sensors in smart homes can include home security systems, health monitoring, entertainment systems (e.g. Stereo, TV), heating and air conditioning, location awareness (who is where in the home) and many others applications.

Cloud based platforms combined with low-cost wireless sensing have made smart home solutions affordable for consumers. At the same time, Smart homes present some very exciting opportunities to change the way we live and work and to reduce energy consumption in the home.

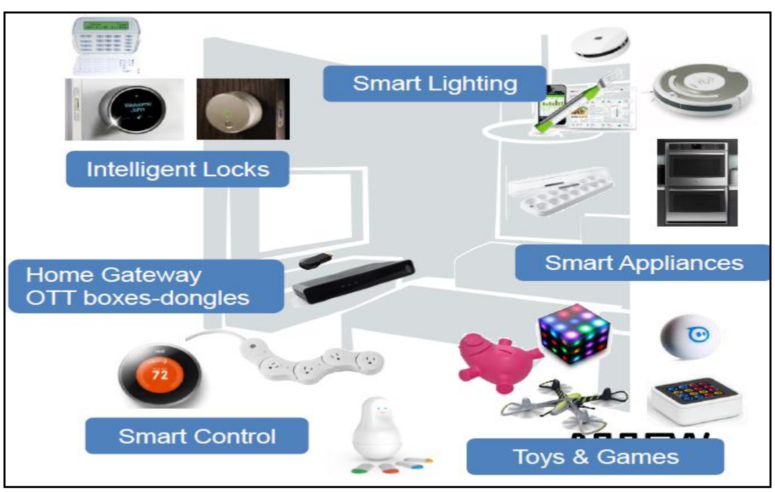

Figure 7: Smart Homes

Health Monitoring

One of the most exciting areas for smart sensors is in monitoring the health of the human body. The name associated with this type of sensor implementation is called Body Sensor Networks (BSN). Health monitoring applications can either be wearable or implanted. The implantable medical devices are those that are inserted inside the human body. Wearable devices are used on the surface of a human body or at close proximity of the user. These body sensors can collect and monitor information about an individual's health and location in hospitals or at home and connect the patient to the doctor through a cloud based system for real time monitoring. Figure 6 shows some common applications where wireless body sensors can be used to monitor heartbeat, blood pressure, body temperature and oxygen level of a patient.

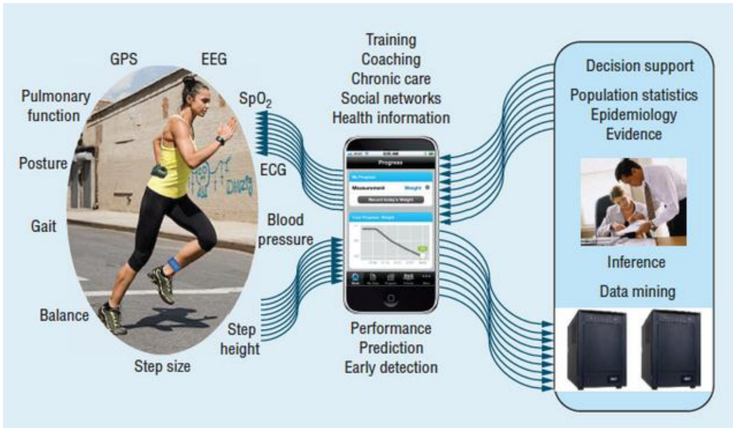

Figure 8: Health monitoring applications

4.0 Sensor Interface

The Sensor Interface is the gate-way between the sensing element and the digitized input to the MCU. It is a transition from the Analog domain to the Digital domain. Figure 9 shows a schematic of a MEMS Sensor-Asic interface. This includes a MEMS sensing element to detect the tiny changes of the environment signal to be measured, A programmable gain amplifier to boost the meniscal signal, a low pass filter to remove undesired noise and finally an analog-to-digital converter to digitize the signal into the digital domain and transfer this to a microcontroller to process the information and act upon the data.

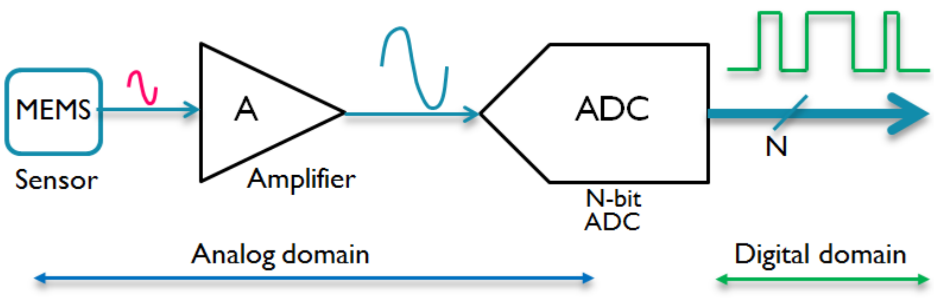

Figure 9: Sensor-Asic interface

MEMS Sensors typically use capacitive sensing to detect the changes in its environment. For example, Figure 10 shows MEMS capacitor used in an accelerometer. This comb like structure contains two conductive plates that are electrically separated. The size of the capacitor is proportional to the number of fingers implemented in the MEMS structure.

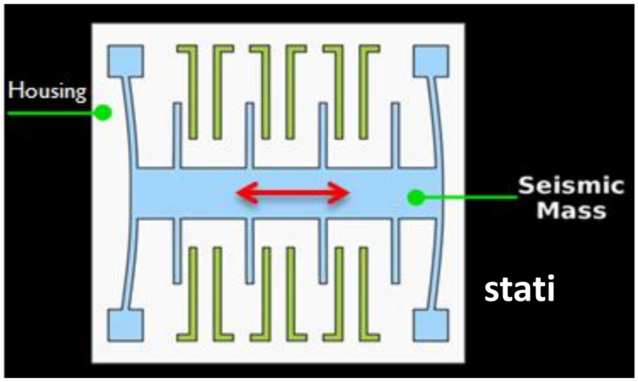

Figure 10: MEMS capacitor comb structure

The operation of this accelerometer sensor is as follows. A proof mass M is connected to a fixed frame by a flexible spring, k. Due to the mass inertia, the proof mass motion will lag the frame motion. To prevent excessive ringing, the vibrations are damped by introducing gas (or liquid) inside the package. The seismic mass is deflected during acceleration and deceleration which results in a change in capacitance. This change in capacitance results in a current flow and the amount of current flowing can be correlated to the acceleration due to the force of gravity. The resulting capacitance change can be measured and amplified with a programmable gain charge amplifier.

All sensors convert energy from one type into another that can be measured and used in different applications. The design of the sensor interface must be optimal in terms of power, noise and distortion. The front-end circuitry of the sensor interface consumes the most power and can be the bottleneck for low power applications. By making the interface gain scalable and having the ADC on the digital supply instead of the MEMS supply, the system can be made more power efficient.

Sensor interface design considerations

One of the challenges in the sensor interface design is that the MEMS devices produce capacitance changes of tiny magnitudes of less than a few attofarads (1 attoF = 10^{-18} F). The sensing elements typically requires a high bias voltage (e.g. 5V), and produce signal voltages of just a few microvolts (µV). The accuracy and stability of the device's outputs are also highly sensitive to variations in the supply voltage and temperature.

Another big concern in sensor interface design is minimizing noise, offset and drift. Due to the low bandwidth of most sensor signals, the performance of the system is limited by DC offset and 1/*f* noise. Hence, any low frequency noise above the thermal noise floor needs to be eliminated or mitigated.

One method to mitigate DC offset is to employ Auto-zeroing. This is a common switch capacitor method for cancelling dc offset to a differential amplifier. Its basic principle is that it applies a zero input to the amplifier, and measures its offset. Then, when the signal is amplified, it subtracts the measured offset from the signal.

There are two types of noise sources to worry about which are the deterministic noise from the power supply and the random noise from the transistors in the circuit. The sensor power supply needs to have very low levels of noise. For example, power supplies in mobile phones are exposed to multiple sources of noise which can easily be coupled to the MEMS sensor supply, and even small amounts of noise can degrade output quality when the output is at the level of just a few μV. The effect of random device noise is just as dramatic in the signal amplification stage for the same reason.

Chopping is a continuous-time technique that uses modulation to get rid of both dc offset and $1/f$ noise. Using this technique, the input signal is square-wave modulated to a higher frequency, *fch* before it reaches the amplifier with offset. Both the signal and dc offset are amplified, after which the signal is demodulated back to baseband, whereas the offset and $1/f$ noise are modulated to *fch*. A low pass filter following the output chopper filters out the modulated offset and $1/f$ noise. The advantage of chopping over auto-zeroing is that the in-band noise is equal to the thermal noise level in chopping, whereas it is always higher in auto-zeroing.

An analog-to-digital converter (ADC) is one of the most critical components of the sensor system. Since most high accuracy signal processing is done in the digital domain, the sensor output signal needs to be converted to a digital signal by an ADC. The ADC should be designed as a low power as possible without sacrificing performance and resolution. Also, in order for the ADC to handle input signal, the MEMS sensor output needs to be amplified to a decent level, something like 400mVpp. Using this technique, we spare the ADC from having to deal with low voltages, which relaxes the requirements on the input capacitor sizes and thereby reduces the ADC power dissipation.

To summarize, some of the design challenges for the Sensor interface include:

Circuit Challenges:

- Low DC offset
- Low Noise
- Low input capacitance
- Impedance Matching
- A low current draw

Typical Solutions:

- Auto zeroing
- Chopping, Filtering
- Auto calibration
- Element matching
- Programmable Gain

MEMS Accelerometer Block Diagram

Figure 11 shows a 3-axes accelerometer from mCube Inc. This is ultra-low power, low noise 3-axes accelerometer with a digital output and a feature set optimized for wearables and the Internet of Moving Things (IoMT) devices. The MEMS sensors 3-axes (x, y, z) data is stored in internal registers after passing through the ADC and low-pass filter. The factory offset and gain calibration is stored in the OTP memory and can be reloaded via the I2C or SPI instruction if the device has been reset and the original settings need to be recovered. The device offers various power saving modes including standby and sleep mode (clocks disabled).

The part uses a Sigma-Delta (ΣΔ) ADC which is one of the most popular converter architecture for high accuracy sensor applications. The accuracy performance is attributed to the noise shaping quality of the oversampling converter. The main advantage of the ΣΔ architecture is that the input capacitor size is reduced by the oversampling ratio. Also, with oversampling and noise shaping, the ΣΔ ADC can achieve higher accuracy with a fewer number of stages which makes it more power efficient.

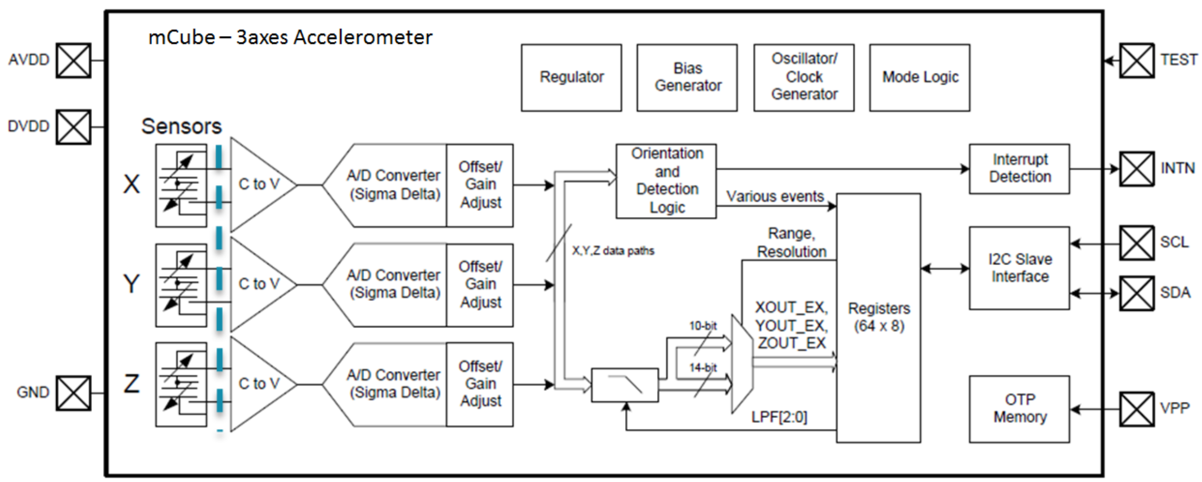

Figure 11: MC3610 3-axes Accelerometer from mCube

MC3610 Feature Set:

- I2C interface, up to 400 kHz
- Programmable low pass filter
- ADC 10-bit or 14-bit resolution, 1024 samples/s
- Active current, typical 150 µA
- Low noise down to 200 ug/√Hz

Summary

This whitepaper has looked into MEMS Sensors and some of the most common applications for monitoring of physical or environmental conditions in homes, cities and wearable devices for health monitoring. All sensors convert energy from one type into another that can be measured and used in different applications. Within the next few years, billions of cloud-connected wireless sensors and actuators will create a safer and smarter world. The number of sensors used in applications is continuing to increase. The market forecast for MEMS chips will top $22 billion by 2018.

There are many challenges in the design of Sensor including low energy consumption, size, reliability and self-maintenance. Energy consumption is the most important constraint in a sensor product since it determines the life-time of the battery operated sensor node. The front-end circuitry of the sensor interface consumes the most power and can be the bottleneck for low power applications. By considering the power budget of each block and carefully optimizing the analog front end circuits, the system can be made more power efficient.

References:

[1] Status of the MEMS Industry in 2014. Yole Développement, Villeurbanne, France, 2014.

[2] Vision and Challenges for Realizing the Internet of Things, European Union 2010,
ISBN 9789279150883.

[3] Fedder GK, Howe RT, Liu T-JK, Quevy EP. Technologies for co-fabricating MEMS and electronics. Proceedings of the IEEE 2008; 96: 306–322.

[4] Esashi M. Wafer level packaging of MEMS. The 15th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS'2009), 21–25 Jun 2009; Denver, CO, USA 2009: 9–16.

[5] Navid Yazdi, Farrokh Ayazi, and Khalil Najafi, “Micromachined inertial sensors,” Proc. of the IEEE, vol. 86, no. 8, pp. 1640–1659, August 1998.

[6] Mohd Azlishah Othman, et.al, “Wearable Health Monitoring System (WHMS) using Wireless Sensor Network,” Aust. J. Basic & Appl. Sci., 2013.

[7] E. Monton, J.F. Hernandez, J.M. Blasco, T. Herve, J. Micallef, I. Grech, A. Brincat, V. Traver, “Body area network for wireless patient monitoring,” IET Communications, vol. 2, 2008, pp. 215–222.

[8] G. Chao, L. Xiujun, and G. C. M. Meijer, "A system-level approach for the design of smart sensor interfaces," *IEEE Sensors Conf.*, vol.1, pp. 210-214, October 2004

[9] Ming Xu1, et.al, “Design and Implementation of a Wireless Sensor Network for Smart Homes,” IEEE, 2010.

[10] R. Frank, and D. Zehrbach; “Testing the System on a Chip” Sensors, vol. 15, No. 9., Sept. 1998.