ROAD TO ULTRA LOW COST MULTI-SENSOR INTEGRATION

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ABSTRACT

The IC industry has gone through fast SOC integration process over the past 50 years. We see MEMS IC sensors will follow the exact path in the years to come. After decades of dreaming, technology advancement, and commercialization efforts, accelerometer is the first one deployed in our daily life with shipment volume reaches 1B units/year. Next sensor to reach 1B units/year will be the magnetic compass. Mainly driven by the mobile market, accelerometer price has dropped from $10/axis in mid 90's to today's $0.10/axis, a 100x drop in 20 years, while compass price has dropped from $1/axis 3 years ago to today's $0.10/axis. As the price is continuously trending towards $0.05/axis, sensing system integration through MEMS-SOC will become the next mainstream technology by combining the advanced MEMS process technology, matured MCU, and sophisticated system algorithm. Based on MEMSIC's MEMS IC commercialization experiences, this paper discusses how the combination of market needs and technology advancement drives the integration roadmap for the integrated MEMS sensing solutions.

KEYWORDS

MEMS, Accelerometer, Compass, IC, Integration, SOC, sensors, algorithm, WSN.

INTRODUCTION

Sensors will be everywhere in our life, just like what happened in electronics over the past decades. A trillion sensors in our life will surely happen. This will not only change our life and culture significantly but also offer new entrepreneurs tremendous business opportunities down the road. The precursor of such huge future trend has already been seen from today's fast growth in sensor applications in mobile phones, consumer electronics and automotives, etc. Over the past decades, Micro-Electro-Mechanical System (MEMS) products exhibited the fastest growth rate compared to a flat growth rate in traditional IC products.

However we currently are only at a very early and primitive stage in terms of sensor technologies and market. This paper discusses the path to the future by referencing the history of the IC industry.

HISTORY ALWAYS REPEATS

Because human nature never changes, our history always tends to repeat. So history is a good reference to project the future. If we look back to the past of electronic industry, it is easy to see why sensors will be everywhere and how various sensors will be integrated.

The IC industry is a history of miniaturization and integration. We started with many discrete devices such as capacitors, resistors, diodes and transistors. Then as the component size got smaller through the innovation of IC process, we brought all components together to form IC's such as amplifiers, converters, memories, and MCU's. As the IC technology advanced further, we started to integrate all functions to form a System On Chip (SOC).

MEMS technology is essentially a miniaturization technology. So it will repeat the history of miniaturization in IC industry, except this time the focus will be mostly on miniaturization of electro-mechanical structures. Today's MEMS technology miniaturizes everything except things one cannot miniaturize such as buildings and bridges, etc. As the sensors size are shrinking down, we will see the integration of many MEMS sensors into one piece. Integration is a critical way to minimize size and cost of sensors to make them portable and affordable. So if we compare the current technology stage of the MEMS with the IC history, we will see MEMS technology and industry is still at infancy. Multi-sensor integration will be merged with processing SOC to form a MEMS-SOC system.

SENSOR IS THE NEXT BIG GROWTH IN ELECTRONIC COMPONENT INDUSTRY

Advancement in electronic technology has come a long way over the past decades. If we look at the IC process capabilities and the kind of SOC chips used in the consumer products we have today, such as computers and mobile phones, the IC industry seems to be quite matured already. But if we include sensors and actuators into the equation, we will see the IC technologies, with MEMS to be merged in, are still far from being matured and complete. There is still a long roadmap in both technology and product yet to be achieved.

Why we have to include sensors and actuators into the IC roadmap? Because a SOC system, no matter how advanced it is in processing power, will not be a smart system until it can sense and actuate (interacting with the nature by itself). The intelligent level of today's system is still far below human's level. A smart system eventually will become an integral part of our human life. This will not happen without sensors and MEMS technologies.

IC industry started with electronic components and then developed the way into systems such as computers. The computers are similar to our brains which have processors and memories. However these computers were all isolated until we have the internet which links many "brains" together to share data and resources. The internet is basically a linear social network of computers. Just being able to link "brains" through internet alone by itself has already changed our life big time. However even with such connected "brain" society, the whole network system still by itself does not have the capability of gathering data and information. Majority of the data and information loaded inside of the network today, such as audio, video, text, etc., actually comes from human manual input, not from the network itself.

A system or a network will not be smart until it has self-awareness to the environment and nature. In fact our own human systems are very smart systems which live in a meshed social network, interacting within the network

(human inter-relations) and outside of the network (self-aware of the natures). Up to today, the IC industry has created incredible accomplishment in building up the "brains" and the internet linkages. But the sensing function of the IC's has not been well developed in the past decades. In fact the maturity of the sensors technologies is way behind that of the signal processing technologies. This simply means we still have a long way to go in technology advancement.

SENSOR INTEGRATION IS THE KEY TO FUTURE SUCCESS

From the view of consumer benefit, a system must be portable and affordable because we need to carry a smart system containing many sensors in our pocket every day. Given the massive number of sensors to be included in a smart system, multi-sensor integration with SOC (MEMS-SOC) is the only way to reach portability and affordability. Integration will reduce overall area and size requirement to save precious PCB space with fewer components to be managed by the OEMs. Total solution cost will be lowered while providing turn-key solution fast design-in process.

However, sensor integration is not as simple as just making a Silicon in Package (SIP) which simply bond multiple devices into one small module. Manufacturers, such as PC makers and phone makers, basically are making the modules by putting various IC's into a box. SIP as a small module in a box does not add true values to the customers. So SIP is not the right integration approach as far as cost and size are concerned.

The right integration must be in silicon or wafer level. Figure 1. shows one of 9 degree of freedom (9DOF) device concept. In this example, MEMS structure such as, but not limited to, accelerometer and gyroscope are fabricated directly on top of CMOS wafer. Such structure is then hermetically sealed by a Capping wafer on top. The TSV provides electrical connection to the other side of CMOS wafer where pillar bumps and solder balls are made. A 3D magnetic sensor wafer or thin film sensor structure is attached to the top of capping wafer.

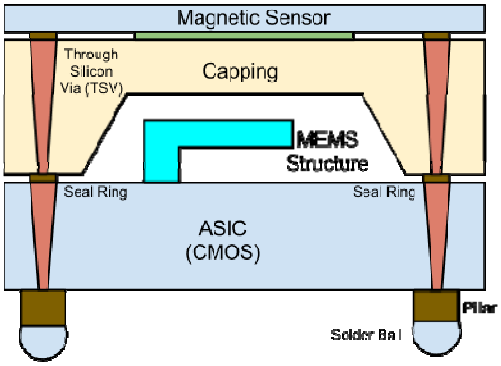

Figure 1: One Concept of 9 DOF Device

Wafer Level Packaging (WLP) and Through Silicon Via (TSV) are the enabling technologies for the sensor integration in this case. They will continue be the most important technologies for effectively integrating different sensors and materials together.

However WLP and TSV technologies alone cannot solve all the problems of integration of multi-sensors and SOC. Monolithic IC integration of MEMS sensors with SOC is the foundation of the ultimate miniaturization and cost down. Below is a picture of single chip monolithic WLP thermal accelerometer, MXC626XC, made by MEMSIC. Measured at only 1.2x1.7mm, it is one of the smallest and lowest cost monolithic accelerometer in the market today, based on our proprietary monolithic CMOS-MEMS technologies. Although MXC626XC has demonstrated a true monolith integration of MEMS sensor with standard CMOS, monolithic integration is still far away for many other MEMS sensors.

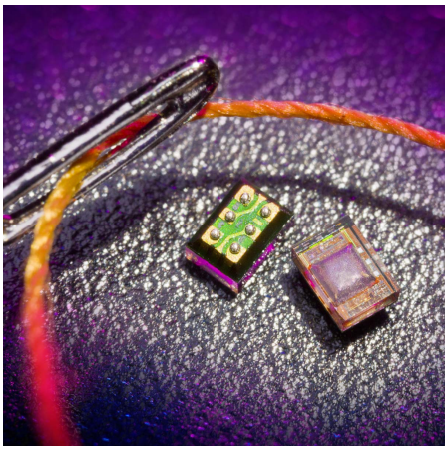

Figure 2: WLP Monolithic Thermal Accelerometer

As we are expecting many other sensors to join in the mass volume market eventually, the sensors that has reached the mass market applications are still limited to accelerometer, compass, and gyroscope which can form the 9DOF inertial sensing system. The integration of these sensors has to start with cost down, size down, and performance up for each individual sensor. But not all these sensors are equal within the 9DOF inertial sensing system. For example, accelerometers and compass have already reached the navigation level of performance while at <$0.10/axis market price. Gyroscope, in contrary, has its performance far below navigation level while at much higher price.

Sensors costing more at less performance will have limited market volume. Each sensor cost should reach <$0.02 per axis in a fully integrated system. This will be the cost level when we really reach a trillion sensor in our life. Very scary, but it will be the reality. Just look at how much we pay for a smart phone today given its powerful functionality. The IC system went through this path, the MEMS sensor will do the same. Again, technology history in IC will repeat in sensors.

ALGORITHMS FOR SENSING SYSTEM

A human capability depends on his/her personal knowledge and skills on top of his/her genetic smartness. The intelligent level of a smart sensing system depends on multi-sensor signal processing algorithm on top of its intrinsic signal processing speed. In fact our human is an

incredible multi-sensor integrated system with smart algorithms including cognitive recognitions of sound (such as voice), light, images (such as patterns), etc., followed by thinking, skills, judgment calls, actions, and many more.

The role and function of the currently popular buzz word "sensor fusion" are still limited to just mixing the signals from multiple sensors, such as gyroscope, accelerometer, magnetometer, GPS, altimeter, etc. and then calculate the position, location, orientation and other information. Figure 3. is an example of 9DOF "sensor fusion" that combines information of gyroscope, accelerometer and magnetometer. 3D gyroscope and 3D accelerometer provide stabilized Roll/Pitch signal. Such signal is then feed into 3D Magnetometer compass algorithm for tilt compensation. Gyroscope rotation is also used to enhance the speed of compass heading signal.

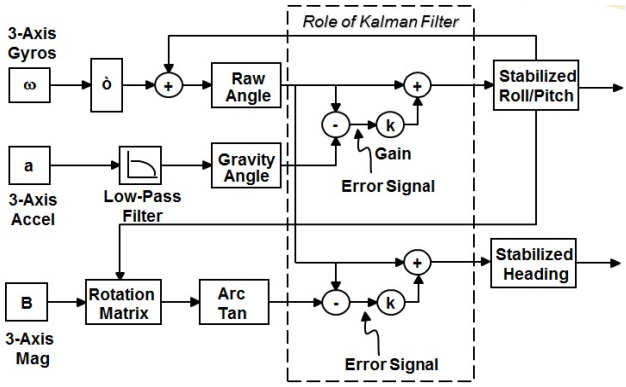

Figure 3: Example of 9DOF Sensor Fusion

Given the simplicity of the physics principles, it is not surprising we see an obvious similarity between the navigation algorithm developed over the past decades in avionics industry for airplanes (as shown in Figure 4) and the "sensor fusion" algorithm developed recently for the portable electronic: both employ multiple inertial sensors such as gyroscope, accelerometer and magnetometer; both have to provide position and orientation information. In physics, they are the same things except application environments are quite different. Thus the algorithms for avionics and mobile phones are different only because of different user environments and experiences.

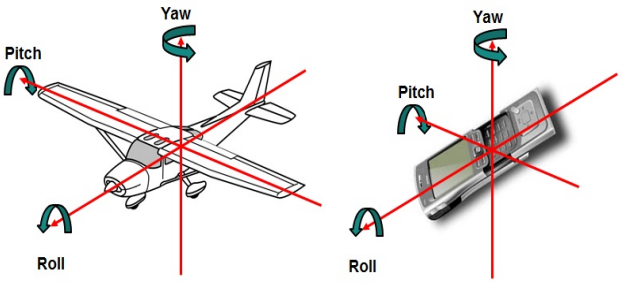

Figure 4: Similarity between Aviation and Phone

Algorithm is a critical part of a smart sensing system integration. Knowledge from the past aviation industry can always be a valuable foundation and starting point. This was a part of the reason for MEMSIC to acquire Crossbow Technologies in early 2010.

An ultimate sensing integration algorithm in the future will cover far beyond the current "sensor fusion" we have today. It will not only blend signals from various sensors, but also further process the signals to extract information. That will also include none-linear iterations of data collection and processing in order to make judgment and decision together with the human system. Eventually the algorithms of the smart sensing system will be merged with the algorithms of human society to form an unified system. By then a linear electronic system (fully predictable) will become a none-linear and chaotic system (unpredictable but under a changing pattern).

INTEGRATED COMPUTING

In most solutions today, sensing integration algorithm lies in external MCU's which is a part a bigger system, such as the processors inside of mobile phones. Such approach gives sensor algorithm plenty of computing power and code/data space at an expense of large power consumption. Localized computing within integrated MEMS sensor SOC has becoming more attractive in many applications. This is enabled by monolithically integrated MEMS and CMOS using MEMS-SOC technologies.

NETWORKS FOR SENSING SYSTEM

Integration of wireless radio with sensors will also be an important part of the sensing system integration.

People around the world have been connected through internet. The most popular terminals for interconnects are computers and mobile phones. Mobile phone is the device everyone will carry every day. This is the reason we see such fast growth in smart phones and sensors. While sensors in the phones are naturally connected with the network, many sensors not in the phones or computers may not always be readily connected. Information from these remote sensors can be linked through a smaller local network such as Wireless Sensor Networks (WSN). Live monitoring of weather (temperature, pressure, humidity, etc.), human activity, traffic, and security, etc., can be implemented using sensor network and such information can then be accessed remotely through internet and mobile phone. In this way, the internet can reach out a huge number of sensors which are locally connected. This will greatly extend human's ability to sensing what is round us.

Figure 5: Wireless Sensor Network

CONCLUSION

By enabling SOC/MCU's to perform self interactions with human and nature, sensors and actuators will make our electronic devices smart. Future smart systems will be everywhere of our life and will become an important extension of human sensing and decision system. A trillion sensors which are all connected together through wireless and wired network will become reality. By then our life will heavily depend on the networked smart sensing system. MEMS IC technology is merely a way of miniaturization and integration of different sensors. We are only at a beginning stage of the next big growth after the boom of the internet.

The internet only connects all computers together, MEMS sensors installed in clothes, phones, cars, computers, toys, and cameras', etc. will make the internet fully alive. A live internet in turn will merge data and activities with our human society. Multiple sensors eventually have to be integrated just like today's SOC. These will be enabled by the advancement of single chip multi-sensor integration technologies yet to be developed. Will we see another boom and market bubble in smart sensing systems like what happened in internet? We would say "very likely".