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Perspective

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Sensors in Network (1) —Origin of Sensor Intelligence—

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1. Introduction

Recently, an attempt to integrate sensors and networks in a high-order dimension has been carried out. Various concepts for this integration have been proposed thus far; for example, sensor networks, ubiquitous sensor networks, ambient sensor networks, Internet of Things (IoT), and Trillion Sensors Universe, which are almost the same concepts in terms of the integration of sensors and networks. Behind the rapid expansion of these concepts are the rapid improvement of the performance of micro-electromechanical system (MEMS) sensors, reductions in their size and fabrication cost, and the realization of their mass production, as well as the establishment of network technology, the advancement of processors and wireless devices, and the realization of small high-capacity power sources. In this perspective series, I will explain the integration of sensors and networks in several sessions. The planned contents include the history of the sophistication of sensors, the outline of sensor networks, fundamental technologies for supporting mass production, the integration of different types of sensor, sensor interfaces, peripheral technologies for connecting networks, stand-alone power sources, and examples and future prospects of sensor networks. In this session, I will describe the history of the sophistication of sensors and the outline of sensor networks.

2. Intelligent Sensors—Proposal of Concept

The history of low-cost mass-produced sensors started with the development of MEMS technologies in the late 1970s, as shown in Ref. 1, which is a survey paper regarded as a bible of MEMS in those days. At that time, various silicon-based MEMS sensors were proposed, and the age of MEMS sensors would have been expected to come in the future. As expected, various sensors were practically applied, for example, sensor control systems for engines that were useful for satisfying the emission control standards in the Muskie Act of 1970 were installed in automobiles, which was followed by the introduction of acceleration sensors for detecting collisions to activate an air bag, gyroscopes for electronic stability control (ESC), pressure sensors for monitoring tire pressure, and recently, various laser sensors and view monitors for automated driving; thus, current automobiles are a typical example of systems equipped with many sensors.

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Moreover, MEMS sensors have been widely used even in cell phones and toy controllers because MEMS sensors with reduced size, power consumption, and price have become available on the market.

In the predawn of MEMS sensors around 1980, the need for sensors in various types and large quantity for advanced systems was already recognized. As microprocessors were developed, digital signal processing was assumed for the sensors. In this case, if multiple sensors transmit raw data towards a processor (known as central processing) as shown in Fig. 1, the processor is overloaded, noise easily contaminates low-level sensor signals, and large-scale hardware is required for the processer (*e.g.*, analog front ends and A/D converters for individual sensors). To solve these problems, an idea of making sensors themselves intelligent/smart was proposed.[2,3] According to Breckenridge and Husson,[3] a smart sensor should be able to perform analytical and statistical calculation, perform all its operations in the simplest form, handle new data acquisition and processing situations by reconfiguring itself, adjust to different environmental condition, interact with other sensors, extract useful information, and make decisions according to the condition. Figure 2 shows a concept of a smart sensor in which a sensing device is integrated with a microprocessor as the core on a single chip. A processor that controls the entire system handles only lean and significant data from the smart sensor, making the loads distributed (known as distributed processing). Unfortunately, integrated circuits and MEMS processing technologies as well as metal oxide semiconductor (MOS) analog circuit technologies were still unmatured around 1980 when the smart sensor was proposed. Hence, the smart sensor was not commercialized despite the fact that some prototypes were attempted in those days. However, some pressure and magnetic sensors incorporating amplifiers equipped with relatively simple bipolar analog circuits to amplify weak sensor outputs and compensate for temperature differences were commercialized.[4] Here, smart sensors and intelligent sensors can be regarded as similar. Some researchers discriminate them by stating that the first one is more related to technological or so-called "smart" aspects; the second one is more related to functional or so-called "intelligent" aspects.[5]

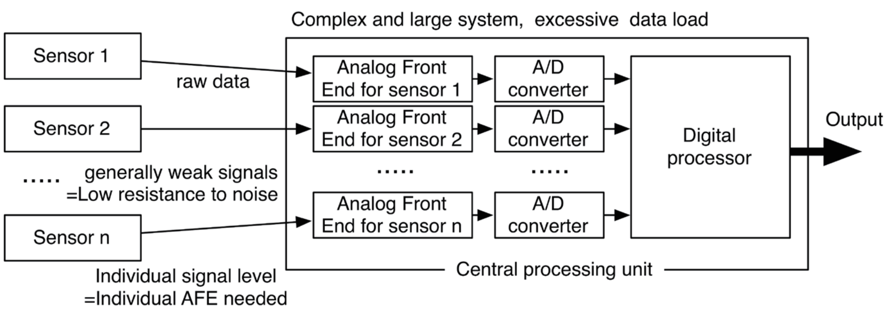

Fig. 1. Sensing system equipped with multiple sensors (central processing).

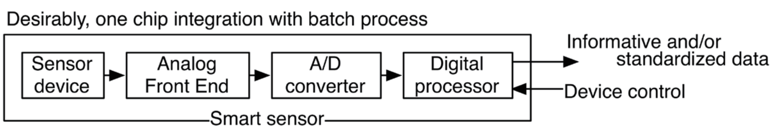

Fig. 2. Concept of intelligent/smart sensors.

3. Current MEMS Sensors

Now that 30 years have passed since the announcement of the concept of smart sensors, many devices that can realize the concept have been placed on the market.—This reminds me of the fact that hardware with a concept close to the Dynabook proposed by Alan Kay in 1972[6] has been finally put into practical use, such as in the form of the iPad, these days. This may indicate that it takes about 30 years for a dream to become reality.—In particular, sensors of mechanical quantities, such as acceleration sensors, gyros, and pressure sensors, have been highly sophisticated. Figure 3 shows examples of MEMS sensors easily available today. They can compensate for variations in characteristics specific to devices and generate outputs only when the arbitrarily set or predetermined conditions of filters and resolution are satisfied; namely, the said sensors exactly satisfy the concept proposed by Breckenridge and Husson.[3] In addition, the current mainstream is sensors with a standard digital output interface, such as an inter-integrated circuit (I^2C) and a 3- or 4-wire serial peripheral interface (SPI), which can be used to simply connect sensors to the microprocessor. These technological developments have facilitated the realization of wireless sensor nodes with a processor.

4. Sensor Network

Figure 4 shows a hardware system (sensor nodes) represented as a sensor network. The system consists of sensors, a processing unit, a radio frequency unit, and a power unit. As mentioned above, sensors (in particular, physical sensors) have been considerably sophisticated, and ultralow-power and multifunctional processors are available today. There are various wireless communication standards, such as ZigBee, ANT, and Wi-Fi. The optimal radio frequency or protocol must be selected when wireless systems are applied. Along with the recent advancement of wearable devices, Bluetooth low energy (BLE) has attracted attention under the assumption that data are transferred via smartphones or for the purpose of reducing the power consumption of sensor nodes. Moreover, several types of one-chip microcontroller incorporating the BLE function into general-purpose microprocessors have become commercially available; for example,

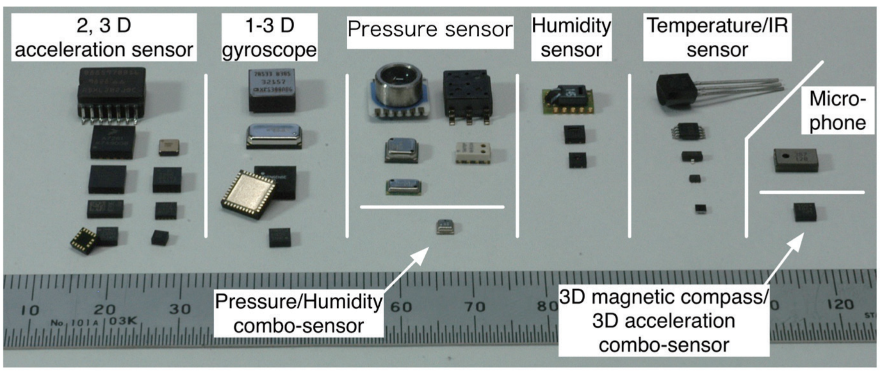

Fig. 3. (Color online) Examples of currently easily available MEMS sensors. Almost all the sensor's output digital signals and can be easily connected to microprocessors. Sensors in the lower parts are newer, i.e., smaller and more complicated, than those in the upper parts.

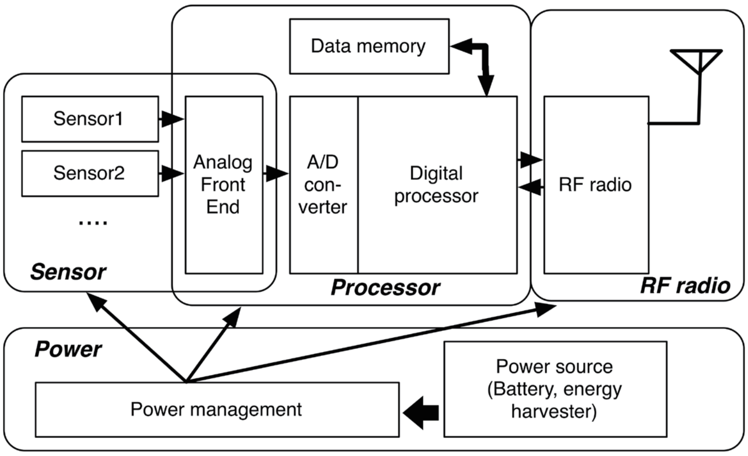

Fig. 4. Outline of sensor network system.

PSoC4 BLE is released from Cypress Semiconductor Corp., and the TZ1000 Series with multiple sensors built in a chip is provided by Toshiba Corp. Wireless sensor nodes can be very easily realized using these microcontrollers. I feel that the current critical issue of the wireless sensor nodes is the power source. Recent researchers' interest has been directed to energy harvesters(7) for collecting surrounding energy. However, the operating principle and structure should be selected in accordance with the operating environment, and the absolute amount of generated power is generally small; thus, the energy harvesters are still a technology in progress. Although they are considered to be essential for systems that have batteries difficult to exchange and are required to continuously operate for a few decades or more (*e.g.*, when applied to structural health monitors for bridges and tunnels), no promising devices have been developed yet. However, technological progress has gradually reduced the power required for sensing systems and improved the output of harvesters. Complete battery-less sensor nodes are highly expected to be realized in the future.

5. Summary

I have outlined the advancement of sensors and network sensing systems. It is said that in the future we will enter the Trillion Sensors Universe, a society in which trillions of sensors are required per year. The "trillion" is not an overestimation. Sensor networks are a composite technology involving information processing, wireless systems, circuits, energy, sensors, and related materials. I expect that *Sensors and Materials* will contribute to the above society in the field of sensors and materials.

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