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Perspective

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Sensors in Network (3)
—What and How Data Should Be Networked?—

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1. Introduction

In the previous sessions, the advancement of sensor devices and their technologies was briefly outlined.(1,2) In this session, I discuss how such sensors are used and incorporated into network systems. One pioneering commercial network system is the DECnet, which was proposed and implemented by the Digital Equipment Corporation (also known as DEC) in the 1970s. In parallel, the Advanced Research Projects Agency Network (ARPANET) project was an attempt to combine numerous computers over a wide area, leading to the launch of the email and bulletin board systems in the 1980s and the World Wide Web system in the 1990s. Owing to the progress in the development of hardware for wireless networks, high-speed low-cost wireless network modules have become easily available since 2000. Currently, networks extend all over the world and laptop PCs, mobile terminals, and sensor systems can be easily and wirelessly connected to the networks.(3)

2. Combo Sensors for Collecting Multiple Types of Data

There are various application targets of sensor networks: for example, 1) distributing sensors over farmlands and monitoring the insolation conditions, ambient temperature, water concentration, soil pH, and the degree of growth of crops for each area will enable the optimal care of crops, leading to an increase in yields and working efficiency, and a decrease in the use of fertilizers; 2) monitoring the building conditions, such as temperature, humidity, brightness, and the presence or absence of persons, for a small area, to appropriately control the local cooling, heating, and illumination conditions will reduce power consumption; 3) installing sensors onto bridges and tunnels at various intervals to detect the deterioration and displacement of their structures and maintain them in appropriate conditions will increase the safety of such structures; 4) collecting bioinformation such as exercise, heart rate, body temperature, and blood pressure will ensure the safety and health not only of humans but also of livestock; and 5) monitoring the conditions of production facilities, such as sound, vibration, and temperature, will enable the early detection/prediction of malfunctions in the facilities. All applications have the commonality of the need of monitoring multiple factors using sensors.

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Here, I describe a long-held personal vision, even though it may be a little premature to envisage its implementation. Assuming that a human is an automaton, it is an excellent automaton. This is because the automaton has multiple types of sensing functions and network interfaces, including voice, gesture, and facial expressions, and it is capable of being updated and using a database and understanding the multiple types of information obtained through the sensing functions. This excellent automaton deserves attention as a model for sensor networks that will advance in various directions in the future.

To realize multiple sensing functions similar to those of humans, the concept of a combo sensor, that is, a device obtained by integrating multiple types of sensors on a chip or in a package, has recently attracted attention. Our research group proposed monolithic integration of multiple types of sensors, and fabricated such a sensor device (Fig. 1) in 2001.[4,5] This sensor device was realized by monolithically integrating a bipolar integrated circuit, a triaxial acceleration sensor, a pressure sensor, a humidity sensor, and a temperature sensor; and we called it the integrated multi-environmental sensor. Various circuits, such as those for analog amplification of each sensor, offset adjustment, and sleep (to stop the system and reduce power consumption), were incorporated into the device. By connecting the output to a network (though wired, at that time), we constructed a demonstrative system for monitoring sensor signals on a web browser at a remote location. At that time, most networks were wired and required network protocols designed using a CPU with large power consumption. We presented the system at the International Conference on Solid-State Sensors and Actuators (Transducers 2001).[4] At the next conference (Transducers 2003), a new session entitled "Environmental Sensors and Systems" had already been set up. It was apparent that more researchers were starting to present sensors for detecting environmental quantities (multiple physics and chemical quantities) at that time.[6,7]

Currently, almost all combo sensors seem to be a hybrid integration of various types of sensors in a package. Typical examples of such devices that have been intensively developed are a device integrating temperature and humidity sensors to detect environmental quantities and one equipped with a pressure sensor (barometer) (*e.g.*, BME280, Bosch), as well as a device integrating a geomagnetic sensor and an acceleration sensor to detect the direction and motion of the sensors (*e.g.*, BMC050, Bosch) and one equipped with an angular rate sensor (gyroscope) (*e.g.*, LSM9DS1,

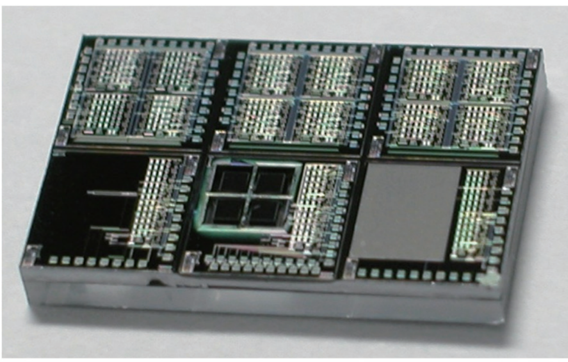

Fig. 1. (Color online) An example of an early combo sensor. It includes 3D accelerometer, pressure sensor, humidity sensor, temperature sensor with analog front-end and stand-by circuit. The technology is out-of-date now: 10 μm feature size, power supply ±5 V, and chip size 10 × 15 × 1 mm^3. However, the idea is the same as for the latest combo sensors.

STMicroelectronics). The last-mentioned example is also called a nine-axis sensor because it can simultaneously measure the geomagnetism, acceleration, and angular rate along each of the three axes. The utilization of such combo sensors enables marked enhancement of the system functions without major expansion of the footprint of the system, hardware, or software. For example, recent iPhones have already been equipped with a pressure sensor, a triaxial acceleration sensor, a triaxial gyroscope, and a triaxial magnetic sensor, as well as many other sensors such as multiple acoustic and image sensors. Unprecedented applications using these technological seeds have been proposed thus far.

For combo sensors, the number of sensing elements will be multiplied resulting in increased complexity of interface circuitry. As the number of sensors increases, the preparation of individual interface circuits for each sensor element is not realistic. In order to reduce circuit complexity, multiplexing of the signal and digital signal processing in the early stage are effective. The multiplexing is shown in Fig. 2(b), where the output type (such as voltage, capacitance, resistance, etc.) and level of the sensor elements are equalized, and sensor signals are multiplexed in time. This minimizes the size of the analog front-end and the number of A/D converters. In this scheme, the calibration data for each sensor element (*e.g.* sensitivity and offset) may be stored in a digital, not analog form (analog trimming) resulting in further reduction of the size of analog circuits. In current digital technology, power consumption has been drastically reduced compared with that of analog processing for filtering, calibration, synchronous detection, etc. Thus the digitizing of the sensing signal in the early stage is preferable. However, it may be necessary that the A/D converter have more resolution in order to secure the room for the digital processing.

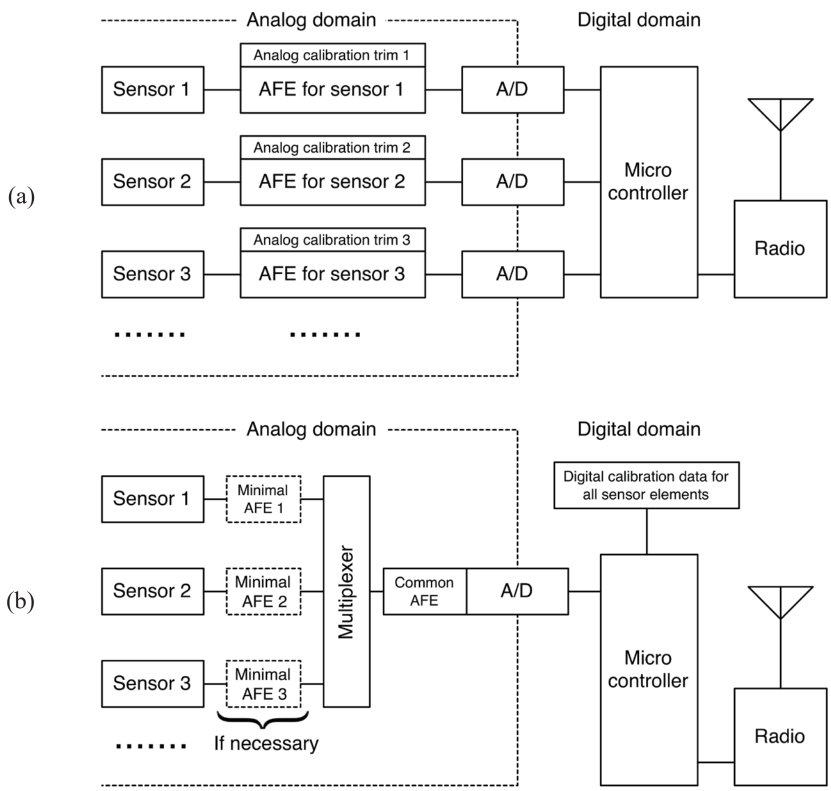

Fig. 2. Interface for combo sensors with (a) individual interface and (b) multiplexed interface.

3. Traffic in Network

For wireless networks using batteries or power harvesters as the power sources, the mean power consumption of the system is a key issue in terms of continuous running time. Recently, the operating power for sensor interface circuits has been markedly reduced; for example, it is only 2 μA at a supply voltage of 1.8 V (3.6 μW) for LIS2DH (STMicroelectronics) with a triaxial acceleration sensor at a sampling frequency of 1 Hz. However, the power used for wireless communications cannot be decreased, in principle, once the transmission power is determined on the basis of the communication distance. Therefore, some modification is necessary to minimize the number of signals transmitted and received (the power of the receiving circuit also increases with frequency and required sensitivity). Moreover, the content and amount of data to be transmitted to networks largely depend on applications, and unified discussion is difficult. Generally speaking, it is necessary to minimize the sampling rate or carry out some pretreatment to extract only the necessary data. For example, in the monitoring of biological motions, the network traffic can be greatly reduced by processing the output signals from a triaxial acceleration sensor into an easily usable form (*e.g.*, the amount of exercise, the number of steps, and physical posture) and transmitting a set of data every second or minute, rather than by transmitting unprocessed raw data. Data that basically require no rapid sampling, such as body temperature and ambient temperature, can be effectively obtained and transmitted by determining the appropriate sampling rate (adaptive variable sampling rate in some cases) depending on the target to be monitored. When extremely complicated processing is carried out at the sensor nodes, power consumption will increase, requiring the optimization of each application. The above-mentioned compression of sensor data is effective for reducing not only the power consumption of sensor nodes, but also that of the traffic of the entire system and infrastructure, including routers and servers as the paths of data transmitted to the destinations. It is also important for using the limited amount of radio frequency band effectively. For general low-power-consumption sensor nodes, the systems for wireless communications and the acquirement and processing of sensor signals should be switched between the active and the dormant or sleep states to decrease the mean current (known as intermittent operation). When the systems are slept, their power consumption is reduced but cannot become zero, because power is consumed for various factors such as state maintenance, leakage current, and clock function. Determining how to minimize the duty cycle (the ratio of the active period to the total period) of the systems, and the time of switching between the sleep and active states (for example, a microsecond-order time is required to reboot a dormant crystal clock oscillator) are the keys to reducing power consumption as well as the amount of data to be transmitted.

4. Network Topology

In general, most of the data obtained at sensor nodes are wirelessly transmitted to the Internet, stored in cloud servers set at remote locations, saved and analyzed, and transferred to and presented at appropriate occasions. At the connection to the Internet, a control node called the coordinator is arranged, and wireless nodes are connected, directly or indirectly, to the coordinator. Figure 3 shows examples of the topology of wireless sensor networks. Generally, the coordinator that manages all data of a local network is connected to the Internet. Sensor nodes are connected to the coordinator directly or via sensor nodes (end device) with a router function. If the connection condition is known and fixed, controlling communications is easy. However, designing

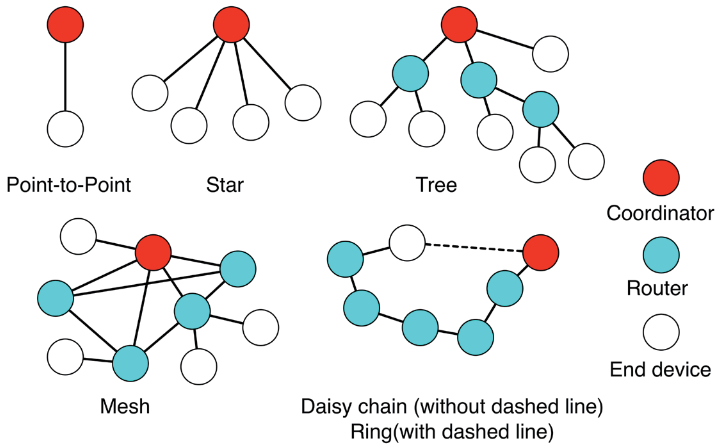

Fig. 3. (Color online) Examples of network topology.

communication protocols becomes difficult if the nodes change dynamically, or if the network topology cannot be determined as the initial state (for example, a smart dust concept[8]—a sensor network is dynamically constructed by distributing many sensor nodes randomly), or rerouting to a preliminary route is required because communications between the nodes are disturbed for some reason. As the protocol becomes more complicated, the power consumption of the system generally increases, requiring the appropriate selection of network topology for each application. Star networks are effective in terms of simple implementation and relatively high robustness (because of the direct connection of the nodes to the coordinator). The daisy chain network is also simple. However, since the connection point to the coordinator is only one (straight connection) or two (ring connection) locations, this network is weak due to malfunction of the nodes. If the number of end devices and the connection distance increase, mesh networks, which have multiple paths from end devices (namely, some paths are "redundant"), are preferred. To date, point-to-point and star networks appear to be popular.

A recently utilized network called Bluetooth low energy (BLE) is also a star network. For BLE, the coordinator and end devices have central and peripheral roles. The number of peripherals that are connected at the same time is, in principle, not limited in the specifications of BLE. The time required for waking up from the sleep state to complete a communication is much shorter than that of the conventional Bluetooth network, greatly contributing to the reduction in power consumption, as mentioned above. However, the amount of data transmitted per packet is only ~20 bytes. Therefore, the benefit of BLE can be obtained only by appropriately selecting data to reduce the amount of data to be transmitted. BLE is extremely compatible with wireless sensor nodes and is expected to become a mainstream of the standard for future systems.

5. Summary

I have described the features of combo sensors as sensor devices that are used in sensor nodes to efficiently collect multiple types of data. In addition, I have discussed the transmission of data to networks and its frequency, and also mentioned network topology. In the next session, I will explain the system for monitoring biological activities as a concrete application example of sensor nodes.

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