Chapter 19
Smart Sensor Systems*

G.W. Hunter, J.R. Stetter, P.J. Hesketh, and C.C. Liu

Abstract Sensors and sensor systems are vital to our awareness of our surroundings and provide safety, security, and surveillance, as well as enable monitoring of our health and environment. A transformative advance in the field of sensor technology has been the development of "Smart Sensor Systems". The definition of a Smart Sensor may vary, but typically at a minimum a Smart Sensor is the combination of a sensing element with processing capabilities provided by a microprocessor. That is, Smart Sensors are basic sensing elements with embedded intelligence. The sensor signal is fed to the microprocessor, which processes the data and provides an informative output to an external user. A more expansive view of a Smart Sensor System, which is used in this article, is illustrated in Fig. 19.1: a complete self-contained sensor system that includes the capabilities for logging, processing with a model of sensor response and other data, self-contained power, and an ability to transmit or display informative data to an outside user. The fundamental idea of a smart sensor is that the integration of silicon microprocessors with sensor technology cannot only provide interpretive power and customized outputs, but also significantly improve sensor system performance and capabilities.

Keywords Sensor • Smart sensor systems

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G.W. Hunter (✉)
NASA Glenn Research Center, 21000, Brookpark Road, Cleveland, OH 44135-3191, USA
e-mail: ghunter@grc.nasa.gov

J.R. Stetter
KWJ Engineering Inc., Newark, CA, USA

P.J. Hesketh
Georgia Institute of Technology, Atlanta, GA, USA

C.C. Liu
Case Western Reserve University, Cleveland, OH, USA

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19.1 Overview

The Smart Sensor possesses several functional layers: signal detection from discrete sensing elements, signal processing, data validation and interpretation, and signal transmission and display. Multiple sensors can be included in a single Smart Sensor System whose operating properties, such as bias voltage or temperature, can be set by the microprocessor. The sensor elements interface to signal control and conditioning stages that will provide both excitation and signal data logging and conditioning. The data acquisition layer will convert the signal from analog to digital and acquire additional parameters of interest to provide compensation when needed for thermal drift, long term drift, etc. The embedded intelligence will continuously monitor the discrete sensor elements, validate the engineering data being provided, and periodically verify sensor calibration and health. The processed data becomes information and can then be transmitted to external users. The user can choose the complexity of the data transmitted: from a single reading to a complete download of the sensor system's parameters.

One major implication of Smart Sensor Systems is that important data can be provided to the user with increased reliability and integrity. Intelligent features can be included at the sensor level including but not limited to: self-calibration, self-health assessment, self-healing, and compensated measurements (auto zero, calibration, temperature, pressure, relative humidity correction). The capability of the Smart Sensor to perform internal processing allows the system not only to provide the user processed data, but also the ability of the sensor to be self-aware and to assess its own health or status and assess even the validity of the processed data. The Smart Sensor System can optimize the performance of the individual sensors and lead to a better understanding of the data, the measurement, and ultimately, the environment in which the measurement is made. Overall, the presence of the microprocessor-sensor combination allows the design of a core system that is adaptable to a changing environment in a given application or that can be modified to meet the needs of a wide range of different applications.

A second major implication of Smart Sensors is the development of a new generation of Smart Sensors that can be networked through the communication interface to have the capability of individual network self-identification and communication allowing reprogramming of the Smart Sensor System as necessary (Fig. 19.1).

Further, the output from a number of sensors within a given region can be correlated not only to verify the data from individual sensors, but also to provide a better situational awareness. Such communication can be between a single Smart Sensor and communication hub or between individual Smart Sensors themselves. These types of capabilities will provide for a more reliable and robust system because they are capable of networking among themselves to provide the end user with coordinated data that is based on redundant sensory inputs. Further, information can be shared in a more rapid, reliable, and efficient manner with on-board communications capability in place.

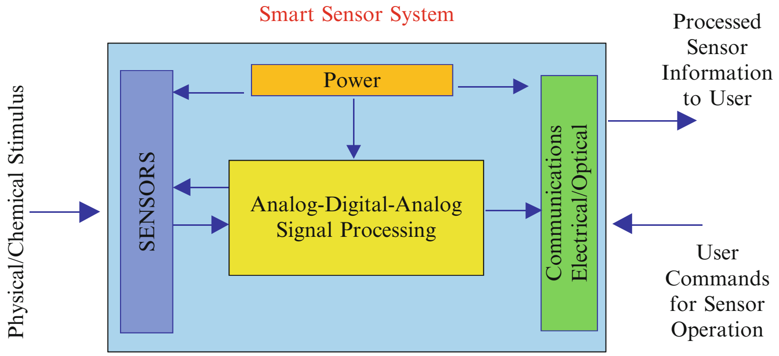

Fig. 19.1 A Smart Sensor System as presented herein. The core of a stand-alone Smart Sensor System includes sensors, power, communication, and signal processing

A driving goal in the development of Smart Sensor Systems is the implementation of systems in a nonintrusive manner so that the information is provided to the user where-ever and whenever needed, as well as in whatever form is needed for the application. In effect, the objective of Smart Sensor research is the development of sensor systems to tell the user what they need to know in order to make sound decisions. While this article is not a complete survey of all the activities in the development of Smart Sensor Systems, it is a brief sampling of some of the enabling Smart Sensor technologies, two examples of Smart Sensor Systems, and a discussion of potential ramifications of this technology.

19.2 Smart Sensor System Components

The components of a Smart Sensor System as depicted in Fig. 19.1 include sensors, power, communication, and signal processing typically provided by a microprocessor. The description of advances in microprocessor technology is beyond the scope of this article, but recent advances are enabling sensor systems to function remotely on very little power. There are many examples of technology advancements in sensors, power, and communications that can enable future Smart Sensor Systems. The ideal goal is to have a self contained Smart Sensor System that is cost-effective, reliable, self-monitoring, reconfigurable, and can operate indefinitely. Simply put, just as microfabrication approaches are enabling the revolution in microprocessor technology and MEMS sensor elements [1], microfabrication and nanotechnology will play a notable role in the development of Smart Sensor Systems [2]. Below are examples of several potentially enabling technologies for Smart Sensor Systems.

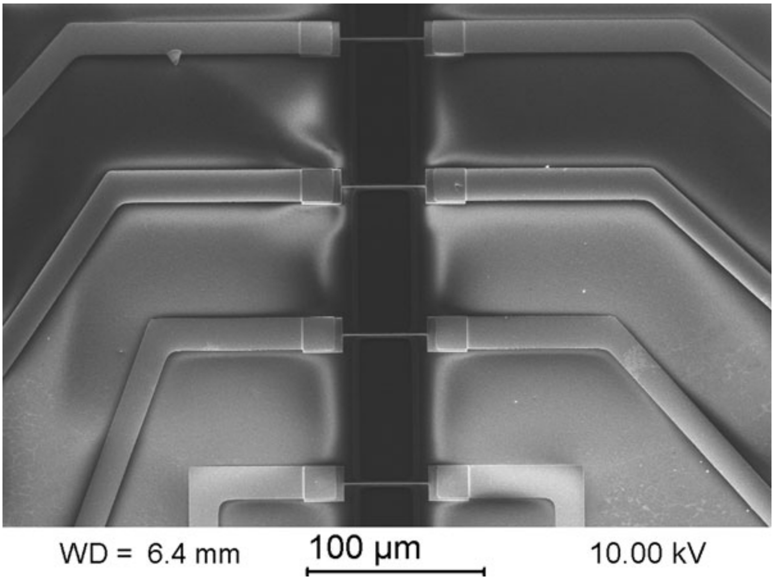

Fig. 19.2 Scanning electron micrograph of an array of four microfabricated polysilicon gas sensors, with 50 × 1 micron (μm) bridge dimensions, designed at KWJ Inc. and built at Georgia Institute of Technology

19.2.1 Low Powered Sensor Elements

Microfabrication methods make it possible to build very small and low power sensors. One example of microfabricated sensors that could be integrated into a Smart Sensor System is a sensor based on a microhotplate. Microfabricated hotplates offer a lower power platform for high temperature metal oxide conductometric sensors. Femtomolar isothermal desorption has been carried out by Shirke et al. [3] with heating rates up to $10^{6\circ}$C/s and minimal power consumption due to the small thermal mass of the microhotplates. An ultra-low power bridge built with polysilicon surface micromachining is shown in Fig. 19.2. This sensor [2] responds to ambient gas changes in nanoseconds having a measured transient response time-constant of 12 μs in Helium. With constant voltage operation, the temperature of the bridge, and hence electrical resistance, is a function of the thermal conductivity of the surrounding gas ambient. For a 50 μm length, 1 μm wide bridge, a sensitivity of 2.05 mohms/ppm for Helium and 0.71 Ω/ppm for methane at 3.6 V operation has been demonstrated. The micro-fabricated sensor elements in Fig. 19.2 have extremely low power consumption, on the order of 4 mW continuous and, <4 μW when operated on a duty cycle to read every millisecond. In principle, this would allow the operation of this sensor for months to years using a single small battery [2]. The microfabrication processing is compatible with CMOS processes and therefore makes integration of the electronic interface for the sensor feasible on a single substrate. Many sensors will require multichip solutions, however, in order to achieve optimal sensing and processing. While approaches may vary for other sensor types, sensor elements that provide data with minimal power consumption can enable long lived Smart Sensor Systems (Fig. 19.2).

19.2.2 Power: Battery or Energy Harvesting

A Smart Sensor System will require energy to support and operate all components including the sensors themselves. If the sensor elements and communication system both have low power designs and are compatible, the total energy for the system is correspondingly low. This can enable lower installation costs and more convenient deployment options. Small scale energy systems for the Smart Sensor applications will generally consider batteries and energy harvesting options, whatever is most suitable for the specific applications. Both primary and rechargeable (or secondary) batteries will be important for our further advancement of the Smart Sensor System. Specifically, it is suggested that the Li-ion, Li-polymer, and metal-air rechargeable batteries can be appropriate energy sources for Smart Sensor Systems. For example, Li-ion and Li-polymer rechargeable batteries have an open circuit potential of approximately 3.6 V, and an energy density of 160 and 130–200 Wh/kg (watt-hour/kilogram), respectively, which will be sufficient for the needs of many Smart Sensor System [4].

Energy harvesting is a process by which energy can be derived from an external source, captured, and stored. Piezoelectric crystals or fibers, thermoelectric generators, solar cells, electrostatic, and magnetic energy capture devices can be considered [5] for local power needs. A piezoelectric energy system will produce a small voltage when it is physically deformed. This deformation can be caused by mechanical vibration that may be generated by the proper mounting and the placement of the Smart Sensor System in an appropriate [e.g., mechanically vibrating] operating environment [6]. Thermoelectric generators consisting of the junctions of two dissimilar materials produce a small voltage in the presence of a thermal gradient. Typical performance of 100–200 μV/°C per junction is achievable. Depending on the location of the Smart Sensor and its power requirement, small energy harvesting systems can derive sufficient energy from its surroundings to provide either total or backup power for a smart sensor application. These are two examples that small energy sources can be used for supporting a Smart Sensor System.

19.2.3 Wireless Communication

The Smart Sensor System will require an electrical interface that will transmit the sensor outputs to an external data collection, recording or acquisition system. Ideally, this interface does not require wiring and can be accomplished by wireless

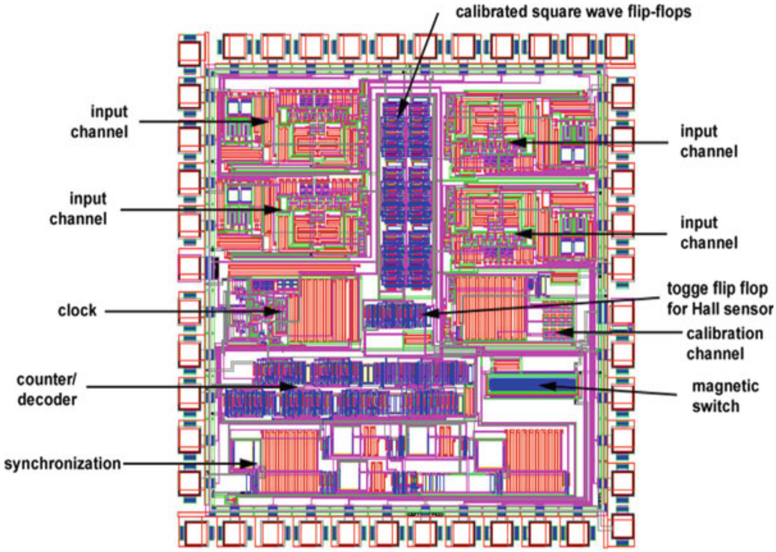

Fig. 19.3 ASIC (application-specific integrated circuit) chip for the wireless multi-channel telemetric microsystem [7]

telemetric methods. A practical telemetry system that can be integrated with the Smart Sensor must be relatively small and have all the required performance functions. The advancement of micro-electronic design and fabrication processing, namely the MEMS technology, provides a technical approach for wireless communication system development. As an example, a multi-channel wireless telemetric microsystem that can be integrated with the Smart Sensor System is described below (Fig. 19.3) [7].

In this telemetry system, four input channels plus a calibration channel are designed to ensure the telemetry system is not malfunctioning. This system has a package size of approximately 1 cm × 1 cm × 0.5 cm (including a small watch battery) with a total weight of 1.0 g. To achieve the specifications of small size, a monolithic integrated circuit (I.C.) chip is fabricated. This I.C. chip is a low power BiCMOS signal processor chip, 2 mm × 2 mm in size. This signal processor chip can also amplify, filter, and time-division multiplex the signals that are in turn transmitted via an RF link contained within the package to an external radio receiver. The receiver drives a demodulator (external) to reconstruct the individual signals for display or analysis by waveform acquisition software. The system also incorporates a Hall-effect sensor providing remote on-off capability for the conservation of power, and it also can be used to support interactive procedures. This example illustrates the needs and the required capability of a wireless multi-channel telemetry system, which can be integrated with a Smart Sensor System. Ultra low power wireless systems are also being designed for interface to biological systems for the purpose of sensory data acquisition and transmission [8].

19.3 Smart Sensor System Examples

A typical Smart Sensor contains much more than just a sensing element, it is a complete functioning system. The sensor has an analog circuit for power management, control, and interface to the digital world. In the digital world, sensor inputs can be processed to reduce noise, integrated with other sensory inputs for compensation, redundancy, and reliability improvements, and then interfaced to output requirements that range from simple digital displays of sensor outputs to wirelessly transmitted and stored data that feed-back to sensors or feed-forward to appropriate system controls. The evolutionary development of a Smart Sensor System is exemplified in Fig. 19.4 in which larger components built with discreet electronic components are used to emulate all the desired smart sensor features. In Phase II, the functions are integrated into smaller, smarter, and more complex integrated systems. One of the enabling features about Smart Sensor Systems is that by using microprocessing techniques this increased complexity can be achieved with less expense than that of larger, hand assembled systems (Fig. 19.4).

An example of a family of Smart Sensor Systems is shown in Fig. 19.5. This family of "Pocket" size gas detectors [9] can measure species including hydrogen, hydrogen sulfide, carbon monoxide, and ozone with selectivity and operate on a single watch battery for a year or more. These systems are specifically designed to be low-cost, low-power, and have a long battery life. Included within the systems are loud alarms (visual LED, 85 dB beeper and vibrating function), a digital display, as well as computed features such as temperature compensated signals, time weighted average dosimetry, data/event logging, and a wireless data download capability in a package weighing less than one ounce. Being able to provide all of this capability in a single package is only possible through the integration of sensor and microprocessor technology and the limiting factor on battery life is typically

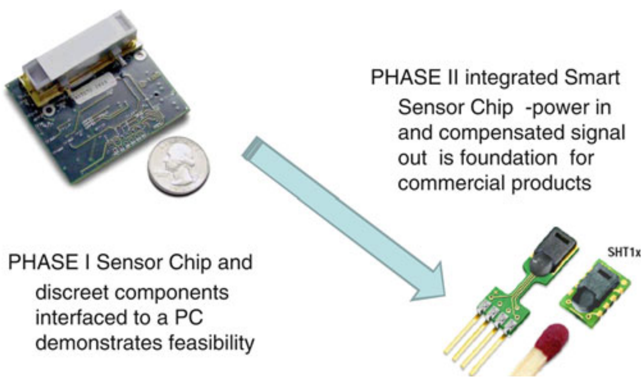

Fig. 19.4 Evolution of smart sensors from larger size discreet components to smaller integrated sensory systems

Fig. 19.5 A family of "Pocket" Smart Sensor Systems measuring a range of individual gases (Courtesy KWJ Engineering Inc. [9])

how often the alarms are enabled, i.e., the sensing for these target analyses takes only micro-watts of power (Fig. 19.5).

A second example of a Smart Sensor System is the "Lick and Stick" Leak Sensor System [10]. This is a multifunctional system with a microsensor array fabricated by microfabrication (MEMS) based technology designed to detect hazardous conditions due to fuel leaks. The complete system has three sensors, signal conditioning electronics, power, data storage, calibration tables, built-in self-test, telemetry, and an option for self-power in the surface area comparable to a postage stamp. The approach is to be able to place sensors in a vehicle, like postage stamps, where they are needed without rewiring or drawing power from the vehicle. The electronics can be programmed to provide the user with certain information required on a regular basis, but much further diagnostic information when needed. A prototype model of the "Lick and Stick" leak detection sensor system is shown in Fig. 19.6a. The ability to have one "Lick and Stick" sensor system send data by telemetry, as well as have several Lick and Stick sensor systems sending data to a central processing hub, has been demonstrated. Figure 19.6b shows the operation of the electronics with the three sensor system simultaneously with data sent telemetrically. Smart Sensors Systems using this "Lick and Stick" system as a core have been adapted to applications as broad as fire detection, breath monitoring, environmental monitoring, and operation on rocket engine test stands [11].

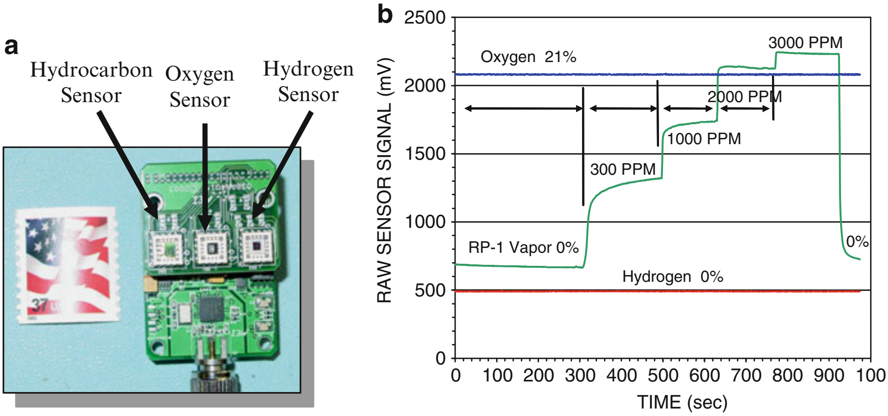

Fig. 19.6 (**a**) A prototype version of a "lick and stick" leak sensor system with sensors combined with supporting electronics. (**b**) Response of three sensors to varying hydrocarbon concentrations in a constant background environment. The sensor signal is sent by telemetry and is the output from the signal conditioning electronics which processes the measured sensor current (Courtesy Makel Engineering, Inc.) [10]

19.4 Future Applications

Smart Sensor Systems potentially represent a new generation of sensing capability, and self-awareness that are essential components of future Intelligent Systems. Driving intelligence down to the component level through the design of Smart Sensor Systems can and will have a profound impact on applications such as food safety and biological hazard detection; safety hazard detection and warning; environmental monitoring both locally and on a global scale; health monitoring and medical diagnostics [12]; and industrial and aerospace applications. Smart Sensor Systems can enable Intelligent Systems, which can monitor themselves and respond to changing conditions optimizing safety and performance. The integration of sensors [13] and algorithms can be used for early warning fire detection [14] or any number of sensor-based applications [15]. The Smart Sensor System approach can achieve distributed sensor systems feeding information from multiple locations to improve the overall understanding of system conditions. This new generation of sensors will possess embedded intelligence to provide the end user with critical data in a more rapid, reliable, robust, economical and efficient manner with a seemless interface to applications.

This article has just begun to scratch the surface of the dimensions of technology development that are associated with Smart Sensor Systems. However, in order to reach the promise of sensory systems, further advancements in both micro and nanotechnology, as well as associated Smart Sensor software algorithms, are necessary. A vision of how nanotechnology including Smart Sensor Systems can revolutionize a range of applications has been published [2]. We look forward to new and creative design in integrated Smart Sensor Systems.

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