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1.1. Introduction:

Since the end of the 1980s, many articles have appeared in scientific [BER 87], [GIA 86] and technical [BLA 87], [JOR 87] books using the term “intelligent”, a word often associated with sensors, transmitters, actuators and instrumentation. Its main function is providing reliable, useful information. However, sometimes we read that the sensor is the weakest link in the measurement chain. [1]

Automation is the use of control systems (such as numerical control, programmable logic control, and other industrial control systems), in concert with other applications of information technology (such as computer-aided technologies), to control industrial machinery and processes, reducing the need for human intervention.

Just about everything today in the technology area is a candidate for having the prefix smart added to it. The term smart sensor was coined in the mid-1980s, and since then several devices have been called smart sensors.[2] The intelligence required by such devices is available from microcontroller unit (MCU), digital signal processor (DSP), and application-specific integrated circuit (ASIC) technologies developed by several semiconductor manufacturers. Some of those same semiconductor manufacturers are actively working on smarter silicon devices for the input and output sides of the control system as well. The term microelectromechanical system (MEMS) is used to describe a structure created with semiconductor manufacturing processes for sensors and actuators. To understand what is occurring today when advanced microelectronic technology is applied to sensors, a brief review of the transitions that have occurred is in order.

As shown in Figure 1.1 we remember that the purpose of a sensor is essentially to provide information, that is, to measure a variable and to communicate representative information of the value of this variable. A sensor is always part of an action/reaction loop[1]:

This action/reaction loop may be “closed” in the technological sense through a certain number of components such as controllers, calculators, Programmable Logic Controllers (PLC) or actuators. The sensor is then an element in an automation loop that provides a representative signal of a physical variable: for example, it provides a signal to a regulator or to a PLC that will itself provide a command signal to be transmitted to an actuator. In the automotive field, a typical example is that of a rotation speed sensor placed on each of the wheels which transmits this rotation “speed” information to the central Anti-Breaking System (ABS), which makes the “right” decision by comparing the rotation speeds of the same axle.
This action/reaction loop could also be closed by a human operator. Still in the automotive context, it is the driver who usually observes the speedometer and either brake, accelerates or reduces gear to adjust the speed of the car to the speed limits. Obviously in this context the speed sensor must be precise and reliable.

The functions of a smart sensor system can be described in terms of compensation, information processing, communications and integration. The combination of these respective elements allow for the development of these sensors that can operate in a multi-modal fashion as well conducting active autonomous sensing.

1.2. Brief History of Smart Sensors:
The first “smart” sensors were developed by internationally well-known manufacturers like Honeywell, Fuji and Control Bailey, who had in a sense already developed precursors to these sensors, at least in terms of concept. These first-generation smart sensors were most often dedicated to numerical control-command systems. In France, work on users’ needs was gathered in 1987 within the publication of a White Book [CIA 87], and completed by a census of services proposed by intelligent sensors in automated production systems [ROB 93].

Figure 1.1  Sensor in an action/reaction loop
1.3. Sensors:
Before the availability of microelectronics, the sensors or transducers used to measure physical quantities, such as temperature, pressure, and flow, usually were coupled directly to a readout device, typically a meter that was read by an observer. The transducer converted the physical quantity being measured to a displacement. The observer initiated system corrections to change the reading closer to a desired value. The typical blocks of a measurement system are shown in figure 1.2.

Many home thermostats, tire pressure gauges, and factory flow meters still operate in the same manner. However, the advent of microprocessor technology initiated the requirement for sensors to have an electrical output that could be more readily interfaced to provide unattended measurement and control. That also required the analog signal level to be amplified and converted to digital format prior to being supplied to the process controller.

Sensors help translate the real world of analog signals and varying voltages into the digital processing realm. Sensors typically convert non-electrical physical, biological or chemical quantities into electrical or optical signals. To be useful, the signal must be measured and transformed into digital format which can be processed and analyzed efficiently by computers. The information can be used by either a person or an intelligent device monitoring the activity to make decisions that maintain or change a course of action. The figure 1.3 classifies signal in six domains.

![General sensing system](image)
Today MCUs and analog-to-digital (A/D) converters typically have a 5V power supply, which has dictated the supply voltage for many amplified and signal conditioned sensors. However, the reduction in the supply voltage from 5V to 3.3V and even lower voltages and the presence of more than one voltage in a system pose challenges not typically associated with even the smartest sensors \[2\]. Separate integrated circuits (ICs) are available to handle the variety of voltages and resolve the problem, but they add to system and sensor complexity commonly used definitions for the terms sensor and transducer must be the first in the list of many terms that will be defined. A transducer is a device that converts energy from one domain into another, calibrated to minimize the errors in the conversion process. A sensor is a device that provides a useful output to a specified measurand. The sensor is a basic element of a transducer, but it also may refer to a detection of voltage or current in the electrical regime that does not require conversion. Throughout this book, the terms are used synonymously, because energy conversion is part of every device that is discussed. The mechanical measurements that require a transducer to provide an electrical output are listed in Table 1.1.
1.3.1. Basis of Characterization:

Sensors, regardless of the classification, are characterized by the specification of various parameters. The parameters of importance largely depend on the application. These parameters include:

- Sensitivity
- Stability
- Accuracy
- Hysteresis
- Drift
- Linearity
1.4. Smart Sensors:

1.4.1. Definition:
A micro sensor integrated with signal-conditioning electronics such as analog-to-digital converters on a single silicon chip to form an integrated microelectromechanical component that can process information itself or communicate with an embedded microprocessor. Also known as intelligent sensor [4].

A smart sensor is simply one that acquires physical, biological or chemical input, converts the measured value into a digital format in the units of the measured attribute and transmits that measured information to a computer monitoring point.

![Diagram of the information-processing model for sensor-based situational awareness](image)

**Figure 1.6** An information-processing model for sensor-based situational awareness

1.4.2. Smart Sensors Hybrids:
If a sensor is combined with analog interface, ADC, and a bus interface on one chip, it is a smart sensor. Three different types of configurations are shown in which all the components are placed on a chip. This is called standardization.
In the first hybrid system, a sensor is connected with ADC and bus interface with the help of universal sensor interface. The second configuration shows the connection of sensor analog system with the digital circuit and bus interface. In the third configuration, sensor is combined with the interface circuit already to provide duty cycle and bit stream.

1.4.3. Integrated Smart Sensors:

If we integrate all functions from sensor to bus interface in one chip, we get an integrated Smart sensor. For it to function properly all the elements are integrated on one node. Though more expensive than a simple sensor, when manufactured at mass level and considering the cost of installing network of the sensors, these chips become more economical. However, for realizing all of the functions on a single chip, IC-compatible micro-structuring technology is being used.
1.4.4. Smart Sensor System:
Smart sensor is a name given to the integration of the sensor with an ADC, processor, and DAC for actuator control and the like; such a setup for furnace temperature control is shown in figure 1.4.

![Diagram of Smart Sensor System](image)

*Figure 1.4 Process system with individual inputs and outputs for each variable.*

The electronics in the smart sensor contains all the circuits necessary to interface to the sensor, amplify the signal, apply proportional, integral, and derivative (PID) control, sense temperature to correct for temperature variations in the process if required, correct for sensor nonlinearity, the ADC to convert the signal into a digital format for the internal processor, and the DAC to convert the signal back into an analog format for actuator control. The processor has a serial digital bus interface for interfacing via the fieldbus to a central computer. This enables the processor in the smart sensor to receive update information on set points, gain, operating mode, and so on, and to send status information to the central computer.

The advances in computer technology, devices, and methods have produced vast changes in the methodology of process control systems. These systems are moving away from a central control system, and towards distributed control devices.
1.4.5. Distributed System:
The distributed system has a microprocessor integrated with the sensor. This allows direct conversion to a
digital signal, conditioning of the signal, generation of a signal for actuator control, and diagnostics.

1.4.6. Smart Sensors Network:
The Smart Sensor Network System integrates all of the required measurement functions (e.g. analog
signal conditioning, analog-to-digital conversion, digital signal processing, etc.) into a small electronic
module that can be placed inside a traditional transducer making it a "Smart Sensor" or in a miniature
module that can interface to existing analog transducers. It consists of multi-drop sensor architecture with
smart digital output sensors interconnected to a network interface controller (NIC) through a common
digital transducer bus, eliminating most interconnecting cables and increasing the system's performance
and reliability.\[6\].

\[Figure 1.5\] Smart sensor block diagram.
1.5. Advantages and Disadvantages of Smart Sensors:

1.5.1. Advantages of Smart Sensors:
The implementation of smart sensors has many advantages over a central control system. These are as follows:

• The smart sensor takes over the conditioning and control of the sensor signal, reducing the load on the central control system, allowing faster system operation.

• Smart sensors use a common serial bus, eliminating the need for discrete wires to all sensors, greatly reducing wiring cost, large cable ducts, and confusion over lead destination during maintenance or upgrades (especially if lead markers are missing or incorrectly placed).

• Smart sensors have powerful built-in diagnostics, which reduces commissioning and startup costs and maintenance.

• Direct digital control provides high accuracy, not achievable with analog control systems and central processing.

• Uniformity in programming means that the program only has to be learned once and new devices can be added to the bus on a plug-and-play basis.

• Individual controllers can monitor and control more than one process variable.

• The set points and calibration of a smart sensor are easily changed from the central control computer.

• The cost of smart sensor systems is presently higher than that of conventional systems, but when the cost of maintenance, ease of programming, ease of adding new sensors is taken into account, the long-term cost of smart sensor systems is less.

1.5.2. Disadvantages of Smart Sensors:
The implementation of smart sensors does have some drawbacks. These are:

• If upgrading to smart sensors, care has to be taken when mixing old devices with new sensors, since they may not be compatible.

• If a bus wire fails, the total system is down, which is not the case with discrete wiring. However, with discrete wiring, if one sensor connection fails, it may be necessary to shut the system down. The problem of bus wire failure can be alleviated by the use of a redundant backup bus.
1.6. Area of Application:
A study on sensors in the machine building industry from 1995 has shown the applications for which sensors are generally needed. It clearly shows an increase in automation, for instance to detect early failure diagnostics of the machines. Therefore, the electronics share of the production costs of machines is gradually increasing to about 10% to 20%. In agriculture, more and more sensors are being used. In greenhouses for example, production is increasingly being automated through the introduction of climate and pest control, water and nutrient management, harvest robots, etc. In car manufacturing, advanced robots are used to perform complicated assembly operations. Figure 1.9 shows approximate share of the sensors in different industries. In all of these fields smart sensors are now being employed.

![Figure 1.9](image.png)
1.7. Examples of Smart Sensors:
We may not yet be aware of the fact but smart sensor technology is slowly seeping into our daily lives. Though more of the research is for the industrial use as shown in the figure 1.10 it is not uncommon in our surroundings.
Here are some examples of smart sensor application.

- Smart Toys
- Smart Cars
- Miniature thermometers and RTDs
- Water quality detector
- Smart dust
- Leakage detection system
- Fingerprint recognition
- Distance measurement
- Pattern-matching
- Non-contact thermometers
- Body sensors

### 1.7.1 Smart Toys:

These days the trend in toys is to make them as life-like as possible. Examples of such toys are the robotic dogs, dolls, cars etc. which move or change directions after sensing objects around them. This is made possible by the installation of smart sensors in them. Another example is the video games in which virtual...
reality is created using gloves and goggles. There are also arcade games which we are now able to play with people on the other side of the world.

1.7.2. Smart Cars:
Modern cars incorporated about 40 sensors in 2005, as depicted in Figure 1.11. It will only be possible to accommodate more sensors if a distributed sensor bus is used instead of a star-connected sensor system.

![Sensors in a car](image)

Figure 1.11  Sensors in a car

Only smart sensors make this economically viable. Otherwise the car breaks down under the load of wires (Figure 1.12).

![Star-connected and distributed-bus sensor systems](image)

Figure 1.12  Star-connected and distributed-bus sensor systems
1.7.3. Miniature Thermocouples and RTDs:

Miniature thermocouples and RTDs are generally used where thermo wells are not necessary and are commonly found in pilot plants, research and development, furnace, and OEM applications. \(^9\)

Traditional thermocouple produces a voltage proportional to the temperature that it measures. This voltage has to be further processed to convert it to a corresponding temperature through an analog-to-digital acquisition and a set of fairly complex algorithms. A smart sensor however, senses the temperature and produces a proportional voltage that is acquired and converted to digital format [ADC – analog-to-digital conversion] then transmitted to a computer wirelessly.

A temperature smart sensor will eliminate the voltmeter by acquiring the measured value, provide any necessary signal conditioning, make the translation from voltage-to-temperature and provide a wireless transmission from the sensor to the Ethernet making deployment easy and at less cost. This provides excellent communications, data reduction and intelligent data development and saves money on deployment and operations. Actionable intelligence is generated so that users are not overwhelmed by huge amounts of data with the need for processing. Users have the opportunity to make efficient, effective and intelligent decisions based on processed data immediately upon receipt.

1.7.4. Water Quality Detector:

Water for consumption should have pH between 6.5 and 7.2. To maintain this pH microprocessor based, multifunctional water quality water indicator is used. ORP (oxidation-reduction potential) is the measurement of the efficiency of the chemical additive in water to kill microbes. It is the only practical method used to electronically monitor sanitizer effectiveness. When sanitizing water for consumption a strong oxidizer like chlorine, bromine, ozone etc. are added to kill the microbes which are threat for human life. As a result some of the oxidizer is used and the remaining should be in the appropriate level to prevent future contamination.

The smart sensor ORP circuit detects the remaining oxidizer and at the same time reports to ORP whether the water is fit for drinking or not. Electronic ORP and pH sensors allow us to monitor and control sanitizer residual and pH automatically.
1.7.5. Smart Dust:

Smart dust is a hypothetical wireless network of tiny microelectromechanical (MEMS) sensors, robots, or devices, which can detect (for example) light, temperature, or vibration. The devices will eventually be the size of a grain of sand, or even a dust particle, with each mote having self-contained sensing, computation, communication and power.

When clustered together, these motes automatically create highly flexible, low-power networks with applications ranging from climate control systems to entertainment devices that interact with information appliances.

A typical application scenario is scattering a hundred of these sensors around a building or around a hospital to monitor temperature or humidity, track patient movements, or inform of disasters, such as earthquakes. In the military, they can perform as a remote sensor chip to track enemy movements, detect poisonous gas or radioactivity.

1.7.6. Leakage Detection System:

The Flood Stopper System is a high-tech water leak detection system that provides protection against flooding due to internal plumbing failures and accidental overflows by automatically shutting off the
water supply instantly upon detection of a leak. The Flood Stopper System is designed for use in residential, commercial, and industrial buildings.

The Flood Stopper System consists of low-profile electronic sensors, a user-friendly control panel, and shut-off valve. Sensors are placed throughout the property where flooding has the potential to occur. The sensors are easily installed near washing machine, dishwasher, refrigerator, bathroom, sinks and water heater. Sensors are connected to a control panel that monitors the sensors. Sensors are hard wired to the control panel. The valve will shut off the main water supply in the event of a leak when it receives a shut off command from the control panel. [10]

1.7.7. Fingerprint Recognition:

It refers to the automated method of verifying a match between two human fingerprints. Fingerprints are one of many forms of biometrics used to identify an individual and verify their identity. This technology uses on two major classes of algorithms (minutia and pattern) and four sensor designs (optical, ultrasonic, passive capacitance, and active capacitance).

A fingerprint sensor is an electronic device used to capture a digital image of the fingerprint pattern. The captured image is called a live scan. This live scan is digitally processed to create a biometric template (a collection of extracted features) which is stored and used for matching. [11]

1.7.8. Distance Measurement:

This technology uses the triangulation method to determine the distance of objects from the sensor. It consists of semiconductor laser and a position sensitive sensor. Laser is made to reflect from the object to the detector. The position of the object is determined by detecting the point on the detector.

Similarly thickness of objects can also be determined using two opposing laser displacement sensors. Sensors are aimed at opposite sides of an object. The total distance between the sensors is known and the two distances of the sides are subtracted to yield the thickness of the object. [12]
1.7.9. Pattern-Matching:

In operation, the sensor uses incident light or backlight to detect the contours of an object and compares them with the contours of one or several models in a reference image. Depending on the degree of conformity, a result is output if a specific model is found. This is particularly useful if there are already several individual objects in the current image section. \[12\]

1.7.10. Non-Contact Thermometers:

For measuring the temperature of hot surfaces without coming in contact with them, piston like laser thermometers are in use. To determine the temperature, the’ pistol’ style infrared thermometer with Laser sight pointer is pointed toward the surface and digital display of temperature is seen. It can be used to determine temperature of any surface ranging from simple body temperature to boilers, engines, grills, refrigerators, ovens, etc. The easy to read display gives you an accurate reading in less than a second and at just the press of a button you can switch between Celsius and Fahrenheit readings. Infrared thermometers provide precise readings with 1-4% accuracy, and from as far away as 180 feet depending on the model used. These instruments are lightweight, rugged, and easy to use. \[13\]

1.7.11. Body Sensors:

Wearable body sensor systems are available to continuously measure and monitor the physiological conditions of workers in real time. Body Media has produced a wearable body sensor system that acquires, analyzes, transmits, and stores physiological data such as energy expenditure, duration of physical activity, number of steps, distanced traveled, sleep/wake states, movement, heat flux, skin temperature, and galvanic skin response. The system is used mainly as a health and safety research tool.

1.8. References:


2. Randy Frank; “Understanding the Smart Sensors”; Artech House; Second edition; Page1-5; 2000


8. Gerard C.M. Meijer; “Smart Sensor Systems”; John Willey & Sons Ltd; Page 1-21; 2008


