Contents –

❖ Chapter 1:
  • Introduction
  • Definition
  • Components of Smart Sensors

❖ Chapter 2:
  • General Architecture of smart sensor
  • Description of Smart Sensor Architecture

❖ Chapter 3:
  • Evolution of Smart Sensors

❖ Chapter 4:
  • Design
  • Hardware and Software Design

❖ Chapter 5:
  • Applications of Smart Sensors
  • Optical sensor
  • Infrared detector array
  • Accelerometer
  • Integrated multisensor

❖ Chapter 6:
  • Advantages

❖ Chapter 7:
  • Importance and Adoption of Smart Sensor

❖ Chapter 8:
  • Industrial Application of Smart Sensors
  • Structural monitoring
  • Geological mapping
  • Other Applications Area

❖ Chapter 9:
  • Conclusions

❖ Chapter 10:
  • Bibliography
CHAPTER 1

Introduction:

The advent of integrated circuits, which became possible because of the tremendous progress in semiconductor technology, resulted in the low cost microprocessor. Thus if it is possible to design a low cost sensor which is silicon based then the overall cost of the control system can be reduced. We can have integrated sensors which has electronics and the transduction element together on one silicon chip. This complete system can be called as system-on-chip. The main aim of integrating the electronics and the sensor is to make an intelligent sensor, which can be called as smart sensor. Smart sensors then have the ability to make some decision. Physically a smart sensor consists of transduction element, signal conditioning electronic and controller/processor that support some intelligence in a single package.

As examples,
1) in order to reduce the number of personnel to run a naval ship from 400 to less than 100 as required by the reduced-manning program, the U.S. Navy needs tens of thousands of networked sensors per vessel to enhance automation,
2) Boeing needs to network hundreds of sensors for monitoring and characterizing airplane performance. Sensors are used across industries and are going global. The sensor market is extremely diverse, and it is expected to grow to $43 billion by 2008. The rapid development and emergence of smart sensor and field network technologies have made the networking of smart transducers a very economical and attractive solution for a broad range of measurement and control applications. However, with the existence of a multitude of incompatible networks and protocols, the number of sensor interfaces and amount of hardware and software development efforts required to support this variety of networks are enormous for both sensor producers and users alike. The reason is that a sensor interface customized for a particular network will not necessarily work with another network. It seems that a variety of networks will coexist to serve their specific industries. The sensor manufacturers are uncertain of which network(s) to support and are restrained from full-scale smart sensor product development. Hence, this condition has impeded the widespread adoption of the smart sensor and networking technologies despite a great desire to build and use them. Clearly, a sensor interface standard is needed to help alleviate this problem.
**Definition:**

Smart sensors are sensors with integrated electronics that can perform one or more of the following functions:

- logic functions,
- two-way communication,
- make decisions

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 via the Ethernet to a computer monitoring point.

*Fig: 1.1- A Smart Sensor*
Components of Smart sensors:

There are two main components of a functional smart sensor:

1) Transducer interface module (TIM):
A TIM is a module that contains the interface, signal conditioning, Analog-to-Digital and/or Digital-to-Analog conversion and in many cases, it also contains the transducer. A TIM can range in complexity from a single sensor or actuator to a module containing many transducers including both sensors and actuators.

This TIM provides the following functions-

- Analog Signal Conditioning
- Triggering
- Analog to Digital Conversion
- Command Processing
- TEDS Storage
- Data Transfer Communications

2) Network capable application processor (NCAP):

An NCAP is the hardware and software that provides the gateway function between the TIMs and the user network or host processor (the transducer channel). The IEEE 1451 standard defines the communications interface between an NCAP or host processor and one or more TIMs. Three types of transducers are recognized by the IEEE 1451 standard; sensors, event sensors and actuators.

This NCAP provides the following functions-

- Communications
- Interface Control
- Message Routing
- TIM Discovery and Control
- Data Correction Interpretation of TEDS Data
- Message Encoding and Decoding
This TIM & NCAP helps to built the Smart Sensors system:

Fig: 1.2 - A Smart Sensor System

Fig: 1.3 – Basic working structure of Smart Sensors.
CHAPTER 2

General Architecture of smart sensor:
One can easily propose a general architecture of smart sensor from its definition, functions. From the definition of smart sensor it seems that it is similar to a data acquisition system, the only difference being the presence of complete system on a single silicon chip. In addition to this it has on–chip offset and temperature compensation. A general architecture of smart sensor consists of following important components:

- Sensing element/transduction element,
- Amplifier,
- Sample and hold,
- Analog multiplexer,
- Analog to digital converter (ADC),
- Offset and temperature compensation,
- Digital to analog converter (DAC),
- Memory,
- Serial communication and
- Processor

The generalized architecture of smart sensor is shown below:

Fig: 2.1 - Internal Architecture of Smart Sensor
**Description of Smart Sensor Architecture:**

Architecture of smart sensor is shown. In the architecture shown A1, A2,...An and S/H1,S/H2...S/Hn are the amplifiers and sample and hold circuit corresponding to different sensing element respectively. So as to get a digital form of an analog signal the analog signal is periodically sampled (its instantaneous value is acquired by circuit), and that constant value is held and is converted into a digital words. Any type of ADC must contain or proceeded by, a circuit that holds the voltage at the input to the ADC converter constant during the entire conversion time. Conversion times vary widely, from nanoseconds (for flash ADCs) to microseconds (successive approximation ADC) to hundreds of microseconds (for dual slope integrator ADCs). ADC starts conversion when it receives start of conversion signal (SOC) from the processor and after conversion is over it gives end of conversion signal to the processor. Outputs of all the sample and hold circuits are multiplexed together so that we can use a single ADC, which will reduce the cost of the chip. Offset compensation and correction comprises of an ADC for measuring a reference voltage and other for the zero. Dedicating two channels of the multiplexer and using only one ADC for whole system can avoid the addition of ADC for this. This is helpful in offset correction and zero compensation of gain due to temperature drifts of acquisition chain. In addition to this smart sensor also include internal memory so that we can store the data and program required.
CHAPTER 3

Evolution of Smart Sensors:

Fig: 3.1 – 3rd Generation of Smart Sensors

Fig: 3.2 – 4th Generation of Smart Sensors

Fig: 3.3 – 5th Generation of Smart Sensors

Sensors have progressed through a number of identifiable generations, as shown in figure. First generation devices had little, if any, electronics associated with them, while second-generation sensors were part of purely analog systems with virtually all of the electronics remote from the sensor. By the third generation,
where the majority of the systems currently reside, at least the first stage of amplification occurred in the sensor module or on the sensor chip itself. Thus, the output from these systems is a high-level analog signal, encoded either as a voltage amplitude or as a variable pulse rate. This signal is digitized remotely and then processed by a microcomputer. Many automotive sensing systems fit into this category. We are now evolving into the fourth generation sensors, where more analog and digital electronics are on-chip, making the sensor addressable and in some cases self-testing with some two-way communication between the sensor and the host microcomputer.

Some large-area visible imaging devices and pressure sensors represent fourth-generation components. On the horizon are fifth-generation sensors, in which data conversion is accomplished on the sensor (or, at least, in the sensor module) so that the bidirectional communication link with the microcomputer is digital. These devices will likely be digitally compensated using field-programmable read-only memories (PROMS) to accuracies not available in sensors today. From a system viewpoint, the standardization of communication protocols and formats is badly needed for this fifth generation of devices. Figure 3.3 shows the block diagram of a generic fifth-generation VLSI sensor. The device is addressable, self-testing and communicates over a bidirectional digital bus. It can measure the outputs of a variety of sensors, use some of these outputs for secondary parameter compensation, perform digital signal processing tasks and retain only the useful and required signals and then communicate the acquired signals with the higher level computer. For example, a gas sensor might sense gas pressure, temperature, flow and include an array of gas sensors to improve selectivity. The required device counts for such a sensor, estimated in the range of ten thousand, are still low enough that the circuitry would occupy no more than a few square millimeters and would not be a major cost factor as most of the cost would be in testing and packaging. Based on the evolution of both sensor technologies and electronic systems, it is evident that solid-state sensors will continue to incorporate more sophisticated electronic circuits. The integration of high-performance solid-state sensors and sophisticated signal processing and control circuitry into a smart sensor module serves a dual purpose: it allows the sensor to become a much more versatile component in terms of its sensing function and accuracy; and will enable the smart sensor to become an active and compatible component of an overall 'sensing system'. It is believed that unless these systems are developed and demonstrated to be capable of surpassing the performance of many of the existing sensors, solid-state sensors will not be fully utilized in terms of their capabilities and features. The development of such systems will naturally require the development of individual components and circuit blocks that make up the overall system.
CHAPTER 4

➢ **Design:**

There are three important aspects in our design { data acquisition, data transfer and data processing}. Major priority is to minimize the total cost of the system while at the same time delivering the amount of accuracy and reliability provided by the proprietary solutions. The system will also be generic enough to be adapted to other areas of environmental measurements. The system synthesizes Field Programmable Gate Arrays and sophisticated IEEE 802.11 wireless networking infrastructure adapted to environmental sensing. We divide the system into three important components each handing a specific task. This modular design accounts for the possibility of incorporating new advancements in each component without disturbing the whole system. Each component will have well defined interfaces. The components are the Data Acquisition Unit (DAU), the Data Transfer Unit (DTU) and, the Data Processing Unit (DPU). As seen earlier, The DAU is responsible for collecting the data from the sensor and responds to data requests from the DTU. The DTU will transport the data from the DAU to the DPU reliably. Finally, the DPU, after gathering the data from sensors, will analyze and store the data for end use.

❖ **Data Acquisition Unit:**

The DAU will consist of a sensor that is connected to a micro-controller implemented on a FPGA through an Analog to Digital Converter (ADC). The sensor will measure the pressure, which is related to the amount of water above it, and sends the analog signal to the ADC. The ADC will convert the analog signal to a digital value and sends the data to a micro-controller when requested, which we have developed. During the course of further improvement, we will need to consider the extent to which we will include the computation of temperature compensation in the DAU. The power for the devices can be provided by using regular A/C power supply with adapter, solar panels or long-life batteries.

Sensor ------- ADC ------ FPGA ------ Antenna

❖ **Data Transfer Unit:**

The data transfer unit is responsible for carrying the data from the DAU to the DPU. Data transfer will be accomplished IEEE 802.11 wireless network protocols. Cellular technology, which is an alternative solution, enables the connectivity between remote locations and the Internet. Cellular phone service currently has a limitation of availability and stability in remote locations across Nebraska. A high
gain IEEE 802.11 network is potentially a better choice because it costs less and the user has more control. The IEEE 802.11 network will utilize TCP/IP network protocol thereby providing the ability to control the DAU to a remote operator. The use of intelligent routing protocols will enable sensors to form networks and thereby routing the information in the absence of direct line of sight to the base station. Our goal is to transfer the data in real-time (recall that once per day is considered to be real time) to the Data Processing Unit (DPU). The challenges that have to be addressed during DTU development are the stability of connectivity and data security. Data security can be provided by IEEE 802.11 Wired Equivalent Privacy (WEP).

**Data Processing Unit:**

The data processing unit is where the data can be manipulated by analysts and/or made available to the public. New archiving and analysis techniques need to be developed to handle the accumulation of potentially large amount of data every day. Most components of the DPU will consist of software that will allow the user to access the data graphically (see Fig. 3.3) or in a tabular format. In future, maps may be considered for data display. A key characteristic of any software that will be developed is that it be flexible and user-friendly. The development of the DPU targets these two goals. For the research to be complete, correct and effective, collaboration and cooperation among the experts in computer technology and water resource management (in case of water management application) is required. The design of such a system needs to be exible enough so that it can be scaled to a variety of applications and for it to provide stable connectivity.

![Fig: 4.1 - Data Processing Unit](image-url)
Hardware and Software Design:

The motive of the smart sensor project is to create 1) a general purpose hardware interface for diverse sensors and actuators, which can be customized for any application through over-the-air firmware downloads and 2) create a data processing infrastructure at the backend to implement applications. The proposed solution consists of a network of sensors, and actuators communicating with the central control unit using standard RF-links. The basic scenario is shown in Figure. The sensors are directly connected to the central control unit (workstation here) through a RF link, which can be Bluetooth or WiFi. Each sensor or actuator is equipped with a reconfigurable generic wireless interface or smart sensor interface. The interface extracts data from the sensors and commands the actuator and provides a data communication interface to the central control unit. A sensor/actuator coupled with smart sensor interface is termed as a smart sensor node.

Software Design:

The digital data extracted by the hardware interface has to be bound by a context and processed to convert it into useful information. This intelligence is provided by the software that resides on the smart sensor interface. The software design of the smart sensor interface is shown in Figure. The software module stack on the smart sensor interface consists of three layers. The bottom layer is the device driver which directly interfaces with the hardware interface and extracts digital data. The device manager interfaces with the device drivers and exposes a multipledata channel interface to the firmware layer. In the software framework, each sensor/actuator is composed of a combination of digital, analog or serial channels.

Establishment of context to the extracted channel data is done at the firmware layer. The firmware layer “composes” the sensor by combining data from multiple data channels. It also implements the application specific functionalities like real-time performance, data communication protocol with central control unit, smart sensor node management, etc. This separation of data acquisition tasks across three layers in the smart sensor interfaces helps support functionalities like over-the-air update of parameters, plug-n-play of sensors, multiple sensor support, multiple wireless technology support, universal data interface etc.
Hardware Design:

The sensors/actuators found in industrial applications can be classified by analog, digital, serial (or combination of these) signals used for data communication. The smart sensor interface interprets sensors/actuators’ signals, and converts it into digital data/commands. For this 14-bit 200ksps ADC, 8 channel 10-bit 9.6ksps ADC, DAC, 16 GPIO, and USARTs are used. The hardware design is
CHAPTER 5

➢ **Applications of Smart Sensors:**

- **Optical sensor:**

  Optical sensor is one of the examples of smart sensor, which are used for measuring exposure in cameras, optical angle encoders and optical arrays. Similar examples are load cells silicon based pressure sensors.

- **Infrared detector array:**

  Integrated sensor is the infrared detector array developed at the solid laboratory of the University of Michigan. The Infrared-sensing element was developed using polysilicon – Au thermocouples and thin film dielectric diaphragm to support the thermocouples. Onchip multiplexer was fabricated by using silicon gate MOS processing. This detector operates over a temperature range of 0 to 100 degree centigrade with a 10msec response time. This chip also contains a separate calibration thermopile, polysilicon resistors, and diodes and MOS transistors to
allow direct measurements of the cold junction temperature both and the thermoelectric power of the polysilicon lines.

- **Accelerometer:**
  
  ![Accelerometer Image]
  
  Accelerometer fabricated at the IBM Research laboratory at San Jose California, which consists of the sensing element and electronics on silicon. The accelerometer itself is a metal-coated SiO2 cantilever beam that is fabricated on silicon chip where the capacitance between the beam and the substrate provides the output signal.

- **Integrated multisensor:**
  
  ![Integrated multisensor Image]
  
  Integrated multisensor chip developed at the electronics research Laboratory University of California. This chip contains MOS devices for signal conditioning with on chip sensor, a gas flow sensor, an infrared sensing array, a chemical reaction sensor, a cantilever beam, accelerometer, surface acoustic wave vapor sensor, a tactile sensor array and an infrared charge coupled device imager. This chip was fabricated using conventional silicon planar processing, silicon micromachining and thin deposition techniques.
CHAPTER 6

➢ **Advantages:**

**Minimum Interconnecting Cables:**

The number of cables and cable lengths dictated by traditional star topologies of interconnecting analog transducers to a central signal processing equipment has a detrimental impact on all aspects of a measurement system. These factors decrease the accuracy and reliability of measurements, decrease system performance, and increase system operating costs. The multi-drop sensor network architecture of the proposed system allows drastic reduction of interconnecting cables. The Smart Sensor System interconnects all of the transducers through a common digital bus cable. The centralized, bulky electronic boxes typical of traditional measurement systems are replaced with miniature modules strategically distributed throughout the setup.

**High Reliability:**

Reliability is improved by reducing the total number of interconnecting cables and including Build-in-Test (BIT) features. Self test adds a higher level of confidence that a given measurement channel is alive and working properly.

**High Performance:**

Large numbers of analog transducers result in difficult-to-manage, large and long bundles of cables carrying analog signals which are susceptible to being corrupted by EMI/RFI noise. Cables carrying digital signals are more immune to these problems and are easier to interface than cables carrying analog signals. Higher measurement accuracy is obtained by digital correction over the operating temperature range of both the transducers’ sensitivity and the analog signal conditioning instrumentation.

**Easy to Design, Use and Maintain:**

The primary concern of users of sensor information is to accurately measure physical phenomena in engineering units such as Pascal, meters, m/sec², g’s, PSI, etc. To achieve this goal, the user needs to take into account installation issues
such as types of transducers to their measurement system; and selecting the proper analog amplifier settings (sensitivity-gain normalization, type of filter, excitation voltage-current, etc.) for each analog transducer.

Transducer Electronic Data Sheet 1 (TEDS) stored in each smart sensor and interface module helps to reduce the complexity of the system design, integration, maintenance and operation. Features such as transducer identification, self-test, test setup configuration, configuration status, etc. can be performed under computer control with minimal need for any manual trimming or adjustments.

The smart sensors and interface modules exhibit plug-and-play features to ease the measurement system usage.

✓ **Scalable -Flexible System:**

The new network measurement system accepts different types of transducers, including traditional analog types as well as new smart network sensors. It allows for easy expansion or reduction in the number of measurement channels. This is possible with the use of Intellibus Interface Modules (IBIM).

✓ **Small Rugged Packaging:**

The proposed measurement system components are small, lightweight and packaged to operate under demanding environmental conditions typical of aerospace applications such as high vibration, high temperature, high pressure, humidity, EMI/RFI, etc.

✓ **Minimum Cost:**

Design, operating and maintenance costs are drastically reduced by implementing a system with all of the above listed attributes. The initial capital investment may be similar or slightly higher than traditional systems. However, this marginal additional expense is far outweighed by savings in other areas.

A standard hardware interface for all transducer types will eventually reduce the capital equipment costs. A standard software interface (standard data interchange) would greatly reduce ongoing operating and maintenance costs.
CHAPTER 7

Importance and Adoption of Smart Sensor:

The presence of controller/processor in smart sensor has led to corrections for different undesirable sensor characteristics which include input offset and span variation, non-linearity and cross-sensitivity. As these are carried in software, no additional hardware is required and thus calibration becomes an electronic process. Thus it is possible to calibrate the batches of sensor during production without the need to remove the sensor from its current environment or test fixture.

- Cost improvement:
  In case of smart sensor inside hardware is more complex in the sensor on the other hand it is simpler outside the sensor. Thus the cost of the sensor is in its setup, which can be reduced by reducing the effort of setup, and by removing repetitive testing.

- Reduced cost of bulk cables and connectors:
  Use of smart sensor has significantly reduced the cost of bulk cables and connectors needed to connect different blocks (i.e. electronic circuits).

- Remote Diagnostics:
  Due to the existence of the processor within the package, it is possible to have digital communication via a standard bus and a built in self-test (BIST). This is very helpful in production test of integrated circuits. This diagnostic can be a set of rules based program running in the sensor.

- Enhancement of application:
  Smart sensor also enhances the following applications:
  i. Self calibration
  ii. Computation
  iii. Communication
  iv. Multisensing

Self calibration:
  Self-calibration means adjusting some parameter of sensor during fabrication, this can be either gain or offset or both. Self-calibration is to adjust the deviation of the output of sensor from the desired value when the input is at minimum or it can be an initial adjustment of gain. Calibration is needed because their adjustments usually change with time that needs the device to be removed and
recalibrated. If it is difficult to recalibrate the units once they are in service, the manufacturer over-designs, which ensure that device, will operate within specification during its service life. These problems are solved by smart sensor as it has built in microprocessor that has the correction functions in its memory.

**Computation:**
Computation also allows one to obtain the average, variance and standard deviation for the set of measurements. This can easily be done using smart sensor. Computational ability allows to compensate for the environmental changes such as temperature and also to correct for changes in offset and gain.

**Communication:**
Communication is the means of exchanging or conveying information, which can be easily accomplished by smart sensor. This is very helpful as sensor can broadcast information about its own status and measurement uncertainty.

**Multisensing:**
Some smart sensor also has ability to measure more than one physical or chemical variable simultaneously. A single smart sensor can measure pressure, temperature, humidity gas flow, and infrared, chemical reaction surface acoustic vapor etc.

- **System Reliability:**
  System reliability is significantly improved due to the utilization of smart sensors. One is due to the reduction in system wiring and second is the ability of the sensor to diagnose its own faults and their effect.

- **Better Signal to Noise Ratio:**
The electrical output of most of the sensors is very weak and if this transmitted through long wires at lot of noise may get coupled. But by employing smart sensor this problem can be avoided.

- **Improvement in characteristics:**
  - **Non-linearity:**
    Many of the sensors show some non-linearity, by using on-chip feedback systems or look up tables we can improve linearity.
  - **Cross-sensitivity:**
    Most of the sensors show an undesirable sensitivity to strain and temperature. Incorporating relevant sensing elements and circuits on the same chip can reduce the cross sensitivity.
  - **Offset:**
    Offset adjustment requires expensive trimming procedures and even this offsets tend to drift. This is very well reduced by sensitivity reduction method.
CHAPTER 8

• *Industrial Application of Smart Sensors:*

  ❖ *Structural monitoring:*

  ○ *It is needed to detect damages of industrial infrastructure.*

  ❖ *Geological mapping:*

  ![Structural monitoring image]
  ![Geological mapping image]
It is needed mainly to detect the minerals on the geological areas.

Digital imaging & interpretation of tunnel geology.

Remote measurements of tunnel response.

**Other Applications Area:**

1. Bluetooth Smart Sensor Module Rear Panel.

2. In-chamber and on-wafer sensors.

3. Monitoring of Temperature Using Smart Sensors Based on CAN Architecture.

4. Compatible sensors with microprocessors.

5. Smart sensors vie for vision applications: smart sensors can provide the functionality needed for simple, low-cost machine-vision applications.

CHAPTER 9

➤ **Conclusions:**

Smart Sensors has developed and proved a new miniaturized Smart Sensor Network Measurement System, which represents a paradigm shift from a centralized to a distributed processing measurement approach. It significantly reduces the number and lengths of cables, the components size, and system weight. It provides greater flexibility in design, configuration and installation. All of these advantages translate into cost savings throughout the life of a program.

The high processing power provided by the DSP and the high level of integration provided by today’s commercial off-the-shelf (COTS) integrated circuits (ICs) allows for this design to be very flexible and capable of easily and quickly integrating functions for onboard or field diagnostics and prognostics such as Kalman filtering, order and trend analysis in a very small, light weight, and cost effective package.
CHAPTER 10

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