2

Smart Sensor Networks

2.1. INTRODUCTION

Users are demanding devices, appliances, and systems with better capabilities and higher levels of functionality. Sensors in these devices and systems are used to provide information about the measured parameters or to identify control states, and these sensors are candidates for increased built-in intelligence. Microprocessors are used in smart sensors and devices. A smart sensor can communicate measurements directly to an instrument or a system. The networking of transducers (sensors or actuators) in a system can provide flexibility, improve system performance, and make it easier to install, upgrade and maintain systems.

The sensor market is extremely diverse and sensors are used in most industries. Sensor manufacturers are seeking ways to add new technology for building low-cost, smart sensors that are easy to use and which meet the continuous demand for more sophisticated applications. Networking is becoming pervasive in various industrial settings. Decisions about the use of sensors, networks, and application software can all be made independently, based on the application requirements. In reality, however, all these function modules cannot be easily integrated due to the lack of a set of common interfaces.

A typical sensor or control network consists of network nodes comprising up to 256 units linked by multiwire cables. Each network node contains a microprocessor device, and a sensor or multiple sensors can be connected to each node through an electronic interface. Every network has its own
custom-designed interface for sensors, and sensor manufacturers have to support various networks and protocols. The purpose of the IEEE (Institute of Electrical and Electronics Engineers) 1451 Standards for Smart Transducer Interface for Sensors and Actuators, is to define a set of common interfaces for connecting transducers to microprocessor-based systems, instruments, and field networks in a network-independent fashion.

The standardized Transducer Electronic Data Sheet (TEDS) specified by IEEE 1451.2 allows for self-description of sensors. The interfaces provide a standardized mechanism to facilitate the plug-and-play of sensors to networks. The network-independent smart transducer object model defined by IEEE 1451.1 allows sensor manufacturers to support multiple networks and protocols. This way, transducer-to-network interoperability can be supported. IEEE P1451.3 and P1451.4 standards will meet the needs of the analog transducer users for high-speed applications. Transducer vendors and users, system integrators, and network providers can benefit from the IEEE 1451 interface standards.

2.2. VIBRATION SENSORS

The ability of modern condition maintenance systems to provide smart interactive control over potentially dangerous or production sensitive machinery, assumes that the data received from connected sensors is correct for all possible fault conditions. No matter what measurement parameter is monitored, there is usually a multitude of different sensors available to choose from, and it would be rare to find just one model for each parameter that could accurately and reliably measure all required ranges. Selection of the correct sensor and correct installation is of paramount importance, especially when it comes to vibration monitoring. High frequency gear mesh measurements, for instance, would require a sensor with a suitably high frequency range, whereas at the other end of the scale, very low speed machinery or monitoring structural movements would require a low frequency accelerometer with high mechanical gain and good resolution.

Smart sensors communicate with their outside world by using the data capture and analysis or control system. Smart sensors use digital communication. There are many alternative paths along which to develop the potential benefits of an agreed protocol. The proposed IEEE 1451 standard has four levels, three of which focus purely on digital interfaces as shown in Figure 2.1, while the fourth level, known as P1451.4, defines an interface for mixed mode sensors with analog signals as well as digital information.
The standard specifies data sets and formats that allow for each sensor to contain an electronic data sheet of information, such that it can be readily identified by the computer from a whole array of other sensors. This additional electronic package uses Transducer Electronic Data Sheet (TEDS). It has to be easy to use, support all different types of transducers, be flexible enough to meet individual needs, and remain compatible with level 1451.3 of the standard. TEDS data should include the following parameters:

- identification, e.g. model number;
- device, e.g. sensor type, sensitivity, and measurement units;
- calibration, e.g. date of last calibration and correction factors;
- application, e.g. channel ID (identifier) and measurement coordinates.

Apart from size restrictions or sensors with special outputs or for high temperature environments, TEDS can be put inside almost any vibration sensor during manufacture, and some data collection systems are available with the requisite TEDS interface. A TEDS sensor enables a system automatically to check on the status, exact position, and any other relevant detail put into the memory, during the normal data collection process. The TEDS function is the first step towards the truly intelligent vibration sensor. With additional integration of an ADC (analog-to-digital converters), and signal analysis such as FFT (Fast Fourier Transform) or frequency band monitoring within the sensor itself, important monitoring decisions can be made directly at the measurement location, and with local node or even individual sensor telemetry, cabling problems can also be eliminated.
No matter how smart the sensor becomes, there will always be the problem of correct sensor selection and deployment, in order to obtain the best information about potential failure.

Once the accelerometer has been correctly sourced, the next step is to mount and position it correctly in order to measure what is required. Accelerometers are designed to give an output in one axis only, so positioning can sometimes be essential for obtaining the best signal. Hand held probes are to be avoided if possible, due to the effect on frequency range and the positional errors that can occur with their use. Stud mounting on a properly prepared surface is always the best method, especially for high frequency measurements. Any effects on signal integrity should be understood and allowed for, or compensated for, in the measurement system.

The market for vibration sensors is driven by application and customer demand towards lower cost, and yet still be rugged, reliable and even intelligent transducers. Production machines with built-in vibration sensors are already available.

2.3. SMART SENSOR APPLICATION TO CONDITION BASED MAINTENANCE

IEEE 1451 is the proposed standard for interfacing sensors and actuators to digital microcontrollers, processors and networks. This standard reduces the complexities in establishing digital communication with transducers and actuators. IEEE 1451 defines the bus architecture, addressing protocols, wiring, calibration, and error correction, thus enabling a building-block approach to system design with plug-and-play modules. System integrators, instrument developers, engineers, and end users can plug IEEE 1451 compliant sensors and actuators together with measurement and communication modules to form a measurement system that allows transducers to interface directly with established networks and control systems.

Techniques for machinery fault prediction under development use multiple sensors with algorithms to extract useful information from the spectral properties of signals. Methods such as wavelet analysis, Hilbert transform analysis, adaptive neural networks, performance analysis, nonlinear characterization and multifunction data fusion with embedded sensors, are applied. In a plug-and-play architecture, sensors and actuators are linked together through a series of common interfaces to modules designed not only to process the signals, but to interface to existing communication networks. This approach eliminates full featured, more expensive components such as computers and stand alone instruments.
In the process control industry, sensors and transducers are connected directly to digital networks, over a common interface, and used in factory automation and closed loop control. The growth in slow speed sensors for measuring temperature, pressure, and position, contributed to the development of digital bus architectures. These systems have bandwidth limitations, proprietary hardware, and require design work to interface them with existing sensors.

Microprocessors, microcontrollers, ADCs (analog-to-digital converters) and their related electronics have become smaller, more powerful, and less expensive. There are advantages in including increased functionality into the transducer. The proposed industry standard interface for the connection of transducers and actuators to microcontrollers and to connect microcontrollers to networks is a logical extension of the General Purpose Interface Bus (GPIB or IEEE 488), except that this brings standardization to sensors instead of instruments. Figure 2.2 shows the building blocks for the implementation of a smart sensor interface.

An example application is a condition-monitoring system for milling machines in a large factory. A measurement system is needed for monitoring the health of bearings inside the milling machine and to detect tool wear or damage. Traditional methods of vibration measurement, using portable data collectors to monitor bearing health, have failed in this application, due to the varying operating conditions of the milling machine. Spindle movement and intermittent cutting operations affect the vibration signatures and can mask the vibration measurements of the bearings completely. The measurement

![Figure 2.2](image.png) Functional block diagram of IEEE P1451.
system must take into account the various states of the machine and record vibration measurements at predetermined intervals.

An intelligent tool-condition-monitoring method is needed to detect tool wear or damage automatically instead of replacing the tool at regular intervals or discovering defects in material after operation. Direct sensing methods have been developed using multiple sensors to detect vibration, force, acoustic emission, temperature, and motor current. Tool wear is a very complex process and can be detected with sensor fusion, feature extraction, and pattern recognition.

A spectrum analyzer or data acquisition system with a dedicated personal computer can be adapted to work in this environment, with various inputs from the control system for timing. This was considered to be too expensive and cumbersome to be implemented across the factory, on every line every machine. A low-cost system needed to be developed that could accept inputs from various sensors, process the information, and notify operators of impending failures or problems. With IEEE 1451 compatible components such as vibration sensors and actuators, a smart transducer interface module and a communications module, a measurement system can be constructed to implement the functions needed and communicate throughout the factory’s network. A solution is illustrated in Figure 2.3.

The IEEE 1451.1 standard defines the Network Capable Application Processor (NCAP). The NCAP is the smart sensor’s window to the external control network that is connected to any transducer, or a group of transducers, with an appropriately configured NCAP. This building block of the IEEE 1451 standard typically consists of a processor with an embedded operating system and a sense of time. The processor has a communication stack for a network protocol. If the NCAP is used with the Ethernet, for example, it will have a TCP/IP protocol stack. Figure 2.4 illustrates an example of an NCAP. In this

![Figure 2.3](image)

**Figure 2.3** IEEE P1451 implementation of machine condition monitoring system.
approach the design of the building blocks is done by the experts in this field who develop the modules to interface smart transducers with the existing networks. A system designer implementing a solution for a process chooses the module for a particular application and plugs it into the design. With additional code built into the NCAP, this module can be used as a micro web server with web pages providing information about the transducers connected to it.

The IEEE 1451.2 standard specifies Smart Transducer Interface Module (STIM). This is a digital interface and serial communication protocol that allows any transducer, or group of transducers, to receive and send digital data using a common interface. This common interface, called the Transducer Independent Interface (TII), is a 10-wire serial I/O bus that is similar to the IEEE 488 bus. The TII implements a serial data exchange with allowances for handshaking and interrupts. TII has defined power supply lines and permits hot-swapping of modules for plug and play capability. Any transducer can be adapted to the 1451.2 protocol with a Smart Transducer Interface Module (STIM). This building block of the 1451 standard is the measuring system. It can be as simple as a switch connected to a 4-bit processor, or as complex as a 255-channel device running an individual process. The STIM performs the tasks of signal conditioning, signal conversion and linearization. With added hardware it can perform functions such as spectrum analysis, fuzzy pattern recognition, adaptive noise canceling or a specific algorithm. The development of STIMs focuses on how to meet individual needs and special applications. Figure 2.5 illustrates one example of a STIM and how it interfaces with an NCAP through the TII.
Information about the STIM and the attached transducers is digitally stored in the format for which is integral to this standard Transducer Electronic Data Sheet (TEDS). This includes transducer identification, channel information, physical location, calibration, and correction data. TEDS provides a standardized set of mechanisms and information that can be used by applications to adapt automatically to device changes, thus supporting plug and play devices.

The IEEE P1451.3 standard defines Distributed Multidrop System (DMS), a digital interface for connecting multiple physically separated transducers, which allows for time synchronization of data. This transducer bus facilitates communications, data transfer, triggering, and synchronization.

A representation of IEEE P1451.3 with the functional blocks of the NCAP, transducer bus controller, and the transducer bus interface modules is shown in Figure 2.6. A single transmission line is used to supply power to the TBIMs and to provide communication to the bus controller. The NCAP contains the controller for the bus and the interface to the broader network. A TBIM supports different transducers and the bus may contain many TBIMs. This allows a distributed network of sensors and actuators to be connected through a common interface.

The IEEE P1451.4 standard defines Mixed-Mode Communication Protocol and Interface to bridge the gap between legacy systems and IEEE 1451.
architectures. This standard allows analog transducers to communicate digital information, for the purposes of self-identification and configuration, over the same medium. A TEDS is defined for traditional analog sensors to store information such as model number, serial number, sensitivity and calibration parameters, inside the transducer. The term ‘mixed-mode’ refers to the operation of the transducer in either its traditional analog (sensing) mode or in its digital (communication) mode, during which transducer can be reconfigured, or its TEDS can be retrieved or updated. The transducer functions normally when the voltage supply is forward biased and will output its analog measurement signal. When the sensor is reverse biased, the traditional analog circuitry is disabled and the TEDS memory can be accessed. The circuit schematic is outlined in Figure 2.7 illustrating the reverse bias technique.

Although this example is specific to IEPE (Integrated Electronics, Piezo-Electric) devices, the preliminary standard generalizes the configuration of this mixed mode interface for a wide range of transducers. Some legacy transducers systems may require more than one line for operation, for instance, certain devices may require a constant voltage source, and a separate line for the transducer output signal. In this case, the analog power line is defined as the data line while in the digital mode. A similar reverse polarization scheme disables the analog circuitry, and activates the digital communication.

While in digital mode, the P1451.4 transducer can identify itself by transmitting the contents of its memory. This is the capability most commonly associated with P1451.4. However, part of this memory may contain information as to how the P1451.4 transducer may be configured. After receiving this information, a host to the P1451.4 bus (likely a 1451.2 STIM) can issue a
command to the transducer to configure itself into a number of different configurations. One immediate use of this capability is to implement a multidrop sensor bus. Figure 2.8 outlines a transducer with such capability.

The transducer in Figure 2.8 contains three distinct components, each of which is enclosed by a dashed boundary. The first, labeled ‘analog transduction’ represents an IEPE type sensor. The second, labeled ‘Digital communication/configuration’ contains an EEPROM and PIO. The third, labeled ‘TEDS logic level controls relay’ connects the analog and digital sections of the transducer.

Figure 2.7  Circuit schematic for IEEE P1451.4.

Figure 2.8  Self configuring P1451.4 transducer.
Communication/Configuration’ adds the mixed-mode capability promised by IEEE P1451.4. Together with the analog transduction component, it forms the transducer outlined in Figure 2.7. However, the digital hardware in this particular transducer has an extra pin, which is held at logical high or logical low upon command. This logic level, in turn, controls the position of switching hardware found in the third component of the transducer. The A position of this switching hardware directs the power/signal line to this particular node. The B position of the switching hardware directs the power/signal line to another transducer.

By arranging these self-configuring transducers appropriately as shown in Figure 2.9, we can construct a multidrop sensor bus of mixed mode transducers. The digital circuitry in Figure 2.8 is always connected to the bus. When the bus is pulled low, all nodes of the network are visible to the controller (this is likely to be a 1451.2 STIM). The protocol of this P1451.4 network allows each node shown in Figure 2.9 to have a unique identification. The network protocol also permits the master to poll the entire bus to identify each node uniquely. With this data, the master consecutively toggles each node to its B (or pass-through) position.

The master commands node 1 to toggle to its A position. The master releases the bus from negative bias. All digital circuitry is then disabled, and only the analog circuitry of node 1 is exposed to the constant current, positively polarized, line bias. The analog transduction section of node 1 ensues to bias and operate in its traditional manner, and high fidelity measurements possible with IEPE sensors can be taken by the master (STIM).

When the measurements phase for that particular node is complete, the master pulls the line low to disable the analog circuitry and wake up the digital circuitry of the entire bus. The master commands node 1 to toggle to its B position, then commands node 2 to its A position. Analog measurements can then be made from node 2. This process is repeated for each of the N nodes on the network.

The hardware interfaces and communication protocols, defined under IEEE 1451, will enable instrumentation manufacturers to design and produce solutions for machinery-condition-analysis systems at a significantly lower cost.
cost than traditional methods. The proposed standard takes advantage of established networks so that sensors and transducers can be leveraged onto networks with familiar, inexpensive, off-the-shelf wiring and networking components. The IEEE standard’s plug-and-play approach allows freedom of choice between transducers, field networks and interface modules. Standard Internet and intranet links allow access to distributed devices from any remote site, and enable customized and familiar IP (Internet Protocol) addressing.

2.4. SMART TRANSDUCER NETWORKING

IEEE 1451 defines hardware and software standardized methods for supporting smart sensor and network connectivity. The standard’s specifications place no restrictions on the use of signal conditioning and processing schemes, analog-to-digital converters, microprocessors, network protocols, and network communication media. IEEE 1451 reduces industry’s effort to develop and migrate towards networked smart transducers. This standard provides the means to achieve transducer-to-network interchange ability and transducer-to-network interoperability.

The IEEE 1451.2 project defines a Transducer Electronic Data Sheet (TEDS) and its data format, along with a 10-wire digital interface and communication protocol between transducers and a microprocessor. The framework of the IEEE 1451.2 interface is shown in Figure 2.10. The TEDS, stored in a non-volatile memory, contains fields that describe the type, attributes, operation,

![Figure 2.10](image)

Figure 2.10 Framework of IEEE 1451.1 and 1451.2 interfaces.
and calibration of the transducer. With a requirement of only 178 bytes of memory for the mandatory data, the TEDS is scalable. A transducer integrated with a TEDS provides a feature that makes the self-description of transducers to the network possible. Since the transducer manufacturer data in the TEDS always goes with the transducer, and this information is electronically transferred to a NCAP or host, the human errors associated with manually entering sensor parameters are eliminated. The manufacturer data and the optional calibration data are stored in the TEDS, so losing transducer paper data is not a concern. With the TEDS feature, upgrading transducers with higher accuracy and enhanced capability, and replacing transducers for maintenance purposes, becomes simply ‘plug-and-play’. The IEEE 1451.2 interface defines STIM. Up to 255 sensors or actuators of various digital and analog mixes can be connected to a STIM. The STIM is connected to a network node called NCAP through the 10-wire transducer independent interface using a modified Serial Peripheral Interface (SPI) protocol for data transfer.

The IEEE 1451.1 standard defines a common object model for a networked smart transducer and the software interface specifications for each class representing the model. Some of these classes form the blocks, components, and services of the conceptual transducer. The networked smart transducer object model encapsulates the details of the transducer hardware implementation within a simple programming model. This makes programming the sensor or actuator hardware interface less complex by using an input/output (I/O)-driver paradigm. The network services interfaces encapsulate the details of the different network protocol implementations behind a small set of communications methods. The model of the networked smart transducer is shown in Figure 2.11.

During the course of the development of the IEEE 1451.1 and 1451.2 standards, some sensor manufacturers and users recognized the need for a standard interface for distributed multidrop smart-sensor systems. In a distributed system a large array of sensors, in the order of hundreds, needs to be read in a synchronized manner. The bandwidth requirements of these sensors may be relatively high, of the order of several hundred kHz, with time correlation requirements in tens of nanoseconds. IEEE P1451.3 defines the standard specification. The physical representation of the proposed IEEE P1451.3 standard is shown in Figure 2.6. A single transmission line is proposed to supply power to the transducers and to provide the communications between the bus controller and the Transducer Bus Interface Modules (TBIM). A transducer bus is expected to have one bus controller and many TBIMs. A TBIM may contain one or more different transducers. The NCAP contains the controller for the bus and the interface to the network that may support many other buses.
In the condition-based monitoring and maintenance industry, analog transducers such as piezoelectric, piezoresistive, and accelerometer-based transducers are used with electronics instruments to measure the conditional state of machinery. Transducer measurements are sent to an instrument or computer for analysis. The idea of having small TEDS on analog transducers and the ability to connect transducers to a network is used in the IEEE P1451.4 standard. An IEEE 1451.4 transducer can be a sensor or actuator with, typically, one addressable device, and is referred to as a node-containing TEDS. The IEEE P1451.4 transducer may be used to sense multiple physical phenomena. Each phenomenon sensed or controlled is associated with a node. If more than one node is included in an IEEE 1451.4 transducer, one of the nodes must have a memory block that holds the node list. The node list contains the identifications of the other nodes.

In order to reduce cabling and interfacing costs, a model using different wiring configurations is chosen as a transducer connection interface. If a single wire model is used, the analog transducer signal transmission and communication of the digital TEDS data to an instrument or a network are done on the same wire, but at separate times. If a multiwire model is used, communication of digital data and analog signals can be accomplished simultaneously. The digital communication can be used to read the TEDS information and to configure an IEEE P1451.4 transducer.
The context of the mixed-mode transducer and its interface(s) are shown in Figure 2.12.

A distributed measurement and control system can be easily designed and built based on the IEEE 1451 standards. An application model of IEEE 1451 is shown in Figure 2.13. Three NCAP/STIMs are used for illustration purposes. In scenario one, with sensors and actuators connected to the STIM
of NCAP No.1, the application software running in the NCAP can perform a localized control function, for example, maintain a constant temperature of a bath. The NCAP reports measured data, process information, and control status to a remote monitoring station or host. It frees the host from the processor-intensive, closed loop control operation. In the second scenario, NCAP No.2, connected with sensors only, can perform a remote process or condition monitoring function, for instance, to monitor the vibration level of a set of bearings in a turbine. In the third scenario, based on the broadcast data received from NCAP No.2, NCAP No.3 activates an alarm when the vibration level of the bearings exceeds a critical point set.

The Ethernet has been used for networking computers for information and data exchange. The TCP/IP (Transaction Control Protocol/Internet Protocol) enables data transfer between computers across the Internet. An industrial Ethernet NCAP, which is IEEE 1451.2 compatible, can be used to build web-based distributed measurement and control applications which enable the access of sensor information and measurements across the Internet.

2.5. CONTROLLER AREA NETWORK

IEEE 1451 smart transducer standard offers true plug-and-play facilities for connecting sensor and actuator devices to field bus and device-level networks. Although the first implementations of the standard have been developed to allow transducer devices to connect to Ethernet networks, thus creating an industrial Ethernet, the standard can also be applied to CAN (Controller Area Network)-based device level networks. The IEEE 1451 standard describes design and implementation for an IEEE 1451.2 STIM (Smart Transducer Interface Module), involving a software port, onto a standard microcontroller. The IEEE 1451.1 standard defined NCAP (Network Capable Application Processor) can be implemented in a CAN node thus realizing a form of gateway between transducer devices and the CAN network, based on the IEEE 1451 standard.

IEEE 1451 introduces a common interface standard to give a network-independent view of devices. Smart transducers can embed local intelligence to support features such as self-diagnostics, local control and analytical algorithms, and can perform self-declaration to the network based on an electronic data sheet. This self-declaration feature allows transducer devices to be connected to the network in a true plug-and-play way.

The first commercial IEEE 1451 implementations are targeted at the Ethernet networks. Ethernet has traditionally played a role as a LAN (Local Area Network), positioned high up in the CIM (Channel Interface Module) model.
However, as the cost of embedded Ethernet solutions decreases, the Ethernet is applied at the field bus level and even at the device network level, but Ethernet does not support various device profiles, in a formal sense, and IEEE 1451 offers a retrofit solution for Ethernet, defining a device level interface for smart sensors. This solution is referred to as industrial Ethernet.

The IEEE 1451 standard, however, is more than an Ethernet solution. The transducer developers need a network-independent standard for device connection. CAN based networks are good candidates for IEEE 1451 implementations and a number of companies are developing these solutions. The IEEE 1451 standard maps the transducer device to the target network based on an object model defined independently of the network. Each network has an NCAP (Network-Capable Application Processor) which maps to the target network profile.

Along with providing a common-software interface standard for transducer devices, a common-hardware interface is also necessary for network independence. The common hardware interface exists where an architectural difference occurs between the IEEE 1451 standard and the more traditional approach for field bus and device level network interfacing.

The IEEE 1451 standard comprises of four complete sub-standards. Each sub-standard may be used as a stand-alone or as a part of an overall IEEE 1451 family solution. The IEEE 1451.1 and 1451.2 standards have been balloted and accepted by the IEEE. IEEE P1451.3 and P1451.4 are under development, hence the prefix P, which denotes a proposed document. Figure 2.10 shows a block diagram for the IEEE 1451.1 and IEEE 1451.2 solutions.

IEEE 1451.1 defines a network-independent information model, enabling transducers to interface to network-capable application processors (NCAPs). It provides a definition for a transducer and its components using an object-oriented model. The model consists of a set of object classes with specified attributes, actions and behaviors used to provide a clear, comprehensive description of a transducer. The model also provides a hardware independent abstraction for the interface to the sensor and actuator. The model can be mapped onto example networks such as DeviceNet, Ethernet, LonWorks and SDS (Smart Distributed System). This mapping is achieved through a standard API (Application Programming Interface). This standard optionally supports all of the interface module communication approaches taken by the rest of the IEEE 1451 family (i.e. STIM, TBIM, Mixed-mode transducer).

IEEE 1451.2 defines the following:

- a TEDS (Transducer Electronic Data Sheet) and its data format;
- a standard digital interface and the communication protocols used between the transducer(s) and the microprocessor;
**IEEE 1451.2** requires that the TEDS are physically located with the transducers (as part of the STIM) at all times. The TEDS contains information describing the transducers that are embodied within the STIM. The amount of detail held within the TEDS will vary with each specific STIM implementation, but critical information will always be present.

IEEE P1451.3 defines a specification for a standard physical interface for connecting multiple physically separated transducers in a multidrop configuration. This is necessary because in some cases, for example, it is not possible physically to locate the TEDS with the transducers (for instance, due to harsh environments). The IEEE P1451.3 document proposes a bus implementation (known as the Transducer Bus Interface Module, TBIM) that is small and cheap enough to fit easily into a transducer. The network overhead developed is optimized to allow maximum data transfer throughput with a simple control logic interface.

IEEE P1451.4 defines a specification that allows analog transducers (e.g. piezoelectric transducers, strain guages, etc.) to communicate digital information (mixed mode) for the purposes of self-identification and configuration. This standard also proposes that the communication of the digital TEDS data is shared with the analog signal from the transducer with a minimum set of wires, fewer than the 10-wire requirement of the IEEE 1451.2 standard.

IEEE 1451.1 and IEEE 1451.2 together define the specification for networked smart transducers. They provide the framework for the sensor and actuator manufacturers to support multiple networks and protocols easily.

As a whole, the family of IEEE 1451 standard interfaces provides the following benefits:

- enable self-identification of transducers;
- facilitate self-configuration;
- maintain long term self-documentation;
- make for easy transducer upgrade and maintenance;
- increase data and system reliability;
- allow transducers to be calibrated remotely, or to be self-calibrated.

The following components are used in the description of IEEE 1451.2:

**XDCR**: an abbreviation for transducer, which is a sensor or an actuator.

**STIM**: Smart Transducer Interface Module (Figure 2.10).
2.5. CONTROLLER AREA NETWORK

A STIM can range in complexity from a simple single-channel sensor, or actuator, to a product supporting multiple channels of transducers. A transducer channel is denoted smart in this context because:

- it is described by a machine-readable TEDS;
- the control and data associated with the channel are digital;
- triggering, status and control are provided to support the proper functioning of the channel

NCAP: Network Capable Application Processor.
- The NCAP mediates between the STIM and a digital network, and may provide local intelligence. The STIM communicates with the network transparently, via the TII that links it to the NCAP.

TII: Transducer Independent Interface.
- The TII is a 10-wire serial I/O bus that defines:

  - a triggering function that triggers reading and writing from/to a transducer;
  - a bit transfer methodology;
  - a byte-write data-transport protocol (NCAP to STIM);
  - a byte-read data-transport protocol (STIM to NCAP);
  - data transport frames.

TEDS: Transducer Electronic Data Sheet.
- The TEDS is a data sheet written in electronic format that describes the STIM and the transducers associated with it, such as manufacturer’s name, type of transducer, serial number, etc. The TEDS must remain with the STIM for the duration of the STIM’s lifetime.

We discuss an example implementation of the IEEE 1451.2 standard to design a STIM. We break down the IEEE 1451.2 standard into its logical parts, and then reorganize these parts into a software model. The resulting software model is shown in Figure 2.14. The 1451.2 STIM contains the following: TEDS; control and status registers; transducer channels; interrupt masks; address and function decoding logic; data transport handling functions; trigger and trigger acknowledge functions for the digital interface to the TII; a TII driver, and a transducer interface. The logical software blocks are shown in Figure 2.15.
- The TII contains the physical lines to support data transport, clocking, triggering and acknowledgment. Each STIM must have a TEDS, which consists of eight different subgroupings, which are:

  - Meta TEDS [mandatory]
Figure 2.14 STIM software architecture.

Figure 2.15 IEEE 1451.2 broken down into its logical software blocks.

- makes available, at the interface, all the information needed to gain access to any channel,
- contains information common to all channels,
- information is constant and read-only.
• Channel TEDS [mandatory, one for each channel]
  – makes available, at the interface, all the information concerning the channel being addressed to enable proper operation of that channel,
  – information is constant and read-only.

• Calibration TEDS [optional]
  – makes available, at the interface, all of the information used by the correction engine in connection with the channel being addressed,
  – information may be configured to be read and write capable, or it may be configured as read-only.

• Meta-Identification TEDS [optional]
  – makes available, at the interface, the information needed to identify the STIM,
  – contains any identification information common to all channels,
  – information is constant and read-only.

• Channel-Identification TEDS [optional]
  – makes available at the interface all of the information needed to identify the channel being addressed,
  – information is constant and read-only.

• Calibration-Identification TEDS [optional]
  – makes available at the interface the information describing the calibration of the STIM,
  – information may be configured to be read and write capable, or it may be configured as read-only (it must be the same as for the calibration TEDS).

• End-Users’ Application Specific TEDS [optional]
  – contains end-users’ writable application-specific data,
  – information is nonvolatile.

• Industry Extensions TEDS [optional]
  – the function of the extension TEDS, the appropriate functional and channel address range where it may reside, and the meaning and type of the data fields will be defined by the creator of the extension.

For the purposes of this implementation, the software was coded in four modules, as follows:

• STIM control, channel data and transducer interface module;
• TII module;
• TEDS module;
• Address and function module.
Figure 2.16 A block diagram of the principal features contained on the ADuC812.

This software was built and run on the Analog Devices ADuC812 Micro-converter development board. A block diagram of the principal features contained on the ADuC812 is shown in Figure 2.16. The ADuC812 contains an 8051 compatible MCU, 8 kb of program flash/EE, 640 bytes of data flash/EE, 256 bytes of RAM, up to 32 programmable I/O lines, an SPI serial I/O port, dual DACs and an eight-channel true 12-bit ADC. The SPI port is an industry standard four-wire synchronous serial communications interface. It can be configured for master or slave operation, and is externally clocked when in slave mode. The data flash/EE is a memory array which consists of 640 bytes, configured into 160 4-byte pages. The interface to this memory space is via a group of registers that is mapped in the SFR space. The 8-kb program flash/EE will ultimately store and run the end-user’s application code.

This board, together with two attached transducers (an AD590 temperature sensor and a digital I/O controlled fan) comprises the STIM. The NCAP used for this implementation was the HP BFOOT 66501. Figure 2.17 shows the mapping between the IEEE 1451.2 software and the ADuC812.

- the STIM is controlled from the program flash/EE, and each channel’s transducer data, status and control registers is held in RAM for the duration of the STIM lifetime;
- the transducer interface is mapped onto the ADCs, DACs and I/O lines;
- the TII is a superset of the SPI port (plus some I/O lines);
the TEDS map into the 640 bytes of data flash/EE, and

- the Address and Function block is stored into the program flash/EE.

'STIM Control and Channel Data' and 'Transducer Interface' modules contain the definitions for the transducer channels (there are 256 transducer channels allowed per STIM). One of these channels must be CHANNEL_ZERO, the global channel that is used for globally addressing all of the implemented channels simultaneously. As channels are added, they must be numbered sequentially, starting from the main control flow of the program. Our particular implementation defines two channels: one sensor (an AD590 temperature sensor) and one actuator (a digital-output controlled fan). As with the TII module, this module contains certain definitions that are hardware-coupled (i.e. the physical lines that the sensor and actuator are realized on).

The TII module defines the physical interface to the NCAP. The TII was implemented as a superset of the existing microconverter ADuC812 SPI port. There are 10 lines in the TII, while there are typically only three or four in an SPI implementation. This module must integrate these lines with their hardware interface, and also provide an abstract layer for software interaction.
Viewing the TII functions from the user’s perspective, this hardware coupling is transparent. The TII API calls allow for the transport of read and write protocol frames, and for detecting and manipulating the states of the TII lines.

The TEDS module defines the TEDS for the STIM. It defines where the TEDS are physically mapped (e.g. Flash RAM, ROM or EEPROM (Electronically Erasable Programmable read only)), how they are written and stored, how they are retrieved and what they contain. The TEDS supported include the mandatory TEDS (i.e. one meta- and two channel-TEDS) and also the optional meta-ID TEDS.

The ‘Address and Function’ module implements all of the main functionality that is defined by the IEEE 1451 standards. It takes care of the data transport, control, interrupt, status and trigger functions. Note that each one of the different function types is preceded by a three letter abbreviation representing the grouping to which it belongs, e.g. the function DAT_ReadMetaTEDS() belongs to the data transport function group. The data transport submodule detects activity on the physical transport lines (by calling TII API functions). This submodule controls the transmission and reception of the TEDS information, the status information and the transducer data.

The aim of the software implementation was to create a complete minimal IEEE 1451.2 realization. This work involved dividing the standard into its various parts, then identifying the compulsory and optional sections. The architecture was designed to meet all of the mandatory specifications, and to allow for expansion to support a full and complete specification. As a result, the code was structured, modular and scalable. As far as possible, the architecture abstracted the software into layers, so that all but the most hardware-dependent functions would also be portable.

The program code took just over 5.5 kB of program Flash/EE. The TEDS took up 268 bytes. For every channel that is added, another Channel-TEDS becomes mandatory. Therefore, the 640-byte data Flash/EE on board the ADuC812 will quickly fill up. The TEDS may also be mapped elsewhere should the need arise.

The end product was tested extensively. The NCAP used was HP BFOOT 66501 (which is also a thin web server) was used to test the system, so it was possible to read and display the TEDS over the WWW (World Wide Web). It was possible to track temperature trend remotely over time, using a Java applet to read the AD590 sensor data from the STIM, via the NCAP. It was also possible to control the temperature at the sensor by triggering the fan to actuate when the sensor value exceeded a pre-set threshold. To achieve this, all that needs to be known is the IP address of the NCAP.

For design engineers who are used to developing device profiles and interfaces for transducer devices on CAN based networks, the IEEE 1451
approach differs. Figure 2.18 shows a conventional solution where a typical transducer device, comprising some sensors in this example, is interfaced to a CAN-based network, say a DeviceNet solution. Here the sensors are interfaced directly to the network node and a single node processor is used to read and condition the sensor data. Figure 2.18 shows the same sensors interfaced to the DeviceNet network, or some other network, but this time the IEEE 1451 standard is employed. A separate processor is used to implement the NCAP at the node level, where the NCAP interfaces to the network on one side and interfaces to the TII at the other side. A separate processor resides in the STIM module.

It is seen that compared with conventional solutions for transducer interfacing, the IEEE 1451 solution includes an additional serial interface, the TII, and an additional processor for the STIM. These additional hardware features make the implementation appear cumbersome. However, the additional hardware in the IEEE 1451 context allows the transducer manufacturer to develop to a common interface standard, which is independent of any particular network. The transducer developer needs to develop only one product where it is anticipated that the various network developers will provide the

Figure 2.18 Conceptual IEEE 1451 based solution.
NCAPs, which are in effect gateways between the target network and the STIM. Thus the transducer device manufacturer will develop expertise in STIM and does not need to have knowledge of the NCAP or the networks other than the NCAPs.

Many of the transducer manufacturers are SME (Small to Medium Enterprise) sized companies and it is easier for such companies to develop a single product to suit all networks. Obviously if some particular network or networks are of volume interest to a transducer manufacturer, then the manufacturer may elect to do a dedicated implementation for such a network or networks. However, the STIM solution is more universal, although at an incremental cost.

IEEE 1451 is not just an industrial Ethernet standard but it is a generic standard which can be applied to many field bus or device-level networks.

The IEEE 1451 offers a useful reference for control and data models to describe sensors and actuators. The standard helps to unify the many different models presented in network standards.

The CAN can explore this standard and implement NCAP solutions. The CAN based networks are used to provide device level solutions, and the

Figure 2.19 The ADuC812 programming model.
IEEE 1451 standard encourages more transducer manufacturers to develop products for networked environments.

Figure 2.19 shows the programming model for the ADuC812. The ADuC812 has separate address spaces for program and data memory. The additional 640 bytes of Flash/EE that is available to the user may be accessed indirectly via a group of control registers in the SFR (Special Function Register) area of the data memory space. The lower 128 bytes of RAM are directly addressable, while the upper 128 bytes may only be addressed indirectly. The SFR area is accessed by direct addressing only and provides an interface between the CPU and all on-chip peripherals.

Figure 2.20 shows how the 1451 implementation makes use of the ADuC812 programming model. The TEDS are located in the 640-byte data Flash/EE, the TII and actuator are directly tied into the peripherals block and the sensor is hanging off of the ADC block. All of these features are accessed and controlled
via the SFR area. The standard data RAM is used for storing the STIM channel transducer data and registers. It must reserve a buffer from which the TEDS may be individually loaded, and into which the TEDS may be read back from the data Flash/EE. Note also that the RAM must contain all local and system variables that are required by the code, and it must also allow for the run-time stack. All of these requirements place limitations on the size of the TEDS buffer, which the end-user should be aware of. All of the programming functions are stored into the program Flash/EE memory. In Figure 2.20, the dotted line shows the logical link between the read/write functions, and the actual writing and reading to/from the TEDS data Flash/EE area. These TEDS function calls are designed to be logically transparent to the end-user, and the method of implementation is not important.

2.6. SUMMARY

Smart sensors communicating with their outside world use digital communication. There are many alternative paths along which to develop the potential benefits of an agreed protocol. The proposed IEEE 1451 standard has four levels, three of which focus purely on digital interfaces, while the fourth level, known as P1451.4, defines an interface for mixed mode sensors with analog signals as well as digital information.

In a plug-and-play architecture, sensors and actuators are linked together through a series of common interfaces to modules designed to process the signals and to interface to existing communication networks. In the process control industry, sensors and transducers are connected directly to digital networks over a common interface, and are used in factory automation and closed loop control.

An intelligent tool-condition monitoring method is needed to detect tool wear or damage automatically instead of replacing the tool at regular intervals or discovering defects in material after operation. Direct sensing methods have been developed using multiple sensors to detect vibration, force, acoustic emission, temperature, and motor current. Tool wear is a very complex process and can be detected with sensor fusion, feature extraction, and pattern recognition.

Microprocessors can support smart sensors and devices. With this added capability, it is possible for a smart sensor to communicate measurements to an instrument or a system directly. Networking of transducers (sensors or actuators) in a system can provide flexibility, improve system performance, and make it easier to install, upgrade and maintain systems.

IEEE 1451 defines hardware and software standardized methods to support smart sensor and network connectivity. The standard’s specifications place
no restrictions on the use of signal conditioning and processing schemes, analog-to-digital converters, microprocessors, network protocols, and network communication media. IEEE 1451 reduces industry’s effort to develop and migrate towards networked smart transducers. This standard provides the means to achieve transducer-to-network interchangeability and transducer-to-network interoperability.

The IEEE 1451.1 standard defines a common object model for a networked smart transducer and the software interface specifications for each class representing the model. Some of these classes form the blocks, components, and services of the conceptual transducer. The networked smart transducer object model encapsulates the details of the transducer hardware implementation within a simple programming model. This makes programming the sensor or actuator hardware interface less complex by using an input/output (I/O) driver paradigm. The network services interfaces encapsulate the details of the different network protocol implementations behind a small set of communications methods.

The IEEE 1451.1 defined NCAP (Network Capable Application Processor) can be implemented in a CAN node thus realizing a form of gateway between transducer devices and the CAN network, based on the IEEE 1451 standard. The IEEE 1451 introduces a common interface standard to give a network independent view of devices. Smart transducers can embed local intelligence to support features such as self-diagnostics, local control and analytical algorithms, and can perform self-declaration to the network based on an electronic data sheet. This self-declaration feature allows transducer devices to be connected to the network in a plug-and-play way.

The IEEE 1451 standard maps the transducer device to the target network based on an object model defined independently of the network. Each network has an NCAP (Network Capable Application Processor) which maps to the target network profile.

Along with providing a common software interface standard for transducer devices, a common hardware interface is also necessary for network independence. The common hardware interface exists where an architectural difference occurs between the IEEE 1451 standard and the more traditional approach for field bus and device level network interfacing.

IEEE 1451.1 defines a network-independent information model, enabling transducers to interface to network capable application processors (NCAPs). It provides a definition for a transducer and its components using an object-oriented model.

IEEE 1451.2 defines TEDS (Transducer Electronic Data Sheet) and its data format, a standard digital interface and the communication protocols used
between the transducer(s) and the microprocessor, an electrical interface, and read and write logic functions to access the TEDS and transducers.

IEEE P1451.3 defines a specification for a standard physical interface for connecting multiple physically separated transducers in a multidrop configuration. The IEEE P1451.3 document proposes a bus implementation (known as the Transducer Bus Interface Module, TBIM) that is small and cheap enough to fit easily into a transducer.

IEEE P1451.4 defines a specification that allows analog transducers (e.g. piezoelectric transducers, strain gauges, etc.) to communicate digital information (mixed mode) for the purposes of self-identification and configuration.

IEEE 1451.1 and IEEE 1451.2 together define the specification for networked smart transducers. They provide the framework for the sensor and actuator manufacturers to support multiple networks and protocols easily.

PROBLEMS

Learning Objectives

After completing this chapter you should be able to:

• demonstrate understanding of smart sensors;
• explain the role of vibration sensors;
• discuss how smart sensors are applied to condition based maintenance;
• demonstrate understanding of smart transducer networking.

Practice Problems

Problem 2.1: How do smart sensors communicate?
Problem 2.2: What parameters should be included in TEDS data?
Problem 2.3: What does IEEE 1451.1 standard define?
Problem 2.4: What does IEEE 1451.2 standard define?
Problem 2.5: What does IEEE 1451.3 standard define?
Problem 2.6: What does IEEE 1451.4 standard define?
Problem 2.7: What are the benefits of using IEEE 1451 standard interfaces?

Practice Problem Solutions

Problem 2.1:

Smart sensors use digital communication. Smart sensors communicate with their outside world by using the data capture and analysis or a control system.
Problem 2.2:
TEDS data should include identification, e.g. model number; device, e.g. sensor type, sensitivity, and measurement units; calibration, e.g. date of last calibration and correction factors, and application, e.g. channel ID and measurement coordinates.

Problem 2.3:
The IEEE 1451.1 standard defines the Network Capable Application Processor (NCAP).

Problem 2.4:
The IEEE 1451.2 standard specifies Smart Transducer Interface Module (STIM).

Problem 2.5:
The IEEE P1451.3 standard defines Distributed Multidrop System (DMS), a digital interface for connecting multiple physically separated transducers, which allows for time synchronization of data. This transducer bus facilitates communications, data transfer, triggering, and synchronization.

Problem 2.6:
The IEEE P1451.4 standard defines mixed-mode communication protocol and interface to bridge the gap between legacy systems and IEEE 1451 architectures.

Problem 2.7:
The family of IEEE 1451 standard interfaces enables self-identification of transducers, facilitates self-configuration, maintains long-term self-documentation, makes for easy transducer upgrade and maintenance, increases data and system reliability, and allows transducers to be calibrated remotely or to be self-calibrated.