

A Unifying Standard for Interfacing Transducers to Networks – IEEE-1451.0

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ABSTRACT

A committee of industry and government technology experts has completed a three-year effort to develop a set of specifications that consist of a unifying set of functions, communications protocols, a common set of commands, and electronic data sheet formats that will serve as the basis for all future IEEE 1451 smart transducer interface standards. This paper will highlight the key features of the proposed IEEE P1451.0 standard and describe how these features are being used in applications, and how they are beneficial to users in achieving data-level interoperability where multiple wired and wireless sensor networks are connected.

INTRODUCTION

Industry and government technology experts have completed a three-year effort to develop a unifying set of specifications that will underlie the development and revision of a broad range of IEEE transducer-to-network interface standards.

As described in the proposed IEEE P1451.0 standards document, this work addresses a broad range of common sensor and actuator interface issues. While working on this IEEE standards project, technologists adhered to several underlying principles including: 1) the use of a network-neutral approach to accommodate various external networks without forcing transducer manufacturers to build different models for each network; 2) scalable solutions that use extensible constructs to provide simple

solutions for certain classes of applications, and feature-rich solutions for other classes of applications; 3) computer language independence to allow a wide range of modern computer languages such as C, C++, C#, Java, and Visual Basic to implement IEEE 1451 standards; 4) the use of electronic data sheets for transducer-specific information; and 5) the use of a correction engine to compensate for non-ideal transducer characteristics.

One of the main goals of this work was to provide a common set of commands to communicate, read, and control any of the entire spectrum of IEEE 1451.x transducers. In the context of this paper, as in the IEEE 1451 standards, the term transducer refers to either sensors or actuators.

Currently, there are six approved or proposed (P) members of the IEEE 1451 family of standards in addition to 1451.0. Each standard provides a set of specific physical interfaces and special features for transducer interfacing including: 1451.2 for low complexity, point-to-point wired, serial connections; 1451.3 for multi-point, high-performance wired connections for distributed systems; 1451.4 single-wire analog/digital shared connections; 1451.5 wireless connections; and 1451.6 CANopen/CAN bus connections.

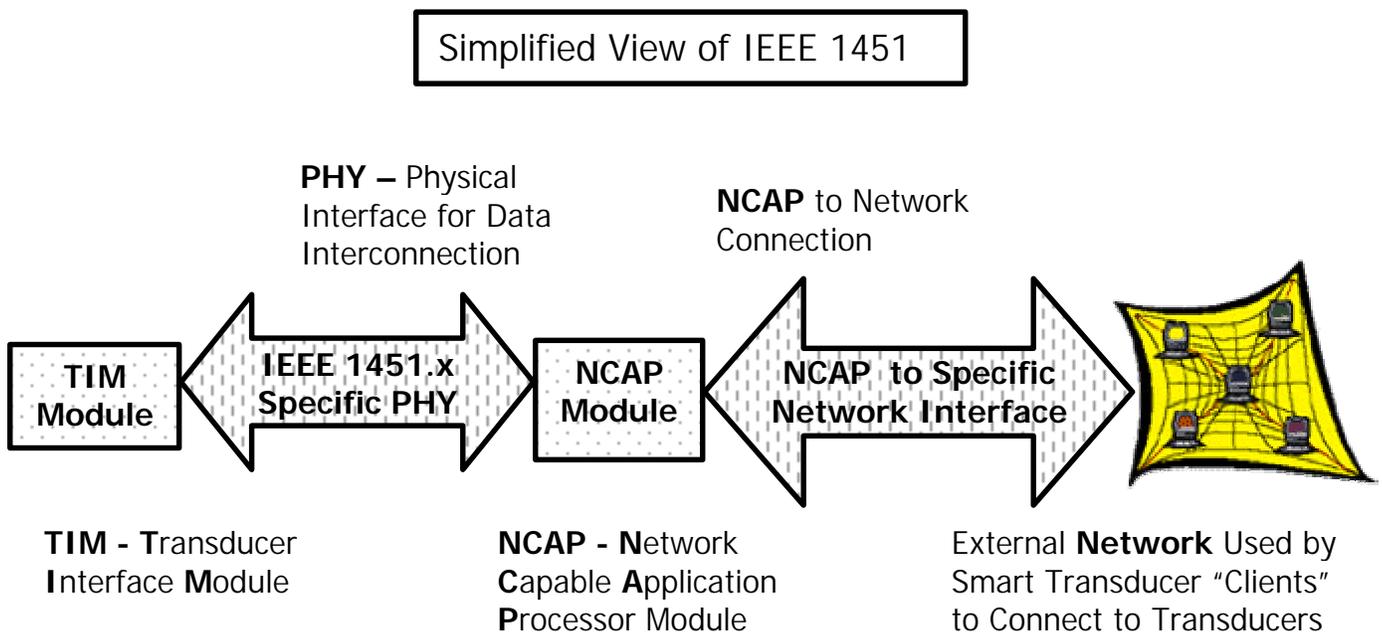


Figure 1 is a simplified overview of the IEEE 1451 architecture. The TIM module on the far left represents the low-level sensor interface electronics and the hardware/software features to communicate to higher-order hosts. The NCAP module contains the gateway hardware/software that interacts with the TIM and the network. Different NCAP gateways work with different networks (Ethernet, Modbus, DeviceNet, etc). But all NCAPs work with IEEE 1451 TIM interfaces. Different members of the IEEE 1451 family use different types of communications hardware/software to connect the NCAP to the TIM including wireless, wired UART, and others.

One of the primary goals of the proposed IEEE P1451.0 standard is to achieve a data-level interoperability when multiple wired and wireless sensor networks are connected, each adhering to a different member of the IEEE 1451 family of interface standards. By providing a common set of commands, electronic data sheet formats, communication protocols, the IEEE P1451.0 standard facilitates interoperability by using shared code to implement the various features across different members of the IEEE 1451 family.

Figure 1 illustrates the basic building blocks of the IEEE 1451 architecture. Details of this architecture can be found in the standard documents developed for each members of the IEEE 1451 family^{1, 2, 3, 4, 5}. The main hardware elements of this approach include the Transducer Interface Module (TIM), the Network Capable Application Processor (NCAP), the PHYsical interface (PHY) data connection between the TIM and the NCAP (including wireless connections), and the external network. One of the main differences between the different 1451 family members is the PHY data connection; that is, different 1451 family members specify different types of data connections between the TIM and the NCAP. For example, IEEE P1451.5 uses wireless connections, IEEE 1451.2 uses wired UART (universal asynchronous receiver-transmitter) connections and IEEE P1451.6 uses the CANOpen™ /CAN bus connection.

The essential software elements of this approach include the Transducer Electronic Data Sheets (TEDS), TIM resident software that communicates with the NCAP, NCAP resident software that communicates with the TIM, and additional NCAP resident software that communicates with the external network. These hardware and software features are described in this paper.

HARDWARE ELEMENTS

TRANSDUCER INTERFACE MODULE – TIM

The Transducer Interface Module performs the functions necessary to respond to requests for sensor data from the NCAP and reports status information to the NCAP. In the IEEE 1451 family of standards, the specifics of converting and conditioning analog sensor signals to formatted digital data are outside the scope of the standard. This aspect of the transducer data interface problem is a vendor-specific, value-added feature. Users are required to perform whatever sensor data conversion and data signal conditioning tasks required by a specific type of sensor for the user's application. Typically, the circuit elements required to accomplish the analog-to-digital conversion and signal conditioning are physically located in the TIM hardware. After the sensor signals are converted to a digital representation, the Transducer-Channel TEDS contains the specifications to accommodate a wide range of digital data formats from simple single byte integers (8-bits) to more complex double precision real numbers (64-bits) and includes features to work with virtually any combination of these types of data elements.

Upon request from the NCAP, the TIM provides a digital representation of the sensor data in a specific data format specified in the TEDS. This data is transmitted across the physical interface between the TIM and the NCAP with the timing for this transfer based on a trigger mode command from the NCAP. The IEEE 1451 standard supports several types of trigger mode commands but the TIM may only

support a subset of these trigger features. Information in the Transducer-Channel TEDS indicates to the NCAP which types of trigger commands are supported by the TIM.

For each transducer channel attached to the TIM, two 32-bit status registers are implemented that provide information about the health and error status of the TIM. These registers can be read from the NCAP and can generate their own service request signal to alert the NCAP to a potential problem.

PHYSICAL INTERFACE DATA CONNECTION – PHY

The physical interface data connection between the TIM and the NCAP is the physical way in which data and commands are interchanged between the TIM and the NCAP. This layer generally uses different mechanisms for different members of the IEEE 1451 family. For example, IEEE P1451.2 standard uses an electrical cable with a UART-based or an enhanced Serial Peripheral Interface (SPI) connection between the TIM and the NCAP. The soon to-be-released IEEE P1451.5 uses commonly available wireless protocols (including IEEE 802.11, 802.15.1 and 802.15.4) to connect the TIM modules to the NCAP. These members of the IEEE 1451 family all use the IEEE P1451.0 set of protocols as the base set of commands, data structures, and communication protocols to implement a transducer to computer network connection.

NETWORK CAPABLE APPLICATION PROCESSOR – NCAP

The Network Capable Application Processor is essentially a gateway between the external network and the IEEE 1451 elements. One of the underlying principles behind the development of IEEE 1451 is its “network neutral” feature which refers to the use of the NCAP. The standard does not specify the details of the NCAP’s connection to the external network. That is, different NCAPs can be developed for different networks so that many types of data fieldbuses can be used with IEEE 1451. The NCAP can be considered to be a two-port gateway in which one port of the gateway connects to the IEEE 1451.x components and the other port connects to the vendor selected fieldbus; each NCAP product is designed to be compatible with a particular type of field bus and to comply with one of the 1451.x standards. The “network neutral” concept enables vendors of NCAPs to provide a common set of software and hardware features for the port connected to the IEEE 1451.x components. It also enables NCAP vendors to implement network hardware and software features for the port connected to the external network based on the selected network specifications.

This concept empowers a supplier of NCAP devices to design and build products to whichever fieldbus standards is most compatible with their market requirements and allows transducer manufacturers to decouple from the fieldbus issues. The sensor and actuator manufacturers only need to comply with the “transducer-side” of the IEEE 1451.x standard which, for transducer manufacturers, mainly involves satisfying the TIM module specifications. This allows sensor and actuator manufacturers to focus their resources on enhancing their smart transducer products with features that are most compatible with their market requirements.

The NCAP contains software that supports communication services between the NCAP and the TIM as well as communications services between the external network and the NCAP. An overview of these software features is included in the NCAP Software section.

EXTERNAL NETWORK & NETWORK CONNECTION

As noted earlier, the external network and network connection is outside the scope of this standard. Operation with different networks will depend on the type of NCAP used in the IEEE 1451 implementation. The NCAP is responsible for implementing the hardware and software protocols associated with the external network. Depending on the network specifications, the NCAP may be required to implement all software and hardware aspects of the network interface including the appropriate network electrical connector.

The availability of NCAPs for use with different networks will depend on market forces and decisions made by NCAP device manufacturers and vendors. It is believed that IEEE 1451 NCAPs can be developed for most industrial fieldbus architectures in use today as well as for most other computer databases.

SOFTWARE ELEMENTS

TRANSDUCER ELECTRONIC DATA SHEETS – TEDS

Transducer Electronic Data Sheets (TEDS) are the data tables that contain specific information about the transducers attached to the IEEE 1451 TIM and global information about the entire IEEE 1451.x implementation. The IEEE 1451 family of standards was developed with the goal of being a low-overhead, simple-to-implement smart transducer interface solution for certain types of low-end applications but also capable of being extended to satisfy the needs of high-end, feature-rich applications. One technique used to achieve this goal was the specification of a minimum set of required TEDS features and other optional TEDS for more advanced features. Another approach was the use of tagged fields within each TEDS structure so that optional fields could be excluded without affecting the rest of the TEDS data structures.

IEEE P1451.0 specifies several types of TEDS structures to accommodate a wide range of potential sensors and actuators; however not all of the TEDS need to be implemented and not all of the fields in any single TEDS need to be included in the TEDS data table. Basically, only four TEDS structures are required:

- Meta-TEDS
- Transducer Channel TEDS
- User's Transducer Name TEDS
- PHY TEDS

In addition to these required TEDS structures, there are several optional TEDS data structures. These optional TEDS may be used at the implementers discretion based on the needs of the transducer application and the feature-set supported by the software used in the specific IEEE 1451 implementation. The optional TEDS structures include the following:

- Calibration TEDS
- Frequency Response TEDS
- Transfer Function TEDS
- Meta Identification TEDS – Text-based
- Transducer Channel Identification TEDS – Text-based
- Calibration Identification TEDS – Text-based
- Command TEDS – Text-based
- Location and Title TEDS – Text-based
- Identification TEDS
- Geographic Location TEDS – Text-based
- End User Application Specific TEDS
- Manufacturer defined TEDS

It should be noted that these TEDS structures generally reside within the TIM hardware element in an electronic memory device such as a Flash memory integrated circuit or EEPROM (electrically erasable programmable read only memory). However, in some situations, the TEDS may be a virtual TEDS and physically located somewhere on the attached network, or Internet linked by an URL. Finally, there are some implementation approaches that locate a copy of the TEDS in the NCAP to facilitate processing information requests from remote, network-based users.

In broad terms, the NCAP utilizes the TEDS information to help identify which TIMs are attached to the NCAP and further identify which transducers are attached to each TIM. In addition, the TEDS supplies information to the NCAP and remote users about each transducer's operating mode, trigger mode, calibration coefficients, functionality, and a wide-range of other use-specific information.

An end user can use TEDS information to determine transducer function, operating parameters, transducer location, the availability and use of high-level commands, and other text-related information.

Meta-TEDS data structure includes information about the entire IEEE 1451 TIM implementation including a unique ID for each TIM, the number of transducer channels connected to the TIM, worst case timing information that applies to all connected transducers for this TIM, and information about groupings of transducers connected to the TIM.

A separate Transducer Channel TEDS must be available for each Transducer attached to the TIM. The Transducer Channel TEDS includes information about the type of transducer (sensor or actuator) connected, the physical units, the useful operating range of the transducer, the type of digital data used by the transducer (integer or floating point), the setup time delays, the data acquisition time delays, and other attributes of the transducer data.

The User's Transducer Name TEDS is a simple location to store the name that the user will associate with a transducer.

The PHY TEDS contains information about the physical connection between the TIM and the NCAP . The details of the physical layer TEDS are defined by each of the 1451.x standards groups.

The optional TEDS are used as needed to provide for a more complete range of interface solutions. The details of these TEDS can be found in the IEEE-1451.0 document⁶. The focus of each optional TEDS is summarized in the title of the TEDS.

TRANSDUCER INTERFACE MODULE SOFTWARE – TIM SOFTWARE

The software contained in the TIM module can include a rich set of communications, data conversion, and signal processing algorithms or, in its most basic form, the TIM can contain the software necessary to respond to NCAP requests and initiate certain service request messages.

The four key features that the TIM must respond to are:

- Responding to TIM discovery queries
- Responding to transducer access requests
- Responding to and, in some situations, initiating transducer management tasks
- Responding to and supporting TEDS management functions.

These key features enable the TIM to interact in various interchanges with the IEEE 1451 NCAP to support the IEEE P1451.0 set of commands and services. In the simplest form, the TIM responds to the NCAP requests and alerts the NCAP with a status message to the existence of any special transducer situations. For example, the types of message alerts sent by the TIM to the NCAP might include a battery needs to be changed, a calibration gas canister is almost empty, or a sensor is outside its normal operating environment. In addition, the TIM must include software features to store and retrieve TEDS information into a non-volatile electronic memory.

In addition to these P1451.0 essential features, the TIM resident software may include features necessary to acquire, convert, and store analog sensor signals as digital data. The TIM may also need to apply calibration and correction engine methods to the acquired sensor data to correct for non-linear calibration coefficients or to compensate for the effects such as temperature-induced measurement distortions. Finally the TIM may include software to support various forms of bi-directional communications with the NCAP or with other TIMs to perform more sophisticated communications such as wireless mesh network functions.

NETWORK CAPABLE APPLICATION PROCESSOR SOFTWARE – NCAP SOFTWARE

The NCAP contains two categories of communications software – one that initiates communications with the TIM and the other category of software interacts with the external network. The software features that interact with the external network, or define communications between NCAPs, are partially specified in the IEEE P1451.1 standard. Some aspects of these communications are outside the scope of

the IEEE 1451 specifications and are dependent on the details of the network selected to work with a particular NCAP.

In a complementary manner, the NCAP software must support the following four main types of TIM software tasks:

- Launching TIM discovery queries
- Requesting access to transducer data and properties
- Initiating transducer management tasks and in some cases responding to TIM initiated service requests
- Requesting TEDS information from the TIM and, in certain cases, caching this information in NCAP memory to improve performance.

The IEEE P1451.0 standard provides a set of Application Programming Interface (API) definitions that explain what type of values should be sent by the NCAP to the TIM and what types of values should be returned by the TIM. These APIs were designed to be symmetrical so that in high-end applications, the TIM could initiate similar types of communications processes from the TIM to the NCAP. The APIs for each of the four key types of software tasks are included in this standard.

The API definitions in this standard are defined such that this communications software must be capable of being implemented with languages like C using low-powered, 8-bit microcontrollers, as well as on high-end computing platforms with programming languages like C++, Java, and Visual Basic, etc. This extensibility feature was an integral part and an underlying goal in each step of the IEEE P1451.0 development process.

EXTERNAL NETWORK SOFTWARE INTERACTIONS

Although the external network hardware and software interfaces are not within the scope of the IEEE P1451.0 standards, some special cases are included in the standard.

From the perspective of an external, network-user connecting to a basic 1451 implementation, the NCAP can be considered to be somewhat analogous to the server in a “Client-Server” paradigm. From this view, the NCAP serves requested data to the remote client on the network.

The IEEE P1451.0 specifies a process for the special case of networks that support the Internet Protocol “hyper text transfer protocol” (http). For this special case, IEEE P1451.0 defines a command communications process between a remote network-based “client” and a network-based IEEE 1451.x NCAP “server”. This capability enables direct communications between the two Internet Protocol (IP) addresses so that transducer data can be transferred across an external network in a manner that is standard for all 1451.x family members. This feature is particularly useful for interoperability among different members of the IEEE 1451.x family. For example, this feature enables a single, remotely located, Web-based client computer to connect and extract transducer data from various IEEE 1451.x-compliant devices installed in locations that are far apart, but all connected to the World Wide Web.

BENEFIT OF IEEE 1451 AND 1451.0

The IEEE 1451 suite of transducer interface standards will facilitate transducer-to-network connectivity and device interoperability. Sensor and actuator manufacturers will benefit from using this family of standards since they can develop products with a single software and hardware interface, but target different types of fieldbuses, by selecting an appropriate NCAP to complete their fieldbus-specific product offering. In addition, manufacturers can exploit advanced software calibration features intrinsic to IEEE 1451-compliant devices.

Transducer system integrators benefit from IEEE 1451 TEDS features which can serve as a self-documenting capability and assist in all life-cycle tasks including setup, daily operations, calibration, maintenance, and end-of-life activities. IEEE 1451-compliant devices will facilitate field replacement efforts due to various IEEE 1451 features including “plug-and-play” setup, self-documenting TEDS, and calibration TEDS.

Software developers benefit from the well-defined standard definition of transducer properties. In addition, IEEE 1451 interoperability features such as the common command set and common IP access allow developers to use the same interface code for a wide range of measurements associated with different types of transducers from different vendors. IEEE 1451 includes hooks for time synchronization across a network and support for multiple languages.

End-users will benefit from the use of IEEE 1451-compliant transducers because of the self documentation, “plug-and-play” setup, and the availability of transducer “properties” including physical units, recommended operating range, calibration data, location, and other self-identification information.

CONCLUSIONS

The IEEE P1451.0 standard has provided a uniform set of commands, electronic data sheet formats, communication APIs, and design guidelines to serve as the basis to facilitate interoperability for the entire family of IEEE 1451 smart transducer – to – digital network hardware and software interfaces. This standard will be used to assure uniformity within the family of IEEE 1451.x interface standards as revisions are made to existing standards. It will provide a solid foundation and ease the implementation for future members of the IEEE 1451.x family of interface standards.

Transducer manufacturers, system integrators, and end-users can benefit from using the IEEE 1451 family of standards. Manufacturers of sensors and actuators will benefit from the use of a single standard for “network neutral” hardware and software interfaces. In addition, IEEE 1451 calibration mechanisms will help manufacturers develop better components.

Transducer system integrators will benefit from the use of IEEE 1451 family of standards through reduced expenditures on transducer-to-network interface development efforts. System integrators will also be able to leverage existing resources by modifying existing IEEE 1451 reference implementations.

For end users, the use of IEEE 1451-compliant products will reduce setup, maintenance, and overall life cycle costs with easy-to-use, plug-and-play features. Other IEEE 1451 features will assist users in

identifying, calibrating, analyzing, locating, and monitoring IEEE 1451-compliant transducers. In addition, end users will benefit from interoperability features designed into IEEE 1451-compliant products.

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About the Author

James Wiczer, PhD is president and founder of Sensor Synergy a developer of software and hardware interfaces for sensors used in industrial monitoring applications. Dr. Wiczer works with various national and international groups to help advance smart sensor standards. Currently, Wiczer is chair of the IEEE-1451.2 Standards Committee tasked with updating the “IEEE Standard for a Smart Transducer Interface for Sensors and Actuators” and is an active member of the IEEE 1451.0 Working Group. Wiczer also serves as chair of various technical conference sessions involving Smart Sensor technologies. Prior to founding Sensor Synergy, Wiczer served for 5 years as technology vice president at Wico Information Technologies developing custom software solutions for business needs. Before his software development role, Wiczer was the manager of the Microsensors R&D Dept. and before that he was manager of the Robotics and Automation Dept. - both at Sandia National Laboratories in Albuquerque, New Mexico. James received his BS degree in Electrical Engineering from Purdue University and his PhD in Electrical Engineering from the University of Illinois at Champaign-Urbana. Wiczer followed his PhD work with an 18-year tenure at Sandia National Labs in Albuquerque, NM. Wiczer's activities at Sandia included: sensor program development; research and development of sensors for various applications using ultrasonic, optical and capacitance phenomena; research and development of sensor devices for industrial process control; and the design and development of specialized optical detectors for adverse environments. Wiczer has published over 60 articles on his research and development work and has been awarded six patents. He is a senior member of the IEEE, Tau Beta Pi, HKN and other professional organizations. For the past 5 years, Wiczer has served as state judging chair for electronics related projects at the annual Illinois state science fair.