1. INTRODUCTION

There are many control networks commonly used to connect transducers (sensors and actuators) in distributed measurement and control (DMC) applications. Figure 1 shows a general DMC application; a network is used to tie different smart transducers to an optional computer which provides a man-machine interface. This figure also shows a connection to a gateway node that provides a connection to the rest of the system. The proposed standard will ease the building and use of the smart transducer nodes presented in Figure 1 [1].

Imagine a situation where the system in Figure 1 is up and running, and the user now requires a more accurate pressure sensor. Depending on the control network employed in the system, the required networked sensor may not be available on the market. This problem exists in part because it is not cost effective for sensor manufacturers to support all control networks. Ideally, system integrators should be able to independently choose the transducers and the network best matched to the application.

![Figure 1: A general distributed measurement and control application](image)

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1 Stan Woods is the chairperson of the IEEE-P1451.2, Transducer to Microprocessor Communication Working Group, under Technical Committee 9 on Sensor Technology of the Instrumentation and Measurement Society.
The upcoming draft standard, IEEE-P1451 offers one solution to this problem by splitting node functionality into two modules as shown in Figure 2. The first module, containing a network capable application processor (NCAP), runs the network protocol stack and the application firmware. The second module, containing the transducer and a transducer electronic data sheet (TEDS), is called a smart transducer interface module (STIM). This functional separation enables transducers to be built independent of the control network in the DMC system.

IEEE-P1451 is a two-part set of standards (P1451.1 and P1451.2) designed to aid transducer manufacturers and application developers in supporting a variety of control networks in a cost-effective manner. The two parts play well together, but may also be used separately. This paper introduces IEEE-P1451, and discusses details related to IEEE-P1451.2. A reference implementation of the proposed P1451.2 standard is described to demonstrate the steps involved in making P1451.2 compatible transducers.

![Figure 2: P1451 modular solution to address multiple networks](image-url)

2. **THE IMPORTANCE OF STANDARDS**

Standards often provide new business opportunities for industry. They can move an industry forward by providing a focus on common ground upon which to build future products. Standards narrow the design decisions in specific technical areas, for example, how information is exchanged between hardware modules in a system. At the same time, standards free designers to focus on higher value features rather than having to reinvent solutions to old problems. Standards benefit end users by enabling the creation of products with longer lifetimes.
3. HISTORY AND IMPORTANCE OF THIS PROPOSED STANDARD
In September 1993, a proposal to develop a smart sensor communication interface standard was accepted by IEEE-TC9. In March, 1994, the National Institute of Standards and Technology (NIST) and the Institute of Electrical and Electronics Engineers (IEEE), hosted the first workshop to discuss smart sensor interfaces, and the possibility of developing a standard interface that would simplify connectivity of smart sensors to networks. Since then, a series of four more workshops have been held, and two technical working groups were formed in February, 1995:

- The P1451.1 working group is defining a common object model for smart transducers along with interface specifications to the model [2] [3] [4] [5]. At the time this paper was written the P1451.1 working group was in the final stages of preparation for balloting the P1451.1 draft standard.
- The P1451.2 working group is defining the TEDS, and the digital interface, including connector pin allocation and the communication protocol between the STIM and the NCAP [2] [5] [6] [7] [8]. At the time this paper was written the initial ballot for the acceptance of P1451.2 as a standard had closed, and the P1451.2 working group was in the process of addressing comments and incorporating them into the draft standard.

The existing transducer market is fragmented, composed of many small companies, most specializing in a small number of transducer types. These companies are seeking ways to build low-cost, networked smart transducers. Many control network or fieldbus implementations are currently available, each with its own strengths and weaknesses for a specific application class. Interfacing transducers to all these control networks and supporting the wide variety of protocols represents a significant and costly effort to transducer manufacturers. A universally accepted transducer interface standard would not only allow for the development of smart sensors and actuators, but would also lead to lower development costs. Therefore, the objective of this standard is not to propose another control network, but to develop a standard that will isolate the choice of transducers from the choice of networks. This relieves the burden from the manufacturer of supporting a cross product of sensors versus networks, and helps to preserve the user’s investment if it becomes necessary to migrate to a different control network.

4. TECHNICAL FEATURES OF IEEE-P1451.2
P1451.2 proposes standardization in the following areas:

- a standard TEDS format with required, optional and extension fields
- a standard set of functionality including addressing, triggering, interrupts, status and control and optional functionality such as self calibration
- a standard digital interface with specified hardware lines, protocol and timing

Figure 3A shows a general hardware block diagram of a smart transducer node from Figure 1, and indicates the location of the P1451.2 digital interface. A TEDS is physically associated with the signal conversion, signal conditioning and transducer blocks shown to the left of the arrow in Figure 3A; the resulting STIM is shown in Figure 3B. P1451.2 defines the digital interface specifically to read sensors, set actuators and access the TEDS.

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2 Technical Committee 9 (TC-9) on Sensor Technology of the Instrumentation and Measurement Society
4.1 Digital interface
The digital interface is not another network; rather it is a point-to-point, synchronously clocked, short distance interface to link NCAPs and STIMs. The digital interface hardware lines are shown in Figure 3B. Communication functions are performed with DIN, DOUT, DCLK, and NIOE. NTRIG and NTRACK implement hardware triggering of all or individual STIM channels. NINT signals exception conditions to the NCAP. SDET indicates whether a STIM is connected to the NCAP and is used to implement hot swap. The NCAP provides power to the STIM circuitry via the +5V line.

4.2 Transducer model
A P1451.2 transducer carries with it information including manufacturer, date code, serial number, limits of use, uncertainty, and calibration coefficients. When power is applied to a STIM, this information is available to the NCAP for use locally and for dissemination to the rest of the system as needed. Once the TEDS is read, the NCAP knows how fast it can communicate with the STIM, how many channels are on the STIM, and the data format of each channel’s transducer [for example whether readings are from a 12- or 16-bit analog-to-digital converter (ADC)]. The NCAP also knows what physical units are being measured and how to convert the raw readings into corrected SI units.

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3 Le Système International d’Unités
The following steps are needed to take a sensor reading:
1. Select the channel.
2. Trigger the sensor.
3. Wait until the STIM indicates that a reading is available.
4. Access the raw sensor reading.
5. Convert the raw sensor reading into SI units using the calibration constants stored in the TEDS.

The steps are similar, except in opposite order, for setting actuators:
1. Convert a setting in SI units into a raw actuator setting using the calibration constants stored in the TEDS.
2. Select the channel.
3. Write the raw actuator setting.
4. Trigger the actuator.
5. Wait until the STIM indicates the action is completed.

4.3 Transducer electronic data sheet
The TEDS is divided into addressable sections as shown in Figure 4. The sections shown with solid lines are mandatory. The sections shown with dotted lines are optional. The optional extension TEDS provide a growth path to the future [8].

<table>
<thead>
<tr>
<th>One per STIM:</th>
<th>One per STIM channel:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meta-TEDS</td>
<td>Contains the overall description of the TEDS data structure, worst case STIM timing parameters, and channel grouping information.</td>
</tr>
<tr>
<td>One per STIM channel:</td>
<td>Contains the last calibration date, calibration interval and all the calibration parameters supporting the multi-segment model.</td>
</tr>
<tr>
<td>Channel TEDS</td>
<td>Application specific TEDS</td>
</tr>
<tr>
<td>Contains upper/lower range limits, physical units, warm up time, presence of self-test, uncertainty, data model, calibration model, and triggering parameters.</td>
<td>For application specific use.</td>
</tr>
<tr>
<td>Extension TEDS</td>
<td>Multiple per STIM:</td>
</tr>
<tr>
<td></td>
<td>Used to implement future and industry extensions to P1451.2.</td>
</tr>
</tbody>
</table>

Figure 4: General layout of a P1451.2 transducer electronic data sheet
4.4 Representation of units

The P1451.2 draft adopts a general method for describing physical units sensed or actuated by a transducer. The method employs a binary sequence of ten bytes to encode physical units. A unit is represented as a product of the seven SI base units ⁴ and the two SI supplementary units ⁵, each raised to a rational power. This structure encodes only the exponents; the product is implicit [8] [9].

4.5 Calibration model

The calibration specification in the TEDS permits the sensor manufacturer to describe a multi-dimensional calibration for each channel. A channel’s calibration curve is expressed as a polynomial function of a subset of the channels in the STIM. To avoid high order polynomials it is possible to specify a segmented calibration where each segment can have a variable width, offset, and number of coefficients [8]. It is expected that the NCAP will have a general correction engine that understands this calibration scheme, so it can run “blindly” no matter which transducer is attached. An example of a multi-segment calibration curve with simple linear segments is shown in Figure 5.

![Calibration Curve Diagram](image)

Figure 5: Example of a multi-segment calibration curve with simple linear segments

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⁴ meters, kilograms, seconds, amperes, kelvins, moles, candelas

⁵ radians, steradians
4.6 STIM examples
The proposed standard supports up to 255 channels on a single STIM. Figure 6 shows examples of possible STIM implementations: a) a single channel temperature sensor, b) eight channel digital I/O, c) a four-channel set of analog sensors, and d) a mix of sensors and actuators.

5. EXAMPLE IMPLEMENTATIONS OF IEEE-P1451.2

5.1 Demonstrations
The working group has organized three demonstrations during the development of P1451 to show the concepts in action across multiple networks.

At the Sensors Expo, May, 1995, the working groups demonstrated moving a STIM between NCAPs connected on the same network and, more importantly, from an NCAP on one network to other NCAPs on different control networks. Three control networks were supported in the demonstration: DeviceNet™, LonWorks™, and Smart Distributed System. Sensors were shown measuring acceleration, air flow, AC current, and pressure.

At NIST in November, 1995, the working groups demonstrated a closed-loop control system using single and multi-channel sensors, measuring temperature and pressure, and multi-channel digital actuators. This demonstration used an early version of the P1451.1 object model.
At the Sensors Expo, October, 1996, NIST demonstrated a reference implementation of P1451.1 and P1451.2. The focus of this demonstration was the P1451.1 object model. A single channel pressure sensor was used as a source of real transducer readings. Laptop computers were used as the NCAPs with Ethernet being used as the network [5].

5.2 P1451.2 reference implementation

A team of researchers at Hewlett-Packard Laboratories (HPL) is developing working prototypes of P1451.2 STIMs. One goal of this project is to aid the final resolution of the P1451.2 ballot comments. As comments are incorporated into the draft, the prototypes will be modified to reflect the changes, and to test whether the changes work. Figure 7 shows a block diagram of the latest demonstration operating with an NCAP connected to Ethernet as the control network.

![Diagram of P1451.2 reference implementation]

The STIM contains a low-cost microcontroller programmed to support the P1451.2 digital interface. This same microcontroller reads the TEDS, and gathers sensor readings from an ADC. The blocks shown with dotted lines are firmware and software functions.

The firmware on the NCAP accesses the STIM through a P1451.2 driver. This driver is used to transfer the TEDS content to the NCAP environment, where the information is used to automatically label portions of a web page. A correction engine supporting the P1451.2 calibration model corrects the raw sensor readings acquired from the STIM. The NCAP’s web page may be viewed simply by pointing a web browser at the NCAP.
The HPL prototype can easily support a wide variety of analog sensors. Assuming the sensor output can be matched to the range accepted by the ADC, all one needs to do is specify a new TEDS, and connect the new transducer. No firmware changes on the microcontroller or NCAP, and no software changes on the PC are required. The graphical user interface will indicate the TEDS information related to the new transducer, and the new corrected variable will be labeled appropriately.

### 5.3 STIM and NCAP support

It will become increasingly easy to support P1451.2 in the future as integrated circuits (ICs) and design tools become available. Figure 8 shows a single IC containing the P1451.2 logic, TEDS and an ADC. A P1451.2 compliant transducer is achieved by connecting the IC to a signal conditioned sensor and designing the appropriate form factor (for example: printed circuit board size and connector.)

![Diagram of STIM and NCAP with P1451.2 support](image.png)

On the NCAP a standard P1451.2 driver is used to access the P1451.2 STIM. This driver supports the P1451.2 interface, understands the TEDS structure and has a correction engine, so that the application firmware may request corrected sensor readings in SI units.

### 6. FURTHER INFORMATION

This paper has provided a brief overview of IEEE-P1451 and described the technical aspects that make it possible to build smart transducers supporting multiple control networks. For specific information on the proposed standard, the P1451 draft documents may be obtained from the IEEE. Persons interested in working group participation and more details on the demonstrations may contact:

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REFERENCES


