Overview and Status Update for IEEE 1451.2: Transducer to Microprocessor Communications Protocols and Transducer Electronic Data Sheet (TEDS) Formats

IEEE 1451.2 Provides a Standard Method for Connecting Transducers to Network Communications Devices

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1. INTRODUCTION

Smart products have as much potential to change the world as the personal computer and the Internet have already changed lifestyles and work. We have smart consumer products, smart industrial products, smart medical products—smart everything!

Increasingly, these smart products are talking to each other. By now just about everyone has heard of Moore's Law regarding the growth of computing power as represented by the number of transistors on an integrated circuit. An equally important "law" is referred to as Metcalfe's Law: "The value of information in a network rises as the square of the number of terminals." We have seen this in the growth of computer networks from simple data-sharing within a single organization to the Internet revolution.

Smart products depend on smart sensors and actuators (collectively called transducers) in order to interact with the physical world. Just what are smart transducers? A key characteristic of a smart transducer is that is operates on its input signal in a logical fashion to increase the value of the information which it processes. A smart transducer is capable of making decisions at the source of the information. It then either acts on that information or passes a high-value message on to a higher-level processor. This local processing converts data into information and helps reduce network bandwidth requirements. Smart transducers also can provide self-identification, self-testing and adaptive calibration, ease of setup, and improved rejection of spurious inputs.

Given these advantages, why are smart transducers not in wider use? One reason is that there has not been a standard way of connecting transducers to network communications devices. Each new product or application required development of new hardware and/or software. The elements of a smart transducer are shown in figure 1. Frequently, the interfaces between these elements, if not the elements themselves, have to be redesigned for each application.

The IEEE 1451.2 standard is the first of a planned family of standards for connecting smart transducers (sensors and actuators) to networks. These standards will enable network-capable but network-independent "plug-and-play" transducers for use in embedded products, networked controllers, and distributed data acquisition systems.

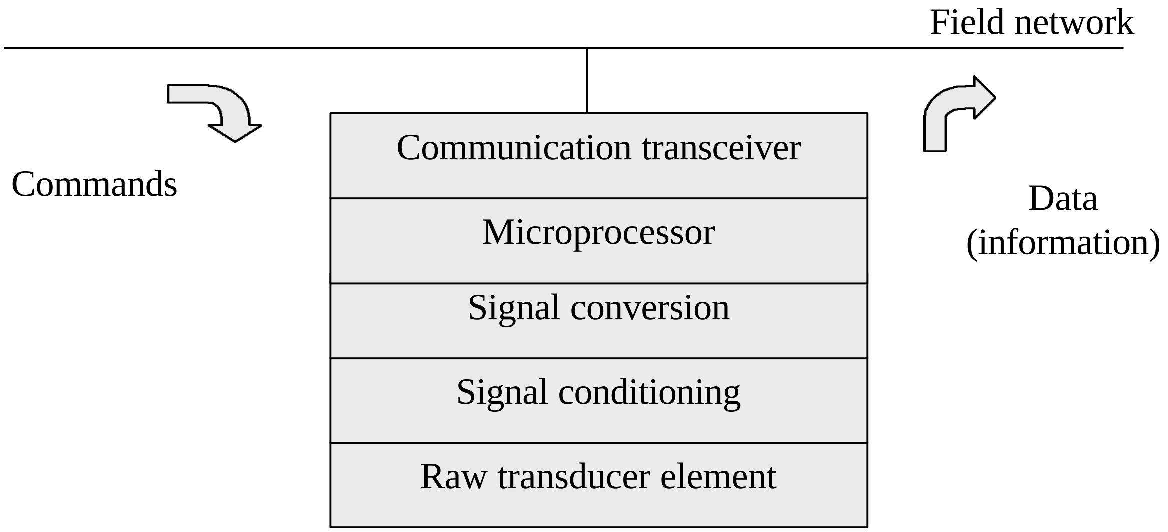

Figure 1. Communicating smart transducer

2. IEEE 1451.2

The proposed IEEE P1451 family of standards covers network-capable smart transducers from the interface to the transducer itself up to a high-level, object-model representation of behavior, attributes, and data communications. Note that the proposed standards are written for *transducers*, a general term which includes both sensors and actuators.

The first member of this family to be approved was IEEE 1451.2, which deals with connecting transducers to microprocessors and other communications devices. The effect of the IEEE 1451.2 standard on figure 1 is shown in figure 2. Any transducer that supports this interface can be used with any communications device that also supports it. The basic functional boundaries and interfaces defined in IEEE 1451.2 are illustrated in figure 3.

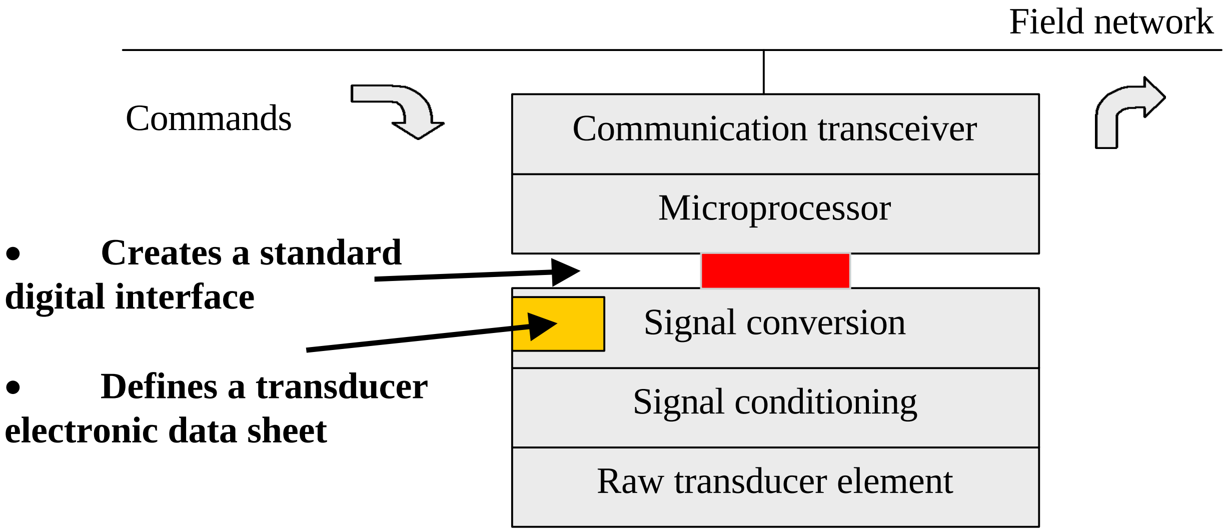

Figure 2. IEEE 1451.2 smart transducer.

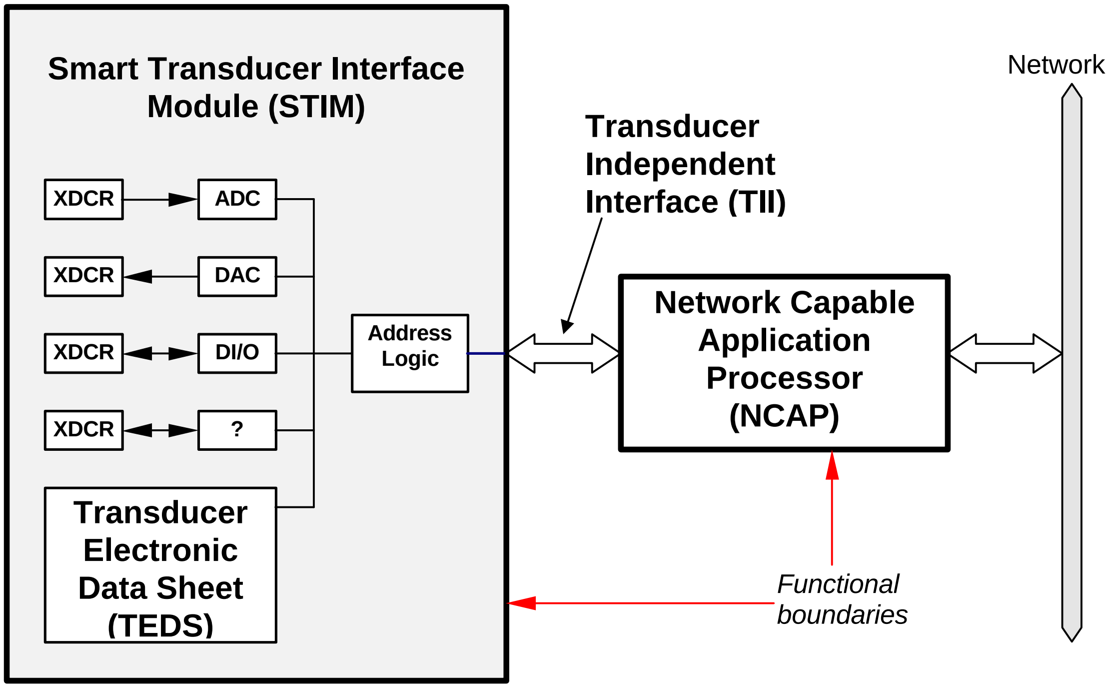

Figure 3. Functions and interfaces from IEEE 1451.2.

The upper part of figure 2 becomes the Network Capable Application Processor (NCAP) shown in figure 3. The lower part becomes the Smart Transducer Interface Module (STIM). Note that the transducers themselves are considered part of the STIM. In fact, in order to provide the critical self-identification features, the transducer must be inseparable from the STIM electronics during normal use. For the basic system definition shown, the intended field break is the Transducer-Independent Interface (TII) between the STIM and NCAP.

IEEE 1451.2 defines several other critical elements of smart transducer operation and of the communications interface. These include the various formats for the Transducer Electronic Data Sheet (TEDS), the transducer functional type (sensor, actuator, buffered sensor, event sensor, etc.), and a general-purpose calibration and correction engine. The normal data format for an IEEE 1451.2 smart transducer is an IEEE 754 floating-point number using standard SI units, although provision is made for using raw analog-to-digital or digital-to-analog converter counts for systems which must wring the last drop of performance out of the available hardware.

The importance of these additional elements of IEEE 1451.2 deserves emphasis—IEEE 1451.2 defines a standard functional model of a communicating smart transducer including functions, data format, and units.

3. ELECTRICAL INTERFACE

The physical connection between the NCAP and STIM is via the 10-pin Transducer Independent Interface (TII). The TII is built around synchronous serial communications based on the SPI (Serial Peripheral Interface) protocol. Several dedicated lines have been added to provide power, ground, and special-purpose control lines. The TII pin assignments are listed in table 1, which also indicates whether each physical signal is considered an input or an output by the NCAP and the STIM.

The TII logical signal definitions and functions are shown in table 2, which also indicates whether each signal is positive or negative logic, and whether it is level or edge sensitive.

Table 1. TII Pin assignments

Pin number	Signal name	Wire color	Direction for NCAP	Direction for STIM
1	DCLK	brown	OUT	IN
2	DIN	red	OUT	IN
3	DOUT	orange	IN	OUT
4	NACK	yellow	IN	OUT
5	COMMON (GROUND)	green	POWER	POWER
6	NIOE	blue	OUT	IN
7	NINT	violet	IN	OUT
8	NTRIG	gray	OUT	IN
9	POWER (+5 VDC)	white	POWER	POWER
10	NSDET	black	IN	OUT

Table 2. TII signal definitions.

Line	Logic	Driven by	Function
DIN	positive logic	NCAP	Address and data transport from NCAP to STIM
DOUT	positive logic	STIM	Data transport from STIM to NCAP
DCLK	positive edge	NCAP	Positive-going edge latches data on both DIN and DOUT
NIOE	active low	NCAP	Signals that the data transport is active and delimits data transport framing.
NTRIG	negative edge	NCAP	Performs triggering function
NACK	negative edge	STIM	Serves two functions: 1. trigger acknowledge 2. data transport acknowledge
NINT	negative edge	STIM	Used by the STIM to request service from the NCAP
NSDET	active low	STIM	Used by the NCAP to detect the presence of a STIM
POWER	N/A	NCAP	Nominal 5 V power supply
COMMON	N/A	NCAP	Signal common or ground

Note that the input and output naming conventions for the logical signals are from the point of view of the STIM.

NINT is the only TII signal line that the STIM is permitted to assert at will. Other than that, the NCAP controls all communications and all message exchanges are originated by the NCAP.

The other STIM outputs are not really under the full control of the STIM. NSDET is a passive signal (pin is tied to common) used to detect the presence of a STIM, and NACK is only asserted in response to an action by the NCAP. The NCAP is the SPI communications master and always controls DCLK. Even in the case of NINT, which might have been more accurately named "service request" instead of "interrupt," the resulting communications are under the control of the NCAP, which is under no timing constraint as to when it responds.

For a simple transducer, NTRIG is used by the NCAP to control the timing of when the new data is taken, in the case of a sensor, or is acted upon, in the case of an actuator. In other words, a simple sensor takes data only when triggered by the NCAP and a simple actuator updates its output only when triggered by the NCAP. More complex transducer function models (buffered sensors, data sequence sensors, event sensors, etc.) make more complex use of NTRIG. A full discussion of the defined smart transducer triggering functions is beyond the scope of this paper.

4. COMMUNICATIONS PROTOCOL

From the point of view of the NCAP, the STIM looks like a memory device. All data and commands are accessed by use of a functional address. A functional address is simply the combination of the requested service plus the channel to which it is addressed. Global communications to the STIM as a whole are addressed to channel 0. This is why a STIM is limited to 255 transducer channels instead of 256.

The basic protocol for a communication between the NCAP and STIM is that the NCAP clocks a functional address into the STIM using the DIN and DCLK signal lines. For a write, the NCAP keeps clocking DCLK and places the data on DIN. For a read, the NCAP keep clocking DCLK and looks for the data on DOUT. For all communications, NIOE serves as sort of a chip select to tell the STIM that the data transport function is active. NACK is used by the STIM to acknowledge data bytes as well as trigger signals.

In order to keep the interface protocol simple, data communications and trigger functions cannot be used at the same time.

5. POWER CONNECTIONS

In addition to the logical signals briefly described above, the TII also is used for supplying power and a common (ground) reference to the STIM. All of the TII lines, including power and common, must be isolated from frame or earth ground by the STIM.

The NCAP supplies up to 75 mA at 5 V. Provision is made for supplemental power, independent of the NCAP, if needed for very sensitive or high power transducers, but power for the STIM interface control circuitry can be provided only by the NCAP. These power and ground isolation requirements are included to reduce the noise transmitted to the NCAP by the STIM, and to minimize the potential for ground loops.

6. PHYSICAL CONNECTOR

One element of the definition of the 10-pin TII that appears to be missing from the above description is that of the physical connector. The IEEE 1451.2 working group attempted to standardize on a connector, but discovered that connectors were just too application-dependent to allow forming a consensus. The applications of interest range from very cost sensitive to very high performance. This is one area where the near-universal applicability of the IEEE 1451.2 standard was almost a disadvantage.

It is likely that various industry segments will develop *de facto* connector standards for the primary applications. A couple of connectors have already been used successfully. Stacking connectors with 5 x 2 headers and ribbon cable have been used for demonstration systems and for benign environments such as where the TII is completely contained within a protective enclosure. Other connectors, such as 15-pin sub-miniature "D"-shell commonly used for computer video cables, are perhaps more appropriate for industrial environments and also have been used.

7. TEDS FORMATS

The IEEE 1451.2 standard presents a very thorough coverage of the elements of network-capable smart transducers, and a complete description of all of its features is beyond the scope of this article. However, two other very important elements that merit a brief description are the TEDS formats and the correction engine.

Eight different TEDS formats are defined in the standard. Of these, two are required and the other six are optional. The two required TEDS structures and two of the optional ones are defined as binary data formats and are machine-readable only. The other TEDS structures are human-readable and are stored as strings in one of several different character sets. As of the time of this writing, eighteen different languages using twenty-one different international string character sets have been enumerated in the standard, with provision for adding more as they are identified.

Defining the TEDS structures was a major part of the effort on the part of the working group. Considerable emphasis was placed on trying to identify all reasonably useful data fields to include, plus provision was made for expanding the TEDS formats by the use of industry extensions. Each TEDS structure includes a length (byte count) and a check-sum for error detection.

A brief description of the TEDS formats follows.

Meta-TEDS data block—Required, machine-readable. As defined in IEEE 1451.2, meta is a Greek prefix which means "that which pertains to the whole or overall entity, or that which is in common or shared with all member entities comprising the whole." The Meta-TEDS contains data which describe the STIM as a whole. This includes revision levels, extensions, a unique STIM identifier, worst-case timing values, number of channels, and other information regarding the STIM as a whole.

One interesting feature of the Meta-TEDS is the STIM unique identifier. The working group wanted to define a system for identifying each STIM from any manufacturer without having to resort to a coordinating committee to assign codes. The resulting identifier is based on a combination of the latitude and longitude of the manufacturing facility and the UTC code for the time of manufacture. A manufacturer may assign codes to different product lines by using slightly different coordinates for each line. The only requirement is that the coordinates must represent locations that are under the physical control of the manufacturer.

Channel TEDS data block—Required, machine-readable. The Channel TEDS defines the functional model, calibration model, physical (SI) units, upper and lower limits, timing restrictions, and any other data needed to fully describe the functioning of each transducer channel. If more than one channel are implemented, then the structure is repeated for each one.

Calibration TEDS data block—Optional, machine-readable. If the correction engine is to be used, then a Calibration TEDS must be included to define the coefficients to be used. In addition, the Calibration TEDS defines the last calibration date and time, as well as the required calibration interval, for each channel.

Meta-Identification TEDS data block—Optional, human-readable. The Meta-Identification TEDS provides the human-readable version of the identification data for the overall STIM. This information is repeated once for each language used. String fields include the manufacturer's name, the model number, the serial number, version codes, date codes, and a product description.

Channel Identification TEDS data block—Optional, human-readable. The Channel Identification TEDS includes information very similar to the Meta-Identification TEDS, except that it is for an individual channel. This is particularly useful when a STIM built by one company contains transducers which were manufactured by one or more different companies.

Calibration Identification TEDS data block—Optional, human-readable. The Calibration Identification TEDS provides a human-readable description of any information deemed relevant to the calibration of each channel. Once again, this structure is repeated for each channel and for each language supported.

End Users' Application Specific TEDS data block—Optional, human-readable. The End Users'

Application Specific TEDS is provided as a place to store any additional human-readable data which is not covered by the specific TEDS fields described above. An example of an end-user field might be a description of the location of the STIM, or even the name and telephone number of the person to call for service. As for all of the human-readable TEDS, the fields are repeated for each language supported.

Generic Extension TEDS data block—Optional, readability not specified. The Generic Extension TEDS is provided to allow for future extensions to the specified TEDS. Each Generic Extension TEDS will be defined in a manner similar to that used in the IEEE 1451.2 standard, and each originating organization will have to apply for a TEDS extension ID number, to be assigned by the IEEE Standards Office. A special extension TEDS ID number is reserved for programming and testing prototypes that include experimental TEDS extensions.

8. CORRECTION ENGINE

The last feature of the IEEE 1451.2 standard to be described is the correction engine. Correction is the application of a specified mathematical function upon transducer data from one or more STIM channels and/or data delivered from other sources. In other words, the correction engine takes the output of one or more transducer channels, plus any other data which may be necessary, and uses a mathematical formula and one or more stored coefficients to produce a *corrected* value for the channel. The output of the correction engine is usually a floating-point number in SI units ready for communication to a user or client process.

The correction engine is reversible, in that it can also be used to convert a floating point input command for an actuator to an integer representing the required raw control input to the actuator.

The correction engine defined for IEEE 1451.2 uses a multinomial (multivariate polynomial) function with a virtually unlimited degree of the polynomial. In order to limit the degrees of the input to the correction engine, the polynomials may be segmented, that is, different sets of coefficients may be used between specified limits of the input values.

The specified correction engine is extremely powerful and has the potential to provide a standardized way of describing the calibration constants and correction coefficients for a broad range of sensors and actuators. It should be noted, however, that use of the correction engine is optional. As mentioned earlier, it is permissible for a system with limited computational capability to use a simple integer data representation rather than having to deal with floating-point mathematics.

9. SYSTEM DESIGN ISSUES

While IEEE 1451.2 provides standard definitions of several elements of a communicating smart transducer system, it still leaves considerable latitude in the design of the overall system. System design issues that have a significant bearing on cost and performance include the ratio of STIMs to NCAPs and transducer elements, the location of the correction engine, the location of any measurement and control loops, and the physical partitioning of the hardware as it relates to the make-or-buy plan for the product.

Few smart products will have a single transducer. The figures in the standard, and the ones used earlier in this paper, illustrate a single NCAP with a single STIM that includes multiple transducer elements. Real-world implementations with multiple transducers can use multiple NCAPs (one per transducer), NCAPs with multiple STIM ports (each supporting a single transducer), a single NCAP with a single STIM with multiple transducers in the STIM, or any combination of these architectures.

The correction engine can run in the STIM, in the NCAP, or even in a separate computer elsewhere on the network. Similarly, any measurement and control loops used can run in the STIM, in the NCAP, or elsewhere in the network.

Performance calculations start with the required updates per second at the system level. From that, you can determine the network loading (messages and bits per second), corrections per second (which translates to floating point operations per second), TII data transactions and bits per second, and finally the required transducer samples per second.

System designers must review these requirements and consider, at a minimum, the physical distribution of the system, the type of network used, the signal conditioning and processing required, the processing power available, the hardware interface speed, and the effect of loss of network communications on the operation of the system. This last consideration is especially important when deciding where any control loops should run.

10. CONCLUSIONS

In conclusion, the IEEE 1451.2 standard is here at last. It defines an interface for connecting transducers to communications devices, as well as a standard functional model for a smart transducer. IEEE 1451.2 provides transducer manufacturers the ability to produce network-capable *and* network-independent smart transducers without having to become experts in each network and without having to decide how many of each network-dependent version of their products to manufacture and stock. With IEEE 1451.2, all transducers are identical regardless of the target control network or fieldbus.

An additional but sometimes overlooked benefit is that it will allow system integrators to upgrade the control network, without having to change the actual sensors. With IEEE 1451.2, not only the transducer manufacturers but also the system integrators will have more freedom from the details of the exact fieldbus implementations.

The approved standard has been implemented by more than one company and inter-company hardware and communications compatibility has been demonstrated. Now you can buy commercial hardware that is tailored for specific real-world applications.

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