

Smart Sensors and Network Sensor Systems

*Two Approaches to Providing Smart Sensor Capabilities:
Incorporating Identification Capabilities per IEEE 1451.4 (Smart Isotron), or
Complete Data Acquisition and Networking Capabilities (Network Sensors)*

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ABSTRACT

This paper describes two different approaches to providing Smart Sensor capabilities in a measurement system. One approach incorporates digital memory chips into analog sensors or associated cabling to store information unique to the particular sensor. Stored information might include sensor model and serial number, manufacturer, sensor type, sensitivity, calibration date and calibration coefficients. Once read by the signal conditioner, the information can be used by the system to automatically identify all sensors, maintain configuration control, automatically set the system gain to normalize output data, and enhance calibration database management.

The other approach, a Smart Sensor Network System, is very suitable for applications where connecting transducers in a multidrop configuration is advantageous. The networking capability can significantly reduce the number of interconnecting cables required. The NETWORK SENSOR provides for the consolidation of analog signal conditioning and digital signal processing functions at the sensor, which results in system

cost reductions, high reliability and improved performance. Other benefits include a standard transducer-to-network interface to accommodate any type of sensor or actuator, a communication protocol which provides for high speed synchronized data collection, and flexibility in configuring filters, sampling rates and other characteristics of each transducer in the network.

KEY WORDS

Smart Sensor, Smart Transducer, Network, Network Sensor, Data Correction, Calibration, RS-485, TBIM, Transducer Bus Interface Module, TBC, Transducer Bus Controller, TEDS, Transducer Electronics Data Sheet, IEEE 1451.2, IEEE P1451.3, IEEE P1451.4.

INTRODUCTION

The Smart Sensor Network System developed by ENDEVCO Corporation was designed to provide an attractive alternative to typical measurement systems using large numbers of sensors. The networking capability provides for a multi-drop

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system that can significantly reduce the number of interconnecting cables required. NETWORK SENSORS combine the analog signal conditioning, digital signal processing and communications functions at the sensor and provide a networked digital output.

To bridge the gap between the highly capable networked digital output transducer used in the Smart Sensor Network System and the current analog transducer, a mixed-mode hybrid is proposed by the IEEE P1451.4 Working group. This approach, as implemented by ENDEVCO, incorporates a digital memory chip inside a traditional IEPE/ISOTRON® (piezoelectric sensor with internal electronics) type sensor, referred to as a SMART ISOTRON®. The information stored in the chip is unique to each sensor (e.g. serial number, sensitivity, calibration date, etc.). The information can be used by the signal conditioner to automatically identify all sensors and correctly configure the output data, helping to simplify system setup, to maintain configuration control and to enhance calibration database management.

TYPICAL MEASUREMENT SYSTEM

Measurement systems of today that have been designed to accommodate large numbers of sensors are very capable systems. They have a variety of features and capabilities that have been developed over the years to satisfy the needs of the test and measurement community.

A typical system can generally be broken down into 4 sections: sensors, analog signal conditioning, analog-to-digital conversion, and digital signal processing & communications. The last 2 sections are usually referred to as data acquisition. See Figure 1.

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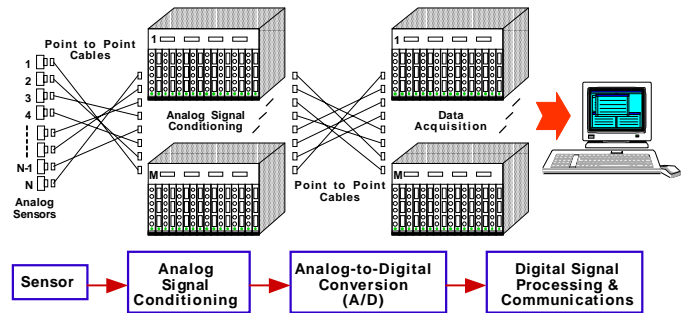


Figure 1 – Typical Measurement System

A variety of different analog sensors are used including accelerometers, pressure sensors, temperature sensors, strain gages and others. As many as four to six wires from each sensor carry analog signals and power to and from the analog signal conditioning. For large numbers of sensors, this will mean large numbers of wires.

Depending on the type of sensor, analog signal conditioners will perform the necessary conditioning of the sensor signal which might include charge conversion for piezoelectric accelerometers, bridge completion for strain gages, filtering, gain adjustment and other functions.

The analog output of the analog signal conditioner is transmitted to the data acquisition system for analog-to-digital conversion, digital signal processing and data manipulation. Analysis, display and storage of processed data is usually handled by the computer system.

ENDEVCO, as a supplier of sensors and signal conditioning systems, is very familiar with these types of systems. We are also very familiar with the types of challenges and problems that exist when these systems are used in various test applications.

SMART SENSOR

One of the challenges of dealing with many transducers and cables is the time required to install so many cables. It can be a tedious exercise and the potential for mistakes is high. It can take a significant amount of time to ensure that the right sensor was connected to the right signal conditioner channel, i.e. configuration control. This is where the Smart Sensor, or in this case SMART ISOTRON, can help.

The SMART ISOTRON is described as a mixed-mode hybrid, incorporating a digital memory chip into a traditional IEPE/ISOTRON (piezoelectric sensor with internal electronics) type sensor (Figure 2).

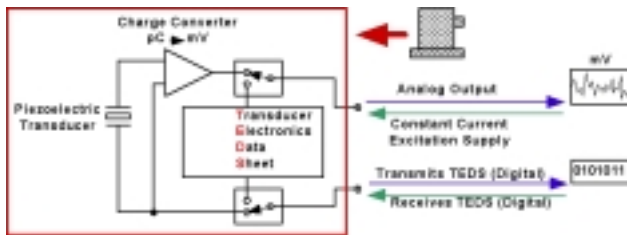


Figure 2 – Smart Sensor Circuitry

This mixed-mode device, under normal operating conditions, would produce an analog output just like a traditional ISOTRON sensor. But upon receiving a negative current excitation (i.e. reverse polarity), the special circuitry inside the sensor will terminate the analog output mode and start the digital transmission. Both the analog and digital modes share the same two-wire cable used by all traditional ISOTRON sensors.

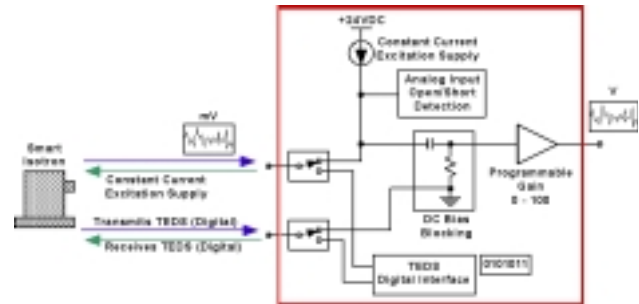


Figure 3 – Smart Signal Conditioner Circuitry

The memory chip carries the Transducer Electronic Data Sheet (TEDS) which is defined by the IEEE P1451.4 committee (“Standard for a Smart Transducer Interface” [1]). The TEDS stores not only the performance characteristics of the sensor, but also any application-specific data. When the digital communication is completed, the sensor switches back to its normal analog mode.

The effectiveness of this 1451.4 approach is very much a function of the receiving electronics’ design and its system approach. In the ENDEVCO Smart Signal Conditioner, for example, the duration of the digital communication mode lasts less than three seconds, independent of the number of channels in the system. Variable gain adjustment is available on the Smart Signal Conditioner so that channel outputs can be normalized for maximum system signal to noise ratio.

Keeping track of which sensor is connected to which channel is now a thing of the past. With the ENDEVCO SMART ISOTRON system, cables between the transducers and the channel inputs can be connected at random during the initial setup. Transducer-specific information, along with application-specific data, will be transferred transparently to the ENDEVCO Smart Signal Conditioner, and passed on to the data acquisition system with no human intervention, and without the headache of tedious cable management and configuration control.

There are additional benefits of using the SMART ISOTRON System:

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- Read/Write Transducer Specific Data

No need to find that misplaced calibration certificate and type all of that information into the computer. Transducer-specific information, such as manufacturer's ID, sensor type, model number, and serial number are stored permanently in the memory chip inside the SMART ISOTRON. Other variables, such as sensitivity, calibration date can be retrieved from and input to the sensor automatically or manually.

- Read/Write Application-Specific Data

With the help of the portable ENDEVCO Smart Handheld Programmer, application specific information, such as channel ID, polarity, orientation, etc., can be input to the sensor on the spot, reduce the chance of making input errors at the computer terminal. These information enable seamless transducer/electronics interface, and allow true plug-and-play capabilities with minimum human intervention.

- Output Normalization and Instant Transducer Swapping

With the most up-to-date sensor sensitivity embedded in the TEDS, the ENDEVCO Smart Signal Conditioner will query the sensors for their ID's and sensitivities during the communication mode and automatically set the gain of each channel to a user-defined system output sensitivity — no need to up-load a separate data base. This output normalization capability allows the user to maximize the dynamic range of the A/D converter, and allows sensors to be switched on the fly without reprogramming. Transducers with different full scale ranges (up to 20 dB) can be mixed and matched in one test without making any setup changes.

- Calibration Data Base Management

With the latest generation of ENDEVCO's

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Automated Accelerometer Calibration System (AACS), calibration data archiving and analysis are simpler than ever. The calibration data is always there when you need it, and trend analysis is only a keystroke away.

- Compliance to Open Standard

The ENDEVCO SMART ISOTRON system is fully compliant with the current proposed IEEE P1451.4 standard.

- Backward Compatibility

When a 1451.4 sensor is used in a conventional ISOTRON system, it will function flawlessly without any performance degradation. In addition, a traditional ISOTRON is fully compatible with the ENDEVCO Smart Signal Conditioner.

These “smart” features combine to improve through-put efficiency and reduce operating cost, very important issues in multi-channel testing operations today.

NETWORK SENSOR

The NETWORK SENSOR combines all 4 functions of the measurement system into one unit.

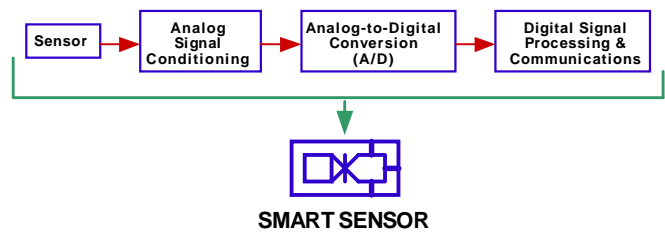


Figure 4 – NETWORK SENSOR Functions

We can begin to see the advantages of this approach over the typical measurement system. Analog signal wires from the sensor to the analog signal conditioning, susceptible to noise and interference in the typical measurement system, are eliminated with NETWORK SENSORS. Analog wires from the signal conditioners to the data acquisition system are also eliminated. In addition, the racks of analog signal conditioning and data acquisition equipment are no longer needed.

The output from the NETWORK SENSOR is digital data or information that has already been conditioned and processed. The digital output data, less susceptible to noise and interference than analog signals, is ready to be displayed, stored or analyzed further.

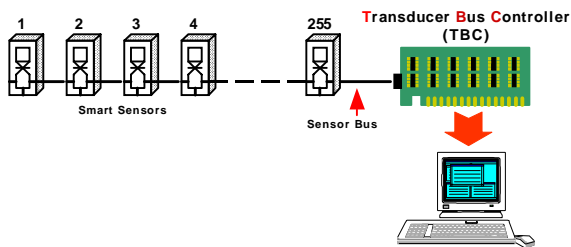


Figure 5 – Smart Sensor Network

Of course, one of the more significant features of these smart sensor systems is the networking capability. The ability of each NETWORK SENSOR to communicate on a sensor bus network is the key to achieving reductions in the number of cables for the measurement system. In this network configuration, multiple sensors can use the same set of wires to transmit data and information and receive commands.

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Another unit, the Transducer Bus Interface Module (TBIM), combines 3 of the 4 functions of the measurement system. The TBIM incorporates the analog signal conditioning, analog-to-digital conversion, and digital signal processing & communications, but it does not include the sensor.

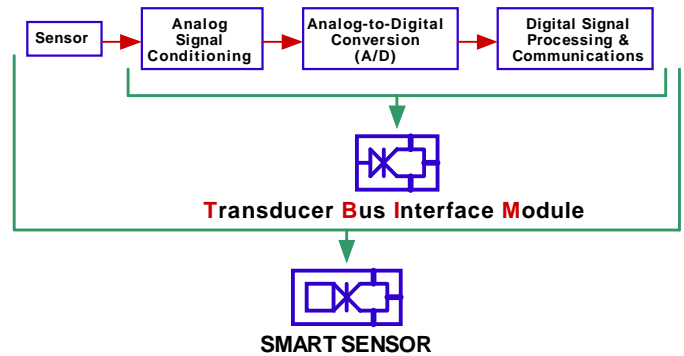


Figure 6 – Smart Sensor Evolution: The TBIM

The TBIM is very useful because it can be used in applications where it is impractical or impossible to use a smart sensor. For example, piezoelectric accelerometers can operate in high temperature environments approaching 1200 degrees Fahrenheit (600 degrees Centigrade), but the electronics needed for a smart sensor are limited to 300 degrees Fahrenheit (150 degrees Centigrade) or less. The TBIM can be remotely located from the accelerometer in an acceptable environment for electronics and provide all of the benefits of the smart sensor network system.

The term “transducer” is used in the TBIM name because a smart device can be more than just a smart “sensor”. In addition to converting analog sensor inputs into digital data and information, TBIMs are equally capable of receiving digital signals and converting them into analog outputs, becoming an actuator. Smart actuators make it possible to assemble complete control (actuators) and feedback (sensors) networks using the same type of communication bus and communication format.

All of these different types of smart transducers are able to communicate on the same standard transducer bus, as depicted in Figure 7.

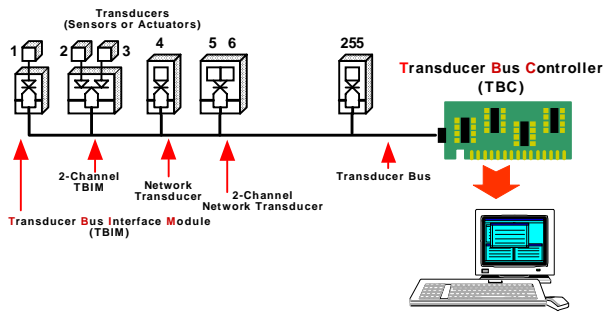


Figure 7 – Networked Smart Measurement System

(“Smart” sensor symbols, such as those being suggested by Endevco in Figures 4 to 7, are intended to help communicate the different possible configurations. They include complete smart sensors that incorporate the sensing element, TBIM modules that interface to the sensor, and multiple channel versions of these devices.)

The Transducer Bus Controller (TBC) is responsible for managing the communications on the transducer bus (see Figure 7). As part of its management of the transducer bus, the TBC is able to configure smart transducers (gain, offset, sampling rate), synchronize sampling rates among multiple smart transducers by software trigger command, establish a digital sampling schedule for all of the transducers on the bus, and time tag data for future analysis and event correlation.

The TBC is also able to initiate smart transducer diagnostics and self-test, an important function that provides the operator with a high level of confidence that a given measurement channel is alive and working properly. Periodic self-check verifies proper operation of a given transducer channel, alerting the operator if the smart transducer is not functioning or is out of acceptable tolerance levels and needs to be replaced or re-calibrated.

Transducer Electronic Data Sheet (TEDS)

Another function of the TBC is to read and write the Transducer Electronic Data Sheet (TEDS). Information about the transducer (e.g. model number, serial number, sensitivity, gage factor, calibration data, etc.) is stored in the smart transducer and is available on the transducer bus in the form of TEDS. Application software properly written will not have to be continuously updated to handle new transducers since all the necessary information to communicate with it will be provided in the TEDS.

If a smart transducer is replaced, the bus will automatically recognize that the old transducer has been removed and will read the information from the new transducer. This allows the bus to automatically track the configuration of the bus at any time, which can save time and money at setup and during testing.

The format for TEDS, as defined by IEEE 1451.2, has the following structure:

- Meta-TEDS
 - Information common to all Channels
 - Version No., UUID, No. of Channels, Command Response Time
- Channel TEDS
 - Information needed to identify and operate each channel
 - Transducer Type, Physical Units, Upper/Lower Range, Accuracy, A/D Resolution, Maximum/Minimum Sampling Rate
- Calibration TEDS
 - Information needed to calibrate each channel
 - Multinomial Correction Coefficients
 - Last Calibration Date, Calibration Interval

NETWORK SENSOR SPECIFICATIONS

One of the first applications of the smart sensor network system developed by ENDEVCO emphasized a desire to accommodate many low-speed sensors, high-speed synchronized data collection, and programmable filters, sampling rates and gain. The following provides a description of the specifications of this bus.

The maximum data baud rate achievable on this RS-485 transducer bus is 5 Mbps (megabits per second) and each data packet length is 48 bits. This translates to an effective data throughput rate of approximately 100,000 samples per second (sps). The number of channels that can be used on a single transducer bus is inversely proportional to the desired sampling rate of each channel, as demonstrated in the formula (1) below.

$$(1) \quad \text{Number of Channels} = \frac{\text{Data Baud Rate (bits per second)}}{\text{Sampling Rate (sps)} \times \text{Data Packet Length (bits per sample)}}$$

For example, a sampling rate of 500 sps would result in the use of up to 200 channels on the transducer bus. Alternatively, a sampling rate of 10,000 sps for each channel would result in the use of only 10 channels on each transducer bus. The maximum number of channels that can be attached to each transducer bus is 255 channels. If more channels are required, additional transducer bus networks can be added.

The data packet length of 48 bits is optimized for high-speed synchronized data collection: 32 bits are reserved for data in floating point format, 2 bits for identifying “data valid”, 2 bits for a “service request”, 4 bits for “support”, and 12 bits for a unique “start/stop” (identifying the start of a data packet to help avoid communication errors with new smart sensors connecting to an already active bus). Manchester encoding provides a transition in the middle of each bit (binary 1 or 0) which is equivalent to a carrier signal associated with analog transmission. Transitions allow a node to identify that another node is transmitting, and also provides a mean of detecting and

recovering the clock signal from the transmitted data.

TBIM Block Diagram – The design of the Transducer Bus Interface Module (TBIM) is depicted in the block diagram shown in Figure 8. The communications interface is accomplished with an RS-485 driver. Input power is conditioned at 10 volts and is used to power the electronics as well as provide sensor excitation voltage. An external clock input is used to achieve synchronous data sampling.

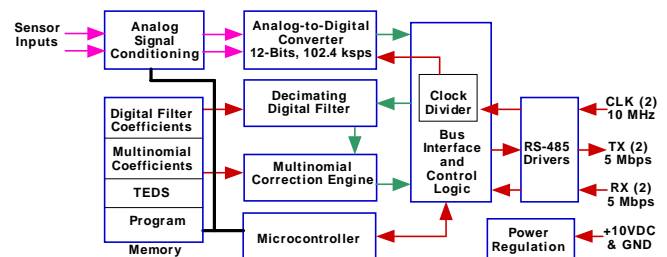


Figure 8 – Transducer Bus Interface Module (TBIM): Block Diagram

A Decimating Digital Filter (DDF) is used in this design to facilitate changes in sampling rates. The disadvantage of changing the sampling rate is the requirement to change the corner frequency of the anti-aliasing filter. Each different analog-to-digital (A/D) sampling rate requires a different corner frequency for the anti-aliasing filter.

Using the DDF, the A/D sampling rate is fixed at a high sample rate (102.4k samples per second) and the digital filtering and decimation in time processing will allow for lower output data rates. The DDF will first perform some digital anti-aliasing filtering and then discard samples to obtain lower output sample rates. The DDF output sample rate is an integer sub-multiple of the A/D fixed sampling rate, which in turn is proportional to the bus clock. The user can change sample rates by varying the bus clock. This approach allows more flexibility with sampling rates without requiring any changes to hardware or artificially limiting the number of sample rates.

The Multinomial Correction Engine is capable of evaluating a generic n th order polynomial with m th variables at a very high speed in order to correct the raw data in real time (i.e. linearization and temperature correction). The coefficients of the polynomial are calculated during the calibration process.

With regard to analog signal conditioning (Figure 9), programmable excitation is needed to maximize excitation voltage across piezoresistive (PR) sensors, which in turn translates into maximum output out of the sensor. The best signal-to-noise ratio (SNR) is obtained with the highest gain at the front-end, which in this case is the sensitivity of the sensor. Resistance from sensor to sensor can vary by as much as +/- 50%, which translate into SNR degradation of up to a factor of 2.

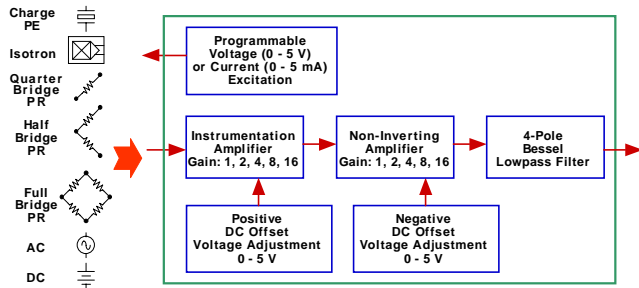


Figure 9 – TBIM: Analog Signal Conditioning

Programmable gain is provided in binary steps to optimize the dynamic range of the A/D converter. If the maximum output signal into the A/D does not span close to the 12 available bits, then we actually get lower resolution and lower accuracy.

Positive and negative offset control is also needed to properly span the signal into the A/D to the ideal minimum (0 count) to maximum (4095 counts) span of the A/D and get the ideal 72 dB SNR of a 12-bit A/D.

Analog to Digital (A/D) Conversion

The A/D sampling rate can vary from 20 to 100,000 samples per second without the need for any hardware changes. It is programmed by

downloading coefficients to the decimating digital filter (DDF) and is proportional (integer sub-multiple) to the bus clock. Lower sampling rates can be obtained by slowing the bus clock.

The A/D in all smart transducers is driven by an internal clock divider and is synchronized by the bus clock sent by the TBC, and the software trigger command from the TBC. This assures that all A/Ds take a sample simultaneously.

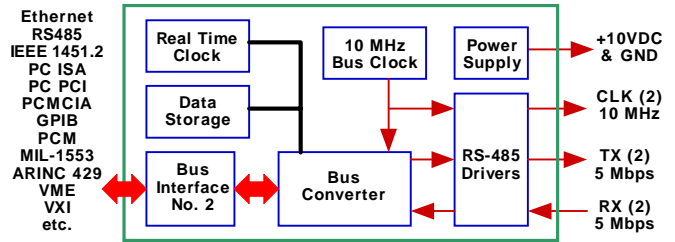


Figure 10 – Transducer Bus Controller: Block Diagram

The TBC provides power and the master clock to synchronize all smart transducers. It also contains enough memory storage (disk or silicon) to retain data collected from all smart transducers connected to the bus if it is unable to transfer it in real time to the host computer. The TBC also contains a real time clock to time tag the data acquired under the trigger command sent by the TBC.

The bus converter, also known as a gateway, provides translation service for the data from the transducer bus and the format required by another network or data bus (e.g. PCI, PCMCIA, Ethernet, CAN, Fieldbus, etc.).

An important capability of the TBC is to automatically assign a bus ID to each smart transducer. New smart transducers that are connecting to an already active bus will not interfere with bus operations until they are assigned a bus ID by the TBC. Automatic self-identification eliminates the possibility of multiple smart transducers with the same bus ID that can be caused by human error. The operator does not have to pre-program the bus address before connecting a TBIM to the bus.

SUMMARY

The difficulties associated with traditional measurement systems can be minimized or eliminated by using IEEE 1451.4 mixed-mode (i.e. analog and digital) Smart Sensors, such as SMART ISOTRON accelerometers, or by using NETWORK SENSORS.

Benefits of utilizing a 1451.4 Smart Sensor with TEDS (Transducer Electronic Data Sheet) include helping to simplify system setup, maintaining configuration control and enhancing calibration database management.

NETWORK SENSORS will offer a reduction in interconnecting cables, salvaging of existing analog type transducers through the use of TBIMS, and the ease of use and maintenance. Reliability of the measurement system can be improved because of the smart sensor self-test capability and the reduced susceptibility to noise of digital signals (EMI, cross-talk, ground loops, etc.).

REFERENCES

[1] IEEE Std 1451.2-1997 "IEEE Standard for a Smart Transducer Interface for Sensors and Actuators - Transducer to Microprocessor Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats", Institute of Electrical and Electronics Engineers, September, 1997.