A SMART SENSOR SIGNAL CONDITIONER

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ABSTRACT

The advantages and benefits of observing the dynamics of structures for purposes of either structural integrity monitoring or product quality control are both well known and established in the marketplace. However the cost of deployment and infrastructure requirements of traditional structural dynamics measurement systems in a production environment have been cost prohibitive. This paper will explore the architectural characteristics and features of a Smart Sensor Signal Conditioner family. Readily deployable signal conditioners can greatly facilitate production deployment of dynamics measurements for purposes of part quality indicators and machine tool wear. This paper will also present a case history and examples of actual deployment within the industrial plant-manufacturing environment, along with actual field data.

INTRODUCTION

Applying dynamics measurements as a direct aid, or indirect diagnostic tool to the manufacturing process has proven benefits. Obvious benefits have been realized in terms of reduced machine downtime through the use of predictive maintenance techniques such as periodic vibration monitoring. An entire industry exists which is dedicated to use of vibration as a predictive maintenance tool. Other applications of vibration measurements to the manufacturing process involve monitoring rolling, cutting, and milling, drilling and grinding processes for chatter and tool wear indications. In these cases the return on investment is not in terms of the manufacturing assets themselves but in terms of quality of the product being produced and efficiency of production itself.

MOTIVATION

Typically the deployment of dynamics measurement systems within the plant floor manufacturing environment has involved one of two approaches, neither of which is very straightforward.

The first approach has been to custom program a commercial FFT analyzer. In this situation we are typically paying the full price for an analyzer and utilizing a small percentage of its capability. Industrial packaging is an issue, and typically involves both environmental sealing, and air-conditioning due to heat dissipation issues.

The second approach has been to utilize a PC as a platform, “plugin” dynamic sensor signal conditioning, Analog to Digital Conversion as necessary, and repackage the completed unit in an industrially hardened package, or purchase an industrially hardened computer chassis to begin with. National Instruments is an example of a company that has done an excellent job of facilitating such approaches.

Both of these approaches involve significant cost, compared to the cost of a dynamic signal sensor, and involve significant engineering effort in order to provide a plant floor ready solution. The typical method of mitigation of these costs has been to concentrate multiple channels in a single package or location, thus driving up software complexity and providing for a single point of failure of the entire system.

Clearly, today's dynamic signal sensors are not directly usable, or infrastructure friendly without some sort of dynamic signal analyzer, or PC analyzer involved. Direct connection to a Programmable Loop Controller (PLC) or other commonly available plant floor controller is not an option due to the typical dynamic signal bandwidths and processing involved. Some implementations of 4-20 milliamps proportional to overall level are just now becoming available however.

REQUIREMENTS

What is required in order to effectively deploy dynamic signal solutions to the production floor on a more cost-effective basis is either smarter sensors, or smarter signal conditioning. The general requirements of this signal conditioning are as follows:

a.) NEMA 4, no fans or special cooling
b.) 24 VDC power w/noise rejection
c.) 1-4 ICP® dynamic sensor support
d.) IEEE 1451 smart sensor support
e.) Flexible communications options
f.) Integral computational capability
g.) Dynamic range matching sensor
h.) Onboard "results" memory
i.) Some digital input / outputs
j.) Some quasi-static signal ability
k.) Flexible signal output expansion

ARCHITECTURE

The architecture chosen to meet the above-mentioned requirements is shown in block diagram form in Figure 1. The package chosen to meet the requirements is shown in Figure 2.

The fundamental design is single board in nature. The sealed NEMA 4 rated unit is designed to operate without fans or special cooling up to and beyond 50 degrees C. Total power consumption is less than 4 Watts, greatly simplifying packaging. DC power at 24 volts was chosen as the nominal supply since it is quite readily available in a plant-manufacturing environment. Significant attention and several design iterations went into noise rejection efforts.

The ICP® transducer power supply is implemented as a software programmable power supply in order to accommodate IEEE P1451.4(1) reverse bias transducer interface requirements. ICP® transducer bias monitoring is preformed in the analog domain so as to permit long term monitoring of sensor health.

24 bit Sigma-Delta converters perform the analog to digital conversion. All converters operate in a synchronous fashion. While most simple applications do not demand it, the sample rate is software programmable between 1 and 96 KHz. This wide dynamic range eliminates the need for any sort of programmable gain in most manufacturing applications, requiring only that the sensitivity of the sensor be carefully selected.

The core of digital signal processing capability of the signal conditioner is a floating point programmable Digital Signal Processor (DSP). The DSP is low-power floating-point unit and is programmable in C, C++, and utilizing 3rd party packages in MATLAB® Simulink®. Program memory is an 8-megabyte FLASH memory, to allow signal-conditioning algorithms to be developed, stored, and executed upon power up of the unit. A significant portion of the FLASH memory may be utilized for long-term results storage. Data storage memory consists of 16-32 megabytes of dynamic ram. Putting this in perspective, this is enough memory to buffer approximately 5 minutes worth of time history at a 5000 Hz bandwidth.

Serial communications, slow speed analog input / output and optically isolated digital input / output are handled by a separate communications processor. This processor also can act as a watchdog processor and affect a total reset if necessary. This processor also contains sufficient resources to communicate with through an IEEE 1451.2 interface to a Network Capable Applications Processor (NCAP(2,3)) with onboard IP address and HTTP server.

Additional high and low speed input / output design flexibility has been provided in the core design to allow multi-board synchronization, high band-width network communications daughter-boards and wireless networking communications support. External battery back up, a battery backed real-time clock and power fail support was also integrated into the signal conditioner to facilitate deployment under harsh and relatively unpredictable conditions.

CASE HISTORY

The Modal Shop was approached by a group of manufacturing engineers associated with Ford Motor manufacturing operations. Their goal was to create a simple, stand-alone, robust, reliable and readily deployable transfer line spindle-monitoring device. The device was to be used on critical machining operations in a production environment. The device was intended to be able to detect nothing more than the fact that something significant is different, and light a light to say "hey, come look at me ". The goal was not to diagnose the fault, but to provide an operator or process engineer with an indication of whether the fault was machining related or not. The types of problems to be detected were bearing failures, and a host of machining related problems such as loose, broken, or missing tool inserts.

Analysis of other monitoring devices and systems revealed that there were either too many sensors, or they were too hard to setup and required extensive tweaking. Therefore one of the goals was to use a single spindle mounted vibration sensor. Setup and configuration of the device was to be as automatic as possible, and installation require no more than a skilled trades worker. Connections were to require no more than sensor and power. Configuration of the device should require no more than an approximation of cycle time, teaching it what signatures of non-rotating, and idling spindles were.

In a 2 year case by case study the approach to generation of the signal-conditioning algorithm was to use actual plant data as much as possible rather than manufactured laboratory data. Actual operating time histories of accelerometer sensed vibration data was collected on more than 250 machines throughout the organization. These time histories were used to formulate cycle detection methodologies and fault detection strategies.

It was quickly realized that no absolute time or frequency domain limit checking routine would suffice, but rather combinatorial time and frequency domain distributions must be learned, adapted and trended over time in order to determine what was "normal" and what was "abnormal" or fault criteria. This normal distribution must be learned as a function of part strikes, or "hits" and stored for up to 10,000 cycles. It was also quickly determined that a key to reliable fault detection was to strictly differentiate between cutting operations and non-cutting operations. Generally speaking, you can expect cutting operations to display smoothly cyclical vibration increases as a function of tool wear, dropping at tool change time. One can also expect non-cutting operation signatures to remain relatively flat over the life of a spindle. The attached figures and data plots, all of which are a function of part strikes clearly indicate when fault conditions are present.

Sixteen critical machines were selected from a Ford Engine Plant, and data was collected for over 6 million machining "hits" and analyzed against the original fault criterion for robustness and reliability. The resulting algorithms were coded and proven first on a PC utilizing stored disk time histories, and then ported to the DSP inside the signal conditioner, and verified by playing the digitized time histories into the signal conditioner.

It was originally envisioned that the device would merely light a light when a fault was detected, and the fault light would be manually reset. It was quickly recognized that there was advantage to connecting the box directly to the local PLC for process feedback. It was also recognized that there was also advantage to providing operations personnel with the ability to "look back" at operational vibration data as a function of "hit" or part processed.

Figures 3 through 6 are derived from actual operating plant vibration data, and are representative of the type of information generated and stored in the signal conditioner.

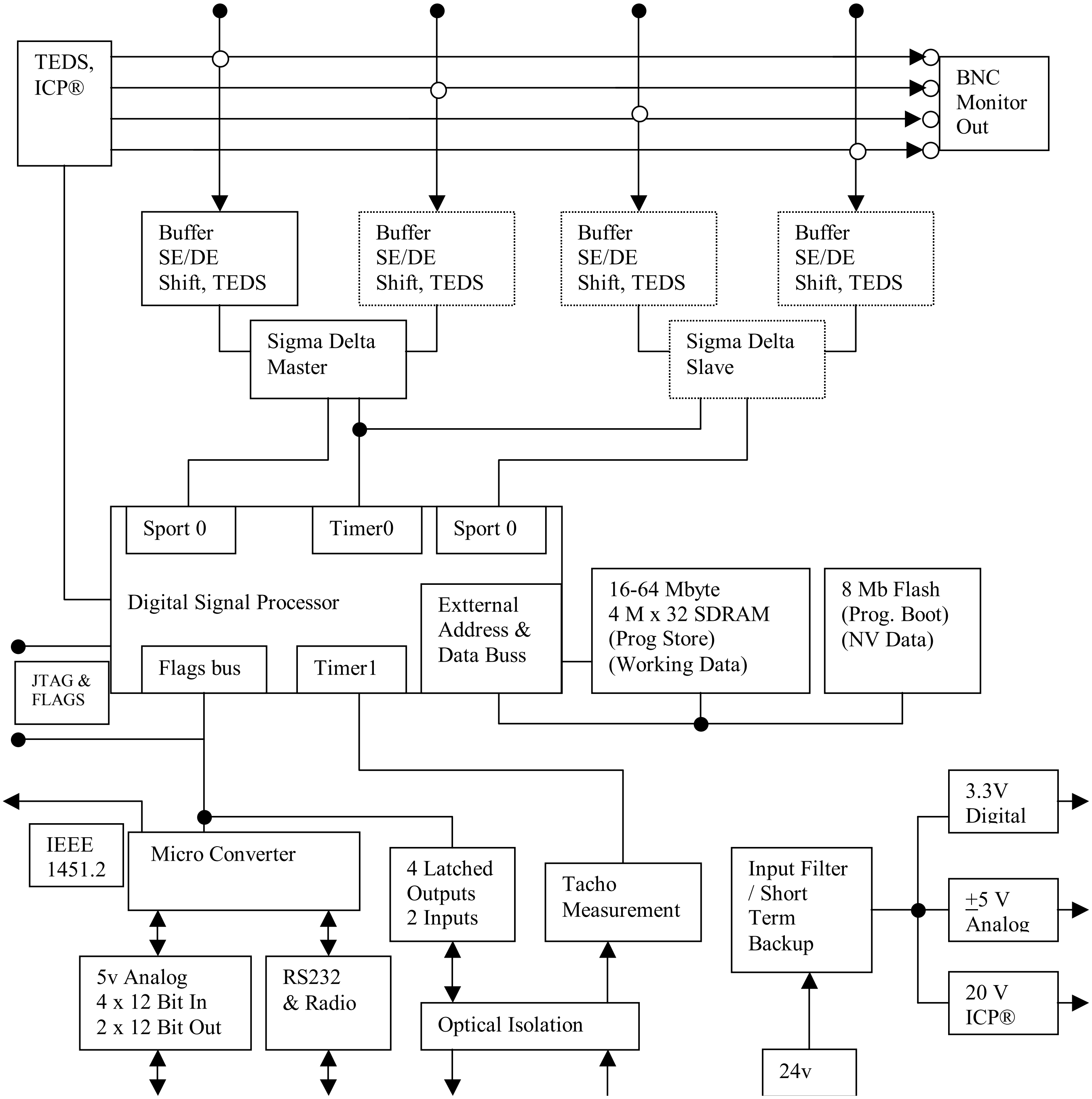
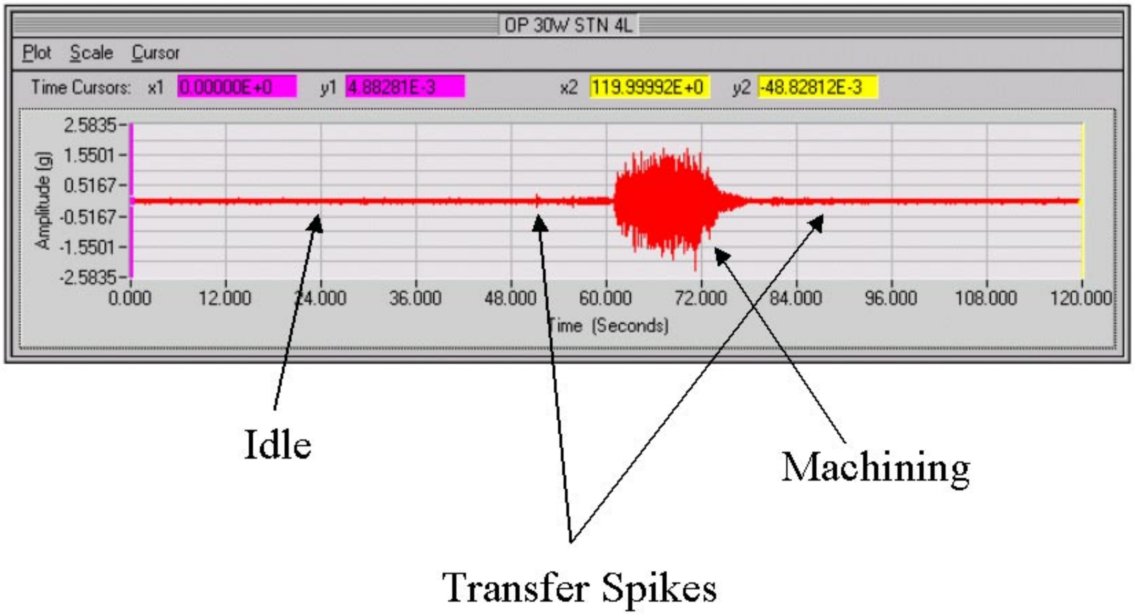


Figure 1 – Block diagram of a Smart Sensor Signal Conditioner

Figure 2 – Smart Sensor Signal Conditioner Packaging



Time Cursors: x1 0.00000E+0 y1 4.88281E-3 x2 119.99992E+0 y2 -48.82812E-3

Figure 3 – Typical machining cycle

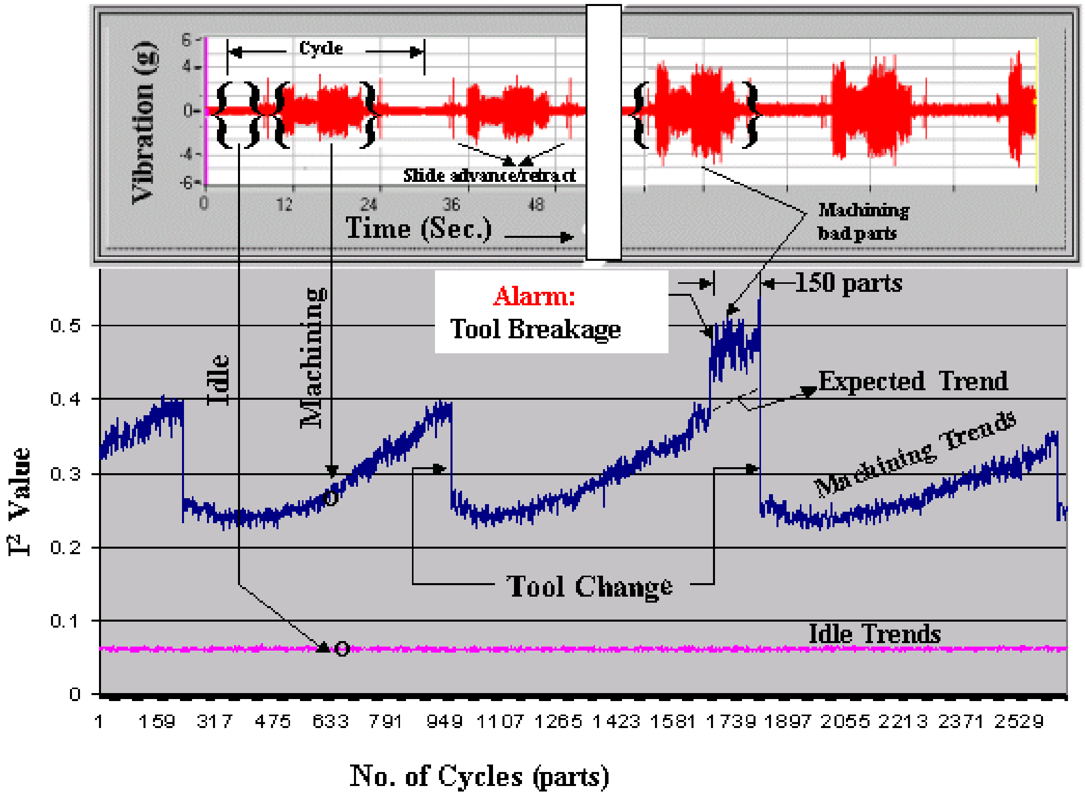


Figure 4 – Water Pump Boring Operation

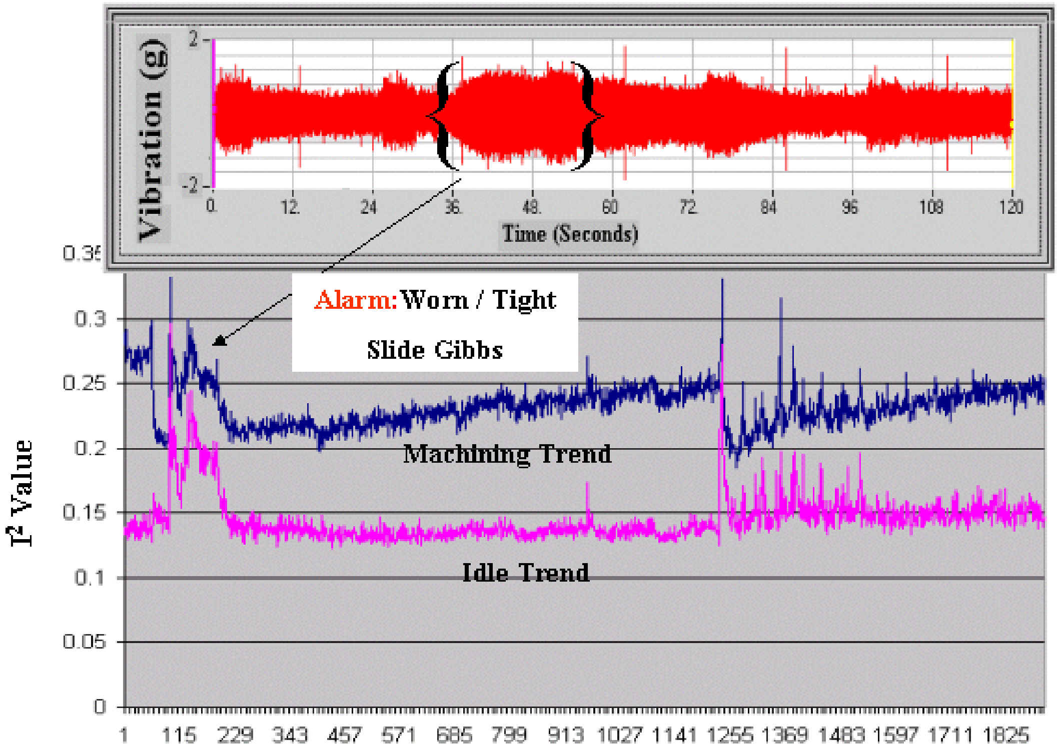


Figure 5 – Cylinder Head Deck Milling

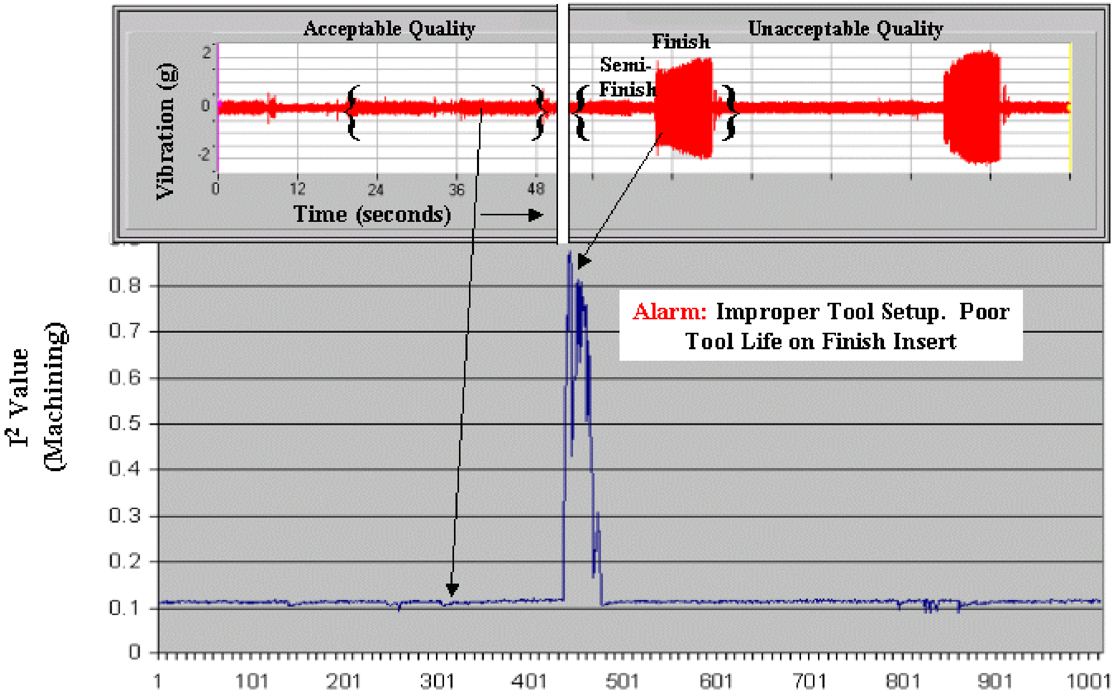


Figure 6 – Cylinder Boring Semi-Finish / Finish operation

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Further information on the IEEE 1451 family of accepted and proposed standards may be found www.ic.ornl.gov/p1451.

REFERENCES

[1] IEEE P1451.4 Proposed Standard for Mixed-mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats

[2] IEEE 1451.1-1999 Standard for a Smart Transducer Interface for Sensors and Actuators - Network Capable Application Processor (NCAP) Information Model

[3] IEEE 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.