REMOVING OLD SENSOR MYSTERY WITH IEEE P1451.3 AND .4 STANDARDS

Robert Sinclair, Dr. Russell Beech, Kevin Jones, Scott Mundon
NVE Corporation.
Eden Prairie, MN

Dr. Charles H. Jones
412 TW/ENTI
Edwards AFB, CA

ABSTRACT

When a sensor is replaced or added to a legacy data acquisition system, information for that sensor has to be incorporated by the software programmer into the main system software – a costly and time-consuming process. The new 'smart' sensors that are being designed according to the new IEEE P1451.3 and .4 standards will have the necessary information contained in their Transducer Electronics Data Sheet (TEDS). A method has been developed to give the old sensors the intelligence to meet the requirements of these new IEEE standards without changes to the legacy hardware and a minor change to the system software.

KEYWORDS

AATIS, NCAP, TEDS, IEEE P1451.3, and IEEE P1451.4.

INTRODUCTION

Many of the existing legacy sensor systems do not have the capability of being interrogated to determine their working status, calibration information, serial number, or manufacturing and service history since the sensors themselves have no intelligence. When defective sensors are detected, replacement generally requires removing the system from service instead of simply unplugging the defective sensor and plugging in a replacement sensor or 'hot swapping.' A major software effort is then required in the ground support equipment (GSE) to input each sensor's unique characteristics on a case-by-case basis.

"Smart' sensors are being designed and developed according to the new IEEE P1451.3 and.4 standards that have the necessary information contained in their TEDS to give them plug-and-play capability. A system is being developed for Edwards AFB, California, which is discussed in this paper, to give old sensors the same plug-and-play capability as the new sensors. The information needed to describe a particular sensor is located with each individual sensor, thus removing the requirement of programming the main system with this information. The IEEE P1451.4 compliant sensor identification transducer electronic data sheet (SITEDS) information is located with each sensor and will be available to the GSE when the particular sensor is inserted into the system. A device called a Network Capable Applications Processor (NCAP) was developed to interface the Universal Smart Transducer Interface Modules (USTIMs) to the Advanced Airborne Test Instrumentation System (AATIS) Party Line bus. Other buses can be interfaced to the USTIMs by simply reconfiguring the NCAP. The legacy sensors with their associated SITEDS are connected to a USTIM, which resides on an NCAP-USTIM Party Line (NUPL) bus with other USTIMs. This bus is connected to the NCAP that, in turn interfaces to an external bus, such as the AATIS Party Line bus. A TEDS meeting the proposed IEEE P1451.3 standard will be contained in each USTIM allowing future expansion with other IEEE 1451 compliant devices.

LEGACY PLUG-AND-PLAY PROBLEMS

A significant challenge is required to bring a legacy system up to the new IEEE 1451 standards without wholesale and costly replacement of the system. Old sensors must be used since many are imbedded in the aircraft. The existing computer system and interface controllers must be maintained in place to eliminate a major software redesign as well as costly hardware replacements. However, from a maintenance standpoint, it is desirable to replace and/or add sensors with all the advantages of the IEEE 1451 standards including 'hot swapping,' automatic sensor identification, automatic calibration, etc. This can be accomplished by adding a small interface module between the sensor and the legacy system that contains the 'smarts' for a particular sensor.

THE IEEE P1451.4 SPECIFICATION STANDARD FOR SITEDS

The IEEE P1451.4 is a draft standard for adding sensor parameter information in a TEDS stored in an electronically erasable programmable read-only memory (EEPROM) that resides in the sensor. The IEEE P1451.4 smart TEDS sensors provide both an analog signal for traditional measurement, along with a serial digital link for accessing the TEDS information for plug-and-play operation. The standard defines two types of mixed-mode interfaces, designated as Class 1 two-wire and Class 2 multiwire interfaces. The Class 1 two-wire interface works with constant-current powered, or Integrated Circuit Piezoelectric (ICP®), transducers, such as accelerometers. The ICP is a registered trademark of PCB Piezotronics, Inc. Class 1 transducers include diodes or analog switches with which the multiplexing of the analog signal with the digital TEDS information on the single-pair of wires is possible. This is shown in the first diagram in figure 8. For other types of sensors, the Class 2 interface uses a separate connection for the analog and digital portions of the mixed-mode interface. The analog input/output of the transducer is left unmodified, and the digital TEDS circuit is added in parallel. This enables the implementation of plug and play transducers with virtually any type of sensor or actuator, including thermocouples, RTDs, thermistors, bridge sensors, electrolytic chemical cells, and 4-20 mA current loop sensors. For example, the second drawing in figure 1 illustrates the implementation of a Class 2 mixed-mode interface with a bridge interface. A Class 2 implementation of the IEEE P1451.4 specification is well suited for a legacy sensor and a SITEDS combination. The memory module that is connected to each legacy sensor will contain the SITEDS. The SITEDS will contain those portions of the channel TEDS that can be predetermined, regardless of the hardware and operation of the USTIM, as well as the sensor-specific data that are required by the USTIM or desired for possible use at the system level. The USTIM will use the SITEDS to create a complete transducer channel TEDS.

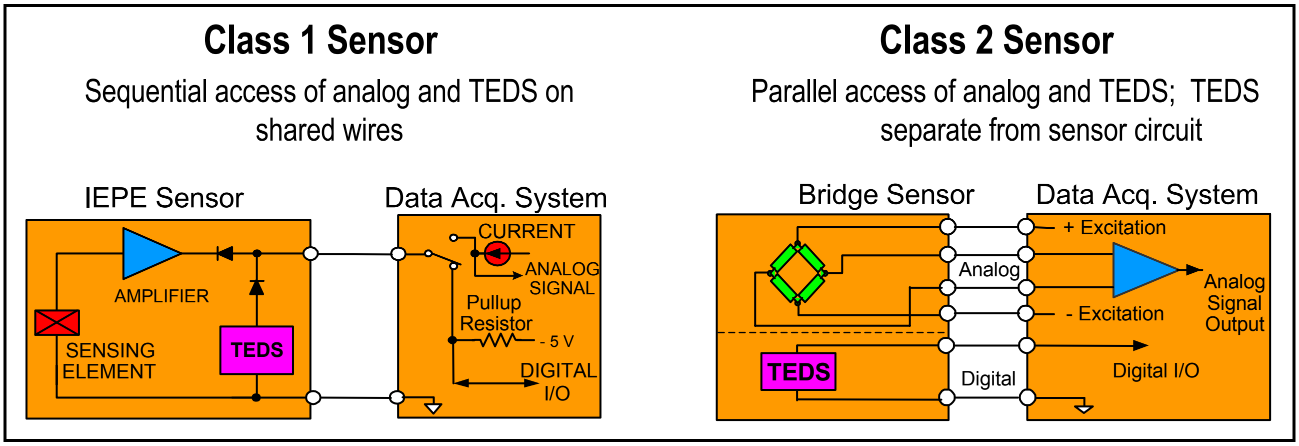

Figure 1. IEEE P1451.4, two types of mixed-mode interfaces

An example of the transducer channel TEDS data that will be determined dynamically, rather than being stored in the USTIM of the SITEDS, is the upper range limit. While all of the data will be unitless digital data, coming from an analog-to-digital converter (ADC), not every channel will necessarily use the full digital range of the ADC output. Depending on the sensor output and USTIM electronics, it may not be practical to scale the sensor signal to utilize the entire ADC output range. Thus, the USTIM will determine the upper range limit of the channel TEDS based on the capability of its analog hardware and on the data that it receives, from the SITEDS, concerning the output of the sensor that is connected to a given input channel.

Because the USTIM will generate a standard format TEDS, as well as having a standard Meta-TEDS stored within it, the unique data set that is contained in the SITEDS, and the flexibility that it affords in sensor configuration, will be transparent to the overall system. The collection of USTIM and sensor/memory units will appear to the overall system to be a standard NCAP and STIM.

Some of the data fields contained in the SITEDS specified in the IEEE P1451.4 are shown in the examples in table 1.

The information required for the channel TEDS specified in the IEEE P1451.3 proposed standard is shown in table 2. Each octet listed in column 5 (table 2) is 8 bits long. The column specifying 'type' designates the data type. Unsigned 8-bit integers are designated by U8C for counting. An unsigned 16-bit integer is designated for counting by U16C and field length by U16L. An unsigned 32-bit integer is designated for counting by U32C and field length by U32L. The F32 designates a single precision real number and F64 a double precision number. A string is implemented with the eXtensible Markup Language (XML) controlled by the document W3C XML 1.0. Physical units are designated by 'Units' and are 10 octets long.

Table 1. Example Contents of the SITEDS for Two Sensors

	IEPE Accelerometer		Bridge (mV/V) Load Cell	
Basic TEDS	Manufacturer ID	34	Manufacturer ID	64
	Model ID	8113	Model ID	24
	Version Letter	A	Version Letter	C
	Serial Number	00461G	Serial Number	0003461
Standard and Extended TEDS	Calibration Date	Jun 14, 2002	Calibration Date	Dec 15, 2001
	Sensitivity @ ref.	1.094E+03 mV/g	Measurement	± 100 lbf
	Reference freq.	100.0 Hz	Electrical output	± 3.01 mV/V
	Reference temp.	23 °C	Bridge impedance	350 Ω
	Measurement	± 50 g	Excitation, nominal	10 VDC
	Electrical output	± 5 V	Excitation, min.	7 VDC
	Quality factor	300 E-3	Excitation, max.	18 VDC
	Temp. coefficient	-0.48 %/°C	Response time	5 ms
	Direction (x,y,z)	x		
User Data	Sensor Location	3A-p2	Sensor Location	R32-1
	Calibration date	April 15, 2003	Cal. record ID	543-01.23

Table 2. Contents of the Transducer Channel TEDS

Field	Description	Type	# octets
—	TEDS length	U32L	4
1	TEDS identifier	U8E	1
—	TransducerChannel related information	—	—
2	Calibration key	U8E	1
3	TransducerChannel type key	U8E	1
4	Physical units	UNITS	10
5	Design operational lower range limit	F32	4
6	Design operational upper range limit	F32	4
7	Worst-case uncertainty	F32	4
8	Self-test key	U8E	1
—	Data converter related information	—	—
9	Data model	U8E	1
10	Data model length	U8C	1
11	Model significant bits	U16C	2
12	Maximum data repetitions	U16C	2
13	Series origin	F32	4
14	Series increment	F32	4
15	Series units	UNITS	10
16	Maximum pre-trigger samples	U16C	2
—	Timing related information	—	—
17	TransducerChannel update time (t_u)	F32	4
18	TransducerChannel write setup time (t_{ws})	F32	4
19	TransducerChannel read setup time (t_{rs})	F32	4
20	TransducerChannel sampling period (t_{sp})	F32	4
21	TransducerChannel warm-up time	F32	4
22	TransducerChannel read delay time (t_{ch})	F32	4
23	TransducerChannel self-test time requirement	F32	4
—	Time of the sample information	—	—
24	Source for the time of sample	U8E	1
25	Incoming propagation delay through the data transport logic	F32	4
26	Outgoing propagation delay through the data transport logic	F32	4
27	Trigger-to-sample delay uncertainty	F32	4
—	Attributes	—	—
28	Sampling attribute	U8E	1
29	Buffered attribute	U8E	1
30	End-of-data-set operation attribute	U8E	1
31	Streaming attribute	U8E	1
32	Edge-to-report attribute	U8E	1
33	Actuator-halt attribute	U8E	1
—	Sensitivity	—	—
34	Sensitivity direction	F32	4
35	Direction angles	Two F32	8
—	Options	—	—
36	Event sensor options	U8E	1
—	Checksum	U16C	2

SENSOR IDENTIFICATION TEDS MODULE

In this system, the sensor/memory units are connected to a USTIM, which is essentially the same as the transducer bus interface module (TBIM) that is described in the IEEE P1451.3 D106/draft standard.

Since the USTIM is able to accommodate a changing number and variety of sensor/memory units, a complete TEDS, as described in the IEEE 1451.2-1997 standard, cannot be predetermined and stored in the memory module. In addition, data that are not incorporated into the TEDS descriptions in the IEEE 1451.2-1997 standard is required by the USTIM in order to properly configure the interface hardware to the sensor/memory unit.

In order to accommodate the unique requirements of the USTIM, a method of creating the overall TEDS and configuring its storage in the system had to be devised. With this method, all of the unique, sensor specific information and portions of the transducer channel TEDS (including appropriate sub-TEDS for the transducer channel TEDS - such as the calibration TEDS) will be stored in the SITEDS. The rest of the TEDS will be stored in the USTIM. Further, portions of the TEDS will vary depending on the number and types of sensors that are connected to the USTIM. These portions of the TEDS will be dynamically created by the USTIM on power-up and in response to changes in the USTIM's sensor configuration.

Figure 2.
SITEDS Adapter

An EEPROM containing the transducer channel TEDS information, resides at the sensor instead of the USTIM, allowing the legacy sensors to become plug-and-play. The 24CXX family of EEPROMs is used since it offers a wider range of available memory and package sizes. For example, 128 x 8 bits of nonvolatile memory can be contained in a small 5-pin SOT-23 package. For many sensor types, this amount of memory may be sufficient for storing transducer Channel TEDS information, assuming calibration data are stored as coefficients as opposed to a large look-up table array.

A voltage regulator accompanies the memory device to provide a stable power source for the memory device. The memory circuit could also tap the sensor excitation voltage. Since the memory is only accessed at power-up, the serial clock and data in-lines will be held in a DC state during normal operation. Hence, cross coupling of the digital to analog signals will not be an issue. Figure 2 shows a SITEDS module contained in a snap-on housing for legacy sensors. The I^2C bus is used to communicate with the USTIMs.

THE IEEE P1451.3 SPECIFICATION STANDARD FOR USTIM

The USTIM described previously is similar to the Transducer Bus Interface Module (TBIM) described in the IEEE P1451.3 standard. Figures 3 and 4 represent two possible contexts for the specification. Figure 3 gives the electrical connectivity that the interface implements. In this representation there are two conductors between the Transducer Bus Controller (TBC) and the TBIMs. These two conductors carry both the power and the signals to implement the interface. In the case of the USTIM, signal and ground are provided over two wires and power is provided over an additional two wires, in particular, 28 V aircraft power. The USTIMs and NUPL bus still conform to the proposed standard since the standard allows the case where more power is required for a particular TBIM than can be supplied over the bus. In this situation, an auxiliary power source can be used. In Figure 4, the proposed standard shows that DC power, a synchronization signal and communications all sharing a single pair of conductors. The interface between the TBIM and the bus, the TBC and the bus, the bus itself and the TEDS that reside in the TBIMs are the subject of the IEEE P1451.3 specification.

A TBIM (USTIM) may be used to sense or control multiple physical phenomena. Each phenomenon sensed or controlled shall be associated with a Transducer Channel in a TBIM (USTIM).

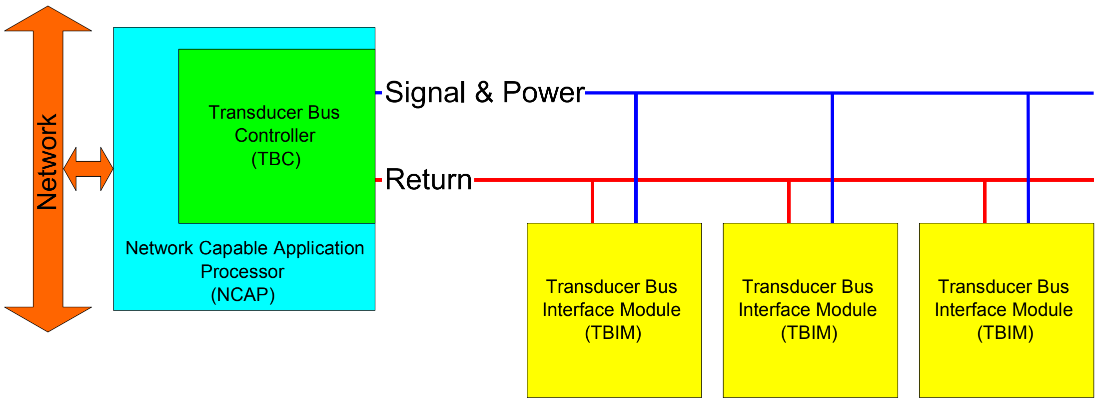

Figure 3. Physical context for the transducer interface specification

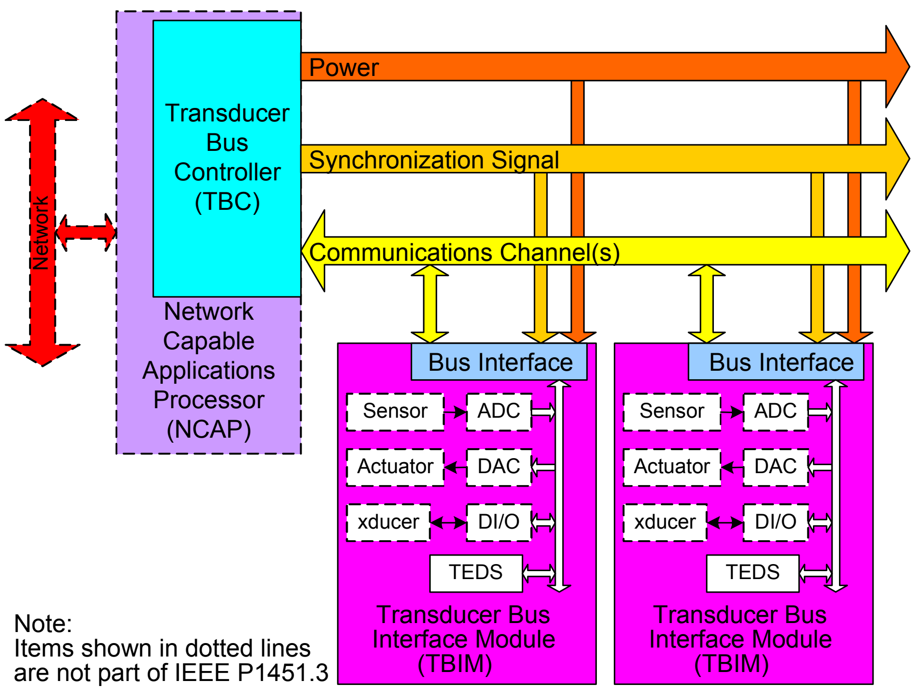

Figure 4. Functional context for the transducer interface specification.

The IEEE P1451.3 standard specifies a synchronization signal as a sine-wave signal that is provided to assure that all TBIMs have access to a clock running at the same frequency. The TBIM communications is implemented using the HomePNA communications standard. In the case of the USTIMs, a synchronization signal in the form of a square wave is provided to all of the USTIMs. However, the HPNA protocol cannot be used since this system has to appear seamless to the legacy system. This design is being tailored to the AATIS legacy system that requires data packets as small as 16 bits to be delivered within a 2.4 µS timeframe. The NCAP must forward the command from the AATIS bus over the NUPL bus to the USTIM and return the data to the AATIS bus within the 2.4 µS timeframe. Since the communication between the NCAP and USTIMs adds another level of communication, the NUPL bus must run at a higher speed. Commands are sent to the USTIMs within 0.8 µS, data conversions occur within 0.8 µS, and the data are returned to the NCAP within 0.8 µS.

LEGACY SYSTEM UPGRADE TO IEEE P1451.3

The legacy system upgrade modules contain the intelligence and TEDS for each sensor. The modules are then connected together on their own four-wire NUPL bus with other USTIMs, thus eliminating the need for the large cabling systems that are currently being used.

Changing to the information contained in the USTIM modules can be accomplished either through the main system, if allowed, or through a laptop computer. An IEEE 1451 TEDS can be loaded onto a USTIM in one of three ways. 1) It can be downloaded from the main system; 2) it can be loaded at the factory; or 3) it can be loaded locally from a floppy disk with a laptop computer. An IEEE P1451.4 compliant TEDS associated with each legacy sensor will be located in a small module called a SITEDS. This module will be located next to the USTIM and plugged into the same connector as the sensor. A general purpose USTIM can be used with a variety of legacy sensors with no changes to its hard circuitry.

Once the USTIM is configured, the main system will be able to detect its addition to the system and automatically download all the information necessary to describe the sensor. Thus, no special software or hardware will be required for the legacy systems. A block diagram of the current AATIS system is shown in figure 5. The USTIM can connect the respective transducers directly to the System Control Unit's (SCU) Party Line bus through a NCAP as shown connected to the heavy black line in figure 5. No additional interfaces are required since RS-232 circuits are built into the NCAP for GSE as well as the interface to the NUPL bus. An in-circuit reprogrammable logic device is contained within the NCAP that could be reconfigured with a laptop computer to accept other protocols.

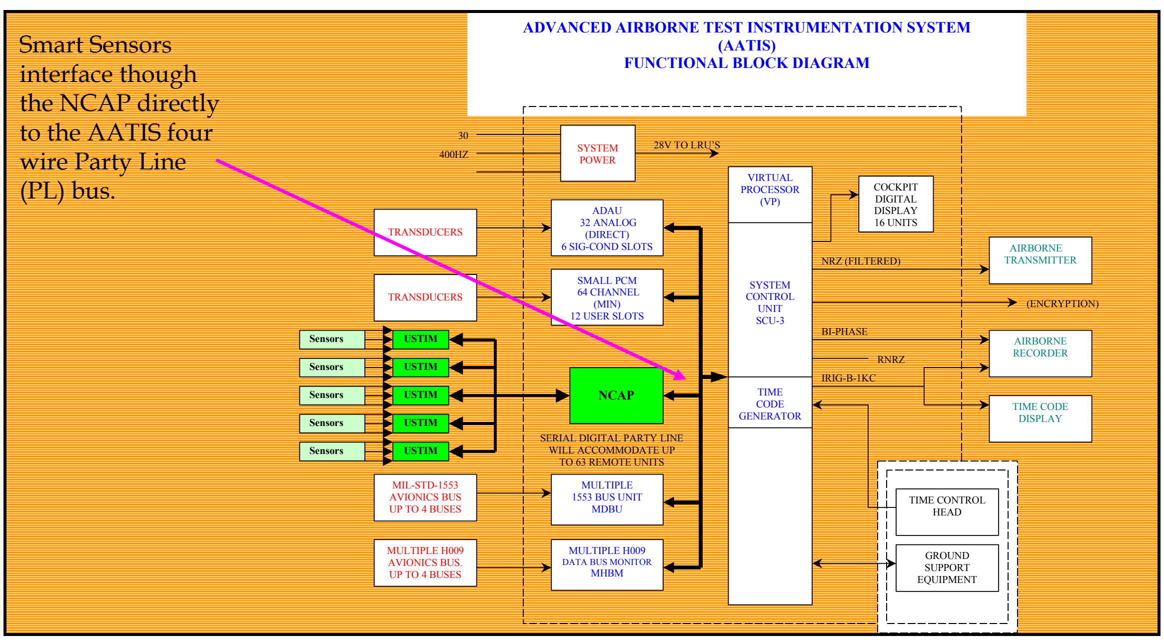

Figure 5. AATIS Block Diagram with USTIMs

NCAP DESIGN

The NCAP provides the interface between the AATIS party line bus, the USTIM, and the GSE. The GSE interface uses the RS-232 (or RS-422) standard. A local Party Line bus, called the NUPL bus, using a RS-485 interface, is used to interface multiple USTIMs to the NCAP. A top-level block diagram of the AATIS system, with the NCAP and USTIMs included, is shown in the left side of figure 6. As can be seen in the diagram of figure 6, the NCAP allows the USTIMs to interface to the AATIS system SCU without an analog to digital acquisition unit (ADAU). It is also clear that the interface between the multiple USTIMs and the NCAP requires only two wires compared to the discrete wiring that is required to connect each individual 'dumb' transducer or embedded sensor to the SCC in the ADAU.

In addition to the three interface blocks (AATIS, RS-485, and RS-232) shown in figure 6, there is one circuit block that controls the data flow through the NCAP. Because the USTIM provides all signal conditioning and data conversion that is required for the transducers and embedded sensors that are connected to it, the NCAP does not need to have any processing capability. Instead, the NCAP is strictly a communication device that multiplexes multiple USTIM modules to the AATIS Party Line bus. This helps to minimize fan-out/loading of the AATIS Party Line bus while still providing access to a large number of transducers and embedded sensors. It also simplifies the USTIM design so that the USTIM can be made smaller and cheaper. The NCAP provides the interface between the three different buses that are used in the enhanced AATIS system, as shown in figure 6.

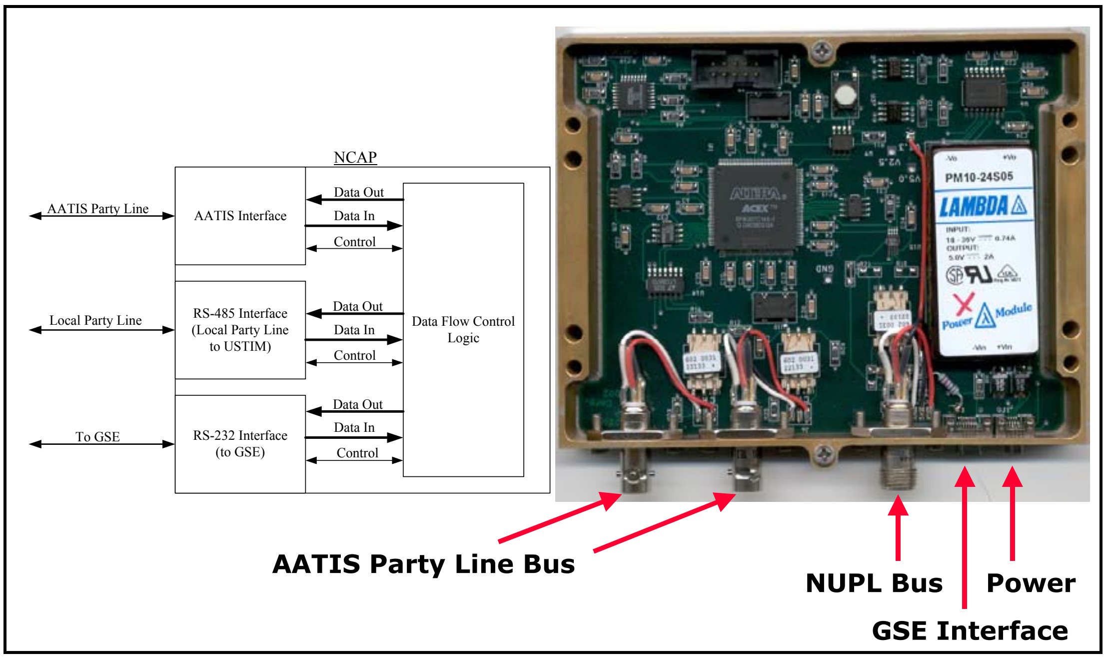

Figure 6. Network Capable Applications Processor (NCAP) Module.

NCAP-USTIM PARTY LINE

The RS-485 interface was chosen for the NUPL bus because it provides the required communication bandwidth with just two wires and readily available COTS components. Programming the USTIMs and loading the TEDS with the GSE is accomplished utilizing a simple, low overhead RS-232 communication protocol. At the command level, (i.e., interpreting and acting upon the transmitted bytes), a simple protocol that is designed specifically for the AATIS system is used. Again, this is being done in order to provide the required data throughput. Because of the additional level of device addressing that must be communicated through the NUPL, the NUPL will operate at two to three times the bit rate of the AATIS Party Line - assuming that a minimal, custom, high level communication protocol is used.

The TEDS information that is contained in the USTIMs will conform to the completed IEEE 1451.2 standard until the IEEE P1451.3 standard is finalized and approved. At that time, the TEDS contained in the USTIM can be converted to that standard. The IEEE P1451.3 standard closely matches the architecture being used in this program, but the communication protocol contains communication overhead, which cannot be used with the AATIS system. For example, a 15-byte communication overhead is used in some cases with the IEEE P1451.3 standard. If two commands are needed, one to trigger the 'smart sensor' and one to read the data, then 32 bytes must be transferred - including the two data bytes. With the minimum AATIS command period being 2.4 µs, this would require a bit rate of over 133 Mbaud on the NUPL bus, which is above the maximum rate of 100 Mbaud allowed in this design.

USTIM DESIGN

A general purpose USTIM, shown in Figure7, was developed which will satisfy the interfacing requirements of most legacy sensors. It was designed to be fully in-system programmable and in-system hardware reconfigurable. It contains a nonvolatile memory for the TEDS information, which can be expanded within a single integrated circuit. Additional features, along with the 8051 core processor, include a high speed 12-bit data acquisition system, a programmable logic element, 8 fully programmable analog channels which have programmable gain and offsets, high speed RS-422 bus interface, and 3.3-volt operation. The block diagram for the USTIM is shown on the left of Figure 7.

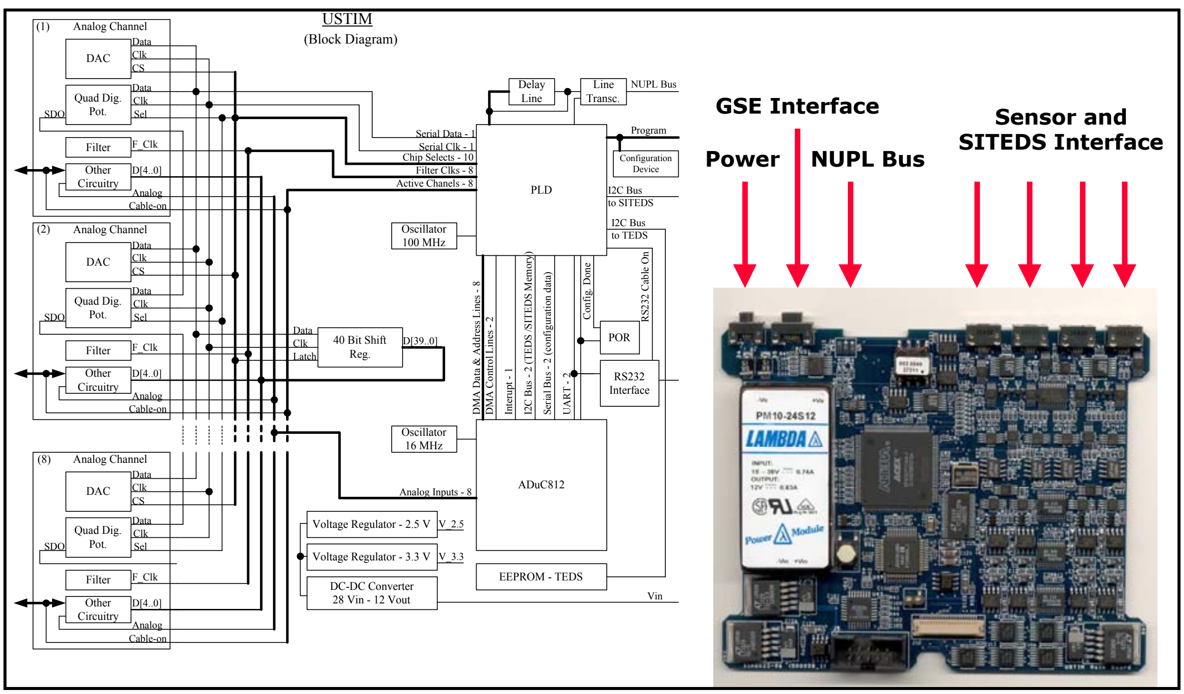

Figure 7. Universal Smart Transducer Interface Module **(**USTIM)

IMPLEMENTING A HYBRID AATIS IEEE 1451-COMPLIANT SYSTEM

The goal is to minimize system impact in downtime for both software and hardware modifications during the transition to IEEE-1451 compliance. Minimizing cost during the upgrade to the IEEE 1451 standard is also important. The existing AATIS system hardware will remain unchanged both during and after the modules are added to convert the sensors to IEEE P1451.4 compatibility. This will be accomplished by containing the sensor software and TEDS information in the USTIMs and using the NCAPs to interface and format the data streams to be compliant with existing AATIS systems. Standard CAIS/AATIS commands will be used to transfer data to and from the NCAP. Since the NCAP contains in-circuit reconfigurable hardware, its characteristics can be modified with software to conform to future system upgrades, bus speed improvements, etc. Figure 4 shows the system block diagram and its connection to the Party Line bus. The NCAP transfers its data to and from the SCU via the Party Line bus. Figure 6 also shows that the NCAP effectively isolates IEEE 1451 compatible devices from the AATIS hardware. All IEEE P1451.4 compliant sensors present a uniform software and hardware interface to the system via the NCAP. All the calibration, identification, etc., is located in the SITEDSs and the USTIMs.

CONCLUSION

The development of the NCAP, USTIM, and SITEDS has paved the way to reduced installation, maintenance, and configuration management for legacy systems such as the AATIS. With the incorporation of these innovations, cabling systems will also be greatly reduced. A low-cost, low-impact transition to IEEE P1451.4 compliant sensors is provided by these components.

ACKNOWLEDGMENT

This work is being supported by Air Force Flight Center (AFFTC), Edwards AFB, California under SBIR contract number F04611-00-C-0052.

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.

2. IEEE Std P1451.3/D3.00, *Draft Standard for A SMART TRANSDUCER for SENSORS and ACTUATORS – Digital Communication and Transducer Electronic Data Sheet (TEDS) Formats for Distributed Multidrop Systems.* Institute of Electrical and Electronic Engineers, March 2003.

3. IEEE Std P1451.4/0.94, *Draft Standard for a Smart Transducer Interface for Sensors and Actuators – Mixed-Mode Communication Protocols and Transducer Electronic Data Sheet (TEDS) Formats.* Institute of Electrical and Electronic Engineers, March 2001.