IEEE P1451.3 A Developing Standard For Networked Transducers

Lee H. Eccles
Boeing Commercial Airplane Company
P. O. Box 3707, M/S 14-ME
Seattle, WA 98124-2207
Phone 206-655-2824
FAX 206-655-7724
E-Mail lee.h.eccles@boeing.com

ABSTRACT

The IEEE P1451.3 standard for networked transducers is designed to support applications in many industries but aerospace representatives have had a major say in what is included in the standard. The standard is written to allow multiple different transducers to exist on a single transmission line. This single transmission line may also carry power to the transducers. A bus is expected to have a single controller and many transducers. Individual transducers may be operated in several modes including a strict master-slave relationship or individual transducers may operate independently from the bus controller. In addition the bus controller can provide a clock to allow all transducers to operate synchronously or the clock can be ignored for asynchronous operation. The standard includes an extensible command set and Transducer Electronic Data Sheets (TEDS) that allows for full plug and play operation of the transducer. If a manufacturer chooses to leave out some of the features that allow for plug and play operation the standard allows for that as well. This paper provides an overview of the features of the standard as well as the types of system that can best utilize these features.

GENERAL CAPABILITIES

IEEE P1451.3 is an attempt to define a standard that will allow a transducer manufacturer to build transducers that have a wide range of price and performance but which are all inter-operable within a system. The standard will allow for simple devices with relatively low data sampling rates and moderate time correlation requirements to be designed and built. At the other end of the spectrum will be devices that have bandwidth requirements to several hundred kilohertz and time correlation requirements in the range of nanoseconds. It is expected that devices from either end of the spectrum will be able to peacefully coexist on the same bus. Figure 1 is a representation of what is expected in the physical realm. As shown in the diagram a single transmission line will be used to supply power to the transducers and to provide the communications between the bus controller and the Transducer Bus Interface Modules (TBIM). A bus is expected to have one bus controller and many TBIMs. The bus controller may reside in a Network Capable Application Processor (NCAP) when the system requires a network with many buses. A bus controller may reside in a host computer or data recorder as well. A Transducer Bus Interface Module (TBIM) may contain from one to many different transducers. Three basic transducer types are recognized in the standard. They are the sensor, the actuator and the event sensor. Different attributes are defined for each transducer type to allow many different modes of operation.

There are a number of functions that will need to be accomplished over the transducer bus. Table 1 is a list of the major functions that will need to be performed. These functions are required by both the very large, complex systems and by the very simple systems consisting of just a few transducers. The IEEE P1451.3 working group is preparing a standard that will allow systems from the very simple to large complex systems to be built using the same interfaces. In order to accomplish this, four different communications channels have been defined. Each of the four communications channels are listed in Table 2 along with a brief description of its expected function. The communications channels will share the medium with the power required to operate the transducers. For high power transducers the power that can be applied over the communications cable may be inadequate so it will be acceptable to power the transducers with a separate power supply.

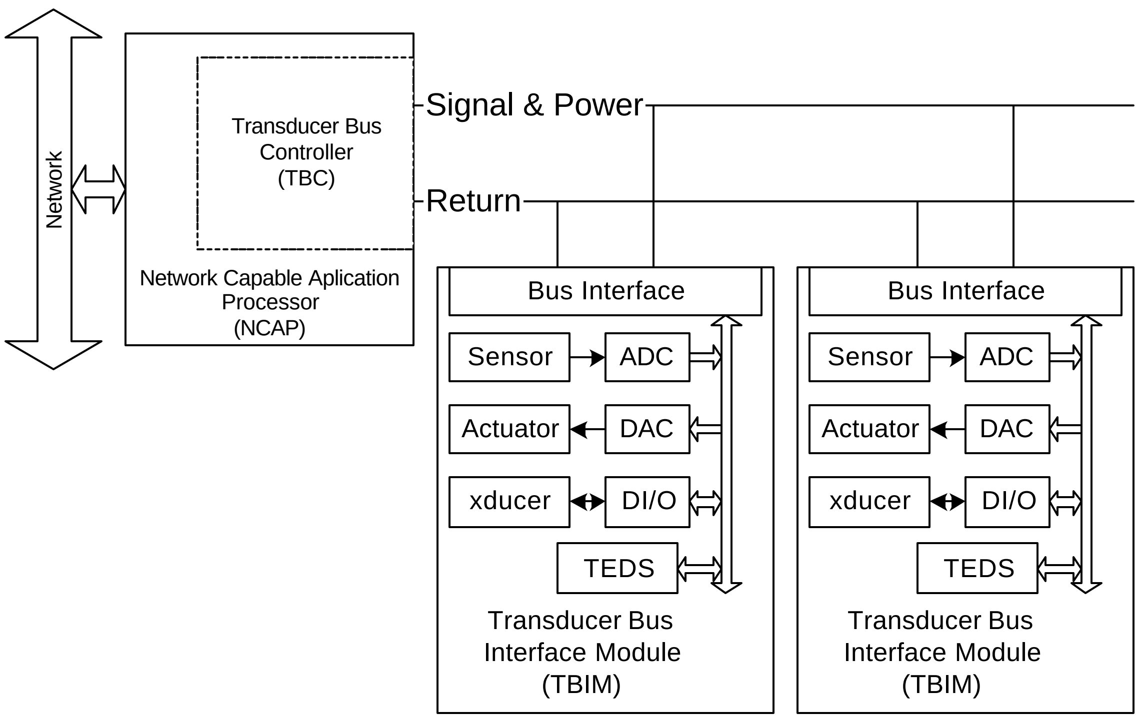

Figure 1 Physical representation of the IEEE P1451.3

TRANSDUCERS

There are four general classes of transducers and various attributes that can be applied to each of them. In addition, transducers may be classified as virtual if they are used to sense or control some condition within a TBIM that does not directly impact the outside world. Virtual transducers and control commands may perform similar functions. The choice of which to use in a given TBIM is up to the TBIM manufacturer. The main difference between the two is that virtual transducers may have TEDS associated with them that allow the system operator to deal in engineering units without a detailed knowledge of the bit patterns required to obtain the desired results. The following paragraphs describe each of the different classes of transducers.

Sensors - A sensor measures some physical parameter on demand and returns digital data representing that parameter. On the receipt of a trigger, the sensor starts the collection and storing of a data set within the TBIM. The data set may contain one or many samples of the parameter. The timing of the individual samples in the data set is controlled by the TBIM and is a function of the operating mode of the sensor. A sensor responds to a read command by returning the appropriate data set. If a new data set is not available, the transducer repeats the same data that was returned on the previous read command with a flag that indicates that the data was previously read.

Event sensor - An event sensor is used to determine that a specific event has happened and the time when the event occurred. The time may be determined and returned by the TBIM or may be determined by the TBC when the event is received. A trigger arms an event sensor to detect the occurrence of an event. The event may be a digital signal transition or an analog signal crossing a setpoint. An event sensor may be configured to signal an event on high-to-low transitions or low-to-high transitions, or both. The present state of an event sensor may be determined by reading the status.

Virtual actuators and sensors within a TBIM may be associated with an event sensor to allow changing analog setpoints, hysteresis, or reading the value being sensed. This association is communicated to the TBC through the grouping information in the Module Meta-TEDS.

Actuator - An actuator causes a physical or virtual output action to occur that is related to the data set sent to the actuator. The actuator output changes state to match the appropriate data set when a trigger occurs. The timing of the data output process is under the control of the TBIM if there is more than one data point in a set.

An actuator may be built which does not require a data set be written to it before it performs an action. This type of device always uses a default data set or no data at all and performs a predefined action upon the receipt of a trigger.

General Transducer - The General Transducer is any transducer that does not meet the timing requirements for one of the other three transducer types. The standard will allow for the General Transducer type but it is not expected to be "Plug and Play." Special software will be required to use it.

TRANSDUCER ATTRIBUTES

The following paragraphs define the operating characteristics that are common to all transducer types. Each attribute describes a particular mode of operation for a transducer. Some of these attributes are mutually exclusive and others can be enabled at the same time. Attributes may be fixed at the time of manufacturing of the transducer or may be programmable.

SAMPLING ATTRIBUTES

The sampling attributes determine the relationship between the trigger and the sampling of the data by a sensor or the application of a sample to the output of an actuator.

Trigger initiated attribute - A transducer with this attribute active begins acquiring or outputting a data set immediately upon receipt of a trigger. The timing of the remaining samples in the data set is under the control of the TBIM. If a trigger acknowledge is required it will be sent as soon as the first sample is processed. A typical example of this type of device would be a sensor that uses a sample-and-hold (S/H) circuit followed by a successive approximation or flash type A/D converter. When the trigger is received, the S/H would be pulsed to store a sample of the data. At this time the trigger acknowledge would be sent to the TBC. The A/D would then convert the data to a digital form and store it in the data set memory in the TBIM. After an interval specified in the Transducer Specific TEDS, the process of sampling, converting and storing a second sample would occur. This process continues until all samples required for the data set are available. At this time the sampling stops until another trigger is received.

Free running attribute - A sensor with this attribute active shall measure some physical parameter autonomously and continuously when enabled. The data being acquired and converted is discarded until a trigger is received. Once a trigger has been received the next sample converted is stored in the TBIM as the first word in the data set. Consecutive samples are stored in the TBIM until the entire data set is completed. At this point the transducer returns to discarding samples until the next trigger is received.

An actuator with this attribute active shall apply the previous data set in accordance with its End of Data Set Operation attribute. As a new data set is received from the transducer bus it will be held in the TBIM until a trigger is received and applied to the output at the appropriate time.

BUFFERED ATTRIBUTE

A transducer with this attribute active has multiple buffers to store multiple data sets. One buffer is being read from a sensor or applied to an actuator output while other buffers are available to be filled. A characteristic of a transducer with this attribute active is that the data available to be read or applied is always the data that was available in a buffer before the most recent trigger.

END OF DATA SET OPERATION ATTRIBUTES

These attributes determine the action that an actuator will take when it reaches the end of a data set. These attributes describe ways to allow actuators to smoothly transition from one data set to another. While this is desirable in most cases, there will be instances when a rapid transition to another condition is required i.e. emergency shutdown. For these cases, a second actuator transducer in the same TBIM may be used which executes the transition to the new condition or control commands may be used.

Hold attribute - This attribute is applied to actuators. An actuator with this attribute active will apply all of the samples in a data set and then hold the last value in the data set until a new trigger is received.

Recirculate attribute - This attribute is only used with actuators. An actuator with this attribute active applies all of the samples in a data set to the output, then returns to the beginning of the data set and repeats the application of the same data set. It will keep repeating this operation until another trigger is received. When returning to the beginning of a data set or to a new data set the appropriate sample interval must be maintained.

STREAMING ATTRIBUTE

A transducer with this attribute active begins to acquire data or to apply data when the initial trigger is received. Subsequent data samples are processed without waiting for a trigger. Since there are limited mechanisms for collision detection on the transducer bus, any TBIM with one or more sensors operating in the streaming mode must be able to support a dedicated data communications channel.

After the first trigger a sensor transmits a new data set as soon as it is acquired. This requires a dedicated data communications channel be available to the TBIM. Multiple sensors within a single TBIM may share this data channel but sensors in another TBIM shall not use it.
An actuator with the streaming attribute active applies the data written to it at the appropriate time after it has been received. An actuator with the buffers attribute active immediately switches to the next buffer after applying all of the data in the current buffer.

TRANSDUCER BUS INTERFACE MODULES

A TBIM consists of four basic elements, Transducer(s), signal conditioning, Transducer Electronic Data Sheets (TEDS) and a bus interface. Of these four elements only two are covered by the standard. The transducers and the signal conditioning are generally outside the realm of the standard. The only thing in the standard that is covered in these two elements is by implication and that is that the output of the signal conditioner must be digital not analog. There are several TEDS that are specified in the standard. Some of them are very tightly specified and others are very loosely specified. The TEDS that are essential to producing a plug and play device are tightly specified so that the system designer knows what to expect and where to obtain the information. Other TEDS are intended to be a way for the TBIM manufacturer to supply information to the operator and is not required for system operation. The bus interface is fully specified by the standard in order for TBIMs manufactured by transducer manufacturers to work with bus controllers supplied by some one else.

TBIM AND TRANSDUCER IDENTIFICATION

Each TBIM must be identified and set up by the bus controller before it is able to function in the system. To identify the TBIM the manufacturer assigns each TBIM a unique identifier called the Universal Unique Identifier or UUID. This identifier is a pattern of eighty bits that are defined using the algorithm originally defined in IEEE 1451.2 to guarantee uniqueness. A procedure is defined in the standard to allow the bus controller to identify the UUID of each device on the bus over the Bus Management communications channel. The identification of the TBIM allows the bus controller to assigns a logical address to the TBIM. Once the assignment of a logical address is accomplished the bus controller can then read the Transducer Electronic Data Sheets (TEDS) to determine the nature and characteristics of each transducer. The TEDS also define the communications capabilities of the TBIM so that the bus controller can set up the communications. At this point it is possible to switch the communications to the TBIM communications channel which operates at a higher speed than the Bus Management communications channel. If it is determined that the system does not need a particular transducer then that transducer can be assigned a logical address of zero and the transducer will not respond again until a different logical address is assigned.

TRANSDUCER ELECTRONIC DATA SHEETS

There are several Transducer Electronic Data Sheets (TEDS) which are defined for this standard. They can be classified in many ways. Some are machine-readable and are used to allow the bus controller to determine the characteristics of the device and others are text based and are used to give a human operator an understanding of the device. Three of the machine readable TEDS are required for system operation and all of the remaining TEDS are optional. For systems where small size or extreme operating environments do not allow the TEDS to be stored in the TBIM, the standard allows the TEDS to be stored on a remote server. A remote TEDS is known in the standard as a "virtual" TEDS. It is desirable that all TEDS be stored within the transducer but it is expected that for reasons of cost and device size some manufacturers will opt to use virtual TEDS at least for the TEDS that are not required for system operation. At the same time most users are expected to prefer TEDS in the TBIM since that makes the overall system more reliable. The marketplace will work out some sort of compromise in this area. We hope that for most applications that the Module Meta-TEDS, the transducer specific TEDS, the Calibration TEDS and the Commissioning TEDS will be stored within the TBIM. This will require something in the range of one kilobyte of non-volatile memory in the TBIM for each transducer.

Required TEDS - There are three TEDS that are required for operation of the system. The Module Meta-TEDS defines the characteristics of the TBIM as a whole. The system the communications capabilities of the TBIM are included in this TEDS. This will include such things as which communications channels are implemented and the range of operating frequencies. It will also define whether or not the TBIM has CDMA capabilities. There is one Module Meta-TEDS for each TBIM. The Transducer Specific TEDS then describe the characteristics of each individual transducer. There is one Transducer Specific TEDS for each transducer in the TBIM. In general these TEDS will be small containing only a few hundred bytes. However, the memory requirements for the TBIM will vary depending on the number of transducers in the TBIM. The third required TEDS is the Commissioning TEDS. This TEDS is provided by the TBIM manufacturer in the form of a sixty-four bytes of memory into which the user may write the parameter name associated with this transducer. This TEDS is not absolutely required for system operation but is needed to support IEEE 1451.1 and is believed to be useful in most systems. It will allow a TBIM to be set up in the laboratory or on the system for a particular application and then installed on whatever bus is convenient. The system can then identify the individual transducers in terms of their intended application rather than their Universal Unique Identifier (UUID).

Optional TEDS - There are several optional TEDS identified in the standard. All of the TEDS allowed in IEEE 1451.2 are included. The optional TEDS which is expected to be utilized the most often is the Calibration TEDS. This TEDS provides the constants necessary to convert the raw data into an engineering units form for sensors or to convert data from engineering units form to the form required by an actuator. Several other TEDS types are included. A Transfer Function TEDS can be used to describe the characteristics of a transducer in response to varying input frequencies. A Control Commands TEDS is used to define additional commands that are not included in the standard. These commands are useful when setting up the electronics associated with a transducer since every different transducer type and manufacturer will require a different set of setup commands.

Manufacturer Specific TEDS – Provisions are made in the standard for manufacturers to define their own set of TEDS that can be used to control or set up individual capabilities within a TBIM. For example, suppose a manufacturer desires to include a programmable digital filter with a TBIM. The manufacturer can define a TEDS that the TBIM knows how to interpret and use information in the TEDS to set up the digital filter. This could be used in either of two ways. If the manufacturer was selling transducers with different frequency response characteristics that were based on a single design, then the manufacturer could define and use this TEDS within the factory and not disclose its existence to the user. If the manufacturer wanted to sell this device and allow the user to program the digital filter then the TEDS would need to be disclosed to the user and the manufacturer would need to describe its structure to the user so it could be written. The use of Manufacturer Specific TEDS allows different characteristics to be downloaded into a TBIM in a standard fashion and if field upgrades to a device are required they can be loaded into the device without removing it from the users system in most cases. All Manufacturer Specific TEDS are optional.

Text-Based TEDS - There are Provisions in the standard for including Text-Based TEDS in the TBIM or as virtual TEDS that will be able to be displayed by a web browser. To this end the Text-based TEDS are to be written in the eXtensible Markup Language (XML) that is becoming popular on the Internet. XML provides the ability to provide information to be displayed as well as information on how to display it. This gives the manufacturer almost unlimited ability to supply data and have it displayed to the user in the desired format. When this is coupled with the capability to provide virtual TEDS manufacturers are expected to be able to supply operating instructions and even complete users manuals in this form. All Text-Based TEDS are optional.

COMMUNICATIONS CAPABILITIES

There are several capabilities that are allowed in the standards that place requirements on the physical layer in the system. The streaming attribute that can be used for sensors requires that TBIMs be able to utilize independent communications channels. The reason that streaming requires independent communications channels is so that the time of the sample can be determined in the bus controller rather than in the TBIM. The desire to be able to time tag the samples in the bus controller rather than in the TBIM is one of cost. One goal of the working group is to be able to minimize the cost of the TBIM since there are many of them in a system at the expense of the bus controller since there is only one bus controller per bus. A similar requirement is placed on the communications by Event Sensors. The event sensor should be as simple or as complex as the manufacturer wants to build and for simple devices the time of the event needs to be determined in the bus controller not the TBIM.

Two physical layers are being defined in the standard. The original physical layer planned for the standard uses cable TV technology and chip sets. Using this technique multiple RF carriers are combined on a single cable. Each communications channel can support a single high bandwidth TBIM or can use one of two techniques to place many TBIM outputs onto the same frequency. The first approach is Time Division Multiplexing (TDM). In this mode of operation the bus controller will issue commands and the devices will respond. With this mode of operation only the device addressed in the command will respond so there is no need for collision detection. This capability can be expanded by using multiple center frequencies to allow multiple devices to respond at the same time by assigning then to different center frequencies. A second technique can be used to place multiple communications channels on the same frequency and that is the use of Code Division Multiple Access (CDMA). CDMA has recently been popularized by its use in cellular telephones. This technique allows many devices to share the same frequency, to transmit simultaneously and not to interfere with each other. The second physical layer eliminates the RF circuits and does all transmissions at the base band. Using this technique in conjunction with TDM allows a large number of devices to be used on the same bus but only one device can communicate at one time. However this technique can be expanded by the use of CDMA. Using CDMA in base band communications allows multiple devices to talk on the bus at the same time without interfering with each other. The frequencies chosen for the RF modulation techniques are such that both the RF and the base band communications channels can co-exist on the same cable.

The RF systems are useful when wide bandwidth channels are required or where very large numbers of channels are requires on a single cable. The other reason for using the RF technique is when the cable length exceeds 100 meters. The RF technique will allow bus lengths of a few kilometers with a properly designed system. As an example of a system that might want to use the RF techniques consider a security system utilizing several video cameras (sensors) and a series of door and window position sensors. This system needs a wide bandwidth channel for each camera that will be transmitting simultaneously. For example lets assume that there are five cameras, one on a door and one each for four windows. Since most activity is expected to occur around the door a dedicated communications channel might be assigned to that camera and the other four cameras could share a communications channel by having the bus controller select which one can use it at any given time. A separate communications frequency could be shared with the position sensors by having the bus controller poll them (TDM). Another option for the position sensors would be to make them event sensors and assign each one of them a different code using CDMA. With this arrangement each of the event sensors can be armed by sending it a trigger and it can report a change of state any time one happens without concern for anybody else being on the channel. Another possible configuration would be to put the cameras on two RF channels and to operate the position sensors on a base band channel using CDMA techniques.

Three communications channels are defined in the standard. They are listed in Table 2. The synchronization clock is not considered a communication channel but is included in the table for convenience.

Table 1 lists some of the functions that are expected to be performed within the TBIMs using one or more of the communications channels.

WIRELESS TECHNIQUES

Wireless techniques are not being included in the standard at this time for several reasons. The major reason being that while wireless techniques are great for many applications, systems with many transducers that must remain in place for long periods of time, the ability to provide power over the communications medium is an overriding need. However, many on the working group have a desire to move to wireless for some applications in the future and some are working on them now. The group is considering wireless when decisions are made with the intention that the standard can be expanded to include wireless capability or a new standard can be derived from this one with minimum changes in the future.

Table 1—Functions performed in a TBIM

Function	Comments
Discovery	Discovery is the process by which that the TBC can learn what devices are installed on a particular bus. It is accomplished using a special procedure based upon reading the UUID in the TBIM.
Bus Set Up	Bus set up involves reading the Transducer Electronic Data Sheets (TEDS) and any other required control structures from the TBIMs and using that information to configure the interface to the bus.
Transducer Set Up	Transducer set up involves reading the TEDS and any other required control structures from the TBIMs and using that information to configure each transducer on the TBIM as required for the system.
Control	Control functions involve the control commands that are required to control the operation of the TBIM while the system is being set up or when it is running.
Status	Each TBIM has a status register or registers that are used to inform the TBC of the condition or state of the TBIM. These registers can be read over the bus.
Service Request	A service request is much like a computer interrupt. As such it allows a TBIM to inform the TBC that something has changed within the TBIM. The main difference between an interrupt and a service request is that there is no guaranteed response time between when a service request is invoked and when the system gets around to servicing it.
Data Reads and Writes	The transmission of data between the TBIMs and the TBC is the primary purpose of this standard. There are several ways that these functions can be performed in the standard depending upon which communications channels are available and being used.
Triggers	A trigger is a specialized command that is used to cause a TBIM to take a specific action. For example a trigger might cause a sensor to take 1000 samples of an input and transfer the data to the TBC.
Synchronization	The bus controller provides a clock that can be used by all receiving TBIMs for any desired purpose. Most commonly it is expected to be used in conjunction with the trigger to synchronize operations between multiple TBIMs
Program Memory Downloads	It will be necessary at times to load the contents of the memory in a device. These facilities may or may not be available to the user since they are mainly intended for use when manufacturing the TBIMS but they may be desirable when upgrading devices in the field.

Table 2 Bus Communications Channels

Function	Description
Bus Management	This bi-directional communications channel provides all of the capabilities required for a system to be able to identify the TBIMs on the transducer bus, determine their capabilities, set them up and operate them. It communicates at a frequency(s) defined in the standard or at the base band and must be in all TBIMs. It operates in a command/response mode and has a relatively low bandwidth. For very simple systems this may be the only communication bus in the system. In more complex systems this communications channel allows the bus controller to discover new devices on the system, set up new devices and run diagnostics without impacting the operation of the rest of the system.
TBIM	The TBIM Communications channel is also bi-directional and provides most of the capabilities of the bus management communications channel but has a higher bandwidth. If RF techniques are used the operating center frequency(s) that can be defined by the system. It cannot perform the discovery function or the initial bus setup (see Table 1). For systems with relatively low bandwidth requirements all data communications may take place over this bus.
Data Transfer	This uni-directional communications channel is used to transfer data from the TBIMs to the bus controller or from the bus controller to the TBIMs. There may be many of these in a system operating at different center frequencies or codes. They can be used for high bandwidth data transfers or they can be shared by many transducers by using Code Division/Multiple Access (CDMA) techniques. These communications channels become important when streaming sensors or event sensors are used in a system. They will also be needed when wide bandwidth channels are required.
Synchronization	This function will be performed by supplying a sine wave clock at a relatively high amplitude over the wires. The frequency of this clock will be defined in the standard once the physical layer is fully defined and will probably be in the 10 to 100 MHz range. For base band operation a square wave clock will be included with the data to perform this function.