Multi-drop, Simultaneous Sampling Sensor Network System for Aerospace Testing and Monitoring Applications

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Abstract: Typical test and monitoring systems are based on separate stand-alone instrumentation and require point-to-point analog wiring, which usually results in cumbersome cabling and connectors, bulky instrumentation, susceptibility to EMI/RFI noise pick up, lack of system flexibility, and a compromised signal-to-noise ratio (SNR). This paper describes a novel Distributed, Simultaneous Sampling Smart Sensor Network system solution with multi-drop sensor architecture and smart digital output sensors interconnected to a network interface controller through a digital transducer bus with power and digital signals sharing the same pair of wires.

Nomenclature

ADC	=	Analog-to-Digital Converter
BIT	=	Built-In-Test
IBIM	=	Intellibus Interface Module
NDI	=	Network Device Interface
NIC	=	Network Interface Controller
PDTB	=	Power-Data Transducer Bus
PE	=	Piezo-Electric
PR	=	Piezo-Resistive
SNR	=	Signal-to-Noise Ratio
TEDS	=	Transducer Electronic Data Sheet
VOTM	=	Vibration Order Tracking Module

I. Introduction

Several different types of measurements are typically required in aircraft testing and on-board monitoring applications, including pressure, temperature, strain, flow, vibration, etc. As many as four to ten wires from each sensor carry small analog signals and power to and from the analog signal conditioning and data acquisition instrumentation. For large numbers of sensors, this translates into large numbers of wires that add weight and occupy significant space. In many instances, a significant amount of time is spent making sure that the right sensor was connected to the right signal conditioner or data acquisition channel (configuration control).

Traditional measurement systems based on analog transducers and stand-alone instrumentation result in bulky electronic boxes and in large, long and heavy bundles of cables carrying small analog signals that are susceptible to EMI/RFI noise pick up, and are difficult to manage. Furthermore, opportunities to add new sensors to existing systems designs are severely limited because of the difficulty in accommodating additional cabling and signal conditioning electronics in the available space.

Aircraft monitoring systems, for example, include hundreds of pounds of cables and connectors. Ground and flight tests of commercial airplanes use approximately 7,000 transducers and associated signal conditioners, and all of those interconnecting cables are very difficult to manage. A typical test setup of a large number of channels is shown in Fig. 1 and 2.

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Figure 1. Ground Aircraft Testing. Bundle of cables covers a jet fighter under structural testing

Figure 2. Flight Aircraft Testing. *Instrumentation racks inside Boeing 777 airplane during flight test*

Typical large commercial get engine testing uses approximately 1,250 transducers for ground test, and about halve this number of sensors for flight testing.

There are different types of analog sensors, such as pressure, temperature, speed, position, acceleration, etc, Each of them requires up to 4 interconnecting wires plus shield, which run approximately 50 feet to a connect/disconnect patch panel. See Fig. 3 and 4.

A measurement system that includes all these sensors resulted in 3,200 interconnecting wires, with a total length of approximately 62,500 feet and weight of 1,939 pounds. The typical cost of instrumentation without including the sensors is $1.3 M and the installation cost is over $256K per aircraft.

Figure 3. Jet Engine Testing

Figure 4. Instrumentation Patch Panels

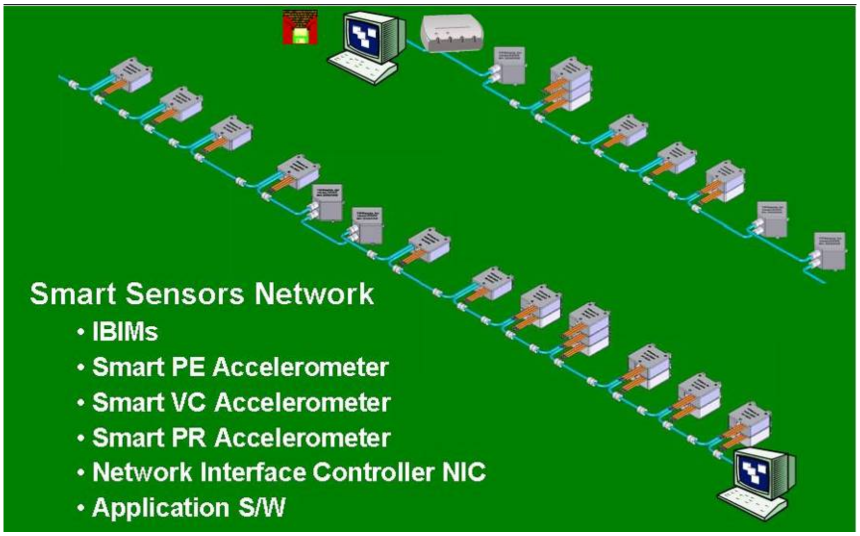

Figure 5. Network Sensor Architecture. Smart Sensors Network system eliminates bundle of cables, makes measurement systems more reliable and more flexible

The Smart Network Sensor solution described in this paper is a multidrop sensor bus architecture with smart digital output sensors interconnected to a network interface controller (NIC) through a common digital transducer bus. This new system integrates all of the required measurement functions in a small electronic module that can be placed inside a traditional transducer, thus making it a "Smart Sensor" with digital output, or as a separate module that will interface any traditional analog transducer to the bi-directional digital bus. The sensor network system reduces cabling and connectors, provides a common interface for multiple types of sensors, easily supports the addition of new sensors, and improves reliability.

Many digital networks presently exist 3 but lack one or more features such as: the ability to synchronously acquire data from multiple distributed nodes, could not be implemented in a small package, or lack the bus speed to acquire data from multiple nodes at high sampling rates. IEEE 1451.3 defined a smart sensor network that addressed many of these technical issues; unfortunately manufacturers have not adopted this standard because of the difficulties implementing it in a small package with low power consumption.

The proposed measuring system was tested at Wright Patterson Test cells and showed that the new networked system significantly reduces interconnecting cables, size and weight. It reduces installation time readiness and maintenance costs. It also increases performance and reliability.

This novel system was developed under the "Hypersonic Sensor Architecture Evaluation, Sensor Testing and Communication Needs" SBIR program funded by the AFRL.

VIP Sensors continues the development of this technology for Jet Engine applications under NAVAIR funded SBIR program title "Multi-component Aircraft Engine Monitoring".

II. Smart Sensor Network System Description

The proposed Smart Sensors Network System is a distributed sensor instrumentation system with synchronous/simultaneous sampling consisting of smart digital output sensors and transducer modules interconnected to a Network Interface Controller (NIC) through a multi-drop digital serial bus (IntelliBus). Small electronic modules called IBIM's (IntelliBus Interface Modules) are used to interface any traditional analog transducer to the bi-directional digital bus (see Fig. 6 and 7).

Smart Networked Sensors include the sensors element, analog signal conditioning, analog-to-digital conversion, and digital signal processing & communications functions in one mechanical package. They communicate directly to the transducer bus.

The IntelliBus Interface Modules (IBIM's) contain all the functions of a measurement system except the sensor element. They make an analog transducer become "smart" so that they can interface to the digital transducer bus. See Fig. 6.

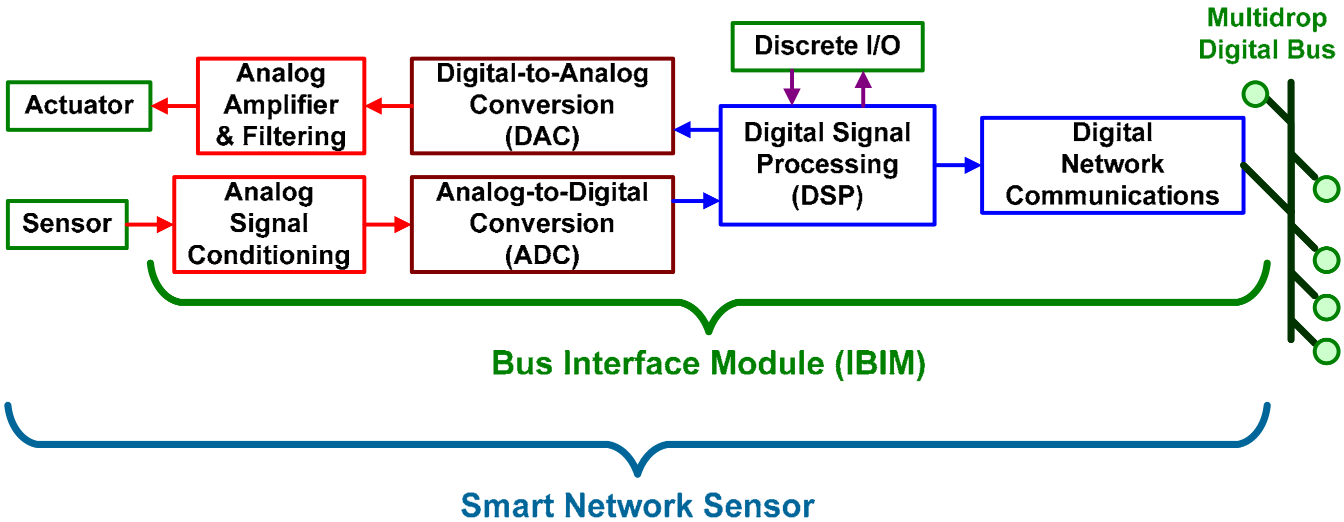

Figure 6. Smart Sensor Functional Diagram

The Network Interface Controller (NIC) provides a gateway between the transducer bus (Intellibus) and an on-board computer or, depending on the configuration, with a downstream wired Ethernet port or telemetry system. The NIC communicates digitally with the IntelliBus Interface Modules (IBIM) through a standard digital transducer bus.

The NIC is the master of the digital network (only 1 IBIM can transmit at any given time after receiving a command from the NIC). The NIC provides DC power and synchronization signals to achieve synchronous/simultaneous data sampling among all the sensors and IBIM's on the Transducer Bus.

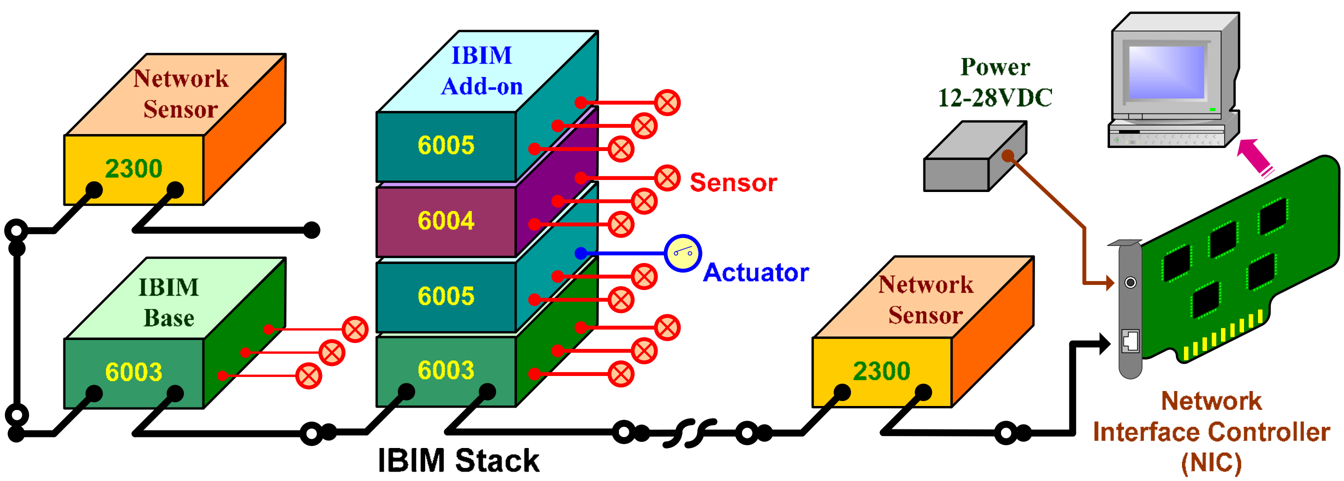

Figure 7. Smart Sensor Network System

IBIM's are designed as stand-alone, distributed sensors and control nodes. Software algorithms are implemented in their internal microprocessor to sense, process the signals, and, based on the obtained data, control actuators and switches. this feature increases the flexibility and attraction of the Intellibus architecture system.

VIP Sensors' newly introduced family of transducer modules may be configured as stand-alone distributed modules as shown in Fig. 8, or they can be stacked in order to increase the channel density per node as shown in Fig. 9 and 10. Up to seven modules may be stacked up with one network interface base unit to form up to 39-channel signal conditioner-data acquisition assembly in 1.5 x 1.5 x 5.8 inches.

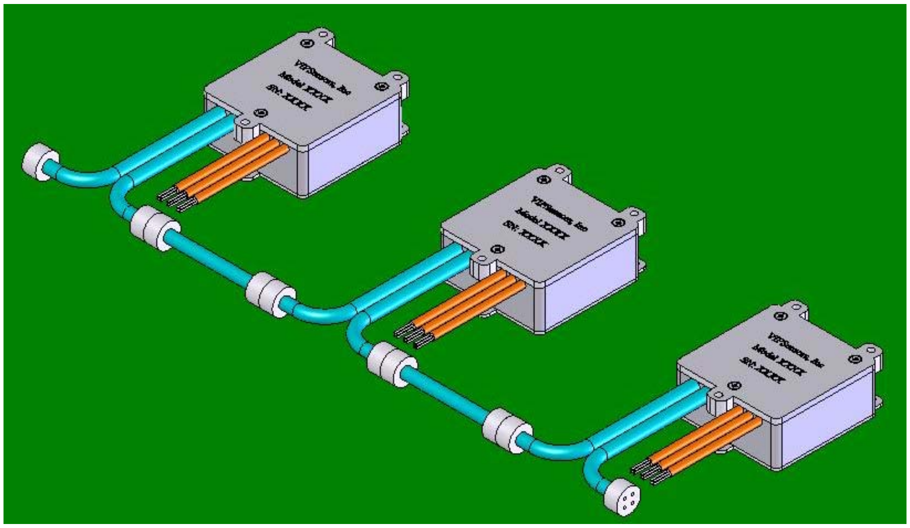

Figure 8. Base Modules - three channels each, one network node per module

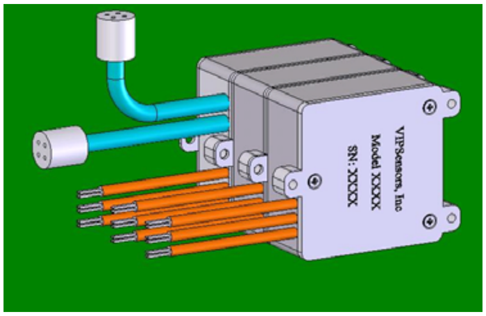

Figure 9. Horizontal module stack configuration

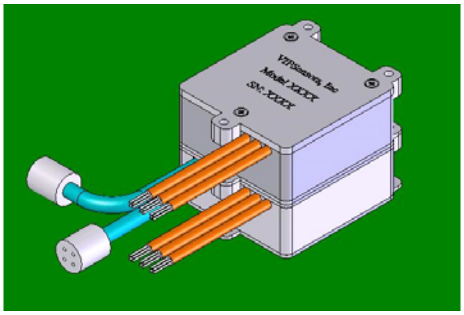

Figure 10. Vertical module stack configuration

IntelliBus, the transducer network bus protocol used in VIP Sensors' newly developed system, is an isochronous, half-duplex, multipoint serial bus running at 15Mbps. Its physical layer consists of a 2-wire shielded-twisted-pair (RS-485) plus power and ground wires. Power can be from 12 to 32 VDC.

All of the sensors and IBIM channels may be sampled simultaneously and synchronously. There are less than ± 9 nanoseconds of cycle-cycle and period jitter. The sample rate of each smart sensor and IBIM in the bus is set independently.

Up to 510 nodes (smart sensors and/or IBIM's) can be addressed by the NIC. The number of IBIM's that can be connected to a NIC depends on the number of channels in each IBIM node, bus speed, power consumption, length of the cable, and sampling rate. The higher the sampling rate, the lower the number of transducer channels. The current design is limited to 15 Mbps bus speed and 7 Amperes DC supply. Twenty-five (25) nodes at 600 feet and 64 nodes at 300 feet have been proven to work properly at the 15 Mbps rate.

Plug and Play is one of the most useful features of the new networked system. Since all devices in the transducer bus each have a Transducer Electronic Data Sheet (TEDS) stored in local non-volatile memory, the NIC is able to do discover what devices are on the bus, and interrogate their configuration settings, status, etc.

Plug and play facilitates replacement of units that are not working properly and facilitates changes in the system configuration. Increasing or decreasing the number of measurement channels becomes an easy task.

Intellibus was originally designed by Boeing and has been deployed successfully in various aerospace programs.

A. IBIM Detail Description

VIP Sensors' newly developed IBIM's have three input channels of low-noise instrumentation amplifiers with programmable gain (0.5 to 1000), and programmable offset that allow conditioning of different transducer types such as strain gages, accelerometers, thermocouples, pressure transducers, etc. Each of the front-end amplifiers is followed by two selectable 3-pole anti-aliasing filters. There is one 16-bit A/D converter per channel with a programmable sample rate of up to 250 ksps, but the aggregate rate for all three channels can not be greater than 300 ksps.

Over-sampled data is acquired simultaneously in all three channels and piped into a powerful DSP processor capable of implementing real time digital signal processing algorithms, such as FFTs, digital filters, data correction over temperature, linearization, etc.

A 64th order, low-pass FIR filter is provided as a standard feature, which allows the selection of various corner frequencies and filter shapes. Different filters (types and comer frequencies) are easily implemented by choosing the proper filter coefficients and storing them as part of TEDS through the transducer bus.

The onboard processor sets each IBIM channel according to the stored TEDS information or any new configuration sent by the NIC. It also performs self test under the NIC command.

IBIMs (base or stand alone units) communicate to the transducer bus through a Network Device Interface (NDI) which handles the Intellibus digital bus protocol. Add-on IBIMs used to form stacks do not have the NDI logic, and they communicate to the NIC through the IBIM base.

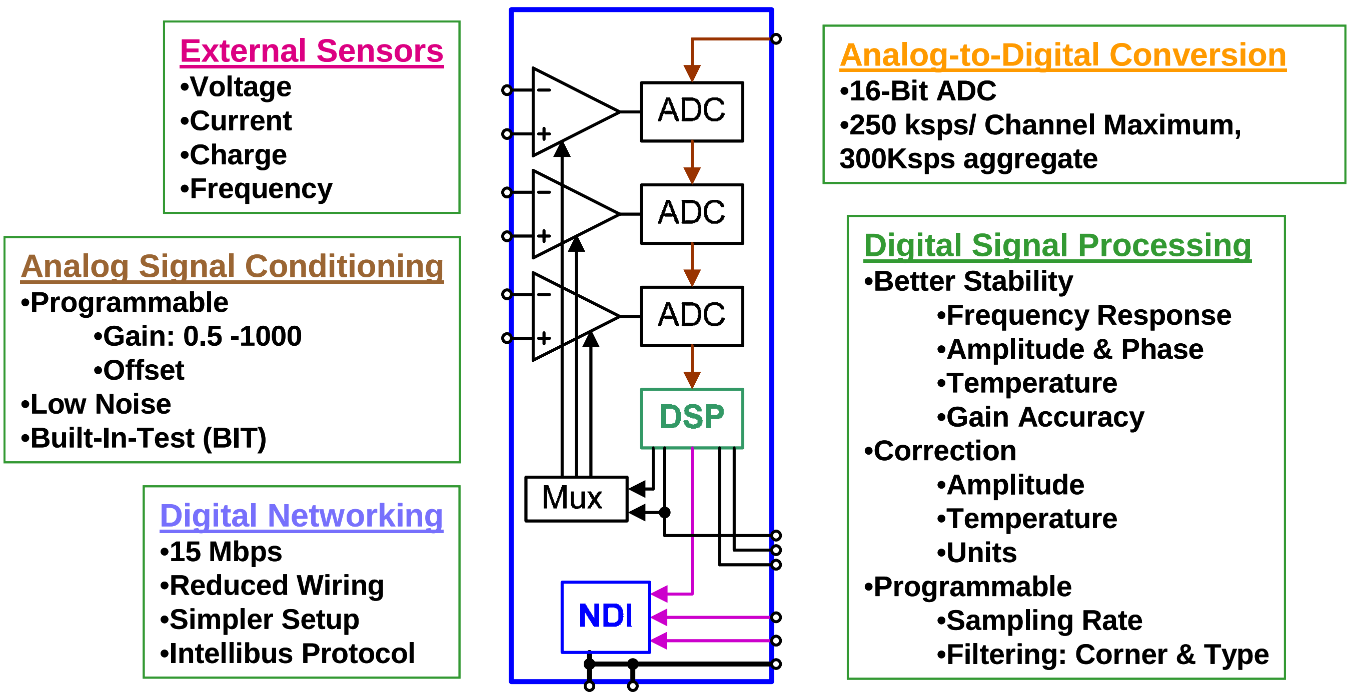

Figure 11. IBIM Block Diagram

B. NIC Detail Description

The Network Interface Controller (NIC) controls the transducer bus activity. It is a gateway between the transducer bus and other commonly used buses such as Ethernet, PCI (computer bus), Arinc429 and Mil-1553 (avionics), etc. The current VIP Sensors NIC is designed as a PCI-X plug-in card and supports two transducer buses.

The NIC controls various functions, such as changing the data collection rate, programming different scales and different filters, and performing data analysis and data fusion in order to better manage the network bandwidth.

The following are some of the functions performed by the Application Software running on the host computer:

- Assigns Channel Addresses
- Reads/Writes TEDS
- Initiates IBIM Diagnostics/Self-Test
- Configures IBIM's Amplifier Settings (Gain, Offset, Sampling Rate)
- Synchronizes Sampling Rate Among Multiple IBIMs by issuing Software Trigger Commands
- Establishes Digital Sampling Schedules
- Time Tagging
- Collects and stores data in disk

III. Smart Sensor Network System for Jet Engine Testing

VIP Sensors continues the development of the Smart Sensor Network technology for Jet Engine applications under NAVAIR funded SBIR program title “Multi-component Aircraft Engine Monitoring”.

The Smart Sensor Network System for Jet Engine Testing consists of a Thirty Two Channel Piezo-resistive (PR) IBIM, a Sixteen Channel PR IBIM, a Sixteen Channel Piezoelectric IBIM, and a Vibration Order Tracking IBIM. See Fig. 12.

Smart Sensors and interface modules are connected to the Network Interface Controller (NIC) through a common Power-Data Transducer Bus (PDTB). Up to eight 4-Channel NIC cards may be housed in a standard off the shelf cPCI rack. The number of NIC cards, smart sensors, IBIMs, and transducer types are specific to each test set up.

The Smart Sensor Network System is designed to acquire data from all the transducers in the bus synchronously and deterministically. The time jitter from channel to channel is under 9 nsec.. All the transducers selected by the NIC to acquire data are sampled simultaneously and data is streamed to the NIC according to a preprogrammed sampling schedule.

There are three major differences between this system and the standard system previously described in section I: (1) the IBIM modules are designed to survive in the harsh jet engine environmental conditions, (2) the Power-Data Transducer bus combining power and digital data in the same pair of wires, and (3) the multi-channel cPCI NIC card with Ethernet interface.

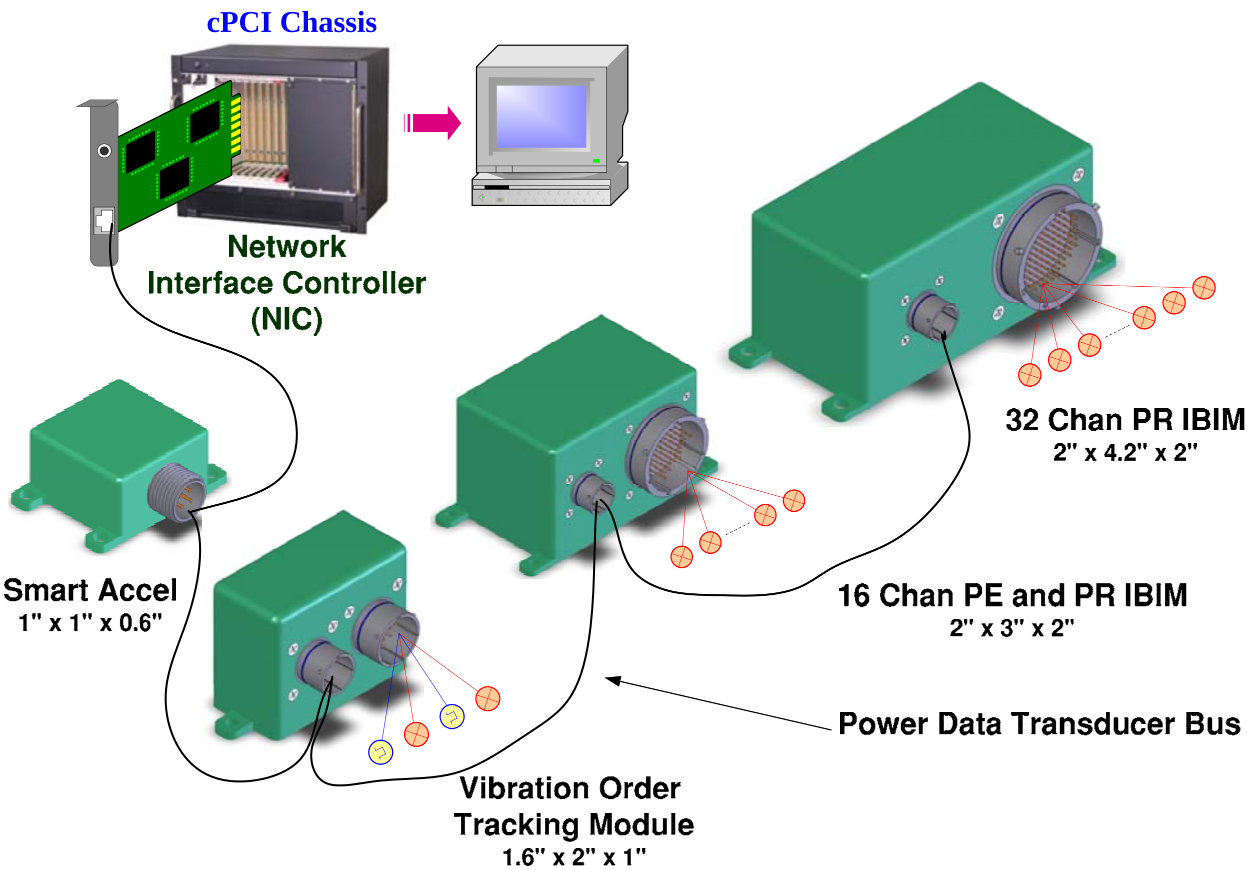

Figure 12. Smart Sensor Network System for Jet Engine Testing: It accepts different transducer types to meet the variety of measurement channels and is scalable to meet different configurations

A. Power-Data Transducer Bus (PDTB)

The Physical later consists of a multi-drop bidirectional digital bus with three wires: a shielded twisted pair that carries the differential digital data and DC power, and a third wire used as grounded and shield. The PTDB was developed, after careful consideration of the application needs (Jet Engine Testing), extensive analysis of different models, and after extensive testing of different prototype schemes.

B. Network Interface Controller (NIC)

The NIC manages the transducer bus activity. It is a gateway between the Power-Data Transducer Bus and Ethernet. It consists of a four-channel transducer buses with a common interconnecting Ethernet port, which supports data rates of 10 /100/1000 Mbps. The card plugs in a 33 or 66 MHz, 32 bit, 3.3V slot of a standard off the shelf cPCI rack

C. Vibration Order Tracking Module

The Vibration Order Tracking Module (VOTM) processes the signals from 2 accelerometer inputs and 2 tachometer inputs and performs order analysis and order tracking. The analog signals are amplified and band-pass filtered before they are digitized by the 16-bit Analog-to-Digital Converters (ADC) to maximize the signal-to-noise ratio (SNR), improve accuracy, and avoid aliasing. Acceleration signals are integrated and converted to velocity at the front-end to avoid saturation of the charge amplifier and maximize dynamic range.

The digitized accelerometer signal is processed through a broadband and narrowband digital bandpass filters and also through an FFT (constant bandwidth). The narrowband digital filter can be set to a fix frequency or set to track to either one of the tachometer signals using a constant-Q digital filter. The frequency response characteristics of the digital filters can be customized by downloading a new set of digital filter coefficients.

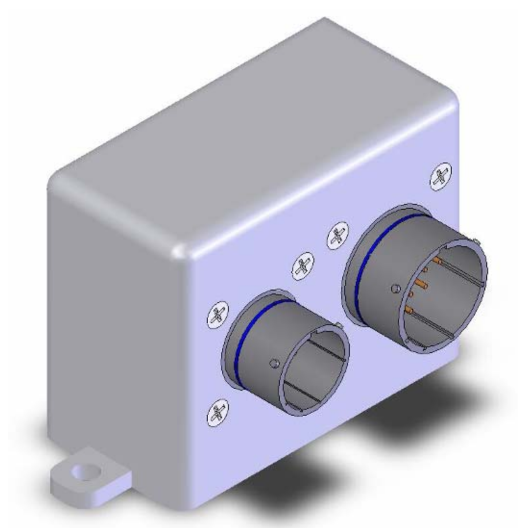

Figure 13. Vibration Order Tracking Module Size:1.6” x 2” x 1”

The VOTM can output FFT, amplitude vibration data (broadband and narrowband), tachometer frequency, and phase if reference index pulse is available in the tachometer signal. Amplitude vibration data can be output in velocity or displacement units. Three (3) types of reference tach index pulse can be detected by the VOTM: greater-than-normal, less-than-normal, and one-per-rev.

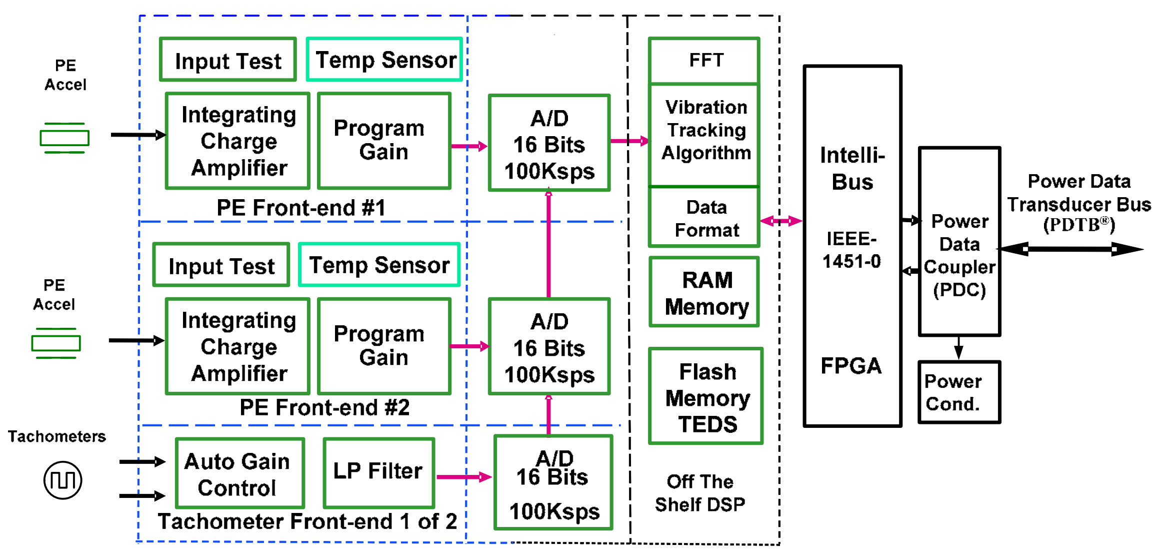

Figure 14. Vibration Order Tracking Module (VOTM) Functional Block Diagram

D. Sixteen Channel Piezo-Electric Transducer Bus Interface Module

The Sixteen Channel Piezoelectric Transducer Bus Interface Module accepts charge signals from 16 transducers such as Piezo-electric (PE) accelerometers and PE pressure sensors. The analog signals are amplified by a low noise charge amplifier with programmable gain (4 to 1000). Each channel is bandpass filtered before they are digitized to maximize the signal-to-noise ratio (SNR), improve accuracy, and avoid aliasing. Each channel has its own independent 16-bit Analog to Digital converter with programmable sample rate up to 250Ksps Over sampled data is acquired simultaneously in all 16 channels and processed by a 32-bit DSP processor capable of implementing real time algorithms such as data correction, digital filtering, temperature correction, and data scaling (i.e. unit conversion.) The processor also provides Built-In-Test (BIT) of the sensor and electronics. Bidirectional data is transferred through the Power-Data Transducer Bus (PDTB) at 15Mbps in a half duplex configuration using IntelliBus protocol.

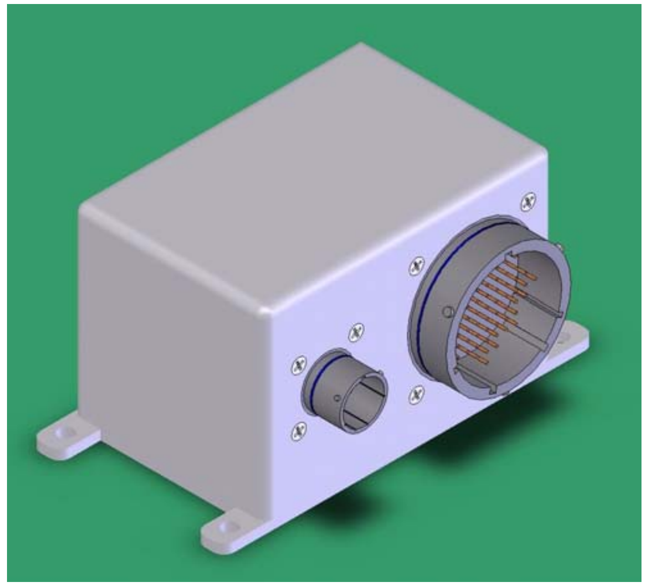

Figure 15. Sixteen Channel Piezoelectric IBIM Size: 2” x 3” x 2”

Mil 38999 connector types are used for the PDTB bus and to interface with the different traditional analog transducers.

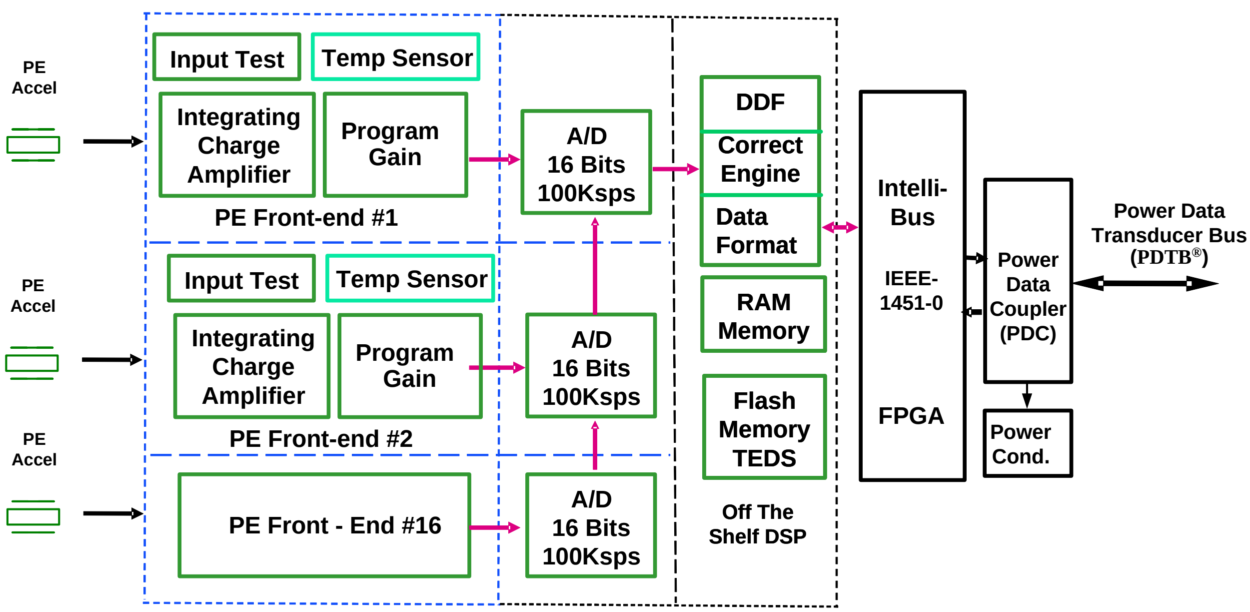

Figure 16. Sixteen Channel Piezoelectric IBIM Functional Block Diagram

E. Thirty Two Channel Piezoresistive Transducer Bus Interface Module

The 32-Channel Differential Voltage Amplifier TBIM Module (BAM32) accepts the signals from 32 resistive bridge (1/4, 1/2, or full bridge) type sensors. The analog signals are amplified by a low noise instrumentation amplifier with programmable gain (4 to 1000) and programmable offset. Each channel is bandpass filtered before they are digitized to maximize the signal-to-noise ratio (SNR), improve accuracy, and avoid aliasing. Each channel has its own independent 16 bit Analog to Digital converter with programmable sample rate up to 250Ksps,

Over sampled data is acquired simultaneously in all 32 channels and processed by a 32-bit DSP processor capable of implementing real time algorithms such as data correction, digital filtering, temperature correction, and data scaling (i.e. unit conversion.) The processor also provides Built-In-Test (BIT) of the sensor and electronics.
Bidirectional data is data is transferred through the Power-Data Transducer Bus (PDTB) at 15Mbps in a half duplex configuration using IntelliBus protocol.
Mil 38999 connector types are used for the PDTB bus and to interface with the different traditional analog transducers.

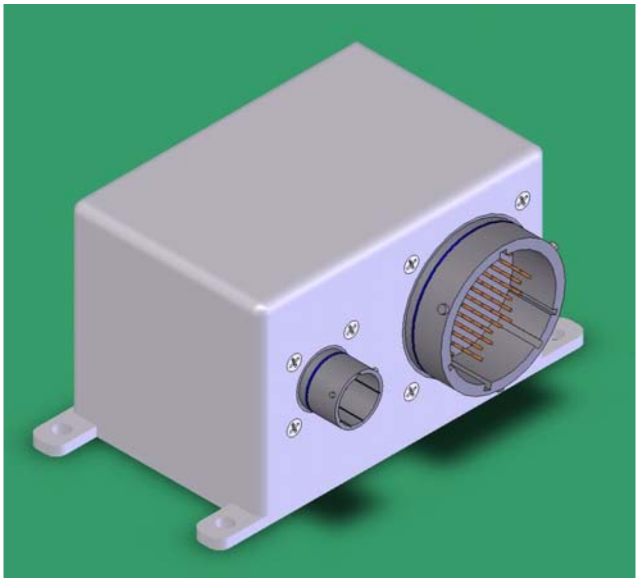

Figure 17. Thirty Two Channel PR TBIM
Size: 2” x 4.3´x 2”

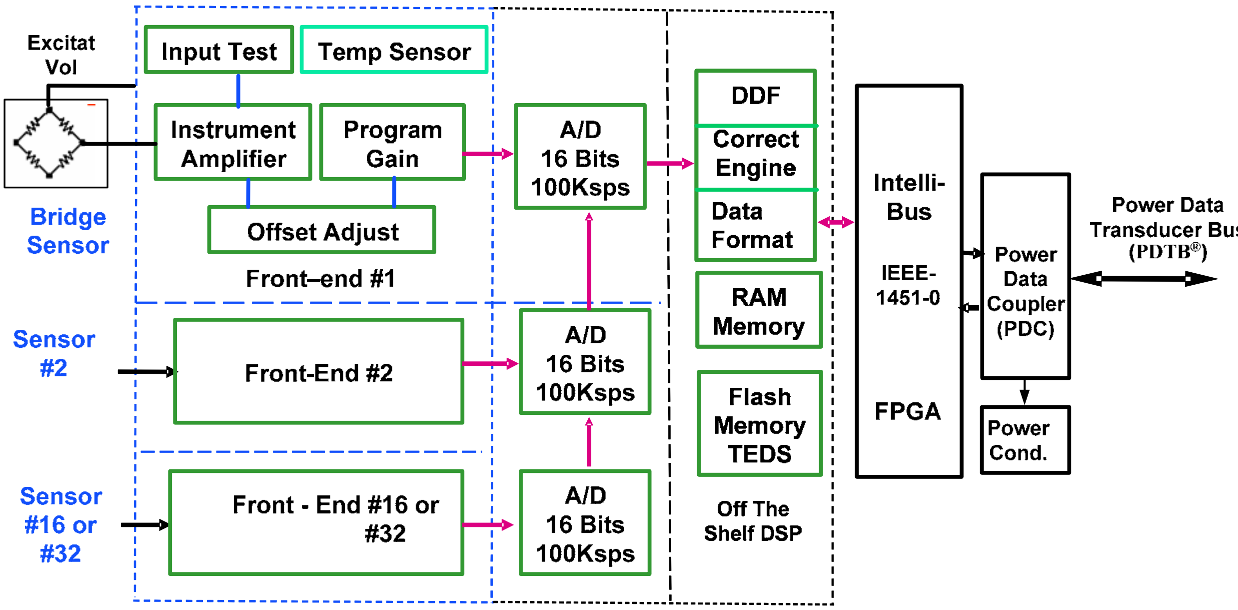

Figure 18. Thirty two Channel Piezoresistive IBIM Functional Block Diagram

IV. Smart Sensor Network Advantages

A significant saving of interconnecting cables, weight, and cost will be achieved if a Smart Sensors Network system for Jet Engine Testing is implemented instead of the traditional approach described in section I and shown in Fig. 2. The new system uses 60 IBIMs, interconnected by 32 network cables. The new patch panel requires 99 contacts versus the 3,200 needed by the present system; and each network cable has 2 conductor plus shield. A total of 13,820 feet of cables is needed versus 62,500 feet of the traditional system; a savings of 48,680 feet of cables. The cable and instrumentation weight of the system is reduced from 1,939 lbs to 343 lbs, a reduction of 1,596 lbs. This new system also promises a $490K saving in equipment cost and significant labor savings to instrument each engine.

The Smart Sensors Network system for Jet Engine Testing has the potential to eventually migrate and become an onboard system which will facilitate the implementation of Prognostic Health Monitoring (PHM) functions.

A. Minimum Interconnecting Cables

The number of cables and cable lengths dictated by traditional star topologies of interconnecting analog transducers to a central signal processing equipment has a detrimental impact on all aspects of a measurement system. These factors decrease the accuracy and reliability of measurements, decrease system performance, and increase system operating costs.

The multi-drop sensor network architecture of the proposed system allows drastic reduction of interconnecting cables. The Smart Sensor System interconnects all of the transducers through a common digital bus cable. The centralized, bulky electronic boxes typical of traditional measurement systems are replaced with miniature modules strategically distributed throughout the setup.

B. High Reliability

Reliability is improved by reducing the total number of interconnecting cables and including Built-in-Test (BIT) features. Self test adds a higher level of confidence that a given measurement channel is alive and working properly.

C. High Performance

Large numbers of analog transducers result in difficult-to-manage, large, and long bundles of cables carrying analog signals which are susceptible to being corrupted by EMI/RFI noise. Cables carrying digital signals are more immune to these problems and are easier to interface than cables carrying analog signals.

Higher measurement accuracy is obtained by digital correction over the operating temperature range of both the transducers' sensitivity and the analog signal conditioning instrumentation.

D. Distributed Simultaneous Sampling

The proposed system has the ability to simultaneously acquire data even though the analog-to-digital converters (ADC) are distributed among the various smart sensor nodes.

E. Easy to Design, Use and Maintain

The primary concern of users of sensor information is to accurately measure physical phenomena in engineering units such as Pascal, meters, m/sec2, g's, PSI, etc. To achieve this goal, the user needs to take into account installation issues such as interfacing different types of transducers to their measurement system; and selecting the proper analog amplifier settings (sensitivity-gain normalization, type of filter, excitation voltage-current, etc.) for each analog transducer.

Transducer Electronic Data Sheet (TEDS) stored in each smart sensor and interface module helps to reduce the complexity of the system design, integration, maintenance and operation.

Features such as transducer identification, self-test, test setup configuration, configuration status, etc. can be performed under computer control with minimal need for any manual trimming or adjustments. The smart sensors and interface modules exhibit plug-and-play features to ease the measurement system usage.

F. Scalable - Flexible System

The new network measurement system accepts different types of transducers, including traditional analog types as well as new smart network sensors. It allows for easy expansion or reduction in the number of measurement channels. This is possible with the use of Intellibus Interface Modules (IBIM).

G. Small Rugged Packaging

The proposed measurement system components are small, lightweight and packaged to operate under demanding environmental conditions typical of aerospace applications such as high vibration, high temperature, high pressure, humidity, EMI/RFI, etc.

H. Minimum Cost

Design, operating, and maintenance costs are drastically reduced by implementing a system with all of the above listed attributes. The initial capital investment may be similar or slightly higher than traditional systems; however, this marginal additional expense is far outweighed by savings in other areas.

A standard hardware interface for all transducer types will eventually reduce the capital equipment costs. A standard software interface (standard data interchange) would greatly reduce ongoing operating and maintenance costs.

V. Conclusion

VIP Sensors has developed and proved a new miniaturized Smart Sensor Network Measurement System, which represents a paradigm shift from a centralized to a distributed processing measurement approach. It significantly reduces the number and lengths of cables, the components size, and system weight. It provides greater flexibility in design, configuration and installation. All of these advantages translate into cost savings throughout the life of a program.

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