IMPROVING SYSTEM ACCURACIES THROUGH DISTRIBUTED DATA ACQUISITION TECHNIQUES

Jon Semancik
VXI Technology, Inc.
2031 Main Street
Irvine, CA 92614
949-955-1894
jons@vxitech.com

INTRODUCTION

Measuring real world parameters such as temperature, strain, pressure and flow may seem trivial to many, but performing these measurements in near the test article in electrically noisy or hazardous environments represents a unique set of challenges. Typical approaches involve placing the instrumentation in a control room that is physically separated from the test article, often by hundreds of feet, and then connecting the transducers to the test article.

A centralized approach such as this provides convenient control room access to the signal conditioning and instrumentation, but also results in creating unintentional sources of measurement error. Errors introduced from long cable lengths, either between signal conditioning and the instrument or by connecting directly to the instrument, include electrical noise, calibration uncertainty, bridge excitation uncertainty, and cable impedance. Additionally, this approach also has significant cost drivers associated with implementation such as cabling, debug, maintenance, and setup.

Instrumentation designers adopting a distributed measurement philosophy must include key functionality, such as internal signal conditioning. Programmable internal signal conditioning, on an individual channel basis, eliminates the need for external cables that can lower measurement quality, increase setup time, and result in additional maintenance. This approach provides protection against adjacent channel over-voltage and noise interference that occurs when measurements are made utilizing common filter circuitry as seen in scanning DMM architectures.

Other essential functionality must include a convenient mechanism for in-place self-calibration, as well as NIST traceable calibration. Complete end-to-end internal self-calibration, at actual test temperature, provides significant accuracy improvements over typical approaches. This compensates for circuitry drift that has occurred since the last full calibration, and should de easily performed by the user. Furthermore instrumentation that interfaces with transducers requiring excitation, such as bridge-based devices, must also provide this functionality.

While employing distributed measurement techniques can greatly improve measurement accuracies by placing the instrumentation near the test article, this also brings with it a new set of challenges such as synchronization, timing, and data management. LXI (LAN Extensions for Instrumentation), has emerged as the next generation instrumentation interface, resolving a number of these issues. LXI leverages Ethernet, the most commonly used open-platform communications interface in the market, based upon technical merit and wide general industry acceptance of the interface by computer manufacturers and users.

Determinism, synchronization, triggering, device discovery, and predictable software driver interoperability are all essential functional requirements. LAN synchronization, incorporating IEEE-1588 Precision Time Protocol (PTP), provides the ability to synchronize multiple devices utilizing only the LAN Ethernet connection. PTP defines a precision clock synchronization protocol for networked measurement and control systems which is designed to enable the synchronization of systems that include clocks of different precision, resolution and stability. The most accurate and deterministic synchronization mechanism between multiple devices involves the implementation of a hardware trigger interface. As a result of this requirement, the LXI standard defines a high-performance trigger interface referred to as TriggerBus. TriggerBus can provide the link between all devices in the test system for both triggering and clock signal distribution.

Developing instrumentation suitable for high-accuracy, repeatable, and dependable distributed measurements not only requires knowledge of the transducer interface, but also the communications and timing aspects. This paper will delve into these areas, and discuss how the next generation instrumentation addresses these challenges from the transducer to the host computer.

DISTRIBUTED DATA ACQUISITION

Distributed measurements provide the user with numerous advantages over more traditional centralized approaches, and have become increasingly popular especially in data acquisition applications. Advances in electronic component designs and packaging, combined with the LXI interface standard, have provided the basis for a powerful new generation of instrumentation.

The strategic placement of data acquisition instrumentation around or near the test article can result in significant advantages. The benefits of this approach include:

- Quicker Setup Due to Instrument Proximity
- Simplified Calibration
- Excitation Source Closer to Bridges
- Cabling Noise Reduced
- Less Debug Time Required
- Less Installation Time Required
- Reduced Costs Associated With Cabling
- Simplified Maintenance
- Improved Transportability

Clearly these benefits encompass the entire operational life of a project including installation, maintenance, support, and calibration. Cost savings begin at the time of installation by greatly reducing the cost of cabling and associated installation, debug and testing. Simplified calibration and excitation by placing instrumentation near the associated transducers further improves system performance. Furthermore, increased accuracies are realized by reducing the effects of noise on transducer cables and difficulties calibrating such devices.

SYSTEM CALIBRATION

It is critical that test engineers are able to confidently rely on their measurement devices, and the integrity of the data they produce. Generally a major part of this confidence is achieved through instrument calibration and traceable verification standards. Specifically, a traceable source is used by the instrument undergoing calibration to both adjust and verify the quality of measurement. Typically, this has been viewed as a painful but necessary process involving system disassembly and downtime.

In most cases, test engineers are required to disassemble test stations and send each individual instrument to their respective vendor's factory for calibration. Some costly workarounds to such a problem include ordering spare instruments for each test station, hiring an outside calibration service, or construction of an in-house calibration laboratory. Reducing these costs and alleviating the downtime associated with the calibration process ultimately benefits all test and measurement applications.

Leading instrumentation manufacturers have invested significant engineering resources to vastly simplifying the calibration process, and have also added features that guarantee measurement accuracy. By taking advantage of the distributed measurement advantages of the LXI, and designing instruments with on-board precision voltage references, calibration becomes more convenient and more reliable than ever. Specifically, the LXI standard allows vendors to embed an easy-to-use calibration process directly into the instrument's firmware, allowing the end user to execute a complete calibration in minutes, at the click of a button. Furthermore, a precision on-board voltage source can extend the calibration capabilities by also offering a "self-calibration" routine which the end user can initiate at any time. This on-board procedure guarantees customers the most precise measurements, regardless of changes in surrounding environmental conditions.

The fully integrated web interface that the LXI specification requires, streamlines the calibration process, making it truly turnkey. The embedded user interface, combined with a built-in internal voltage reference, makes calibration in any location more convenient and cost effective. All that is necessary for many instruments to perform a complete NIST traceable calibration is a host computer and precision voltmeter. Simply connect the voltmeter to the instrument utilizing banana jacks, access the web interface using a standard internet browser, and click the button that commands the instrument to perform the automatic factory calibration.

The instrument's firmware can be configured to recognize and communicate with a number of different voltmeters, including the most commonly used instruments, to measure the on-board precision voltage source. Storing this value, the instrument can route the source back through the input signal paths and reliably perform internal adjustments. When compared to other approaches, this takes very little user interaction, and no calibration software development investment. Furthermore, the simplified equipment setup enables the process to be executed almost anywhere. Instead of sending the instrument to the metrology lab, test engineers can send the metrology lab to the instrument.

In addition to a turn-key, cost effective, full calibration procedure, additional features can guarantee the highest level of measurement accuracy before each and every data acquisition sequence. Specifically, the device can be designed with a self-calibration procedure that is executed directly from software or a web browser interface. Before any measurement is initiated, users can initiate a self-calibration sequence which routes the precision source back through the input signal.

This process makes minor gain and offset adjustments by routing the source through the actual signal path. Whenever the device undergoes any changes in its surrounding thermal environment, which is typical with many data acquisition applications, this process can be executed to ensure the highest degree of measurement quality.

LAN SYNCHRONIZATION

LAN synchronization, incorporating the IEEE-1588 Precision Time Protocol (PTP), highlights another fundamental advantage of LXI Class B devices that is ideal for distributed measurements. This completely over-the-wire approach provides an ideal mechanism to synchronize multiple instruments separated by hundreds or thousands of meters.

PTP defines a precision clock synchronization protocol for networked measurement and control systems. The protocol is designed to enable the synchronization of systems that include clocks of different precision, resolution and stability. Sub-microsecond accuracy can be achieved with minimal network and local clock computing resources, and with little administrative attention from the user.

There are several ways in which PTP can be implemented ranging from user level software control, to kernel-level driver modifications, to hardware implementations utilizing dedicated FPGA devices. The highest level of precision is obtained when hardware implementations assist in the time stamping of incoming and outgoing network packets or frames; delay fluctuations can be in the nanosecond range with this approach. PTP provides multiple device synchronization while eliminating the need for external cabling between devices. Utilization of this approach is less accurate than hardware triggering; however, Giga-bit Ethernet can provide synchronization times in the hundreds of nanosecond range which may be suitable for slower data acquisition rates common with thermocouple measurements.

Below are examples of PTP implementations and associated relative synchronization accuracy comparisons between these various approaches (See Figures 1-3 and Table 1.)

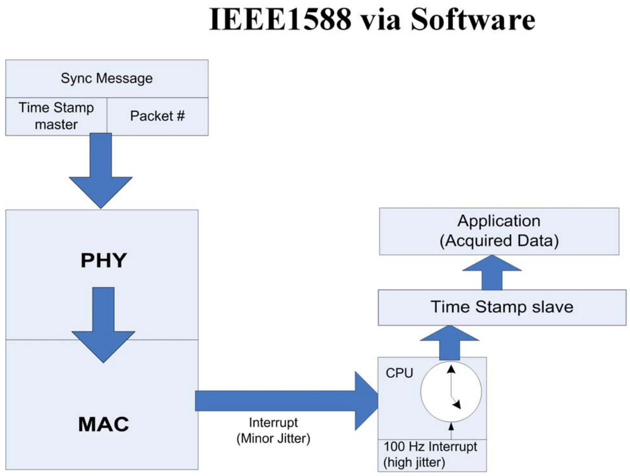


Figure 1.

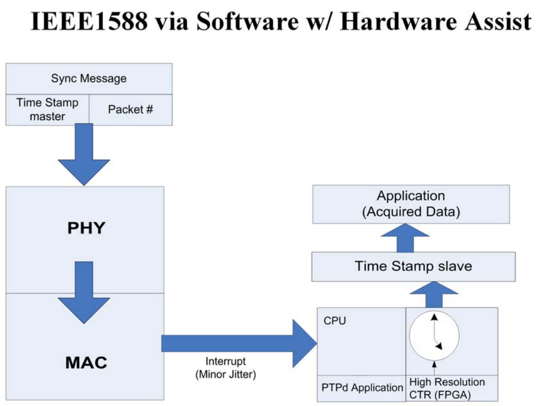


Figure 2.

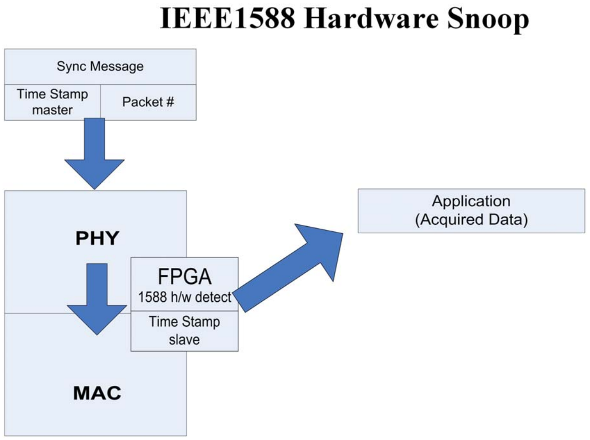
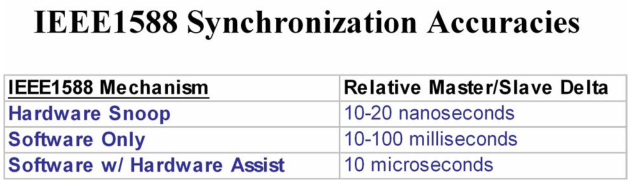


Figure 3.



IEEE1588 Synchronization Accuracies

IEEE1588 Mechanism	Relative Master/Slave Delta
Hardware Snoop	10-20 nanoseconds
Software Only	10-100 milliseconds
Software w/ Hardware Assist	10 microseconds

Table 1.

HARDWARE SYNCHRONIZATION

IEEE-1588 provides incredible advances in over-the-wire synchronization; however, there will always be instances where additional accuracy is required. The most accurate and deterministic synchronization mechanism between multiple devices involves the implementation of a hardware trigger interface. As a result of this requirement, the LXI standard defines a high-performance trigger interface referred to as TriggerBus. The LXI TriggerBus is required in LXI Class A devices, and provides the link between all devices in the test system for both triggering and clock signal distribution.

Deterministic trigger generation and propagation between multiple devices is accomplished with an eight-channel, multipoint low voltage differential signal (LVDS) interface. This architecture permits individual lines to be configured as a source and/or receiver and supports external, time based or software generated triggering as well as clock distribution. Common topologies are supported including star, daisy-chain, and hybrid configurations providing the flexibility to distribute the trigger lines as dictated by the application requirements. Additional flexibility is realized with the addition of a star hub; this device permits very tight trigger tolerances to be maintained throughout a large distribution network. See Figure4.

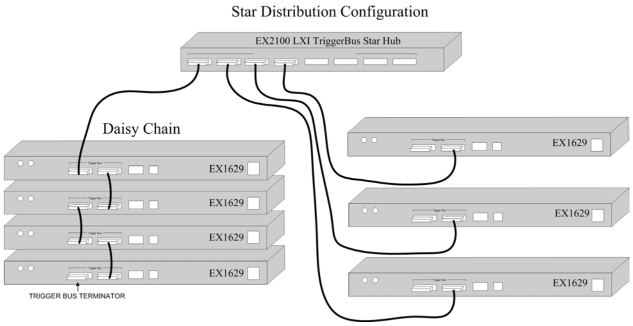


Figure 4.

Many data acquisition applications require a large number of parallel-channel instruments to be synchronized to a common clock or trigger pulse. Furthermore, the clock signals are often linked to a system clock such as IRIG-B or GPS for overall time correlation. The TriggerBus interface simplifies the process of distributing these signals, and when proper cabling and interconnects are used, ensures low channel-to-channel skew.

INTEGRATED SIGNAL CONDITIONING

The nature of distributed instrumentation requires that all aspects of the measurement device must be made available at the point of placement. Therefore features such as cold junction compensation, filtering, shunt calibration, and transducer excitation must all be accessible and integrated into the remote instrumentation.

One of the most commonly used temperature measurement devices is the thermocouple. Thermocouple transducers generate a low-level voltage when two dissimilar metals are placed in contact with one another; this voltage is commonly referred to as thermal electromotive force, and the signal is in the microvolt level range. A Type-K thermocouple, for example, will generate 39uV at 1°C with a full scale operational range of approximately 60 mV.

Gain stages are implemented to ensure that the signal is amplified to a level where fine changes in temperature can be resolved. A gain of 100 would amplify a 1200°C Type-K thermocouple (48.838 mV) input to a level of 4.8838 V. Without the necessary gain stages, the measured signal will have significantly less resolution and be more susceptible to noise fluctuations.

Furthermore, microvolt level signals are also very susceptible to the effects of 60 Hz interference and instrumentation must provide significant bandwidth limiting for rejection purposes. This is particularly important in industrial environments where the thermocouple is exposed to significant electrical noise from motors, generators, welding devices, lighting, and other sources.

Many thermocouple measurement devices, such as DMM based systems, provide some level of programmable 60 Hz rejection. However, this bandwidth limiting is achieved through the setting of the ADC integration rate. Specifically, 60 Hz rejection is improved by integrating over an integer number of power line cycles (PLC). This approach may reduce the effects of 60 Hz noise, but it results in substantially slower channel sampling rates.

Less accurate PC based relay multiplexer devices, in an apparent effort to reduce costs, typically do not offer any analog filtering and rely on averaging or other software techniques to manipulate the data. This can present difficulties when accurate, clean data is required across the measurement spectrum. It may become necessary to add additional external filtering circuits in an effort to improve the signal integrity. This may result in lower noise, but increases system complexity and cost.

Leading edge instrumentation designers do not rely on the ADC to provide bandwidth limiting, nor do they rely on software over-sampling and averaging techniques. Bandwidth limiting is instead done in each channel's signal conditioning path; the approach permits each channel to be independently set to a specific cutoff frequency.

A flexible approach would allow for multiple cutoff frequency ranges; multiple selections between 4 Hz and 1 kHz bandwidth would be appropriate. 4 Hz is suitable for most thermocouple and low-level voltage measurements and maximizes the 60 Hz rejection. Higher cutoff frequency selections are suitable for fine gauge thermocouples and higher speed voltage measurements (See Figure 5).

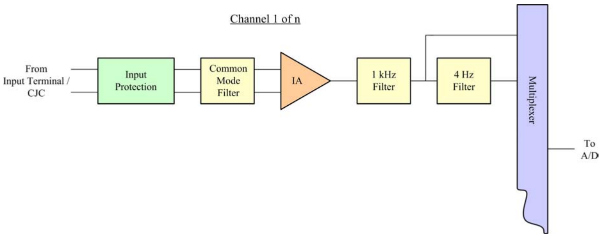


Figure 5.

Rejecting noise and amplifying the signal are only part of the equation in obtaining high accuracy temperature measurements; the cold junction compensation (CJC) circuit is arguably at the heart of a truly accurate thermocouple. Even an isothermal block with significant thermal mass will slowly change temperature in phase with the ambient surroundings; therefore, measurement errors will be guaranteed if these effects are underestimated, or not correctly addressed especially when the instrumentation is distributed.

The accuracy of a typical multiplexer PC card and DMM based system is, in general, about 1.0°-1.5°C. The reason for this varies, and certainly includes issues such as low thermal mass isothermal blocks, incorrect or insufficient CJC sensor placement, or poor location of the terminal blocks in respect to adjacent sources of heat such as power supplies, and displays. Additionally, the bulk of the error in most implementations can be attributed to poorly designed CJC sensor circuits, and input-to-CJC thermal coupling mechanisms.

Precision temperature measurement instruments will incorporate multiple high-precision CJC mechanisms, significant thermal mass, careful placement of parts that generate internal temperature gradients, and self-calibration functionality. The CJC sensor is typically a precision thermistor device, and it is not uncommon for several of these devices to be located at strategic points on the isothermal block. Higher channel count systems will also incorporate multiple isothermal blocks, with additional thermistors, to eliminate gradients at different connection points (See Figure 2). A system level measurement accuracy of 0.2°C to 0.4°C is possible when focusing on these details.

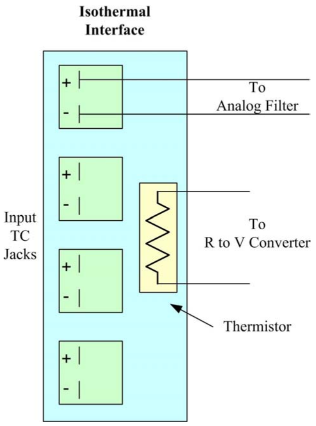
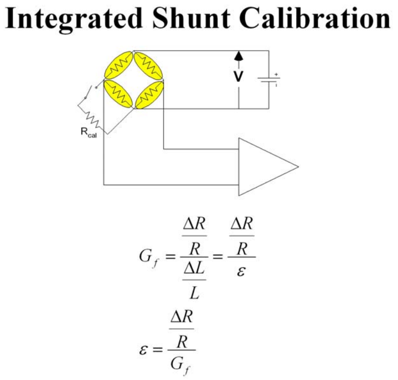


Figure 6.

Many of the issues addressed for thermocouple measurements are also of concern when performing distributed bridge measurements. Unlike thermocouples that generate a voltage based on a dissimilar metal junction, bridge devices require excitation sources, bridge competition resistors, and shunt calibration capabilities.

A distributed measurement instrument must be able to programmatically enable shunt calibration or modify the type of bridge completion required without sending a technician to each location. Shunt calibration can quickly provide the user with a high degree of confidence relative to the integrity of the transducer and associated cabling (See Figure 7).



$$G_f = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}} = \frac{\frac{\Delta R}{R}}{\varepsilon}$$

$$\varepsilon = \frac{\frac{\Delta R}{R}}{G_f}$$

Figure 7.

Measurement confidence is critical and ensuring that the excitation voltage is accurate is another aspect of obtaining valid strain measurements. A comprehensive solution will not only incorporate built-in excitation, but would also provide independent ADC circuitry to measure the excitation voltage. Conversion to micro-strain is then accomplished utilizing the actual measured value at the transducer, thus resulting in more accurate measurements.

CONCLUSION

Distributed data acquisition implementations can greatly simplify the end users installation and maintenance as well as provide savings in time and material; however, measurement accuracy can not be sacrificed. Instrumentation designers adopting a distributed measurement philosophy must include key functionality, such as internal signal conditioning, excitation, and noise rejection.

Providing instrumentation with communication interfaces based on industry standard LXI will also ensure that Ethernet connectivity and performance will not be compromised. Full feature solutions must incorporate Class A support if the implementation is to provide the necessary synchronization and timing functionality. This approach will ensure time correlation between thousands of channels, distributed around a test article, with tremendous architectural flexibility.