Design Leverage and Partnering in the Design of a Pressure Scanning Analog-to-Digital Converter

The HP E1414 pressure scanning VXIbus analog-to-digital converter completes HP's VXIbus offering for jet engine and wind tunnel test applications by providing the ability to make pressure measurements.

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Development of the HP E1414 pressure scanning VXIbus analog-to-digital converter (ADC) product was highly leveraged from the HP E1413 64-channel scanning ADC product. The development of the HP E1414 was also guided by a partnership with Pressure Systems Incorporated (PSI), a Virginia-based company. PSI is a company with expertise and high visibility in the field of pressure transducers and systems that calibrate and measure those transducers.

The HP E1413 scanning ADC was created to solve customers' needs for versatile and custom data acquisition solutions in jet engine and wind tunnel test applications. These applications require many channels of voltage, strain, resistance, and temperature measurements that must be acquired rapidly and accurately while the engine is operating under rigorously specified and controlled test conditions. These tests require very expensive test facilities. A key cost factor is how quickly the measurement system can make the necessary measurements and how flexible it is in being reconfigured for various test setups.

The HP E1413 performs these measurements with the needed flexibility. It offers high data throughput, scalable channel count (another card can be added to get more channels without speed degradation), mixed measurements (voltage, temperature, strain, resistance) in engineering units, and full data acquisition speeds (100,000 readings per second). Calibration is quickly and easily accomplished with an in-circuit calibration subsystem.

One measurement type the HP E1413 does not provide is pressure. This is especially critical in jet engine and wind tunnel test applications. These applications require many pressure channels in addition to the previously mentioned mixed measurements. Pressure measurements in these applications have the same requirements of high data throughput, scalable channel count, and results reported in engineering units at maximum data acquisition speeds.

With pressure measurements as the missing link, the project team searched for experts in the field of pressure measurements and set up a partnership. Pressure Systems Incorporated (PSI) is a recognized leader in electronic pressure scanning and has much experience in jet engine testing and wind tunnel measurements. PSI also has an existing product line of pressure measuring scanners and calibrators that provide all of the needed functionality to make the measurements. However, these scanners and calibrators do not operate within the C-size VXIbus platform that allows the high throughput and mixed measurements that customers often need.

Our systems approach to providing all of the desired throughput features and all of the required mixed measurements was based on the C-size VXIbus platform and the partnership with PSI. This approach combines the new HP E1413 and E1414 VXIbus modules with PSI pressure scanners and calibrators, other VXIbus modules, and compiled SCPI (Standard Commands for Programmable Instruments) programs. This combination provides the performance and measurement versatility required to satisfy these demanding applications.

Pressure Scanning ADC

The HP E1414 pressure scanning ADC is a C-size VXIbus module that allows the user to make scanned pressure measurements on up to 512 channels at rates up to 50 kHz when attached to pressure scanners manufactured by PSI (see Fig. 1). It provides measurements either in volts or converted to engineering units such as psi, Pascals, or mmHg. The measurements are made available to the VXIbus backplane at full scanning speeds and maintain accuracy to the specified 0.05% of full-scale pressure levels determined by the pressure scanners. The HP E1414 has most of the software features of the HP E1413 in addition to calibration modes specific to the pressure measurement environment. Fig. 2 shows the layout of the HP E1414 and E1413 VXIbus modules.

The majority of the hardware and software for the HP E1414 was developed first for the HP E1413 and directly reused with minimal changes for the HP E1414. The areas of hardware that are nearly identical include the VXIbus backplane interface circuits with register sets and address decoders, the CPU and engineering units conversion engine composed of the digital signal processing (DSP) chip and supporting memory parts, the trigger and timer circuitry, the FIFO memory and current value table memory control subsystem, the ADC, and the calibration subsystem. Much of the circuitry of these sections is implemented using field programmable gate

Fig. 1. The C-size VXIbus module containing the HP E1414 pressure scanning ADC.

arrays and programmable array logic (PAL). The PAL and all but one of the six gate array designs of the HP E1413 were reused without change in the HP E1414. Only the ADC gate array is different because of the special scanning measurements of the PSI scanners. However, even that redesign was accomplished by deleting from and adding to the HP E1413 design.

The physical printed circuit board layout of the HP E1414 was originally copied directly from the physical layout of the HP E1413 for those sections of the board that had little or no change. The areas of the board that had to be different between the two designs were simply added into the areas of the board layout where unneeded parts from the HP E1413A had been deleted. This greatly reduced the time and cost to produce the HP E1414 printed circuit board once the HP E1413 board was designed. Parts that were deleted from the HP E1413 for the HP E1414 include 60 of the 64 channels with the calibration relays for each channel and the signal conditioning plug-ons. This left ample space for the 50-watt switching power supply that supplies power to the pressure scanners, the controlled-rise-time address line drivers that select PSI pressure scanners, the extra RAM for storing real number coefficients and tables for 512 channels of pressure, and the HP-IB circuitry to communicate with the PSI 8400 mainframe and pressure calibration units.

The ADC calibration scheme of the HP E1413 was also used in the HP E1414. Even though the HP E1414 does not have all of the onboard calibration needs of the HP E1413 (the HP E1414 does not have resistance or current-source calibration needs), those calibration resources that are common were

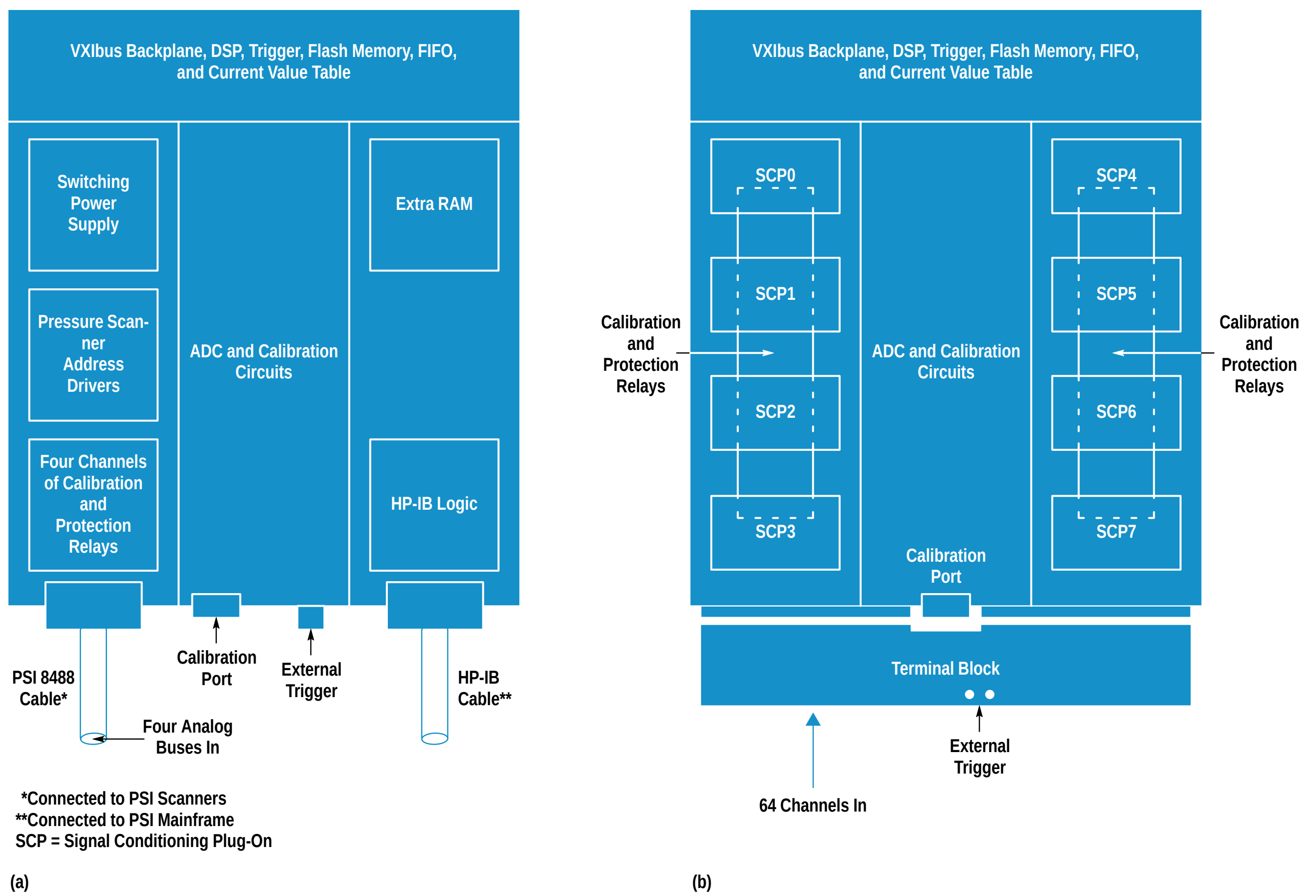

Fig. 2. The similarities and differences between the components on the (a) HP E1414 and (b) HP E1413 scanning analog-to-digital converters.

copied directly from the HP E1413 along with much of the software and calibration procedures for performing calibration of the HP E1414's ADC.

Software was leveraged from the HP E1413 in the areas of the status subsystem, trigger setup and control, accessing the FIFO memory and current value table, programming of the DSP flash memory, and the VMEbus memory subsystem. These areas represented over 50% of the software development.

Differences

The parts of the design where the two products differ greatly are actually fewer than the areas of commonality, but these differences are required to transform the HP E1413 into a pressure scanning ADC.

The HP E1414 has no signal conditioning plug-ons. It has only one intended input source, namely the pressure scanners from PSI. These scanners represent a family of products that all interface in a common way that is already preconditioned and eliminates the need for further signal conditioning of the input signals. Input signals are always preconditioned by PSI hardware to ±5V full scale.

The HP E1413 performs many different kinds of measurements depending upon the signal conditioning plug-ons, but the HP E1414 performs only voltage or pressure measurements. The HP E1413 provides built-in tables for converting measured volts into resistance, temperature, or strain. The HP E1414 performs a five-point pressure calibration and generates its own conversion tables to convert measured volts into pressure each time the pressure scanners are calibrated.

The HP E1413 can only scan across its onboard captive 64-channel multiplexer and make mixed measurements on those channels. The HP E1414 sources power to a maximum of 512 PSI pressure scanner channels and provides the necessary digital addressing to select and measure those channels. The current value table for both products can hold 512 readings, but the HP E1413 only makes use of the first 64. This is a good example of how the requirements for the HP E1414 were built into the HP E1413 design.

The HP E1413 can autorange the ADC to the best range for the level of the input received. The PSI scanner electronics always precondition the electrical output of the pressure transducer to produce a signal that is within a ±5V range for a full-scale input pressure. This means the HP E1414 only needs one measurement range, namely a 5V range. The HP E1413 uses binary ranging to aid in the conversion of volts to engineering units and at one time included ranges such as 1V, 4V, 16V, and so on. For the HP E1414 the 4V range was insufficient to cover the 5V output range and the 16V range would have resulted in reduced resolution. Fortunately, there was room for one more range-setting resistor in the precision resistor pack in the HP E1413. The 5V range resistor value needed for the HP E1414 was included in the empty resistor position and one precision resistor pack now serves the needs of both products.

The HP E1414 must interface to the PSI interface electronics and scanners in a predetermined way since these devices are a standard product from PSI and were in existence before the HP E1414 was conceived. The HP E1414 essentially replaces

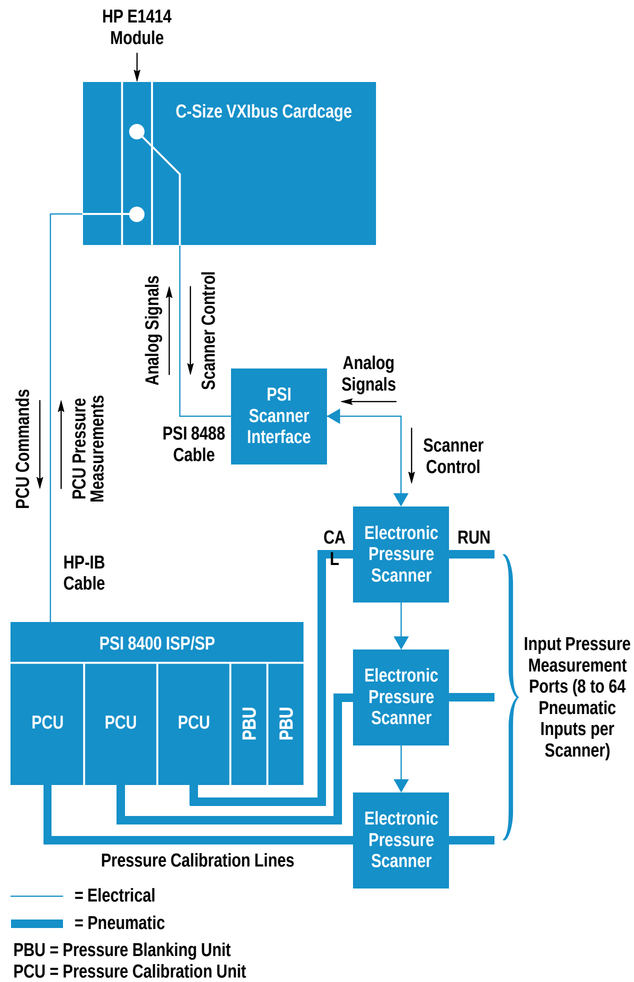

Fig. 3. Standard system configuration for the HP E1414 connected to the PSI 8400 for calibration and pressure measurement. Up to 512 pneumatic inputs can be connected to the HP 1414.

the scanner digitizer unit that normally plugs into the proprietary backplane of the PSI 8400 mainframe (see Fig. 3). The connection to the pressure scanners is via the PSI 8488 cable which includes four analog buses, digital addressing, and power to drive the scanners. (The PSI pressure scanner can permit up to four channels to be addressed at one time, each sourcing one of the four analog buses.) The HP E1414 contains all of the needed address line drivers as well as an onboard dc-to-dc converter power supply to provide up to 50W of power for the PSI electronics. This scheme greatly simplifies the use of the combined HP E1414 and PSI scanners by making all of the necessary connections with one common cable and no external power supplies required.

As shown in Fig. 2, the HP E1413 has channel multiplexing circuitry for 64 channels. It has a relay switch for each channel, which is used for calibration and input protection. Sixty of these channels along with their associated relay switches are deleted in the HP E1414 design. This leaves enough surface area to support the control and power circuits for driving the PSI scanner address lines and the HP-IB port. The HP E1414 itself only scans through four analog channels, representing the four analog buses in the PSI 8400 system.

PSI pressure scanners are limited to 50-μs minimum switching times between analog samples, which translates into 20-kHz maximum scanning rates. However, since up to four channels can drive their respective analog buses simultaneously, a technique called parallel address mode can be used, which effectively permits scanning the ADC at up to 80 kHz. This is accomplished by sampling one channel on an analog bus and then closing the next channel on that same analog bus immediately afterward. This permits each channel to settle for more than its required 50 μs before it is measured. However, since PSI 8488 cable lengths can range up to 100 meters and introduce capacitive loading, the scanning rates for parallel address mode are specified only to 50 kHz.

Pressure Sensor Calibration

The system-level calibration of the PSI scanners requires special software and hardware to guarantee that accurate pressure measurements are taken. This calibration begins by first positioning a piston contained in each electronic pressure scanner to the CAL position (see Fig. 3). The CAL position connects all input pressure ports on the pressure scanners to a single input called CAL. Then, five known pressures over the range of the transducer are applied to the CAL port via a PSI pressure calibration unit. The HP E1414 communicates via the HP-IB (IEEE 488.1, IEC 625) with the PSI 8400 mainframe, which houses the pressure calibration units. Up to 64 readings are taken and averaged by the HP E1414 with the analog signals obtained via the PSI 8488 cable. A five-point volts-versus-pressure curve for each scanner port is calculated, and a linearization table is generated and downloaded into the HP E1414's digital signal processor (DSP) memory for high-speed conversion. Once the calibration is completed, the piston in each scanner is driven in the opposite direction to the RUN position. In the RUN position unknown pressure inputs from the device under test are directed to the now calibrated pressure scanners. The pressure blanking units shown in Fig. 3 are used to fill empty slots in the PSI 8400 mainframe since its backplane consists of both electrical and pneumatic signals.

Different Memory Requirements

The HP E1413 has linearization tables already built into its memory, and it supports NIST-traceable transducers and custom linearization for up to 64 channels. The HP E1414 must support custom linearization tables and calibration coefficients for up to 512 channels, which requires much more RAM. This added memory is provided by increasing the available RAM from 128K 16-bit words to 512K words. The added memory requirement was anticipated early in the design of the products and decoding for it was built into the gate arrays and PAL of the HP E1413 so that these designs could be directly reused.

Common Development Tools

The same development tools were used for both products. The use of HP 9000 Series 700 workstations networked together within the design and manufacturing groups greatly enhanced the design leverage efforts by allowing easy access to common files and application software tools. Two of these applications, which run on the HP 9000 Series 700 workstations, are the Design Capture System (DCS) and the Printed Circuit Design System (PCDS). DCS allowed copies of design schematics to be easily copied and modified for the definition and production documentation of the board's circuit design as well as the internal circuit design of the gate arrays. PCDS allowed copies of one printed circuit board design to be easily copied and modified for the definition and production documentation of the physical printed circuit design. Deletions from the HP E1413 board design left about 50% of the board layout available, allowing the HP E1414-specific circuit sections to be placed in the spaces vacated by the deletions.

The RMB-UX programming language, a version of HP BASIC, allowed easy programmatic testing of the product features and performance specifications through computer-controlled test suites. Porting the HP E1414 driver to multiple platforms required both compiled SCPI and C programming, but the HP E1414 is easily programmed from the HP E1405/6 VXIbus command module[1] using RMB-UX over the HP-IB. This makes production testing, troubleshooting, HP ITG (Interactive Test Generator) programming, and operational testing much more accessible to a wide range of individuals who may not have an embedded computer or who are not familiar with programming in C. Since PSI was familiar with RMB-UX and the PSI 8400 is an HP-IB device, they found it quite easy to learn the HP E1414. RMB-UX also provided a simple means of updating the HP E1414's onboard flash program memory as firmware revisions were made. Test programs written in RMB-UX for exercising the HP E1413 circuitry were easily modified to provide similar testing of the slightly different HP E1414 circuit sections.

Common Schedules

The HP E1413 and E1414 were envisioned as two needed parts of a total solution to customers' problems and therefore they were both under development at the same time. The HP E1413 is the more generic and higher-volume product. With this basic project priority, the HP E1414 was always planned to be behind in the schedule by about two months. This allowed the HP E1414 to take advantage of the work done on the HP E1413 and avoid repeating some of the short-term design iterations that the HP E1413 experienced. Overall, the HP E1414 design was much less iterative than the HP E1413 because of the planned schedule spacing between the two products. This allowed the project team to work heavily on the specific HP E1414 designs while the HP E1413 team was deeply involved in solving problems that were common to both products.

Partnership between HP and PSI

PSI is highly experienced in solving real-world pressure measuring applications. The company was organized originally to take advantage of the development of piezoresistive pressure sensors when these devices became a reality. Their inputs on how to implement and verify calibrations and linearizations were invaluable in achieving the overall system accuracy that the HP E1414 is able to deliver when used with PSI's scanners and calibrators.

PSI has developed a very good customer base and an understanding of the nature of pressure measurement problems over many years. This knowledge allows the HP E1414 to be presented effectively to people who are interested in making these multichannel scanned pressure measurements. These customers may not previously have been users of VXIbus products, which offer broader capability. Conversely, many of the users of VXIbus systems have not been able to take advantage of the PSI pressure measurement capability because PSI did not have an offering in the VXIbus format. Therefore, the HP E1414 allows PSI users access to a new architecture that is becoming more widely used.

The pressure scanners, the electronic interface hardware to the pressure scanners, and the pneumatic calibrators are all manufactured and sold separately by PSI. HP does not manufacture any of these items for use with the HP E1414, but without them the HP E1414 could not perform any pressure measurements at all. The HP E1414 has the built-in intelligence to automate the control and sequencing of the PSI hardware elements to provide a VXIbus pressure measuring system that takes advantage of the existing PSI hardware functionality.

The HP E1414 had to interface with an existing product definition and user model. To create a complete pressure measuring system solution from hardware that comes from two different companies, the HP E1414 had to be compatible with the operational paradigm of the already existing PSI 8400 system. This means that the pressure-measuring control language, terminology, channel-numbering scheme, and calibration methodology had to keep the same look and feel as in the PSI 8400 system. PSI channel numbers correspond to a numbering scheme of rack or modular pressure scanners. This channel numbering scheme identifies a particular address to send out on the PSI 8488 cable, and it also dictates which analog bus within the cable is sampled. It was also important that the HP E1414 take advantage of all of the work that has been done on SCPI to make system programming easier and faster. This presented the software designer with a challenge in merging the strengths of SCPI with the need to present a familiar interface to the experienced PSI equipment user.

The new HP E1414 pressure measurement language expands in some areas from the PSI language. For example, the command to configure the pressure calibration unit in PSI 8400 language is:

```
PC1 CRS, LRN, Pressure Mode, Tolerance, Maximum Pressure
```

where CRS refers to a particular PSI 8400 frame and slot where a pressure calibration unit might be addressed, and LRN is a number between 1 and 12 representing a symbolic name assigned to that pressure calibration unit. The symbolic name is then required for other commands in the PSI system. The corresponding HP E1414 SCPI language representation is:

```
CALibrate[:PRESsure]:MODE CRS, Pressure Mode
CALibrate[:PRESsure]:TOLerance CRS, Tolerance
CALibrate[:PRESsure]:MAXPressure CRS, Maximum Pressure
```

Note the adherence to the CRS designation. The LRN symbolic name is now an internally generated parameter, so the programmer only needs to remember the slot position of the pressure calibration unit in the PSI 8400 mainframe.

Another expansion of the SCPI language permits the programming and query of a specific parameter that is not available in the PSI system. This becomes very important when supporting the HP E1414 product from menu-driven software packages such as HP VEE[2] and HP ITG.

Testing the HP E1414/PSI System

Pressure calibrators, transducers, and the associated peripheral components can be very expensive since these are pneumatic devices that require precision mechanical and electrical fabrication. Fig. 3 represents a single HP E1414 configuration with PSI components. Some systems could be much larger and include five or more pressure calibration units, 500 to 750 pressure channels (which requires multiple HP E1414s), and multiple racks to hold the pressure scanners. Testing the software and hardware on such large systems required sharing expensive equipment between HP and PSI. The project team was able to develop the HP E1414 and its software driver on a system with just two pressure calibration units and only six pressure scanners. Multiple HP E1414s could have been used to simulate large-point-count systems under certain conditions. However, for the most part the project team had to rely on PSI for large-system testing, since they are the pressure transducer manufacturer and frequently assemble large-point-count systems to be shipped to customers.

To minimize the need for such a wide array of expensive equipment and to reduce the many-hour testing time required to verify proper operation of software and hardware, an HP 9000 Series 300 computer with a B-size VXIbus mainframe containing DAC cards was constructed by the project team to simulate the operation of the PSI 8400, calibrators, and pressure scanners. Each B-size DAC channel was connected to one of the four analog buses on each HP E1414. Some were chained from HP E1414 to HP E1414, and some had separate DACs. A DAC connected to an analog bus simulated a pressure calibration unit. Any HP E1414 channel measured on that analog bus read the voltage output from the associated DAC.

The simulator program was written in HP RMB and used the HP 98624A HP-IB card configured as a nonsystem controller. Another HP 98624A card was used to communicate with the B-size VXIbus frame. The simulator was written to simulate up to eight pressure calibration units and permit simulation of an indefinite number of pressure scanning ports when HP E1414s have their analog buses chained to the same DAC. The time investment in this simulator had big returns. Tests could run quicker since no real pneumatic devices were resident in the system. This approach reduced the wear on such devices when executing long comprehensive tests by eliminating them from the tests. Other engineers writing drivers for HP ITG could use the simulator rather than an actual HP/PSI system to do their development. This permitted concurrent development of the HP E1414 and HP ITG drivers. DACs were easier to manipulate under software control to simulate air leaks, failure conditions, and input voltage overloads. It was also easier to characterize the measurement integrity of the system by having direct control of input voltages.

Many of the regression tests for the HP E1413 were easily modified to test the HP E1414. Changes consisted mainly of channel-numbering differences between the two products. These tests included triggering, measurements, FIFO memory and current value table integrity, and interrupts. The self-test code for the HP E1414 was literally duplicated from the HP E1413 code with only deletions and changes in channel count and numbering. This code initially took weeks to write for the HP E1413, but it was leveraged to the HP E1414 and tested in less than a week.

PSI currently runs every system they build, whether VXIbus-based or not, through the HP E1414 configuration to verify that various combinations of pressure calibration units and pressure scanners properly operate with the HP E1414. PSI's dedication to detail and understanding of pressure measurement problems has uncovered a variety of potential problems. Many of these types of problems would only be recognized by someone with many years of pressure scanning experience. Their experience saved many hours of trial and error that would have been wasted by the project team.

Customer Support and Training

Repairing or replacing an HP E1414 card when it fails is a straightforward operation that is well-defined within HP. The SCPI command `*TST?` performs a reasonably comprehensive self-test of the HP E1414's hardware and can pinpoint most failures. However, some problems may reside elsewhere such as in the computer platform, the PSI hardware, the tubing or cabling, or improper programming sequences. Determining where a problem lies can be frustrating when some or all of these factors combine.

Since the HP E1414 driver can run on HP 9000 Series 300 to 700 machines running the HP-UX* operating system, Radisys EPC-7 DOS/Lynx systems, or on the HP E1405/6 VXIbus command module, the combinations of possible failures escalate. In addition, PSI did not develop the HP E1414 driver nor do they have the resources to support all these platforms. To resolve these issues, a common troubleshooting technique and hardware configuration was established that is usable by both HP and PSI that has the best interests of the customer in mind.

The HP E1405/6 command module has already been the HP customer engineer's tool for isolating problems in the VXIbus environment. It is a helpful tool since it contains or can be programmed with all the HP VXIbus card drivers, is an HP-IB device and a VXIbus resource manager, has a terminal interface port, and can run HP Instrument BASIC for easy access to instrument drivers and hardware. In addition, the HP E1405/6 has a comprehensive debugging language to help resolve potential VXIbus card conflicts and failures. With HP Instrument BASIC and an external HP-IB flexible disk drive, the HP customer engineer can run diagnostic programs that can help isolate where problems might reside. This eliminates the need for the HP customer engineer or the PSI support engineer to be an expert with every computer platform.

PSI has written a comprehensive autoaccuracy and test diagnostic that communicates over the HP-IB with the HP E1405/6 command module from a portable PC or HP 9000 Series 300 computer. With this diagnostic, the HP customer engineer or the PSI support engineer can more quickly isolate system difficulties. If the conclusion is that the problem is related to the computer platform or the VXIbus hardware, then the HP support organization can help resolve the problem. If it is related to the pressure scanning equipment, PSI can help resolve the problem. In either case, a common diagnostic tool is available for both companies.

With this common diagnostic tool available, support training now focuses on understanding the system from that perspective. This tool helps reduce the number of variables resulting from multiple computer platforms.

Conclusion

Partnering with experts increases the certainty that the needs of the customer will be met by the product. The expert partner not only provides knowledge of the customer needs but also has gained valuable experience through time spent in actually solving those needs and understanding real-world applications. PSI had this type of knowledge in the area of pressure measurement in jet engine testing and wind tunnel applications, while HP provided the high-speed ADC conversion and at-speed engineering units conversion and VXIbus system knowledge to address the overall test system throughput issues.

Leveraging one product design from another can be very positive. The same team and tools that develop the first product can help develop the second. This second development effort can be done either simultaneously or in series, but the effort to do the second one is going to be less because all of the various activities involved in the development are now simply refinements or modifications of the original. The mental images of how the first product was done guide the developers in identifying how the required differences in functions can easily be achieved. This carries over into all aspects of the development including design, test, production systems, and learning products development.

The results we were able to achieve on the HP E1414 leveraged development have met nearly all of the objectives and schedules that we originally set forth. The HP E1414 was released to production with only two printed circuit board design cycles: the first prototype and the released version. This is always a project objective but in many cases unforeseen problems that come up late in a development can force yet one more turn of the board design. Through the work done on the HP E1413 and a two-month delayed schedule plan, the HP E1414 was able to incorporate many of the early changes from the HP E1413's first boards into the first board of the HP E1414. The overall system performance has met or exceeded all of our expectations and the combined PSI hardware (interfaces, scanners, pressure calibration units) and HP E1414 work well together. The system accuracies are as good as a PSI 8400 system can supply in nonVXIbus systems. Testing at both HP and PSI has shown that large-point-count systems can be configured and operated effectively while achieving 0.05% of full-scale accuracies.

Acknowledgments

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