On-the-Fly Engineering Units Conversion

An algorithm has been developed that provides engineering units conversion in real time (10 microseconds) in the HP E1413 scanning analog-to-digital converter instrument. The algorithm converts numbers to IEEE 754 standard 32-bit floating-point format.

by Christopher P.J. Kelly

The HP E1413 is a VXIbus 64-channel scanning analog-to-digital converter (ADC) that is used in data acquisition applications. These applications usually measure real-world phenomena such as temperature using a variety of transducers. These transducers (e.g., thermocouples) convert the phenomenon of interest into a voltage, which is connected to a channel of the ADC. The ADC then converts this voltage into a binary digital number that represents the voltage applied to its input. In Fig. 1, for example, the temperature T of a flame is sensed by a thermocouple. The thermoelectric voltage V is applied to the ADC, which generates a digital binary number N1 whose value is determined by V, so its units are typically microvolts. The challenge is to provide a fast engineering units converter to change N1 into a floating-point number N2 in units of temperature such as degrees Celsius.

In the thermocouple example, the relationship between temperature and thermoelectric voltage is described by NIST (the U.S. National Institute of Standards and Technology, formerly National Bureau of Standards) using a high-order polynomial. For a type E thermocouple, for example, NIST models its thermoelectric behavior using a 13th-order polynomial. Considerable computing power is required if this polynomial must be evaluated in real time (10 microseconds in the case of the HP E1413).

Need for Conversion

Why is engineering units conversion important? The reason lies in the nature of the task of continuous on-line data acquisition and the coupling between the instruments and the controller in a VXIbus instrument system.

In continuous on-line data acquisition, measurements are made and recorded continuously for an indeterminate period of time. During this period, data may also be displayed for operators or used for adjustment of the experimental conditions (control). The data should be available in useful and understandable units of measure so that operators and control systems can view and operate upon it easily. Recorded data also should be in a form such that no additional processing is required for the data to be useful, thus helping ensure the correctness of experimental results. For short-duration experiments the data may be buffered in a raw format while a converter slowly massages it into a useful form. But when data is acquired continuously, the acquisition system must be able to convert the data at full speed or eventually the buffers will overflow.

The VXIbus architecture also allows a new, tight coupling between instruments and their controlling CPU. This permits a large increase in system throughput if the instruments are

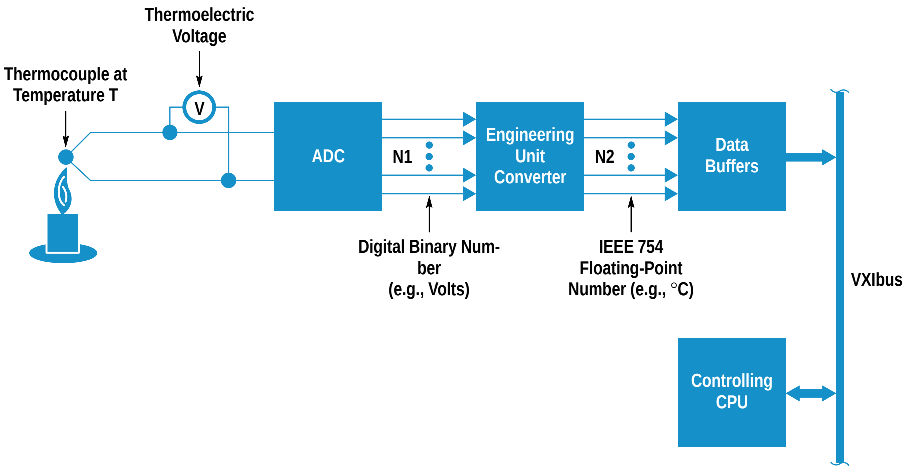

Fig. 1. The components involved in converting a temperature measurement into a floating-point number.

designed to take advantage of the architecture. In some non-VXIbus instrument systems the instruments are coupled to the controller using a communications link, and control or data messages are exchanged by explicit input/output transactions. However, in a VXIbus system the controller can be connected to the VXIbus backplane through its address and data bus, and the instruments' control and data registers appear as memory addresses in the memory map of the VXIbus CPU. In many cases, the CPU actually plugs into the VXIbus cardcage and draws its power from the backplane. In this model, no explicit I/O transactions are required to operate the instruments, so no I/O device drivers or layers of communications protocol are needed, and operations can proceed at full computer backplane speeds.

With this tight coupling between the computer and its instruments, if the instrument is designed to behave like a memory device, the control program can access real-time data at full CPU speeds as if the instrument were part of its memory. If the data is in a computer-native format, the computer can store, display, and manipulate the data immediately, with no format or units conversion. For most of today's computers the IEEE 754 standard floating-point number format is native and is operated upon directly by the floating-point processor in the CPU. If the instrument is able to transfer its measurements in this format, the computer has no burden of translation from a special format to one it can process directly. This means that data can be acquired more rapidly and tighter experimental control can be maintained than with alternative systems of similar cost.

In previous systems, these tasks were often handled by the controlling CPU if the data was required in real time. As data rates rose, considerable CPU power was necessary to do all these tasks in the available time. Some systems used multiple CPUs to handle the load, but the overhead of synchronization and communications among the CPUs also grew to absorb a considerable fraction of the available processing power.

The goal of the HP E1413 engineering units converter is to make it possible to realize the full speed potential of the VXIbus architecture by providing all necessary conversions in the instrument in real time. Each of the 64 input channels requires its own engineering units conversion since transducer types or calibration may vary from one channel to the next. For the HP E1413 this means 100,000 measurements per second are converted to engineering units, formatted according to IEEE 754, and made available to the controller over the VXIbus backplane. 100,000 measurements per second means 10 microseconds per measurement.

Bounding the Problem

Upon first examination of the challenge of on-the-fly engineering units conversion for this product, several factors worked to simplify the problem. First, the ADC only produces a 16-bit binary number as a result of the conversion, meaning that the technique used for the engineering units conversion does not need to exceed 16 bits of resolution. Whatever format is used for reporting results, the measurement itself is intrinsically resolved to one part in 2^{16} (65,536). The second mitigating factor is that although the ADC has five operating voltage ranges, these ranges are related by powers of two. This means that changing ranges only requires shifting the 16 bits from the ADC right or left in an accumulator to maintain correct measurement scaling. Finally, the entire scanning ADC system is calibrated in true volts. This calibration includes multiplexers, filters, attenuators, and gain stages all the way back to the transducer wiring. Every channel is individually calibrated to measure voltage applied to its input terminals. This corrects for any channel-to-channel variation in offset voltages resulting from relay contact thermoelectric voltages and variations in the amplification of the signal-conditioning channel amplifiers. Thus, no postmeasurement correction is necessary, allowing the measurement to proceed at maximum speed.

This third factor means that all engineering units conversion coefficients can be calculated in advance, referenced to absolute voltage. If the system were calibrated in some arbitrary ADC voltage units, we would require dynamic computation of coefficients based on the state of calibration of each individual ADC, a production engineering nightmare.

Efforts have previously been made to speed up engineering units conversion in similar systems, and a variety of shortcut techniques have been developed. These techniques generally trade off accuracy, speed, and memory table size, and each technique has strengths and weaknesses. These techniques include development of low-order polynomials to approximate the NIST equations with fewer terms and hybrid lookup-table-with-correction-factor techniques. In the limit, it is possible to perform simple table lookup, with the ADC reading being used as an address index into an array of results. This technique is very fast, but uses a lot of memory for the lookup tables. In the case of the E1413, with 16 bits of resolution and 64 separate channels, this technique would have required 16 megabytes (64 channels × 16 bits of resolution × 4 bytes per result = 64 × 65536 × 4 = 16 megabytes) of tables, too expensive a solution. On the whole, we needed a technique that would precompute as much of the problem as possible, leaving little remaining work to be done in real time.

New Algorithm

The HP E1413 engineering units conversion algorithm uses a linear approximation technique to convert the ADC binary voltage numbers into engineering units. The technique divides the operating voltage range of the ADC into a number of segments of equal size and fits a straight line to the data in each segment. The number of segments can be adjusted to provide an acceptable level of conversion error, with more segments yielding lower error. In our case, we found that 128 segments were sufficient to limit errors to acceptable limits.

In Fig. 2, the algorithm is represented schematically. On the left, a digital binary number from the ADC is divided into two sections. The high-order bits are used to address a table of engineering units conversion coefficients. The low-order bits enter the numeric processing pipeline and are multiplied by the slope coefficient for this table segment, resulting in the product (P). This product is then added to the offset coefficient for this table segment, which represents the value of the engineering units conversion equation at the beginning of the segment. The result (R_0) is now in engineering units, and in a simple model can be used as output. This process of lookup, multiply, and add can be accomplished

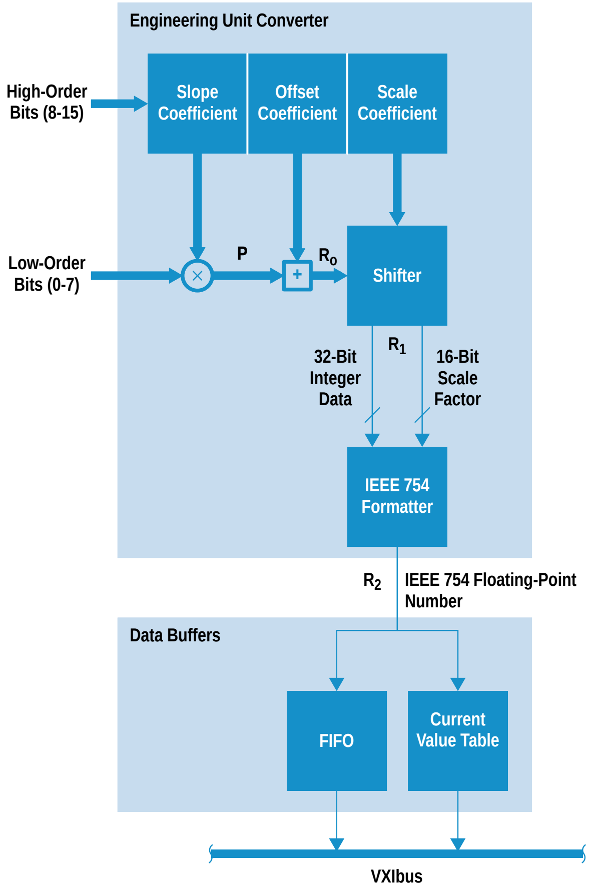

Fig. 2. A block diagram of the engineering unit conversion process.

very quickly compared to evaluation of a high-order polynomial. In fact, the process is simple enough to be performed entirely in a simple hardware state machine consisting of ROM, multiplier, adder, and clock control devices.

In the HP E1413, additional steps are added to keep the resolution of the conversion up to an acceptable level. In general, an engineering units conversion equation will have relatively high slope coefficients in some parts of the curve and relatively low slope coefficients in others. The comparative sizes of the slope and the offset will also change over the width of the conversion curve. To keep the resolution of the conversion process up to acceptable levels when using integer arithmetic, the HP E1413 conversion also includes a third, scaling, coefficient. This factor is used to adjust the scale of the slope and offset coefficients, and is corrected for in a postconversion rescaling (right or left shift as appropriate). The scaled result (R_1) is then reformatted according to IEEE 754 before the result (R_2) is presented to the controlling CPU.

To show graphically how the algorithm operates, Fig. 3 shows the thermoelectric voltage curve for a hypothetical temperature transducer. On the vertical axis we see temperature and on the horizontal axis we see the resulting voltage. The curve illustrates a nonlinear relationship between temperature and voltage. When the ADC measures the transducer, it puts out a digital binary number V_{meas}. When this voltage is presented to the engineering units converter, it is found to fall into voltage segment n, because its voltage lies between the beginning voltage of the segment (V_n) and the ending voltage of the segment (V_{n+1}). When the engineering units converter receives V_{meas}, it divides it into high-order bits, which have a value of n, and low-order bits, which indicate how far into the V_n segment the actual voltage lies.

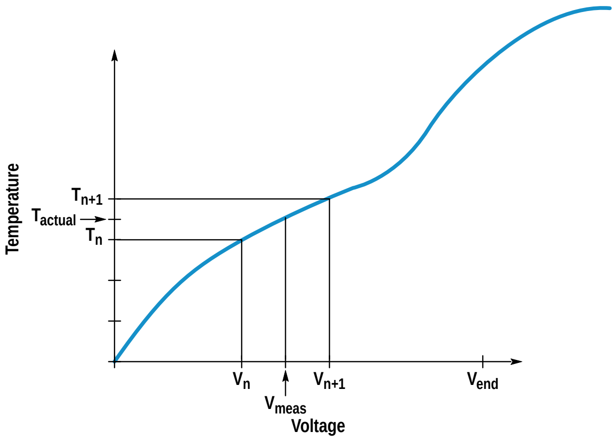

Fig. 3. Thermoelectric voltage curve for a hypothetical temperature transducer.

The engineering units converter next uses the high-order bits to look up the nth segment slope coefficient from the conversion table. The slope coefficient is multiplied by the low-order bits, whose value is ($V_{meas} - V_n$). The product of this multiply has a value of ($T_{actual} - T_n$) on the vertical axis. That is to say, the product is equal to the distance above the base temperature of the segment where the true temperature lies. The second step of engineering units conversion is to fetch the offset coefficient (T_n) from the coefficients lookup table and add it to the product of the multiply. The result of this addition is now in units of temperature. This value is now scaled and converted to floating-point number format, and is available for use by the controlling CPU.

Results

The multiply-add sequence is a core function in most digital signal processing (DSP) algorithms. It is a function optimized by most DSP processor chips into a very fast operation. This makes the architecture of DSP processors well-suited to the engineering units conversion algorithm, for which multiplication, addition, and speed are all important. The HP E1413 uses a Texas Instruments TMS320C51 DSP processor chip as its onboard CPU, and is able to execute this algorithm in the available 10 microseconds, along with other functions such as measurement sequence control. The processor also handles measurement trigger counting and timing functions during measurement sequences and calibration and measurement setup commands when the instrument is not actively acquiring data.

As mentioned above, the algorithm can be adjusted to trade conversion accuracy for coefficient table size. In the HP E1413, the algorithm divides the engineering units space into 128 segments, which yields 512-word conversion tables for each transducer. Since the thermocouple is one of the target transducers for this product, it is instructive to evaluate the errors generated by the algorithm when using thermocouples. Fig. 4 shows a graph of the algorithm errors when the transducer is a Type E thermocouple. The largest errors occur near 0°C and are nearly 0.05°C. Over most of the temperature range the errors are below 0.005°C, far below the ASTM

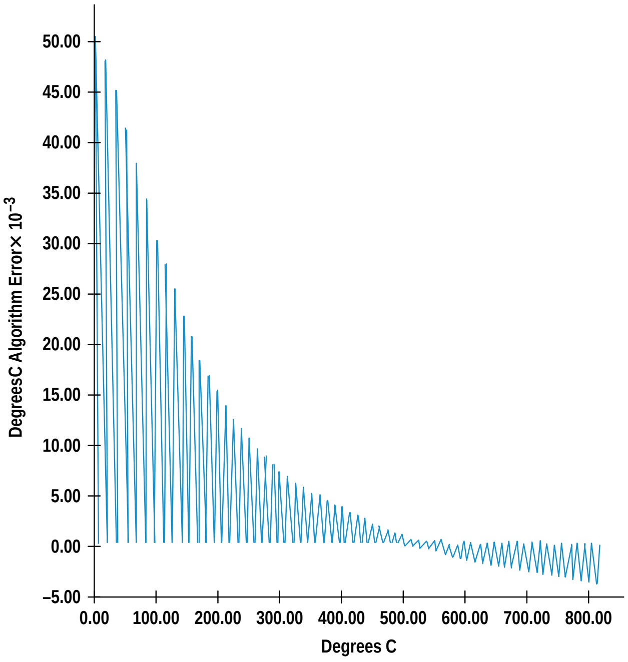

Fig. 4. Engineering unit accuracy with a Type E thermocouple.

manufacturing error specification for the thermocouple wire itself, which rises to ±4.4°C above 800°C.

The shape of the error curve is determined by the rate of change of the thermoelectric voltage for the thermocouple over temperature. The thermoelectric voltage change per degree of temperature change is called the Seebeck coefficient of the thermocouple. As the Seebeck coefficient changes, the algorithm must approximate a curving line segment with a straight line. This leads to a small error in the middle of the line segment, with almost zero error at the endpoints. The greater the curvature of the function being approximated, the greater the error. The errors generated by the conversion algorithm are far below the measurement errors of the analog hardware or those of the transducers themselves.

Summary

The new segmented linear approximation algorithm allows real-time conversion of analog measurements into engineering units. The algorithm provides ample conversion accuracy for the target hardware and transducers, and executes in less than ten microseconds using the microprocessor in the instrument. Performing this conversion in the instrument allows the complete measurement system to make usable measurements faster and at lower system cost than was possible with previous instruments.

Acknowledgments

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