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Thermocouple scanner: RUTHLESS SURVIVOR

Flight test and harsh industrial conditions pose a challenge.

By Charles Matthews

Temperatures have historically been a difficult problem for instrument engineers.

The growing use of Ethernet interfaces in aerospace and industrial process applications has created a need for an intelligent thermocouple scanner to operate on an Ethernet network and complement intelligent pressure scanners.

The scanner must be able to accept several different thermocouple inputs, convert the signals to engineering units using National Institute of Standards and Technology tables, and output the data over a TCP/IP Ethernet link.

The scanner must be able to withstand the harsh environments required for flight tests, turbine tests, and other turbo machinery development testing. Here is the design process that brought an instrument that meets all of the environmental and operational characteristics for a laboratory production facility or development test cell.

COMMON PROBLEMS INHERENT

Thermocouples are sufficient for most measurements, due to the availability of very accurate correction tables. But the actual measurement has always had a relatively high degree of uncertainty. Here are the most common problems:

- Thermocouples require a stable, known reference junction.
- Secondary junctions can cause significant errors.
- They are subject to noise problems.

For high accuracy measurements, engineers necessarily have to use resistance temperature detector (RTDs). However, RTDs present engineers with a new set of problems:

- RTDs require special signal conditioning.
- Calibrations are difficult at best.

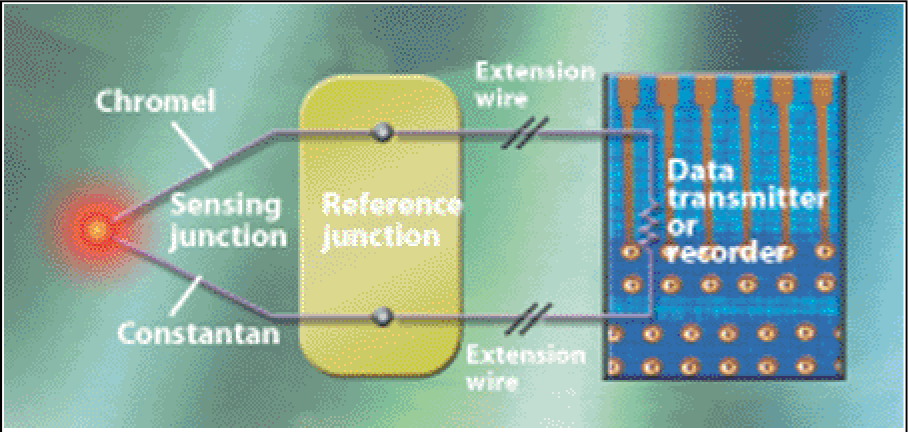
- They are limited in temperature range.
- Size can be a problem.
- They are not vibration resistant.

Mitigation of these three problems inherent to thermocouples would enable an engineer to secure a very accurate measurement over a very wide range of temperatures.

Taking the measurement and converting it to engineering units close to the source of the measurement and then transmitting over a high-speed digital connection to a host computer would eliminate the two most common problems in thermocouple measurement.

If the instrument packaging and electronics could also provide a stable reference junction, then an engineer could use thermocouples for measurements that RTDs have historically handled.

Thermocouple circuit



This temperature-measuring component consists of two dissimilar conductors-in this case, Chromel and constantan-welded together at their ends to form a junction. As heat applies to the junction, a voltage develops across it. This voltage is proportional to the temperature rise.

This article came from Matthews' ISA 2001 paper, which he presented in Houston. To see details of the prototype testing phase not in this article, read the original paper online at www.isa.org/journals/intech/uetspaper.pdf.

Source: NASA John H. Glenn Research Center

ASSEMBLE A DESIGN TEAM

This design team approached the problem of coming up with an intelligent thermocouple scanner by interviewing potential users, reviewing a market survey compiled with the help of sales representatives, and meeting with consultants.

The resulting design specification called for a scanner consisting of a universal temperature reference junction (UTR), an interface board, a microprocessor board, and a power supply.

The scanner would have to function in ambient temperatures from –30° C to +50°C and withstand vibration and shock levels consistent with flight test applications. The specification required that the scanner pass the CE requirements for both light and heavy industrial environments.

The initial design would accept up to 16 different shielded thermocouple inputs. The input configuration would be adaptable. Brass lugs would be available for users to connect thermocouple wires directly to the UTR. The UTR could also be adapted to accept various types of thermocouple connectors.

The scanner communication would be Ethernet TCP/IP. For configuration only, the design included a secondary RS-232 connection. The target accuracy of the instrument was ±0.5°C over the normal usable range of the input thermocouple.

TEMPERATURE REFERENCE JUNCTION

The two major sources of error in thermocouple measurements are secondary junctions and reference junction errors. Good instrumentation practices can eliminate errors in secondary junctions.

These practices include, but are not limited to the following:

- Minimizing the number of connection points in the thermocouple wire. It is best to have one continuous run.
- Making sure to use the proper type of extension wire, with no sharp bends or kinks.
- If connectors are absolutely necessary, making sure the metallurgy of the connector is certain.
- Thermocouple connectors have come with mismarked tabs, such as Alumel tabs marked as Chromel.
- Knowing the temperature of the connection point. It should be constant.

Reference junction errors are more difficult to eliminate. An error in the measurement of the reference junction temperature will be a bias error that directly affects the final calculated temperature.

There are three accepted methods to correct for reference junction temperature:

1) Maintain the reference junction at a known fixed temperature.

2) Allow the reference junction temperature to vary, and either introduce a compensating emf (voltage) into the circuit or account for the temperature in software.

3) Allow the reference junction temperature to vary, and adjust the readout instrument mechanically.

There are, of course, variations to each of these techniques. But effectively, all of the variations are performing only one of these fundamental tasks. The errors introduced into the measurement vary with the method used.

- A triple-point-of-water cell, an ice bath, or a constant temperature oven can generate a known fixed-reference temperature. Errors from the first two of these could be as small as ±0.0001°C. A constant temperature oven may induce errors of ±0.1°C. Although they offer excellent accuracy, the cell and the bath are not practical for a multichannel instrument. A constant temperature oven is a good alternative but adds size, weight, and cost.
- Hardware, software, or a combination of the two provides electrical compensation. This may include the use of a zone box to keep all of the thermocouple junctions at a constant temperature. Errors

from these methods will generally be ±0.1° to ±0.3°C, depending on which scheme measures the reference junction temperature.
- This technique calls for the readout device to be mechanically connected to a mechanical temperature indicator in the instrument and leads to errors that can exceed ±0.3°C. This is the least practical option.

This design team’s first decision was to use the electrical compensation method, #2, for the reference junction. The plan incorporated an existing sixteen-channel passive UTR. This product is an aluminum plate with three brass screw terminals (positive, negative, and shield), for each of the 16 inputs.

The brass screw terminals are electrically isolated yet thermally connected to the UTR plate. This UTR used a calibrated RTD to measure the temperature of the plate.

After initial testing, the team discovered that small temperature gradients existed across the UTR. The errors resulting from this were large enough to prevent the instrument from meeting the target accuracy.

The team redesigned the UTR plate to include a second RTD to provide a more accurate measurement of the UTR temperature. A second set of tests showed that the UTR temperature error maxed out at ±0.05°C by averaging the two RTDs.

HOUSE CRITICAL COMPONENTS

Recall that a major source of errors in thermocouple measurement is secondary junctions with temperature gradients at the junction points.

Keeping all of the junction points at the same temperature can minimize this. Thus, the designers decided to house all of the critical components and connections to the signal board in a zone box.

The zone box and internal mounting plates are aluminum to improve heat conduction and prevent hot spots from forming inside the module. The external components are stainless steel to help isolate the module components from ambient temperature changes.

Initially, the designers insulated the zone box to prevent temperature gradients, but tests showed that the accuracy of the reference junction temperature measurement was better if they heated the zone box and the UTR above ambient temperature.

With insulation on the instrument top cover, the UTR temperature remained several degrees above ambient temperature. This created an effect similar to the effect an internal oven might have had on the instrument without adding the oven components and controls.

By keeping the UTR temperature above the ambient temperature, small changes in ambient temperature have no effect on the UTR temperature. Tests showed that the response time of the UTR and zone box combination was about four hours.

This very slow response prevented temperature gradients across the UTR, making the junction temperature insensitive to fast ambient temperature changes.

A CALIBRATION NIGHTMARE

The signal board proved to be the most difficult part of the project. The initial design was an analog input section consisting of 16 isolation amplifiers, one for each thermocouple input, in order to achieve 1,000-volt DC isolation.

The output of each input amplifier multiplexed to a programmable gain instrument amplifier. The signal from this amplifier passed to a 16-bit analog-to-digital (A/D) converter and finally passed to the microprocessor board.

In theory, this appeared to be a good approach to prevent errors from grounded thermocouples and noise from DC voltage spikes. Although the board worked exactly as the team had planned, it turned out to be a calibration nightmare.

Calibrations required several hours, as each input amplifier had several trim pots to adjust. Small temperature changes within the zone box caused large output errors. These errors could not be controlled but were merely minimized by recalibrating the unit whenever the UTR temperature changed more than 0.5°C.

This was not practical for a unit that might install in an outdoor test facility, where temperature swings could exceed 40°C during a test.

After some experimentation, the design team incorporated a 22-bit A/D converter for each thermocouple input. This solved several problems.

First, the microvolt signals from the thermocouples converted to a digital signal almost immediately after leaving the reference junction. This minimizes the effect of noise and circuit drift.

Second, the signal-to-noise ratio increased from 100 to 160 decibels.

And finally, any drift in the A/D converters could easily be corrected by permitting periodic zero and span correction of the A/D converters via a software command.

When this command executes, the A/D converters switch off-line, the spans compare to a reference voltage, and the inputs short to get an updated zero. The process can require up to several minutes, depending on the setting of the average variable.

Once the engineers had implemented this second design, the project progressed smoothly to the prototype testing phase. **IT**

Behind the byline

Charles Matthews has more than 35 years of experience in instrumentation as a technician, engineer, and metrologist. He works for Scanivalve Corp. as the product support manager. He is a longtime ISA member and has taught the Pressure Measurement Short Course at the ISA Aerospace Symposium for the past three years.