# Microcomputer Based IR Temperature Transducers

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Microcomputer based IR temperature transducers are superior to the readily available analog types because in situ computing can be used to correct detector imperfections, provide three-figure emissivity compensation settings (including real-time control of emissivity compensation during individual measurements), and process transducer data, transmitting only salient information and thereby reducing data load on the data acquisition system (DAS) (see Figure 1).

The µC makes it possible also to calibrate the transducer in real time without bothering the DAS unless a failure mode is detected. In situ data logging and buffering for asynchronous polling by the DAS is available. The data rate of the transducer can be matched to the data rate of the DAS.

## CORRECTING DETECTOR IMPERFECTIONS

The thermal-type IR detectors used in moderate-temperature IR thermometers all suffer from shortcomings, but these can be corrected by sophisticated data processing techniques available with digital computers. The sensitive area of the detector and its image spot on the target are conjugate images of each other formed by the optics. Also, since Planck's equation defines a spectral quantity, an increment of radiant power, $dW_T$, for each micron of spectral bandwidth in the IR spectrum is radiated from the target spot to the IR detector according to the equation:

$$dW_T = \frac{\epsilon_T C_1 \phi}{\lambda^5 \left(e^{C_2/\lambda T_T} - 1\right)} d\lambda$$

Furthermore, since the optical system and its media are linear, bilateral systems, an increment of radiant power $dW_D$ is transmitted from the detector's sensitive area to the target spot according to the equation:

$$dW_D = \frac{\epsilon_D C_1 \phi}{\lambda^5 \left(e^{C_2/\lambda T_D} - 1\right)} d\lambda$$

The net incremental radiant power flow from the target spot to the sensitive area is:

$$dW_{net} = dW_T - dW_D$$

or:

$$dW_{net} = \frac{C_1 \phi}{\lambda^5} \left[ \frac{\epsilon_T}{e^{C_2/\lambda T_T} - 1} - \frac{\epsilon_D}{e^{C_2/\lambda T_D} - 1} \right] d\lambda$$

where:

$C_1$, $C_2$ = absolute constants
$\phi$ = optical gain of the IR focusing optics
$\lambda$ = wavelength in microns
$\epsilon_T$ = emissivity of the target surface
$\epsilon_D$ = emissivity of the detector surface

then:

$$W_{net} = \frac{C_1 \phi}{\lambda^5} \int_{\lambda = \lambda_1}^{\lambda = \lambda_2} \left[ \frac{\epsilon_T}{e^{C_2/\lambda T_T} - 1} - \frac{\epsilon_D}{e^{C_2/\lambda T_D} - 1} \right] d\lambda$$

From this basic energy balance equation, the target temperature is an exponential function of the detector temperature $T_D$.

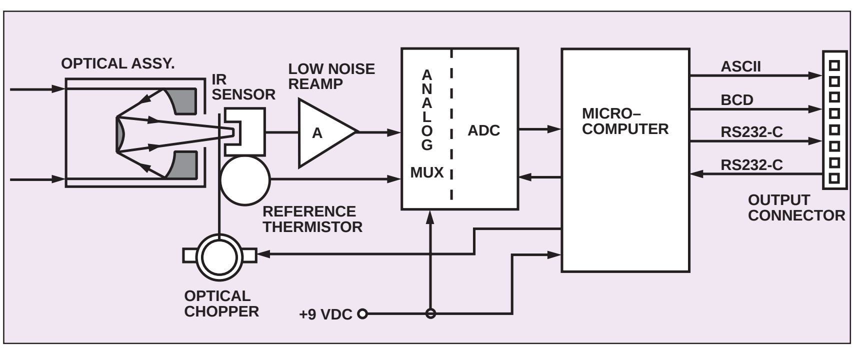


*Figure 1*

The output signal from the IR detector is a minute voltage proportional to the difference in temperature between the target and the detector body itself. To obtain an accurate measurement of the target temperature, it is therefore necessary to accurately measure the detector body temperature and add the processed difference temperature provided by the IR detector.

If our embedded computer can improve the accuracy of either of these component temperature measurements, the overall target temperature measurement is enhanced. In fact, the accuracy of both of these component temperature measurements is significantly improved using computer enhancements, as explained later.

Another troublesome detector error source that can be completely corrected with the computer is DC drift caused by ambient temperature variations. The detector body temperature $T_D$ is probably the most important variable the computer uses to improve overall system accuracy. The techniques by which the computer obtains this variable with greatly enhanced accuracy are outlined below.

$T_D$ spans the range of the natural environment, from roughly -50 to 100°C. Over this range, the most precise and accurate temperature measuring transducer is the thermistor. It is rarely used as the temperature reference element for IR thermometers, however, because its output signal is highly nonlinear, and, although extremely stable, its as-manufactured nominal values vary widely from unit to unit (production spread).

Most IR thermometer manufacturers are limited to simple analog correction techniques for their detector reference elements and so must abandon the more accurate and stable thermistor for a less accurate but easier to use element such as an integrated circuit, which outputs a linear current with temperature.

Highly nonlinear transducer responses are no problem for a computer, however, because they can be characterized with a Taylor series polynomial of the form shown in Equation 6 with an order, n, high enough to give arbitrarily perfect linearization correction for any transducer's curve:

$$A + BX + CX^2 + DX^3 + ... ZX^n$$

An algorithm for a general solution of the equation is held as a subroutine in program memory, while the transducer-specific coefficients A,B,D,C ... Z are held in firmware (EEPROM). Given the power of modern µC's, complex mathematical operations like this are practically free of hardware costs and can be performed in real time quickly enough not to affect the overall reading speed. The bottom line is that actual detector case temperature measurements of 0.05°C absolute accuracy are routine.

The IR detector itself is another temperature transducer with a highly nonlinear and temperature-dependent response:

$$E_0 = R \cdot W$$

where:

$E_0$ = detector output in volts
W = IR electromagnetic radiant power in $W/m^2$
R = responsivity (constant of proportionality)

Responsivity is also a nonlinear function of $T_D$. It is typically grossly corrected in the industry with a simple linear gain correction produced by a temperature sensitive resistor in the preamplifier feedback network. With an embedded µC, a third-order Taylor series correction using the real-time values computed for $T_D$ will effect a complete error correction for less cost than the temperature sensitive feedback resistor. These techniques allow the price of new computer based digital IR temperature transducers to be no greater than that of their analog predecessors, even with greatly enhanced performance and accuracy.

$W_T$, the net radiant target signal power impinging on the detector, is highly nonlinear with target temperature $T_T$; for low-temperature targets ($T_T$<1000°F), it is also highly dependent on the detector temperature itself ($T_D$). $W_T$ is a spectral quantity that depends on the spectral window it passes through, as calculated from Planck's equation. For very wide band IR thermometers measuring high-temperature targets, this characteristic approaches the fourth order of the Stefan-Boltzmann law:

$$W \approx K \sigma T_T^4$$

where:

$T_T$ = absolute target temperature
$\sigma$ = Stefan-Boltzmann constant
K = a nonlinear function of $T_D$

In present-day IR thermometers, K is usually combined with R of Equation 7 and a single linear compensation correction is applied, even though they have differing slopes in $T_D$. With Taylor series digital corrections, only three or four coefficients need to be stored for use with the general purpose Taylor series algorithm to effect nearly perfect corrections of both coefficients independently.

The critical linearization of the $T_T^4$ term (in the equation above) is usually left to linear approximation techniques. The instrument's entire scale span is divided into a convenient number of curved sections, usually between 6 and 12, and each section is approximated by a straight line that can be easily handled by analog techniques. Unfortunately, each section is accurately corrected at only two temperatures; other temperatures in the section can be read out in error by as much as the entire accuracy specification of the instrument, which was fixed at one of the accurate points of the highest section. Thus the ± linearity error specification is usually equal to, and in addition to, the span accuracy specification of the instrument.

In digital IR thermometers with embedded µC's, a Taylor series polynomial with as many as 7 terms, solved in real time, can effectively solve the fourth-power relationship between detector output voltage and target temperature.

Detector zero (or DC) drift is another imperfection that can be effectively corrected with an embedded µC. Thermal detectors usually have negligible long-term zero drift under stable ambient conditions but are quite susceptible to thermal transients. Errors of several degrees are common when taking an instrument with a simple thermal detector from one room to another with a different ambient temperature.

An effective way to correct this error is periodically to completely block the incoming IR radiation signal from the target with an optical chopper, while measuring the remaining error signal and storing its value in computer memory for later subtraction from the measured composite signal. This procedure can be performed as often as necessary or convenient under adaptive computer control. Whenever an inactive time interval can be identified by the computer, the procedure can be cycled without interrupting the useful flow of information. If this asynchronous chopping is done frequently as compared to the drift rate of the detector, nearly perfect DC zero restoration can be achieved.

## DIGITAL TARGET EMISSIVITY COMPENSATION

Extremely precise (three-figure) emissivity corrections can be called up either from as many as 10 values stored in resident EEPROM, or from complex, real-time programs dependent on target time-temperature relationships. An example of the latter is a program for compensation of the emissivity of an induction heated steel part, which oxidized as it heats to higher temperatures. The emissivity may be quite low ($\sim$0.1) at low temperatures, but as it is rapidly heated, an oxide film forms on its surface, which raises the emissivity according to its time-temperature history. This time-temperature integral can be easily calculated by the computer and the corresponding emissivity value applied to the temperature readout in real time.

## EMBEDDED DATA PROCESSING CHORES

Transducer data can be preprocessed at the point of measurement to extract the pertinent information for transmission to the mainframe data processing system. For instance, only excess limit or out-of-range data may be desired. In this case, set point values can be programmed into the embedded computer firmware so that only data above (or below) the set point will be transmitted, perhaps on a priority interrupt basis. On a serial digital interface bus, a priority interrupt hierarchy can be defined that will maximize the number of drops (transducers) a single wire will accommodate.

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## AUTOMATIC CALIBRATION

A smart transducer can be programmed to identify windows in data flow patterns where a preprogrammed calibration procedure can be performed without affecting useful data flow. For instance, if the IR thermometer is measuring the temperature of cans proceeding down a conveyor belt, a gap between successive cans is sensed and the dead time during the gap is used to cycle the calibration procedure. The master DAS need not be aware of the individual transducer's calibration details unless an out-of-limits condition occurs and the affected transducer initiates a priority interrupt alarm.

## INTEGRAL DATA LOGGING AND BUFFERING

Both volatile and nonvolatile data logging are built into the transducer. Volatile data logging with the resident RAM is used to assemble and temporarily store on-line data either for use in computations or to wait for bus polling. This ability to locally process and format data reduces the data transfer time to the processor. Furthermore, because even fast IR thermometers are relatively slow (~ms) compared to electronic DASs (~µs), very little time is needed to service an individual digital IR thermometer on a data bus. The data can often be compressed into 50 µs/s, allowing dozens of drops (transducers) on a single-wire pair (see section on Interface Management). Nonvolatile data logging, via the embedded EEPROM, is used to store significant historical data such as maximum, minimum, average, mean, and out-of-limit values for indefinite times.

## IN SITU DIGITAL CONTROL INTELLIGENCE

The powerful integral microcontroller can also be programmed to act on the incoming temperature data to perform external control functions. There are 16 multipurpose µC control ports available for command inputs from external signals such as simple switch closures or photo-detector signals, or for control outputs such as power relays. Each port can directly drive an optically isolated solid-state relay capable of controlling a 10 kW load operating at 1600 V differential from the transducer.

There are also four precision, low-level analog inputs available that can accept auxiliary inputs from thermocouples, RTDs, or other IR detectors for support functions. The simplest of these might be detection of temperatures above or below a preset threshold that has been programmed into EEPROM. This set point could even be automatically programmed by the computer in response to input variable history. As many as four set points can be monitored and controlled simultaneously. Among the more complex control functions are complete local closed-loop PID control of a process temperature entirely by the transducer with no external help from other control electronics.

## INTERFACE MANAGEMENT

The computer's data processing power minimizes the hardware complexity of the transmission lines by managing both electrical power and data transmission flow for the transducer. For example, the computer can function as a traffic cop to time share a single line among several dozen transducers for both power and two-way data transmission. In addition, when the line is used for power transmission, other transducers can be connected to it and powered up at the same time. When the computer disconnects line power, data can be transmitted so quickly that many connected transducers can be polled before the next power up. The bottom line is that inexpensive BNCs can be used with the transducers and a simple 2-wire party line can service up to 16 transducers over a distance of 1000 ft.

Another performance advantage accrues from the all-digital data transmission, which is far less susceptible to RFI/EMI than is analog data transmission. Because the binary data transmission is serial in nature and is formatted for bilateral transmission on a single line, a single fiber-optic line can be substituted to provide complete immunity from RFI/EMI, up to and including lightning strikes. Finally, the savings on multipin connectors and individual multiconductor cables is enough to pay for the µC, not to mention the greatly enhanced reliability from a single line system vs. six conductors.

## SUMMARY

The superiority of µC based IR temperature sensing instruments over present generation analog IR thermometers is apparent. This statement is supported by the enhanced accuracy of temperature measurements of the difference between the target and detector body, and the measurement of the detector body itself. Also to be noted is the ability of the microcomputer based instrumentation to replace the linear approximation techniques. Extremely precise emissivity correction is another plus, as are the automatic calibration, integral data logging, and in situ digital control intelligence capabilities. The reduction in the cost of the interface between the host computer and the transducers can be substantial. An extremely sophisticated IR temperature measurement system can be provided at a cost that is equal to or less than previously available analog systems with limited capabilities.