Sensor Selection 101

Optimal Temperature Sensor Selection:
Your First Step to Achieving Accurate Temperature Measurement

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There’s no simple solution to achieving accurate temperature measurement. It’s a combination of knowing the inherent accuracy of particular sensor types, but also how environmental factors can create further measurement uncertainty and the sensor calibration techniques available to reduce this uncertainty.

Thermocouples

Thermocouples are the smallest, fastest and most durable temperature measurement solution. They can withstand very high temperatures, harsh mechanical punishment and are simple to operate. Their size allows for rapid temperature response times and the sensing junction can often be placed very close to the desired point of measurement. The durability and simplicity of this sensor type makes them ideal for embedding into other devices.

However, the thermocouple is most at risk from accuracy, noise and precision error. When extreme accuracy and precision is required, many of these shortcomings can be compensated for – simply by using short runs of insulated and shielded thermocouple wires with balanced, low-pass filtered differential amplifiers (to avoid common-mode voltage offsets), as well as through relatively complex calibration procedures.

Lack of alloy homogeneity presents additional challenges. Deviations in metal purity and alloy homogeneity result in thermocouple temperature profiles deviating from the National Institute of Standards and Technology (NIST) standards, which become particularly problematic when long runs are required. When high accuracy is required without calibration, a thermocouple type that consists of a minimum number of elements like a type T, J or G should be used.

Thermistors

Thermistors are ideal for measuring applications that require high accuracy sensitivity over a relatively narrow range of temperatures (typically less than 300˚C). However, they cannot endure high temperatures or mechanical stresses like thermocouples, which makes them difficult to use in applications and assembly operations where these influences are not well controlled. To compensate for this limitation, the sensor can be encased in a protective metal enclosure - but this will be at the cost of thermal responsiveness. Some special version thermistors are capable of working to temperatures of 1000˚C.

Despite being less subject to different types of error, local signal conditioning is still recommended for thermistors (though it is much simpler than that required for thermocouples). Because thermistors tend to be larger than thermocouples, they have correspondingly slower response, and may also be subject to additional location and heat transfer error than equivalently placed thermocouples.

Near their maximum sensitivity point, small changes in temperature produce relatively high changes in resistance (a non-linear response). However, away from the maximum sensitivity point, thermistors are less able to resolve changes in temperature. Padding resistors may be added in a voltage divider circuit to obtain a more linear response.

Thermistors are capable of being made relatively uniform in batches, but batch-to-batch variations can be problematic when high precision or accuracy is required. Additionally, there are no NIST standards for thermistors, so there may be additional manufacturer-to-manufacturer response variations.

RTDs

RTDs are suitable when extremely stable and precise measurements are required, or when accuracy over a prolonged time is the most important factor (the accuracy and precision of an RTD often exceeds that of both a thermistor and thermocouple). RTDs follow Deutsche Industrie Normen (DIN) and/or Joint Information Systems Committee (JISC) national standards and with good tolerance specifications, off-the-shelf RTDs are very consistent regardless of their batch number.

RTDs are very delicate, and while the melting temperature of an RTD element is sufficiently high enough to survive many high-temperature manufacturing operations, they do not tend to survive aggressive mechanical operations (such as compaction), which results in them being difficult to embed into custom mechanical devices. This limitation can be reduced through the use of metal-sheathed assemblies that remove the fragility, but this is at the cost of response time. Additionally, their larger size typically results in slower response times than comparable thermocouples.

For a typical 100ohm RTD, wire and termination resistance associated with long lead lengths and multiple connections can become a significant source of error. To achieve the highest accuracy, three or four-wire RTDs are often used. The electronics can be constructed to dynamically remove error associated with lead resistance, but there is also a trade-off in terms of cost and the number of wires required to perform the measurement.

Noise from external sources can create additional measurement problems, but can be mitigated in much the same way as thermocouples – by using differential, ungrounded, and shielded elements. These effects can also be limited through optional electronics that perform 10% duty cycle measurements to limit self-heating power without reducing signal strength. However, the trade-off for utilizing low-level signals (power) to drive an RTD is that even further measures may then be required to minimize the effect of external noise.

Sensor Considerations

When building your knowledge base on sensor types, be sure to consider inherent accuracy in terms of durability, range of operation, and susceptibility to external noise influences. Also examine how the sensor will be used in terms of temperature range, the required level of accuracy and repeatability, handling/installation endurance, whether it will be calibrated/grounded, and the type of environment it will be used in.

A basic awareness of the inherent accuracy of particular sensor types is important, but goes only a short way toward the goal of achieving optimally accurate temperature measurement. It is the broader knowledge of how sensor choice, sensor placement and a wide variety of environmental factors can contribute to sensor error, as well as having a familiarity with calibration techniques that can be used to reduce this uncertainty, that ultimately leads to optimum sensor selection and measurement accuracy.

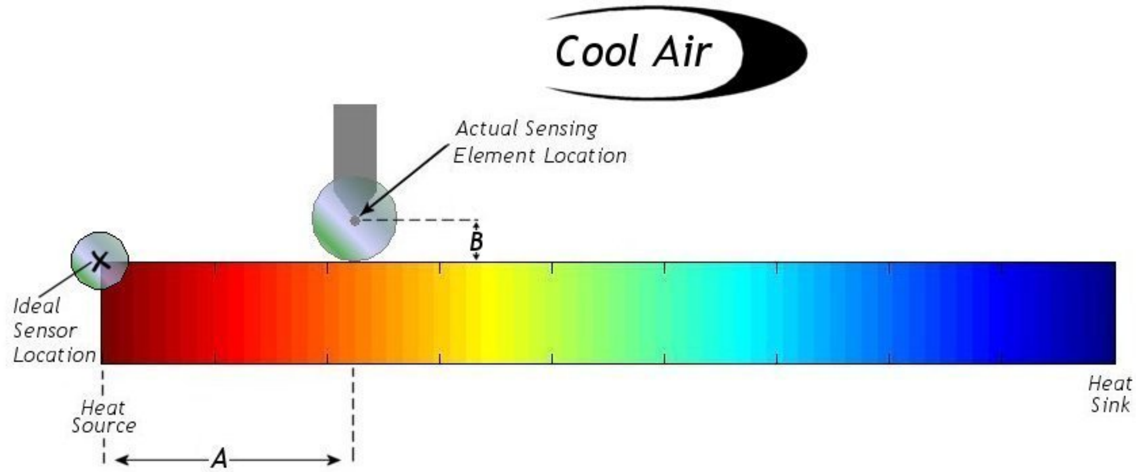
Location and Transient Errors

It is nearly impossible to sense temperature exactly where you need it. At the very least, the sensor itself has a finite size that displaces the sensing element from its attachment - resulting in the sensor being at a different location than the desired measurement location. Thermistors and RTD's are at greater risk for location error than an equivalently placed thermocouple - simply because of their size.

If surrounding heat sources and sinks are known, location errors can be compensated for. However, this can be difficult in many systems and will result in location errors resisting calibration. The simplest solution, which avoids complex calibration techniques, is to utilize a small sensor and place it as close to the temperature source as possible.

Figure 1 illustrates how errors in sensor location can affect temperature measurement accuracy. Location error 'A' is a direct result of the entire sensor being displaced from its desired location, typically because of interference. Location error 'B' is a direct result of the sensor element being displaced from the intended surface by its encasement.

Figure 1 – Location Error



Transient errors are dynamic thermal errors, which are typically very difficult to compensate for. This is because every material within the thermal system has its own unique thermal conductivity and capacity. Of the three most popular sensor types, it is the thermocouple that typically best minimizes transient errors because it is the smallest sensor with the smallest time constant.

Heat Transfer Error

Sensors receive conductive, convective and/or radiative inputs that contribute to measurement inaccuracy. In *figure 1*, these types of errors can be represented by ambient conditions that heat up or cool down the sensor – often along specific pathways such as along the thermally conductive electrical wires used in thermistors, RTD's and some thermocouples, from a nearby heating element. In this instance, heat from a local source travels up the copper wire to the sensing element and distorts the measurement. E and J thermocouples use alloys that are less conductive, which makes them ideal for mitigating this kind of error.

Self-Heating Error

The third form of measurement error applies to Thermistors and RTDs, and results from heat dissipating inside the sensing element itself. This causes the temperature inside the sensor to rise, which makes the measured temperature less indicative of the environment. Strategies for minimizing this include keeping the current low or pulsing the sensor with a low duty cycle to keep the average power dissipated in the sensor low.

Atmosphere & Environmental Influences: Moisture, Oxidation & Reduction

For all three sensor types, operating or cycling them near their temperature limits can cause deterioration, which then results in a drift from the initial profile. Thermistors and RTDs are usually well sealed from the environment, which makes them less susceptible to internal corrosion. However, these sensors are usually connected to copper wires, which increase the risk of lead wire deterioration.

For RTDs, this lead-wire corrosion problem is mitigated by using 3-wire or 4-wire units that effectively measure the resistance of the sensing element, versus the connection wire. This helps give RTDs the greatest overall stability of the three sensor types. Thermistors usually exhibit some initial drift, but are generally stable after initial aging. Thermocouples exhibit more complex behavior because the voltages produced are a direct result of the dissimilar metals used, as well as their alloy formulation, which both change as the metal ages and deteriorates.

When attempting to measure temperature on a surface, forced airflow on and around a sensor can contribute to a false reading due to heat transfer error. This is because convective currents add or remove heat from the sensor and/or measurement surface. If the atmosphere is at a different temperature than the surface, or the measurement environment is moist, the heat flow associated with convection must be considered as if it were another heat source or sink.

Mechanics, Acoustics, Vibration and Triboelectric Effects

Small wire gages and fragile sensors should be avoided in applications that subject them to extreme mechanical motion, vibration or high intensity acoustics. The most common wire failures occur near connection points, where there is the greatest amount of flexure. However, mechanical motion or vibration can also stimulate internal resonances inside the sensor - leading to early failure. Thermocouples are generally the most durable of the three sensor types because many of the alloys used in the wires are more ductile – allowing them to handle additional motion.

Besides fatigue, cables in motion can also generate low voltage triboelectric effects. For microvolt sensors - such as thermocouples or RTD’s - these effects could become another contributor to measurement uncertainty if the motion stimulating the effect is of the same order as the thermal responsiveness you intend to measure.

Magnetic, Capacitive, RF and Grounding Effects

Thermocouples and RTDs generally have the lowest noise immunity of the three sensor types. By shielding and properly grounding these sensors, their immunity from potential noise offsets can be further improved. This is true for offsets caused by capacitive, radio frequency (RF), and offset currents, but immunity from magnetic sources is not so easily achieved.

The environment in which sensors operate can often contain large motors and solenoids, or high current devices that can cause transient currents or magnetic surges. For sensor types that require stimulating electronics (thermistors and RTDs), these power droops could potentially affect the power supplies and sensing circuits inside the sensor electronics, which subsequently affects temperature readings. Additionally, large inductive spikes can create circulating currents that alter ground potentials near the sensors. This effect then biases the voltage read from the sensor and creates a false reading.

When thermistors are used to measure temperatures near their lower extremes, the resistance may approach 100K or more. When this happens, long runs of thermistor wire can create an antenna that adds noise to the measurement system. While most of this can be filtered out, the potential for biasing the measurement becomes greater because direct current (DC) charge collects (known as the electret effect).

The best method to protect from outside electrical and magnetic sources is to keep the sensor and lead wires away from them, shield them, and/or pay close attention to electronics isolation and grounding. Keeping sensor lead wires short and converting the signals into digital form, as close to the measurement point as possible, can also help minimize noise.

Sensor Calibration Techniques to Reduce Measurement Uncertainty

A common way to correct for inherent accuracy errors is to calibrate the sensor in a controlled isothermal liquid bath and compare temperature readings against a standard reference. Alternatively, point calibration – immerging sensors in an ice bath (0.01˚C is standard) or other standardized freeze point (such as a gallium freeze bath at 29.7646°C) - is an alternative way to characterize accuracy, providing assumptions can be made as to how the accuracy at the calibration points can be extrapolated to predict the accuracy at other temperatures.

If only relative accuracy is important, an array of sensors can be calibrated to each other by immersing them in a common bath at a known temperature (0˚C for an ice bath). The temperature in the bath can then be slowly raised, while tracking all sensor responses. To achieve the best results, the calibration bath should span the same temperature range as the intended measurement. Additionally, the rate of temperature increase should be slow, relative to sensor responsiveness, which will reduce time-transient errors.

The limiting factor for minimizing inherent sensor error is the uncertainty (including both the accuracy and precision) of the calibration process. Generally, thermistors and RTD’s have better inherent accuracy than thermocouples, but all three types of sensors will require calibration to achieve accuracies down to 0.1˚C. However, it is more challenging to calibrate thermocouples than thermistors and RTDs because calibration must consider both hot and cold junction temperature errors.

Putting it all Together

Sensor selection goes beyond having a sound knowledge of the inherent accuracy of particular sensor types. In selecting the best sensor for an application, environmental factors must also be considered for potential sources of error. It is also equally important to be familiar with the strategies that can be used to minimize environmental influences and maintain the best level of temperature accuracy.

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