Introduction

As the world grows ever smarter, the use of electronic systems in industrial, consumer, home automation and other areas has become progressively commonplace. With this trend comes the increasing need for the electronic systems to be aware of elements of the operating environment, whether it be a refrigerator making sure to keep the milk cold, a water heater ensuring the shower is not too hot or too cold or a glucose meter knowing that the ambient temperature is within the specified range for correct test strip operation, temperature sensing is everywhere. There are many different methods and devices that may be used to measure temperature within an electronic device, and this paper will discuss some considerations and available options when selecting a temperature-measuring device. Due to its ultra-low-power nature, the MSP430 microcontroller is well-suited for monitoring temperature within many different devices.

Sensor type – Thermistor

One of the most common and lowest cost methods of temperature measurement can be achieved with a thermistor. In its simplest form, a thermistor is a temperature-dependent resistor with the resistance changing as the temperature varies. In an ideal world, this response would be linear; however, this is not the case. For most practical uses, this non-linearity must be corrected. This can easily be achieved by using the analog-to-digital converter (ADC) of an MSP430 microcontroller to measure the resistance and linearize the result by a look-up table, linear interpolation or other, more complex mathematical methods.

Thermistors are available as both surface mounts or through-hole PCB-mounted components, making them a good, low-cost option for PCB level, or enclosed housing temperature monitoring. For many industrial or automotive uses, thermistors are available enclosed in
Texas Instruments

An introduction to MSP430™ microcontroller-based temperature-sensing solutions

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a housing for easy mounting, or as a completed temperature probe. The MSP application report SLAA129 (Implementing an ultra-low-power thermostat with slope A/D conversion) describes a method of using a thermistor to create an ultra-low-power thermostat using a low-cost, but high-precision comparator-based slope-conversion method. Extending this implementation to use one of the MSP430 microcontroller’s integrated ADCs with linear interpolation based on multiple calibration points or a lookup table is easily possible and can result in higher accuracy.

Another common type of temperature sensor is the thermocouple, which is created by connecting two dissimilar metals together. When this junction is subjected to a temperature gradient, a very small voltage is generated, typically in the range of 10s of μVs/°C. Thermocouples are common place within industrial automation and process-control systems, and like thermistors, they exhibit a non-linear output response which requires correction. As the thermocouple measures a temperature difference between two points to realize this as an absolute temperature, it is necessary to use a known temperature reference commonly referred

Table 1. Common temperature measurement devices

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Thermocouple</th>
<th>RTD</th>
<th>Thermistor</th>
<th>Semiconductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature range (typical values)</td>
<td>Very wide</td>
<td>Wide</td>
<td>Narrow</td>
<td>Narrow</td>
</tr>
<tr>
<td></td>
<td>−200°C to +2000°C</td>
<td>−200°C to +650°C</td>
<td>−50°C to +300°C</td>
<td>−50°C to +200°C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Repeatability</td>
<td>Fair</td>
<td>Excellent</td>
<td>Fair to good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Long-term stability</td>
<td>Poor to fair</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Sensitivity (out)</td>
<td>Low</td>
<td>Medium</td>
<td>Very high</td>
<td>High</td>
</tr>
<tr>
<td>Linearity</td>
<td>Fair</td>
<td>Good</td>
<td>Poor</td>
<td>High</td>
</tr>
<tr>
<td>Response</td>
<td>Medium to fast</td>
<td>Medium</td>
<td>Medium to fast</td>
<td>Medium to fast</td>
</tr>
<tr>
<td>Size/Packaging</td>
<td>Small to large</td>
<td>Medium to small</td>
<td>Small to medium</td>
<td>Small to medium</td>
</tr>
<tr>
<td>Interchangeability</td>
<td>Good</td>
<td>Excellent</td>
<td>Poor to fair</td>
<td>Good</td>
</tr>
<tr>
<td>Point (end) sensitivity</td>
<td>Excellent</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Lead effect</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Self heating</td>
<td>No</td>
<td>Very low to low</td>
<td>High</td>
<td>Very low to low</td>
</tr>
<tr>
<td>Overall advantages</td>
<td>Self powered, simple, inexpensive, rugged, variety of physical forms, wide range of temperature</td>
<td>Most stable, most accurate, more linear than thermocouple</td>
<td>High output, fast, two-wire ohms measurement</td>
<td>Most linear, highest output, inexpensive</td>
</tr>
<tr>
<td>Overall disadvantages</td>
<td>Non-linear, low voltage, reference required, least stable, least sensitive</td>
<td>Expensive, slow, current source required, small resistance change, four-wire measurement</td>
<td>Non-linear, limited temperature range, fragile, current source required</td>
<td>T &lt; 250°C, power supply required</td>
</tr>
</tbody>
</table>

Figure 2. Example of an industrial screw-in thermistor temperature sensor

Sensor type – Thermocouple
to as the cold junction temperature. A thermistor is often used for this purpose. There are several options for linearizing and calculating the absolute temperature of the thermocouple junction. These almost always require some digital processing, but the required processing can easily be carried out within a microcontroller such as one of the MSP430 devices.

Depending on the measurement accuracy required, the system designer is presented with a number of options, and the choice of the components used within the analog path will greatly determine the quality of the resulting output. Texas Instruments (TI) provides many solutions for thermocouple signal-chain options, but only two examples will be discussed here. One option would be the use of a dedicated analog front end (AFE) device such as the LMP90100 together with an MSP430 microcontroller. Offering a high-performance 24-bit sigma-delta ADC, matched programmable excitation current sources, fixed (FGA) and programmable gain amplifiers (PGA), this highly integrated device offers a complete AFE solution for many temperature measurement sensors and applications. An example of such a high-performance measurement system would be a chemical processing plant with precise monitoring needs. The LMP90100 AFE may also be used as a precision input stage for two-, three- and four-wire resistance temperature detector sensors. Full documentation for the LMP90100 AFE device may be found on TI’s website at [www.ti.com/product/lmp90100](http://www.ti.com/product/lmp90100).

In application note SNAA134, a user can quickly interface the temperature sensor AFE together with an MSP430 microcontroller for a low-power, remote temperature sensor for recording and processing.

![Figure 3. Typical high-level application diagram of LMP90100](image)

If the application requires lower power or a smaller form factor and cannot use a dedicated AFE, the MSP product portfolio offers analog integration that enables direct temperature measurement with thermistors. One of the key features of MSP430 microcontrollers is the integration of high-performance analog building blocks. These building blocks include ADCs, digital-to-analog converters (DACs), comparators and operational amplifiers. Within the MSP430 microcontroller product range, two main ADC architectures are used offering different resolutions depending on system requirements. Both 10- and 12-bit successive approximation...
converters (SAR) plus, 16- and 24-bit sigma-delta converters may be chosen depending upon individual product selection. By utilizing these analog peripherals, it is often possible to implement a system using fewer external components, resulting in an overall lower cost system solution. These analog building blocks are summarized in Table 2 below.

<table>
<thead>
<tr>
<th>MSP430™ Family</th>
<th>ADC</th>
<th>DAC</th>
<th>Comp</th>
<th>OpAmp</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1xx</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>F2xx</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>G2xx</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>F4xx</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>F5xx</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>F6xx</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>FR5xx</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

*Table 2. MSP430 microcontroller analog options*

The MSP application report SLAA216 (Implementing a single-chip thermocouple interface with the MSP430x42x) describes a method where two of the three sigma-delta 16 ADCs included in the MSP430F42x device are used to implement a cold-junction-compensated thermocouple. These ADCs each have a dedicated PGA which allows a single-chip solution to be built. One ADC with PGA set to a gain of 1 is used to monitor a thermistor to measure the cold junction reference temperature, while a second ADC is used with PGA set to a gain of 16 for the thermocouple input. Both sensors are linearized in the microcontroller and then an absolute thermocouple temperature is calculated using the known cold junction reference temperature.

A second compensated thermocouple example is shown within application report SLAA501 (Implementing a thermocouple interface with ADC12_A). In this implementation, the integrated 12-bit SAR converter of the MSP430F5529 microcontroller is used. As the MSP430F5529 device does not include any integrated operational amplifiers, an external gain stage must be used. Linearization and absolute thermocouple temperature are calculated resulting in an average measurement current of ~2.5 µA for a 1-SPS temperature reading. The software flow diagram is shown in Figure 4. These simple thermocouple systems would be accurate enough for many domestic thermostat, or building management systems.

Like the thermistor, the RTD sensor element exhibits...
Resistance temperature detector (RTD)

A variation in resistance when the element is subjected to a change in temperature. RTD elements are typically constructed of a single, pure metal wire wound around a glass or ceramic bead. TI application report SNOA481 discusses various analog considerations and recommendations that should be considered when implementing an RTD interface. These vary greatly depending on whether a two-, three- or four-wire RTD sensor is being used. As with thermistors and thermocouples, the transfer function of temperature against resistance for RTDs is also non-linear by nature. Linearization options include a simple look-up table, or a more math-intensive polynomial expression.

Semiconductor

There is a growing trend in some market segments to utilize semiconductor sensors for PCB-level temperature measurement as an alternative to using PCB-mounted thermistors. Analog sensors can take advantage of an available system ADC, have a tiny footprint and don’t need the linearization required by thermistors. The digital interfaces offered by some of these sensors can enable simpler system integration. Available in a variety of form factors and with features including analog and digital outputs as well as programmable thermostat trip points, these devices offer the system designer a flexible choice when it comes to selecting the right device. TI has more than 100 temperature-measurement IC solutions available, but in the interest of brevity, we will focus on three example system solutions.

Integrated circuit analog output temperature sensor

Another common and simple-to-use temperature sensor is the integrated circuit analog output temperature sensor. These devices are available as standalone analog outputs or include simple temperature switch outputs that can be used to flag over-temperature error events. IC analog output temperature sensors have a linear transfer function so do not require the signal conditioning that thermistors do, simplifying system design and shortening design cycles at comparable system cost.
Shown in Figure 6 is the LM94022, a simple precision analog sensor, connected to an ADC. The LM94022 operates at a supply voltage as low as 1.5 Volts. A class-AB output structure gives the LM94022 strong output source and sink current capability for driving heavy loads. This makes the LM94022 well suited to source the input of a sample-and-hold analog-to-digital converter with its transient load requirements. While operating over the wide temperature range of −50°C to +150°C, the LM94022 delivers an output voltage that is inversely proportional to measured temperature. The LM94022’s low 5.2-µA supply current makes it ideal for battery-powered systems as well as providing a low self-heating of 0.01/°C without additional circuit complexity. Two logic inputs, Gain Select 1 (GS1) and Gain Select 0 (GS0), select the gain of the temperature-to-voltage output transfer function. Four slopes are selectable: −5.5 mV/°C, −8.2 mV/°C, −10.9 mV/°C, and −13.6 mV/°C. In the lowest gain configuration (GS1 and GS0 both tied low as shown in Figure 6), the LM94022 can operate with a 1.5-V supply while measuring temperature over the full −50°C to +150°C operating range. Tying both inputs high causes the transfer function to have the largest gain of −13.6 mV/°C for maximum temperature sensitivity. These inputs can also be driven by logic signals allowing the system to optimize the gain during operation or system diagnostics.

Another device, the LM57 (Figure 7 on the next page), includes a precision, dual-output, temperature switch with an integrated analog temperature sensor. The LM57’s trip temperature (TTRIP) is programmable by using two external 1 percent resistors. The VTEMP output is inversely proportional to temperature, thus has a negative temperature coefficient to the measured temperature. In-situ verification that the comparator and output circuitry are functional after system assembly is built in using the TRIP-TEST pin. As it draws only 28 µA max from its supply, it has very low self-heating, about 0.02°C in still air. Please refer to App Note SNOA547B, AN-1984 LM57 Temperature Switch vs. Thermistors, which details using such a device.

Specified for operation from −40°C to 125°C, the TMP103 is a low-power (3-µA active power), ±1°C accurate digital output temperature sensor with 1°C resolution. With its 0.79 × 0.79-mm wafer chip scale package, it is suited for space-constrained applications such as smartphones, tablets and other hand-held consumer devices. One significant benefit of these sensors is the ease of use they offer. As with many of TI’s temperature-measurement ICs, the TMP103 device requires no further calibration after leaving the factory.

**Example 2 – TMP103 + MSP430 microcontrollers**

Specified for operation from −40°C to 125°C, the TMP103 is a low-power (3-µA active power), ±1°C accurate digital output temperature sensor with 1°C resolution. With its 0.79 × 0.79-mm wafer chip scale package, it is suited for space-constrained applications such as smartphones, tablets and other hand-held consumer devices. One significant benefit of these sensors is the ease of use they offer. As with many of TI’s temperature-measurement ICs, the TMP103 device requires no further calibration after leaving the factory.
The TMP103 is available with eight pre-programmed IIC addresses allowing multiple devices to be placed on the same bus, as shown in Figure 8 below.

These devices are primarily used to monitor the temperature at the printed circuit board (PCB) level within devices such as smartphones, but by connecting such a sensor to an MSP430 microcontroller, numerous other application spaces open. For example, by connecting the TMP103 sensor to an MSP430FR57xx device, which implements innovative and ultra-low-power, non-volatile ferroelectric random access memory (FRAM), an ultra-low-power temperature data logger could easily be created. While most microcontrollers limit the number of data points that can be stored to their non-volatile memory because of limited write cycle endurance, FRAM has nearly infinite endurance and consumes very little power, eliminating the need for external EEPROM in applications requiring frequent recording of temperature data points.

Example 3 – TMP006 + MSP430 microcontrollers

A new and innovative solution for measuring temperature is the TMP006 infrared temperature-sensing IC. This device is designed to measure the temperature of an object without the need to make physical contact with it. Using innovative TI MEMS technology, Infra-Red (IR) radiation energy creates a measurable
effect within the sensor device. The integrated analog and digital signal processing converts this measured radiation energy into a relative temperature, that the MSP430 microcontroller then converts to the absolute temperature based on stored calibration coefficients. With its low-power operation and small form factor, this device is suited for a variety of commercial and industrial applications such as measuring the case temperature of a piece of equipment, or measuring the temperature of an item where physical contact is not achieved easily.

By pairing the TMP006 device with an MSP430 microcontroller, many low-power temperature measurement or logging systems may be realized, whether it be a simple, hand-held, non-contact thermometer, or part of an industrial wireless sensor network.

Figure 9 below, shows the basic block diagram within the TMP006 IR temperature sensor.

In many simpler applications, it is often possible to use the integrated temperature sensor within the MSP430 microcontroller to give a localized temperature reading. Due to the ultra-low-power nature of the MSP430 device, it experiences very little self-heating effect and can therefore give an excellent indication of the surrounding ambient air temperature. Slight device-to-device variations of temperature sensor offset and gain may be present so, depending upon the application, it may be necessary to carry out individual device calibration to remove or reduce these factors. A single-point calibration can be used to remove the offset variation and, if required, gain variation can be reduced by adding a second calibration point — additional calibration points can further improve accuracy. Figure 10 on the following page shows an example of how a two-point temperature calibration may be made. By using two temperature test points, a simple \( Y = MX + C \) straight line equation may be made, allowing the user to calibrate for both gain and offset variations between devices. This method can be extended to include a piecewise linear interpolation scheme with any number of points, allowing very high accuracy using only the integrated temperature sensor and analog on many MSP430 devices.
Figure 10. Two-point temperature calibration

Summary
This paper discussed a few of the many options for temperature measurement, ranging from a single thermistor with a microcontroller and a few external components, to more advanced temperature-sensing solutions such as the LMP90100 AFE or the TMP006 IR MEMS temperature sensor. In almost every case, there is the need for some level of analog signal conditioning, often built from op-amps and an ADC available with TI’s MSP430 microcontrollers. This digital signal will usually require some digital processing for sensor linearization or absolute temperature conversion. Offering ultra-low-power consumption, a high level of analog integration and an extensive development ecosystem, the MSP microcontroller portfolio meets the requirements of today’s varied temperature-sensing applications.

Further reading
- SLAA216 Implementing a single chip thermocouple with the MSP430x42x application report
- SLAA501 Implementing a single chip thermocouple with the MSP430 ADC12 application report
- SNA134 MSP430 Interface to LMP90100 24bit Sensor AFE application report
- SNA195A AN2265 LMP90100 / LMP90098 (24-bit) and LMP90080 / LMP90078 (16-bit) 4-Wire RTD Interface application report
- SLAA129 Implementing An Ultralow-Power Thermostat With Slope A/D Conversion application report
- SLAA151 Interfacing the MSP430 and TMP100 Temperature Sensor application report
- SNOA481 Practical RTD Interface Solutions application report
- SNOA547B AN-1984 LM57 Temperature Switch vs. Thermistors application report

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