

Temperature Measurement Circuits for Embedded Applications

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INTRODUCTION

This application note shows how to select a temperature sensor and conditioning circuit to maximize the measurement accuracy and simplify the interface to the microcontroller. Practical circuits and interface techniques will be provided for embedded applications with thermocouples, Resistive Temperature Detectors (RTDs), thermistors and silicon integrated circuit temperature sensors. The attributes of each temperature sensor and the advantages of analog, frequency, ramp rate, duty cycle, serial and logic output solutions will be discussed. An analog output thermocouple circuit will be compared with a frequency output RTD oscillator circuit, along with design examples using serial and analog output silicon Integrated Circuit (IC) sensors. In addition, a Programmable Gain Amplifier (PGA) circuit will be shown that can increase the effectiveness of the Analog-to-Digital Converter (ADC) bit resolution of a non-linear thermistor sensor.

DEFINITIONS

The following terms are used in this application note:

- Accuracy is the difference between the true and measured temperature
- Common Mode Rejection Ratio (CMRR) is defined as the ability of the amplifier to reject a signal which is common to both inputs
- Input Offset Voltage (V_{OS}) is the voltage that must be applied to an amplifier to produce a zero volt output

- Local sensors are located on the same PCB as the microcontroller
- Precision is the ability to measure a small temperature gradient and determines the interchangeability of the sensor
- Remote sensors are located at a distance from the microcontroller's PCB
- Repeatability is the sensor's ability to reproduce previously measured values
- Stability is defined as the long-term drift of the sensor over a period of time

SENSOR-TO-MICROCONTROLLER INTERFACE OPTIONS

The sensor interface option is selected by evaluating the complexity of the sensor circuitry, in addition to the required hardware and software trade-offs of the microcontroller. The available sensor interface options that are proportional to temperature include:

- Analog
- Frequency
- Ramp Rate
- Duty Cycle
- Serial Output
- Logic Output

Analog Output

Thermocouples, RTDs and thermistors can be interfaced to an amplifier circuit to provide a voltage which is proportional to temperature. Analog output silicon sensors are available that integrate the sensor and the signal conditioning circuit. Figure 1 shows a block diagram of a typical analog interface circuit.

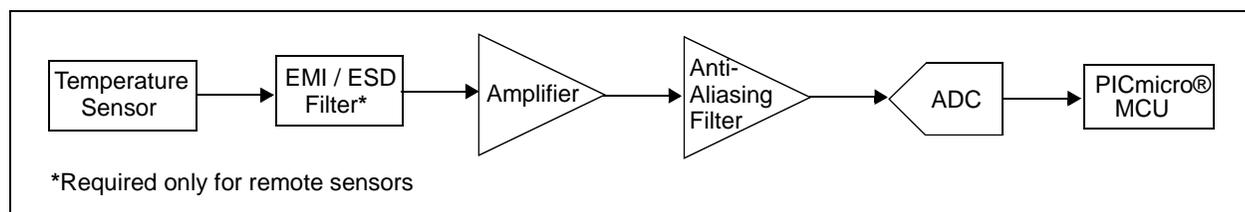


FIGURE 1: Block Diagram of an Analog Output Sensor.

Frequency Output

Oscillators provide a frequency output proportional to temperature that can be interfaced to a microcontroller, as shown in Figure 2. While a Resistor-Capacitor (RC) operational amplifier (op amp) oscillator can accurately measure the resistance of an RTD, this circuit is typically not used with a thermistor because of the large logarithmic change in the sensor's resistance over temperature. The main advantage of a frequency output is that an ADC is not required. A frequency output is also useful in applications where the sensor conditioning circuitry is combined with a remote sensor. A logic-level output signal is less sensitive to noise than an analog output signal that transmits information to the microcontroller.

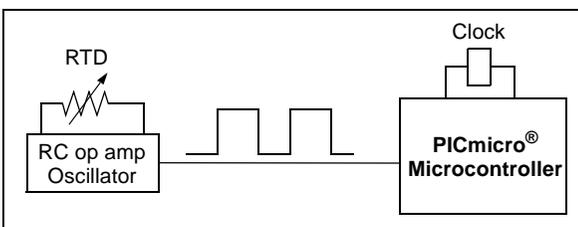


FIGURE 2: Block Diagram of a Frequency Output Sensor.

The accuracy of the frequency measurement is directly related to the quality of the microcontroller's clock signal. Precision high-frequency microcontroller clock oscillators are readily available. However, they are relatively expensive. The two options available to measure frequency are the fixed time or fixed cycle methods. The microcontroller resources required for determining frequency varies depending upon the processor bandwidth, available peripherals and desired measurement accuracy.

FIXED TIME METHOD

The fixed time method, shown in Figure 3, consists of counting the number of pulses within a specific time window, such as 100 ms. The frequency is then calculated by multiplying the count by the integer required to correlate the number of pulses in one second. This measurement approach inherently minimizes the effect of error sources (such as jitter) by averaging many oscillator pulses in the time window. The fixed time method utilizes a firmware delay or hardware delay routine. The firmware can poll for input edges, though this consumes processor bandwidth. A more common implementation uses a hardware timer/counter to count the input cycles during a firmware delay. If a second timer is available, the delay can be generated using this timer, thus requiring minimal processor bandwidth.

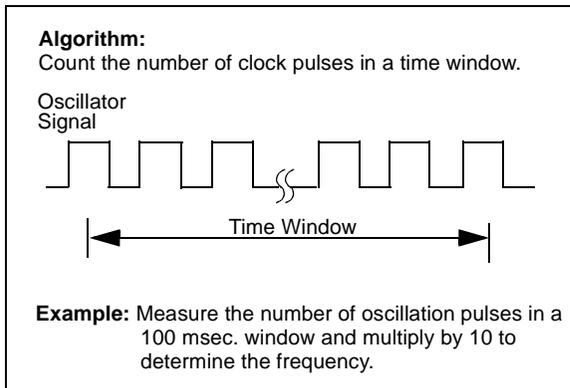


FIGURE 3: Frequency Output - Fixed Time Method.

FIXED CYCLE METHOD

In the fixed cycle method, shown in Figure 4, the number of cycles measured is fixed and the measurement time is variable. This approach measures the elapsed time for a fixed number of cycles. The number of cycles is chosen by the designer based on the desired accuracy, input frequency, measurement rate and the microcontroller clock frequency (F_{OSC}). F_{OSC} determines the minimum time an edge can be resolved. The measurement error will then be proportional to the total amount of time versus F_{OSC} . Increasing the number of cycles measured will increase the measurement time and reduce the error. Increasing F_{OSC} will also decrease the minimum time to resolve an edge, thereby reducing the error.

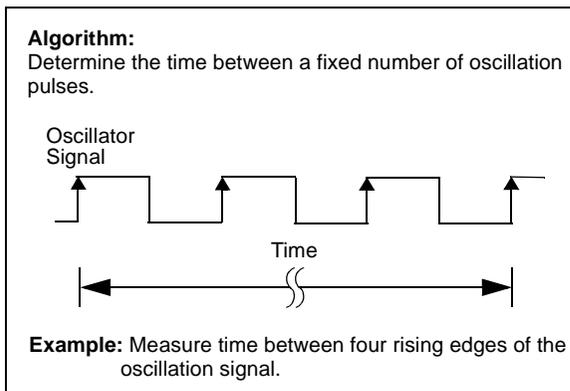


FIGURE 4: Frequency Output - Fixed Cycle Method.

The fixed cycle method can utilize firmware to both measure time and poll the input edges. This, however, is processor-intensive and has accuracy limitations. For example, a more common implementation is to utilize the Capture/Compare/PWM (CCP) module of a PICmicro[®] microcontroller configured in the Capture mode. This approach uses the 16-bit timer TMR1 peripheral and has excellent accuracy and range.

Ramp Rate Method

The resistor-capacitor (RC) ramp rate method shown in Figure 5 provides a simple solution for resistive sensors, such as thermistors. This method provides a low-cost solution with an accuracy of approximately $\pm 1\%$. When voltage is applied to a RC combination, the capacitor's voltage will increase exponentially and the ramping time can be measured with a comparator. The accuracy of the RC timing method can be improved by comparing the ramp rates of a sensor resistor (R_{Sensor}) and a known resistance (R_{REF}) to reduce the effects of temperature and component tolerance.

The RC timing method can be implemented using the circuitry inside a microcontroller. The timing measurement begins by configuring the GP1 pin as a logic '1' output and GP2 as an input. This connects R_{SENSOR} to a logic-high voltage ($V_{OH} \cong V_{DD}$), while R_{REF} is disconnected from the circuit via the high impedance of an input pin. The I/O pin AN0 is configured as an input and connects the capacitor to a comparator inside the microcontroller. The time required for the capacitor voltage to ramp-up to the reference voltage of the comparator ($V_{TH} \cong V_{REF}$) can be determined through either a hardware or software timer. Once the measurement is completed, the GP1 pin is toggled to a logic '0' output to discharge the capacitor. The configuration procedure of GP1 and GP2 is then reversed in order to measure R_{REF} .

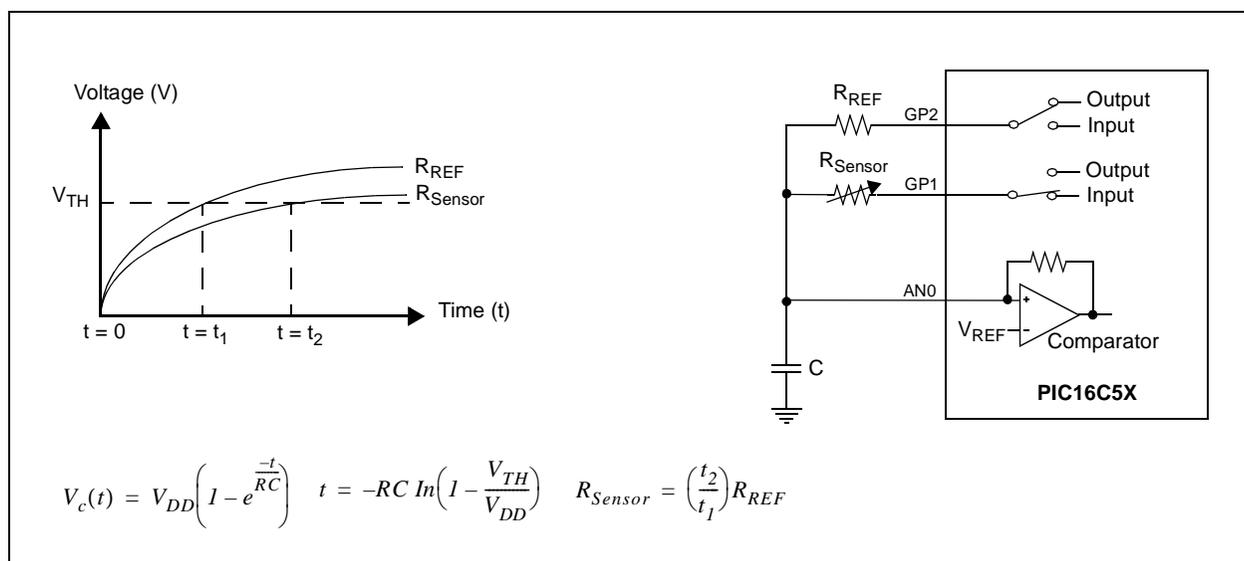


FIGURE 5: Ramp Rate Method.

Duty Cycle Output

Silicon IC sensors that provide an output proportional to the duty cycle of a digital signal are available, as shown in Figure 6. These sensors typically have a constant "on" time (t_1) and a variable "off" time (t_2). However, it is often necessary to calculate the t_1 -to- t_2 ratio in order to achieve the specified sensor accuracy. It is possible to have a duty cycle output with a thermocouple, RTD or thermistor. However, the circuit is relatively complex when compared to other signal conditioning options.

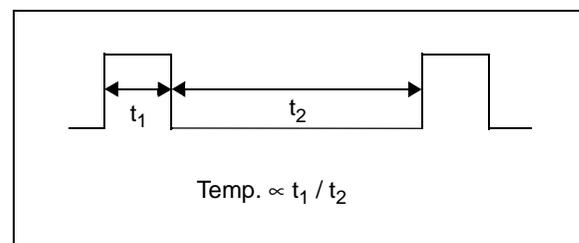


FIGURE 6: Duty Cycle Output.

Serial Output

Serial output sensors measure temperature and communicate with the processor via a standard serial data protocol, such as the SPI™, I²C™ or SMBus protocols. Silicon IC sensors are available that integrate the temperature sensor, ADC and temperature detection logic on a single chip. Thermocouple and RTD ASICs are available that have an amplifier, ADC and linearization logic integrated into a single IC. Serial output sensors offer the advantage of reducing the system component count, as well as using digital logic to provide a linear output.

Figure 7 provides an example of the timing diagram of the SPI serial output of the TC77 silicon IC sensor where the temperature data is represented by a 13-bit two's complement digital word. The SPI serial interface consists of the Chip Select (CS), Serial Clock (SCK) and bidirectional Serial Data (SI/O) signals. Communication with the TC77 is initiated when the CS goes to a logic '0' and the SI/O then transmits the first bit of data. The Least Significant Bit (LSB) is equal to 0.0625°C. The SCK input is provided by the microcontroller and data is transferred on the rising edge of SCK. Once 13 bits of data have been transmitted, the SI/O line is then tri-stated.

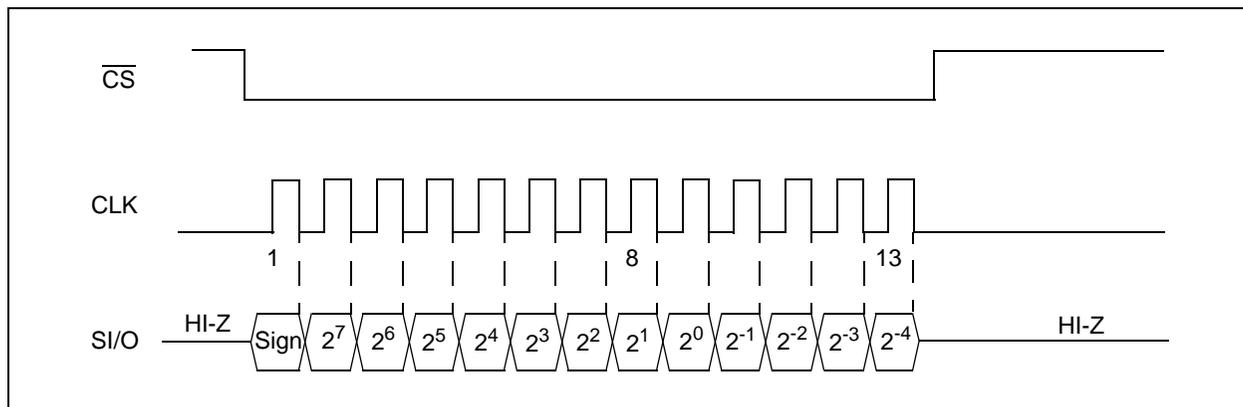


FIGURE 7: TC77 SPI Serial Output Silicon IC Sensor.

Logic Output Sensors

Logic output sensors are sometimes referred to as temperature switches because they typically function as a thermostat to notify the system that a maximum or minimum temperature limit has been detected. Figure 8 shows an example of a thermistor and silicon logic output sensor.

The features of logic output sensors include:

- Logic level output
- Output indicates that the temperature is above (or below) a preset value
- Available in both push-pull and open-drain configurations
- Output signal can be either active-low or high
- Either factory or user-programmable temperature settings

Logic level output sensors are similar to analog output sensors, except that the output amplifier of the sensor is a comparator. The comparator circuit sets the switch point of the sensor through either internal or external resistors. The output is typically not latched and, thus, the switch will turn-off when the temperature falls below the temperature set point. Note that it is necessary to have hysteresis so the switch does not "chatter" when crossing the temperature setpoint.

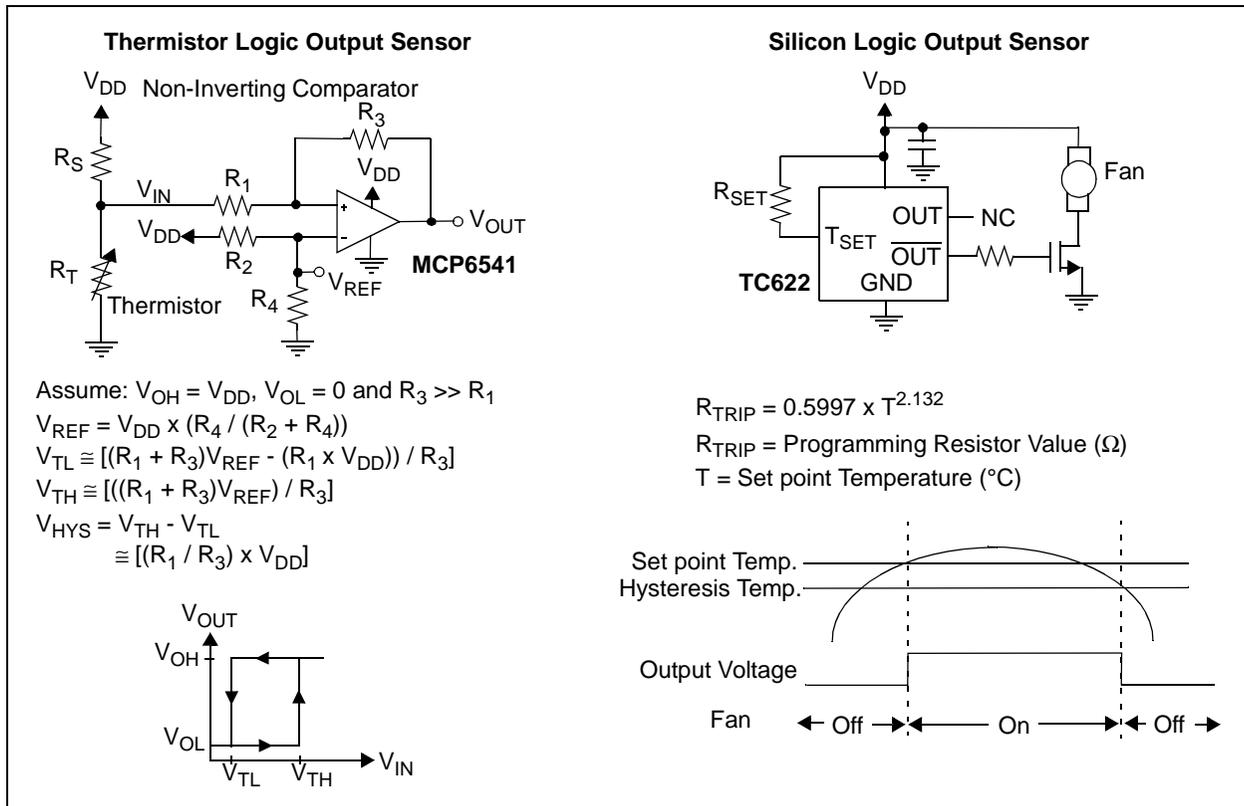


FIGURE 8: Logic Output Sensors.

Most logic output sensors are available in either a hot or cold option, as shown in Figure 9. The hot and cold options are used to allow the flexibility of using the switch in either hot (temperature increasing) or cold (temperature decreasing) sensing applications. The hot and cold options ensure that the hysteresis is in the appropriate position, either below or above the temperature set point.

For example, assume that the temperature switch is being used to turn on a cooling fan. The setpoint is 75°C and the hysteresis is 10°C . A sensor with the hot option will switch to the active logic level at 75°C . The sensor will remain in the on condition and the fan will run until the temperature drops to 65°C , or 10°C below the temperature setpoint.

In contrast, assume that a cold option switch is used in an application that requires a heater to turn on to prevent freezing. Assume that the temperature set point is 0°C and the hysteresis is 10°C . The cold option sensor will switch to the active logic level at 0°C and turn on the heater. The sensor will remain in the on condition until the temperature increases to 10°C , or 10°C above the temperature set point.

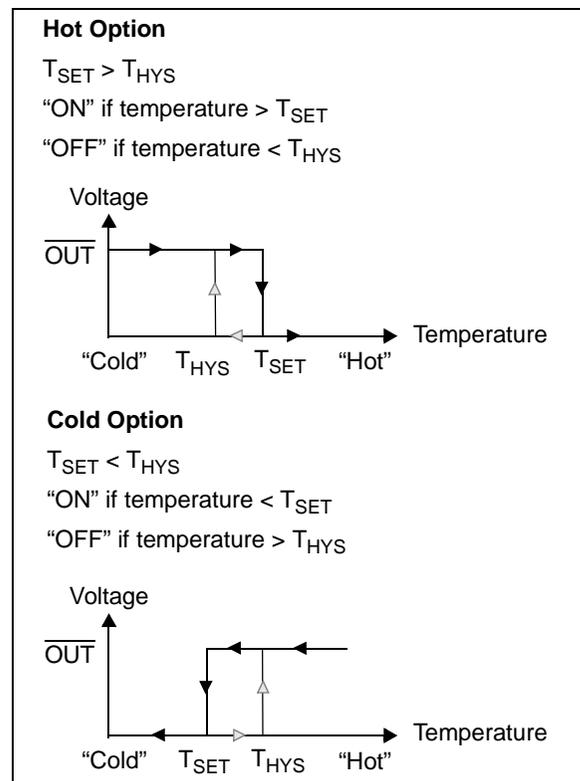


FIGURE 9: Logic Output Sensors - Hot and Cold Options.

SYSTEM INTEGRATION ISSUES

Local versus Remote Sensing

The location of the sensor relative to the conditioning circuit, as shown in Figure 10, plays a key role in selecting the appropriate interface and noise reduction circuit. Local sensors are located relatively close to their signal conditioning circuits. Therefore, the noise environment usually is not as severe as remote sensors. In contrast, remote sensors are connected to the amplifier via long wires that often introduce noise into the electronics. A non-inverting amplifier circuit is a good choice for a local sensor, while a remote sensor requires a differential measurement in order to cancel noise. All sensors should be considered as remote sensors in high-noise environments or precision applications to take advantage of the high CMRR and noise reduction of a differential amplifier.

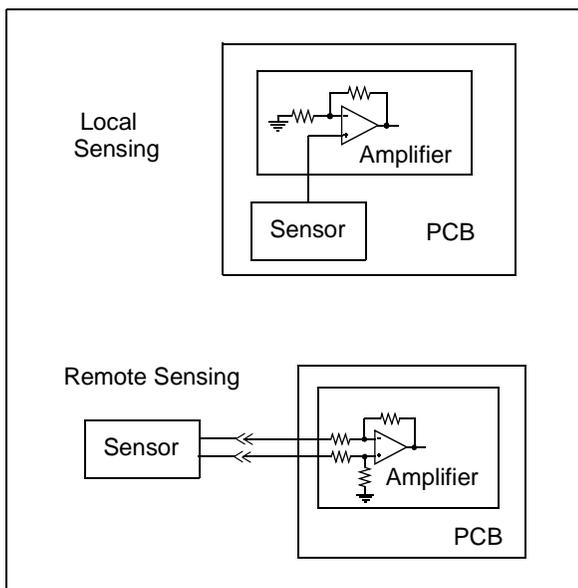


FIGURE 10: Local versus Remote Sensing.

Noise Reduction Techniques

Accurate temperature measurements require careful attention to noise reduction techniques. The high CMRR of the differential amplifier reduces noise. However, grounding, shielded cables and Electromagnetic Interference/Electro-Static Discharge (EMI/ESD) filters are also required to prevent noise from degrading the accuracy of the measurement.

Grounding

Figure 11 shows four basic methods of grounding a sensor. A grounded source has its negative terminal connected to ground at the sensor, often by virtue of the mechanical mounting of the sensor. In contrast, a floating source connects the sensor's negative terminal to ground at the amplifier.

The preferred grounding configuration for a remote sensor is shown in circuits B and D. These circuits provide for a two-wire differential measurement that can be implemented with either a differential or instrumentation amplifier. A differential measurement requires that the common mode voltage level of the signal source does not exceed the amplifier's maximum input voltage specification. As shown in circuit D, adding bias resistors to reference the input signal to a known voltage can solve this problem and the resistors will not affect the measurement, if they are relatively large.

The grounding methods of circuits A and C provide a single-ended input measurement that should only be used with a local sensor. The separate sensor and amplifier grounds of circuit A can produce an offset voltage due to the difference in the voltage potentials of the two grounds. In local sensor applications, the magnitude of ΔV_{GND} is small and either an inverting or non-inverting op amp can be used. The configuration of circuit C should be used with caution in low signal output sensors such as thermocouples. Noise can be induced into the measurement via the thermocouple wires and the magnitude of the sensor voltage will be affected by ground bounce or switching noise at the amplifier's ground.

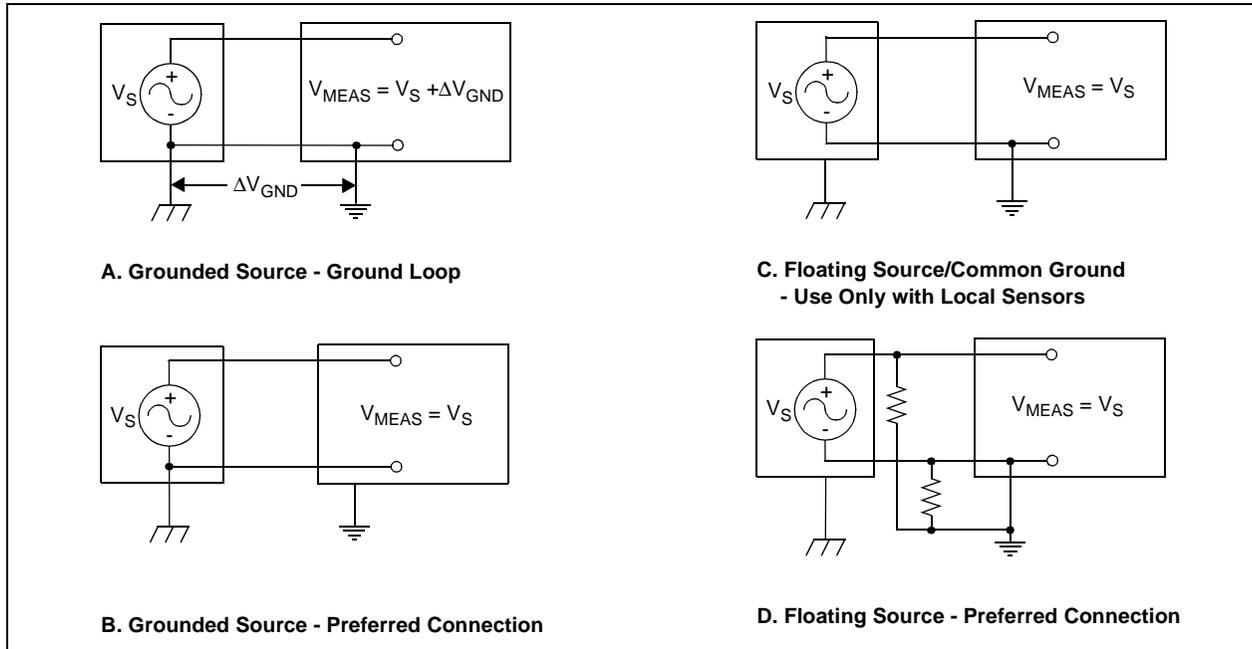


FIGURE 11: Accurate Measurements Require Careful Grounding.

Shielded Cables

A shielded cable is an effective tool to prevent radiated interference from introducing a noise voltage on the signal wires. Shielded twisted-pair cables reduce the loop area of the victim signal and minimize the voltage induced on the sensor signal lines. The noise signals on each wire in the cable will be essentially equal, which is the assumption needed for the high CMRR feature of a differential amplifier to cancel the interference. For most applications, it is recommended

that the shield be connected to ground only at one point. In applications using a metal enclosure, the shield's connection to chassis ground can occur through the mechanical connection of the cable connector to the box. Figure 12 provides an example of a remote RTD measurement using a shielded cable.

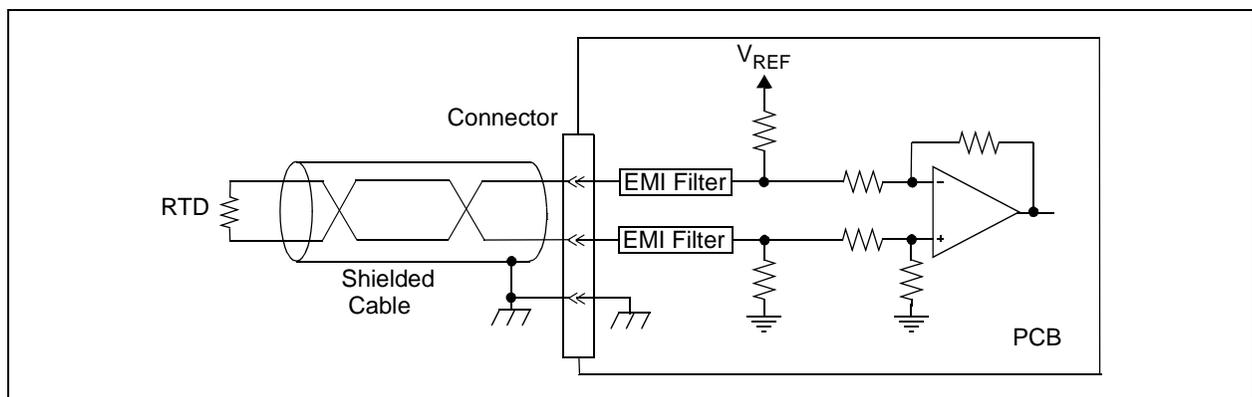


FIGURE 12: Use Shielded Cables and EMI Filters for Remote Measurements.

EMI/ESD Protection

EMI and ESD filters function as both a noise filter and a protective device to the circuit on the PCB. An IC input pin should never be connected directly to a remote sensor because EMI or ESD overvoltage failures will likely occur. Ferrite beads, capacitive feed-through filters, RC filters and transient-voltage-suppressor (TVS) zener diodes are popular devices that can be used to provide protection for the sensor circuit.

Ferrite beads, capacitive feed-through filters and RC filters function as filters and only limit the slew rate of a transient-input voltage. A voltage-clamping device (such as a TVS zener diode) is required to limit the input voltage to a safe value that will not damage the IC amplifier. Though a TVS device is similar to a standard zener diode, they are designed to turn on fast and dissipate a short duration, high-peak energy voltage transient. In contrast, a zener diode is designed to clamp a steady-state voltage for a long duration.

In many applications, a combination of different EMI/ESD filter devices are often used. One option is to use a capacitive feed-through filter that is located inside the connector, in addition to TVS and RC filters which are placed on the PCB board, as shown in Figure 13. Feed-through capacitors are typically mounted on a conductive chassis, with the mechanical mounting forming the ground connection. The noise signal is filtered at the connector before the signal reaches the PCB. The effectiveness of the filter is usually very good because the inductance associated with the ground connection is minimized. The TVS diodes on the PCB ensure that the transient voltage is limited to a safe value, while the RC filters provide additional filtering to the instrumentation amplifier.

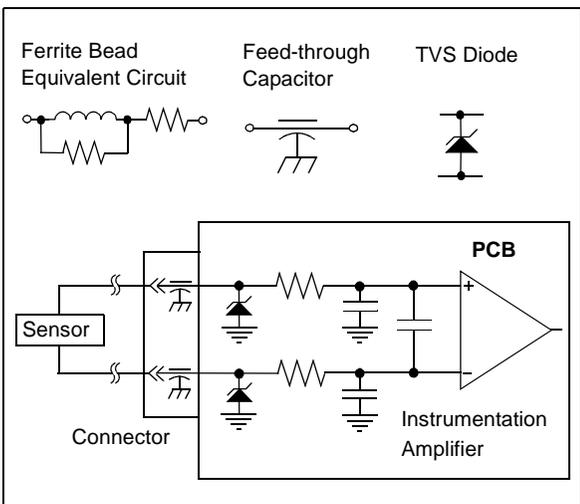


FIGURE 13: Remote Sensors May Require Multiple EMI Filter Devices.

Figure 14 provides the design equations for a RC filter which can be used with differential and instrumentation amplifiers. The RC combinations of R_1/C_1 and R_2/C_2 are used to form common mode filters and reduce the noise which is common to both input lines. The common-mode resistors and capacitors should be matched as close as possible and the resistors should have a tolerance of 1% or better, while the capacitors should be at least 5%. Capacitor C_3 forms a differential mode filter that attenuates the signal with respect to the difference in the voltage potentials of the two inputs. C_3 also compensates for any mismatch of R_1/C_1 and R_2/C_2 , which is important because the difference in the R/C combinations degrades an amplifier's CMRR.

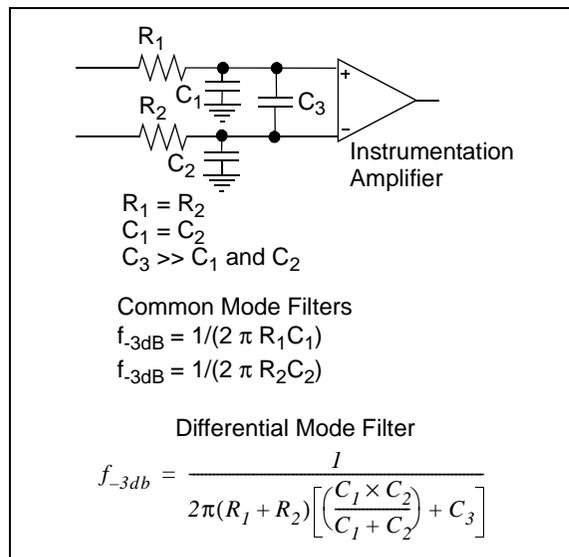


FIGURE 14: Providing EMI/ESD Overvoltage Protection with Resistors and Capacitors.

Fault Detection Capability

It is often necessary to identify a failed sensor, especially in remote-sensing applications. Differential amplifiers can be used to implement a Built-In-Test (BIT) circuit that can determine an open or short failure at the sensor. Figure 15 shows circuits that can be used to detect a failed RTD and thermocouple. A logic inverter gate can be used to monitor the voltage divider network of a RTD. Another approach to provide BIT to a sensor is to add pull-up or pull-down resistors, or both, as shown in Figure 15.

The typical failure mode of RTDs and thermocouples is an open-circuit failure. Wire wound RTDs are constructed from a relatively small gauge wire and are prone to vibration failures. Thermocouple wires can also fail due to vibration because the wires get brittle over time when exposed to high temperatures. Also, the voltage at the amplifier inputs resulting from noise can be equal in magnitude to a functional thermocouple.

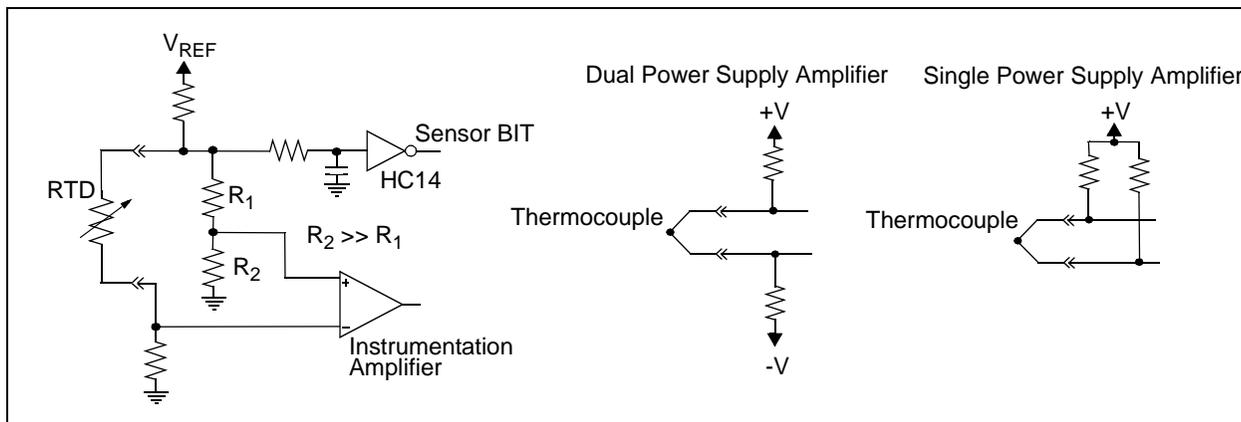


FIGURE 15: Remote Sensor Fault Detection Circuits.

Amplifier Selection Criteria

Two key op amp specifications in a sensor amplifier are V_{OS} and CMRR. V_{OS} is important in sensor applications when the input signal is of the same magnitude as V_{OS} , while the CMRR ratio is critical in reducing the noise signal induced on the long wires of a remote sensor. Other op amp specifications, such as the AC frequency characteristics are less important because the frequency content of a temperature sensor is typically less than 100 Hz. The op amps used in oscillators are relatively immune to DC specifications

such as V_{OS} . The important parameters for oscillators are the amplifier's frequency response and the Gain Bandwidth Product (GBWP). The op amp's GBWP should be at least a factor of 100 times the maximum oscillation frequency.

SENSOR SELECTION CRITERIA

Table 1 provides a summary of the attributes of thermocouples, RTDs, thermistors and silicon IC sensors.

TABLE 1: ATTRIBUTES OF THERMOCOUPLES, RTDS, THERMISTORS AND SILICON IC SENSORS

Attribute	Thermocouple (type K)	RTD	Thermistor	Silicon IC
Range	-184°C to 1260°C	-200°C to 850°C	-55°C to 150°C	-55°C to 125°C
Temperature (t) Accuracy	Greater of $\pm 2.2^\circ\text{C}$ or $\pm 0.75\%$	Class B = $\pm [0.012 + (0.0019 t) - 6 \times 10^{-7} t^2]$	Various, $\pm 0.5^\circ\text{C}$ to 5°C	Various, $\pm 0.5^\circ\text{C}$ to 4°C
Output Signal	$40 \mu\text{V}/^\circ\text{C}$	$\approx 0.00385 \Omega / \Omega/^\circ\text{C}$	$\approx 4\% \Delta R/^\circ\text{C}$ for $0^\circ\text{C} \leq t \leq 70^\circ\text{C}$	Analog, Serial, Logic, Duty Cycle
Linearity	Fair	Excellent	Poor	Good
Precision	Fair	Excellent	Poor	Fair
Durability	Good at lower temp., Poor at high temp, Open-circuit vibration failures	Good, Wire wound prone to open-circuit vibration failures	Good, Power derated with temperature	Excellent
Thermal Response Time	Fast (function of probe material)	Fast (function of probe material)	Moderate	Slow
Cost	Low	Wire wound – High, Thin-film – Moderate	Low	Moderate
Interface Issues	Cold junction compensation, Small ΔV	Small $\Delta R/^\circ\text{C}$	Non-linear resistance	Sensor located on PCB

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Thermocouples

Thermocouples are the most common sensor used in high-temperature measurements. A thermoelectric electromagnetic-force (emf) or voltage results when two dissimilar metals are joined together that produce an output voltage that is proportional to temperature. Figure 16 shows a block diagram of a typical thermocouple system. The thermocouple probes are typically located remotely from the amplifier circuit and are

connected to the amplifier via the thermocouple wires that enter the enclosure through a connector. The cold junction occurs at the point where the copper wires of the PCB meet the Alumel and Chromel connector pins. The cold junction will be formed at the inside wall of the enclosure if the connector uses Alumel and Chromel pins. The temperature of the cold junction or “isothermal block” is estimated by a sensor that is located as close as possible to the connector on the PCB.

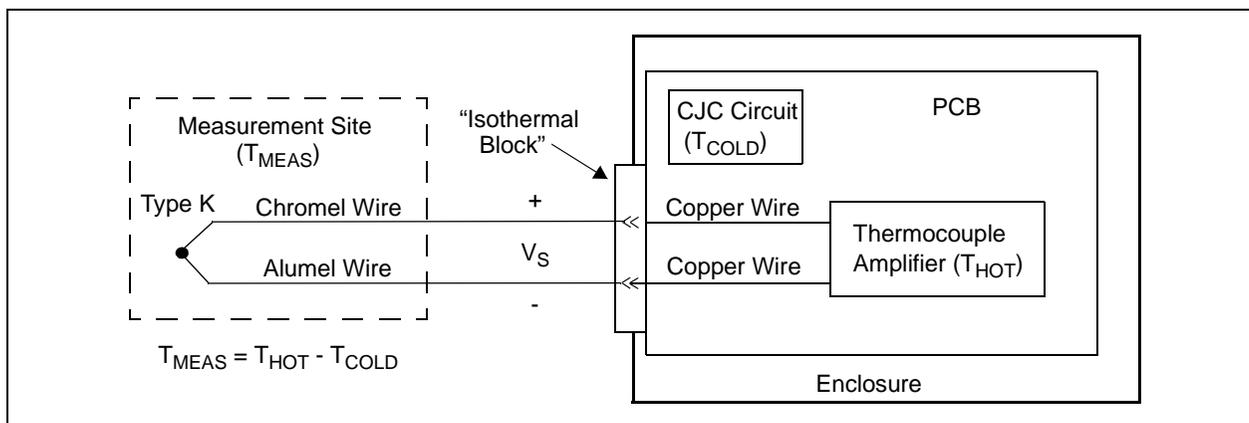


FIGURE 16: Thermocouple Basics – Typical Measurement System.

RTDs

RTDs are the standard sensor chosen for precision sensing applications because of their excellent repeatability and stability characteristics. RTDs are based on the principle that the resistance of a metal changes with temperature. A RTD can be characterized against temperature to obtain a table of temperature correction coefficients. The correction can be added to the measured temperature to obtain an accuracy greater than 0.05°C. RTDs are available in two basic designs: wire wound and thin film. Wire wound RTDs are built by winding the sensing wire around a core to form a coil, while thin film RTDs are manufactured by depositing a very thin layer of platinum on a ceramic substrate.

Thermistors

The main advantages of thermistors are that they are inexpensive and available in a wide variety of packages. Thermistors are built with semiconductor materials and can have either a positive (PTC) or a negative (NTC) temperature coefficient. However, the NTC devices are typically used for temperature sensing. The main negative feature of thermistors is that the change in resistance with temperature is very non-linear at temperatures less than 0°C and greater than 70°C.

Silicon Integrated Circuits

Silicon IC sensors provide an accurate temperature measurement for a steady-state or relatively constant temperature. However, their thermal response time to a rapid change in temperature is poor. Silicon sensors provide a non-contact temperature measurement. Thus, the location of the sensor is important. These sensors measure temperature by monitoring the voltage of a diode located on the IC die, as shown in Figure 17. The substrate of the die is typically grounded and connected to the PCB's ground plane via a bonding wire and the lead of the package. The ground pin of the IC provides a low-impedance thermal path between the die and the PCB, allowing the sensor to effectively monitor the temperature of the PCB board. The thermal path between the top of the package to the ambient air and between the bottom of the package and the PCB is not as efficient because the plastic IC housing package functions as a thermal insulator. Silicon sensors provide a measurement of the temperature of the PCB's ground plane and the ambient air temperature has only a small effect on the measurement.

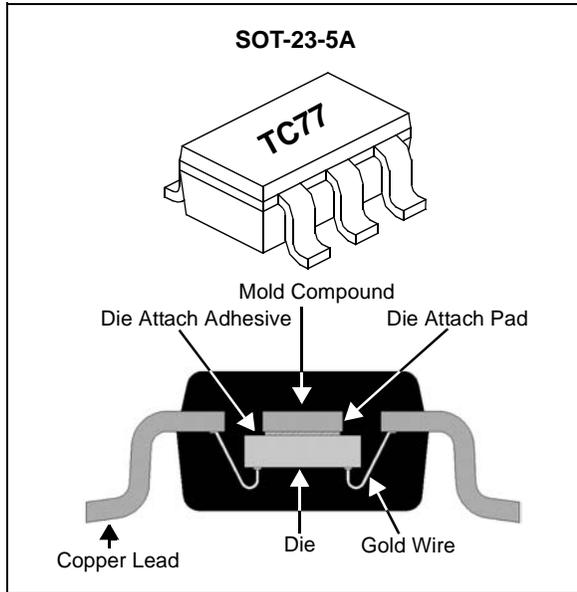


FIGURE 17: Cross-section of the TC77 Silicon IC Sensor.

Noise immunity can be provided to silicon sensors by using a decoupling capacitor and a good PCB layout. A 0.1 μF to 1 μF decoupling capacitor should be inserted between the power supply and ground pins. The PCB should be designed with the standard layout guidelines used for a low-noise circuit. The temperature sensor's main thermal path to the PCB is through the ground connection. Thus, the size of the ground pad at the sensor should be as large as possible. A good PCB layout keeps high-frequency clock and switching power supply PCB traces away from the sensor pins.

DESIGN EXAMPLES

Thermocouple Circuits

DUAL POWER SUPPLY CIRCUIT

Figure 18 shows a circuit that can be used for a remote thermocouple-sensing application. A TC913A auto-zeroed op amp was selected as the amplifier because of its low V_{OS} of 15 mV (max.) and high CMRR of 116 dB (typ.). Auto-zero, chopper and instrumentation amplifiers are good thermocouple amplifiers because of their good V_{OS} and CMRR specifications. The thermocouple inputs are tied to a positive and negative supply through 10 M Ω resistors, so that the circuit can detect a failed open-circuit thermocouple. The gain of the amplifier was selected to be 249, which provides a temperature coefficient (TC) of 10 mV/ $^{\circ}\text{C}$.

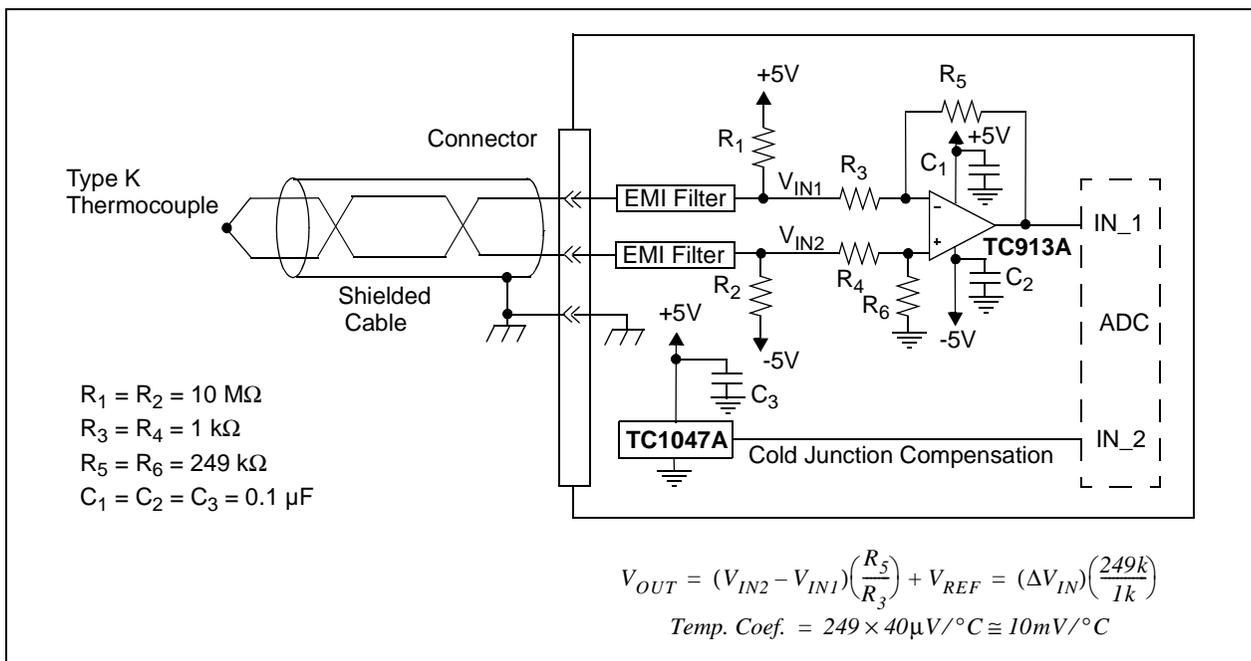


FIGURE 18: Schematic of Dual Supply Voltage Thermocouple Amplifier.

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The microcontroller computes the actual temperature by subtracting the cold junction temperature from the temperature determined from the thermocouple amplifier. The cold junction temperature is measured with a TC1047A silicon IC analog output sensor that is located on the PCB. The actual cold junction occurs where the thermocouple wires meet the copper wires, which is typically at a connector. Placing the TC1047A adjacent to the connector can minimize the cold junction error ($T_{CJC_Location}$) that results by placing the temperature sensor on the PCB. The voltage output of the TC1047A is listed below.

$$V_{OUT} = [(Temp. (^{\circ}C)) \times (10 \text{ mV}/^{\circ}C)] + 500 \text{ mV}$$

The TC1047A provides an output voltage of 10 mV/ $^{\circ}C$ with an offset of 500 mV.

The accuracy of the thermocouple amplifier and cold junction circuits were estimated to be $\pm 5.4^{\circ}C$ by using the root-squared-sum (RSS) equation. The common mode voltage noise signal entering the circuit from the thermocouple leads was assumed to be equal to 10V. It is important to use tight tolerance resistors for the differential amplifier in order to achieve a high CMRR. 0.1% resistors were chosen for R_3 , R_4 , R_5 and R_6 . The analysis shows that the majority of the measurement error is due to the error of the cold junction compensation.

$$CMRR \text{ Resistors} \approx \frac{1 + \text{Amplifier Gain}}{4 \times \text{Tolerance}} = \frac{1 + 249}{4 \times 0.001} = 62500 = 95.9 \text{ db}$$

$$\text{Error CMRR Resistors} = \frac{V_{CM-NOISE}}{CMRR \text{ Resistors}} = \frac{10V}{62500} = 160 \mu V \cong 4^{\circ}C$$

$$CMRR \text{ Amplifier (TC913A)} = 116 \text{ db (typ.)}$$

$$\text{Noise Attenuation} = \frac{1}{630,957}$$

$$\text{Error CMRR Amplifier (TC913A)} = \frac{V_{CM-NOISE}}{CMRR \text{ Amplifier (TC913A)}} = \frac{10V}{630,957} = 15.8 \mu V \cong 0.4^{\circ}C$$

$$V_{OS} \text{ error} = \frac{V_{OS} (TC913A)}{\text{Temp. Coef. (type K)}} = \frac{15 \mu V}{40 \mu V/^{\circ}C} \cong 0.4^{\circ}C$$

$$T_{CJC_Sensor} (TC1047A) \text{ error} = 3^{\circ}C \text{ (max.)}$$

$$T_{CJC_Location} \text{ error} = 2^{\circ}C \text{ (est.)}$$

$$\begin{aligned} \text{Total error}_{\text{Worst Case}} &= CMRR_{\text{RESISTORS}} + CMRR_{\text{AMPLIFIER (TC913A)}} + V_{OS} + T_{CJC_Sensor} + T_{CJC_Location} \\ &= 4 + 0.4 + 0.4 + 3 + 2 = 9.8^{\circ}C \end{aligned}$$

$$\text{Total error}_{\text{RSS}} = \sqrt{(4)^2 + (0.4)^2 + (0.4)^2 + (3)^2 + (2)^2} = 5.4^{\circ}C$$

SINGLE POWER SUPPLY CIRCUIT

Figure 19 provides a low-cost, single power supply thermocouple amplifier circuit using a quad op amp. The buffered input differential amplifier topology is similar to an instrumentation amplifier and offers the feature of equal and high input impedance at the amplifier inputs. An instrumentation amplifier with integrated

gain resistors can also be used to implement this circuit. The gain of the amplifier was selected to be 249, providing a temperature coefficient of 10 mV/°C. The thermocouple inputs are biased to $V_{DD}/2$ through 10 MΩ resistors, providing the ability to detect a failed open-circuit thermocouple.

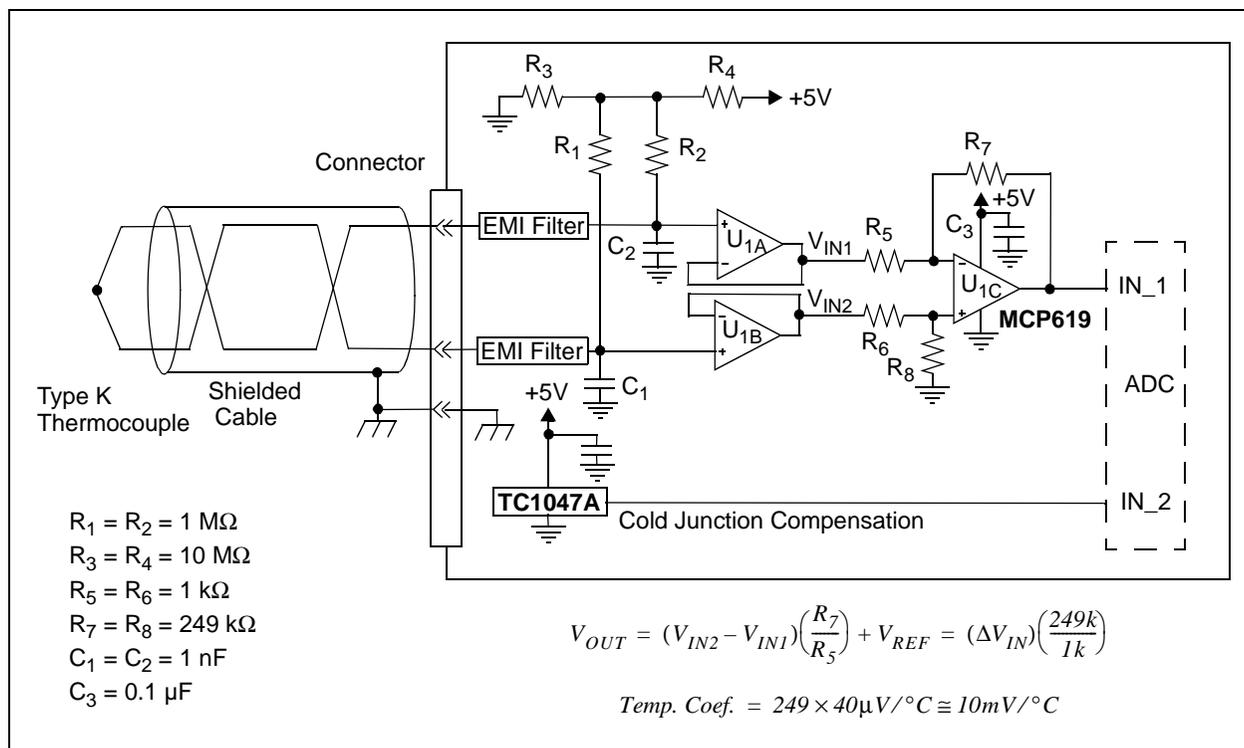


FIGURE 19: Schematic of Single Supply Voltage Thermocouple Amplifier.

RTD Oscillator Circuits

Oscillator circuits can be used to provide an accurate temperature measurement with an RTD sensor. The state variable oscillator provides an output frequency that is proportional to the square root of the product of two temperature-sensing resistors and is a good circuit for precision applications. The astable multi-vibrator or relaxation oscillator provides a square wave output with a single amplifier and is a good alternative for cost-sensitive applications.

The components must be chosen carefully so that the change in the oscillation frequency results primarily from the RTD and not from variation due to the component tolerance, temperature coefficient and drift rate. Metal film resistors, metal foil resistors and NPO porcelain capacitors are recommended to minimize the component error. Capacitors are relatively poor in performance when compared to resistors. Typically, the capacitor limits the accuracy of the oscillator. Furthermore, precision capacitors are only available in relatively small values. The state variable oscillator requires two 100 nF capacitors, while the relaxation

oscillator uses a 0.68 μF capacitor to produce a nominal oscillation of 1 kHz. The state variable and relaxation circuits have an uncalibrated measurement accuracy of approximately 1°C and 3°C, respectively. The difference is primarily due to the capacitor error.

An application that requires an accuracy of better than ±1°C may require a temperature calibration and burn-in procedure. A temperature compensation algorithm can easily be implemented using the E² non-volatile memory of a microcontroller to store temperature correction data in a look-up table. The temperature coefficients are obtained by calibrating the circuit over temperature and comparing the measured temperature against the actual temperature. A burn-in or temperature-cycling procedure can significantly reduce the drift of the resistors and capacitors. Burn-in procedures are useful because the majority of the change in magnitude of resistors and capacitors occurs within the 500 hours of a life test.

STATE VARIABLE OSCILLATOR

The state variable oscillator shown in Figure 20 consists of integrators A_1 , A_2 and inverter circuit A_3 . Each integrator provides a phase shift of 90° , while the inverter adds an additional 180° phase shift. The total phase shift of the three amplifiers is equal to 360° and

an oscillation is produced when the output of the third amplifier is fed back to the first amplifier. The addition of capacitor C_4 helps ensure oscillation start-up. The dual element RTD represented by R_1 and R_2 is used to increase the difference in the oscillation frequency from the minimum to the maximum sensed temperature.

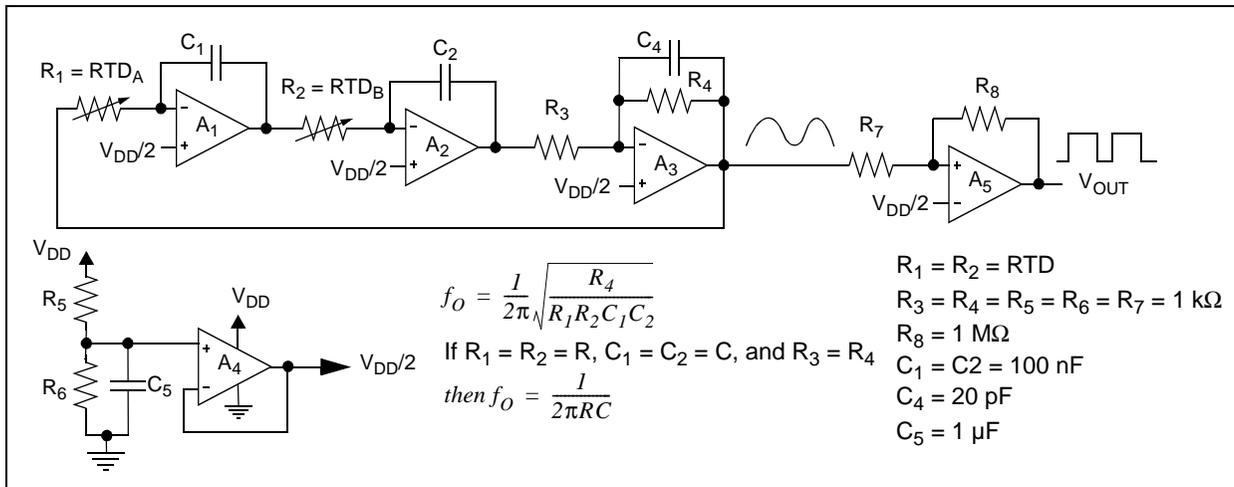


FIGURE 20: State Variable RTD Oscillator.

The state variable circuit offers the advantage that a limit circuit is not required if rail-to-rail input/output (RRIO) amplifiers are used and the gain of the inverter stage A_3 is equal to one (i.e., $R_3 = R_4$). In contrast, most oscillators require a limit or clamping circuit to prevent the amplifiers from saturating. Amplifier A_4 is used to provide the mid-supply reference voltage ($V_{DD}/2$) required for the single-supply voltage circuit. Resistors R_5 and R_6 form a voltage divider, while capacitor C_5 is used to provide additional noise filtering. A comparator circuit A_5 is used to convert the sinewave output to a square wave digital signal. The comparator functions as a zero-crossing detector with a switching threshold that is equal to $V_{DD}/2$. Resistor R_8 is used to provide additional hysteresis (V_{HYS}) to the comparator.

Design Procedure:

Set $R_1 = R_2 = R$, $C_1 = C_2 = C$, $R_3 = R_4$ and R_0 is the RTD resistance at 0°C .

1. Select a desired nominal oscillation frequency.
2. $C = 1 / (2\pi R_0 f_0)$.
where: $R_0 = \text{RTD resistance @ } 0^\circ\text{C}$.
3. Select an op amp with a GBWP $\geq 100 \times f_{\text{max}}$
where: $f_{\text{max}} = 1 / (2\pi R_{\text{min}} C)$ and $R_{\text{min}} = \text{RTD resistance at coldest sensing temperature}$.
4. Select $R_3 = R_4$ equal to 1 to 10 times R_0 .
5. Select C_4 using the following equations:
 $f_{-3\text{dB}} = 1 / (2\pi R_4 C_4)$
 $C_4 \approx 1 / (2\pi R_4 f_{-3\text{dB}})$
where: $f_{-3\text{dB}} \cong \text{op amp's GBWP}$

RELAXATION OSCILLATOR

The relaxation oscillator shown in Figure 21 provides a simple circuit to interface a RTD to a microcontroller. This circuit requires only a comparator, capacitor and a few resistors to generate a frequency output that is proportional to the RTD resistance. The accuracy of this circuit is limited by the poor tolerance and large temperature coefficient available with the required, relatively large, capacitor C_1 .

The relaxation oscillator functions as a comparator. Resistors R_2 , R_3 and R_4 form a voltage divider that sets the hysteresis and voltage trip levels. Resistor R_1 and capacitor C_1 form the RC time constant that determines the charge and discharge rate or oscillation frequency. If V_{OUT} equals V_{DD} , C_1 charges from the comparator's low threshold (V_{TL}) to the high threshold (V_{TH}), causing V_{OUT} to toggle to V_{SS} . If V_{OUT} equals V_{SS} , C_1 discharges from V_{TH} to V_{TL} and V_{OUT} switches to V_{DD} . The voltage-switching process then repeats, which generates the oscillation.

The accuracy of the relaxation oscillator can be improved by using a comparator rather than an op amp for the amplifier. A comparator offers several advantages over an op amp in a non-linear switching circuit, such as a square wave oscillator. An op amp is intended to operate as a linear amplifier, while the comparator is designed to function as a fast switch. The switching specifications (such as propagation delay and rise/fall time) of a comparator are typically much better than an op amp's specifications. Also, the switching characteristics of an op amp typically consist of only a slew rate specification. The accuracy of the relaxation oscillator can be improved by using a higher

resistance RTD and a higher performance comparator. The trade-off, however, will be that the comparator's current consumption will be much higher.

Design Procedure:

Set $R_1 = \text{RTD sensor}$, $R_2 = R_3 = R_4 = R$ and $R \cong 10 \times R_0$, where: $R_0 = \text{RTD resistance at } 0^\circ\text{C}$.

1. Select a desired nominal oscillation frequency.
2. $C_1 = 1/(1.386 R_0 f_0)$
3. Select a comparator with an Output Short Circuit Current (I_{SC}), which is at least five times greater than the maximum output current, to ensure start-up at cold and a relatively good accuracy.

$$I_{OUT_MAX} = V_{DD}/R_{1_MIN}$$

$$I_{SC} = I_{OUT_MAX} * 5$$

where: $R_{1_MIN} = \text{RTD resistance at coldest sensing temperature}$ and V_{DD} is equal to the supply voltage.

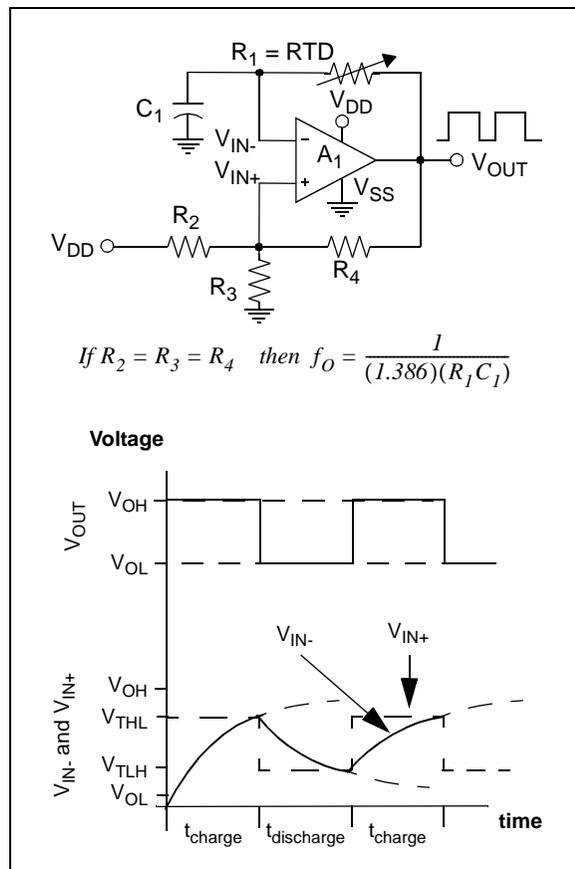


FIGURE 21: Relaxation RTD Oscillator.

Thermistor Circuits

VOLTAGE DIVIDER CIRCUIT

Thermistors offer the advantages of a high sensitivity (ΔR vs. temperature) and a linear change in resistance between approximately 0°C and 70°C . Figure 22 shows the conventional circuit used with thermistors. The circuit consists of a voltage divider and a voltage-follower op amp with a gain of one. The voltage divider network consists of reference voltage V_{REF} and series resistor R_S . A low-pass, noise-reduction filter is formed by R_2 and C_1 . The equation listed below can be used to select R_S .

$$R_S = \frac{R_{T1}R_{T2} + R_{T2}R_{T3} - 2R_{T1}R_{T3}}{R_{T1} + R_{T3} - 2R_{T2}}$$

Where:

$R_{T1} = \text{thermistor resistance at the low temperature.}$

$R_{T2} = \text{thermistor resistance at the mid-point temperature.}$

$R_{T3} = \text{thermistor resistance at the high temperature.}$

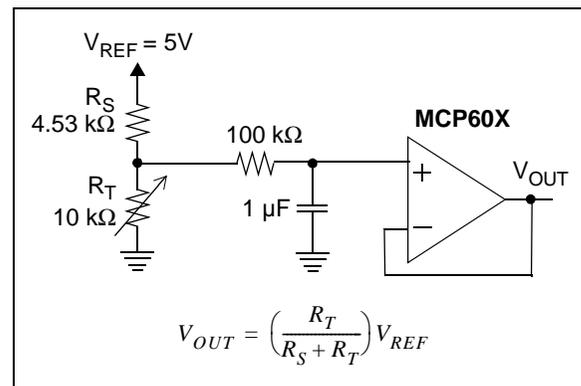


FIGURE 22: Voltage Divider Circuit.

A plot of the output of the divider circuit is shown in Figure 23. While a microcontroller can use a software routine to improve the linearization, a high-bit ADC is required to resolve the small change in the output voltage at temperatures less than 0°C and greater than 70°C . Figure 24 shows the change in voltage or slope of the output voltage. The ADC must be able to resolve a voltage of approximately 50 mV at 35°C and a voltage of less than 20 mV at temperatures less than -5°C and greater than 90°C . Table 2 provides the resolution of an ADC, assuming that the ADC's Effective Number of Bits (ENOB) is equal to one bit less than the maximum available resolution. If this aggressive ENOB assumption is made, an 8-bit ADC is required to measure temperatures between 10°C and 60°C , with an 11-bit ADC being required to measure temperatures at the cold and hot end points.

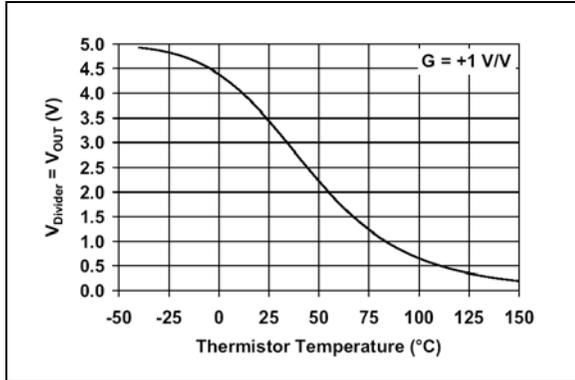


FIGURE 23: V_{OUT} vs. Temperature.

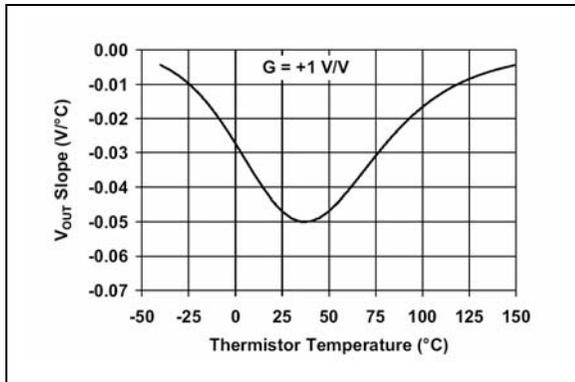


FIGURE 24: ΔV_{OUT} vs. Temperature.

TABLE 2: ADC RESOLUTION

ADC (N-bits)	2^N	Ideal ADC Volts/bit ($V_{FS} = 5V$)	ENOB (N - 1)	ENOB Volts/bit ($V_{FS} = 5V$)
8 bits	256	19.5 mV	7-bits	39.0 mV
9 bits	512	9.77 mV	8-bits	19.5 mV
10 bits	1024	4.88 mV	9-bits	9.77 mV
11 bits	2048	2.44 mV	10-bits	4.88 mV
12 bits	4096	1.22 mV	11-bits	2.44 mV

PROGRAMMABLE GAIN AMPLIFIER (PGA) CIRCUIT

A PGA circuit can be used to increase the gain of the amplifier at the temperatures where a small change in the output voltage is difficult to detect. Increasing the output voltage as a function of temperature allows a lower bit ADC to accurately resolve the relative small differences in the thermistor's resistance at cold and hot temperatures. The circuit shown in Figure 25 uses the MCP6S21, which uses a SPI interface to select a gain of 1, 2, 4, 8, 16 or 32 V/V.

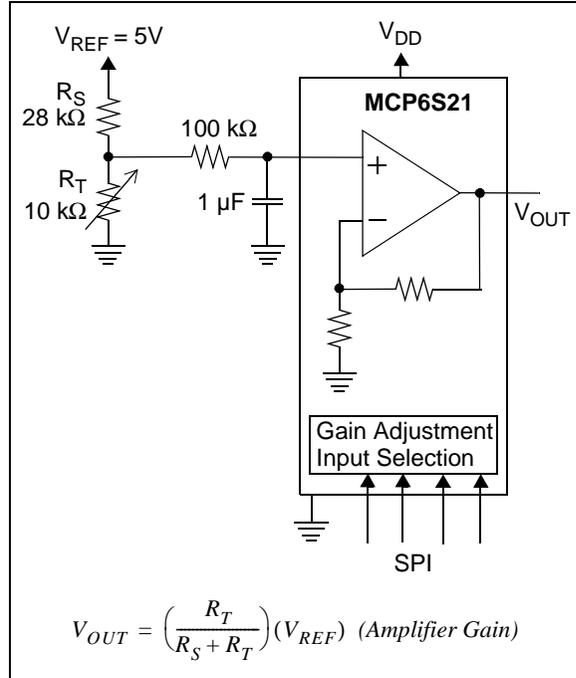


FIGURE 25: PGA Thermistor Circuit.

TABLE 3: GAIN CHANGE POINTS WITH HYSTERESIS

Gain Change (V/V)	Temperature (°C)	V_{OUT} (V)
1 → 2	37.0	0.885
2 → 4	57.0	0.451
4 → 8	77.0	0.236
8 → 16	97.0	0.1288
16 → 32	118.5	0.0708
16 ← 32	114.5	0.0789
8 ← 16	93.0	0.1448
4 ← 8	73.0	0.268
2 ← 4	53.0	0.516
1 ← 2	33.0	1.012

The output voltage of the PGA circuit is shown in Figure 26. The gain of the amplifier is adjusted as a function of temperature with the values shown in Table 3. The advantage of the PGA circuit is shown by comparing the V_{OUT} slope plots of Figure 24 and Figure 27. The V_{OUT} slope for the PGA circuit has a minimum value of 30 mV for temperatures greater than 35 °C, which means that only a 9-bit ADC is required. In contrast, a voltage divider with a gain of one will require an 11-bit or higher ADC to provide an equivalent temperature resolution. The resolution of a thermistor circuit is important in applications such as overtemperature shutdown circuits.

An accurate thermistor is required for the PGA circuit to provide an advantage with the variable gain. A BC Components™ #2322 640 5103 thermistor was chosen that has a resistance tolerance of 1% at 25°C and a ΔR accuracy of 0.75%, which corresponds to a temperature accuracy of approximately 0.2°C at 25°C and 1°C at 100°C. The accuracy of a standard thermistor is typically $\pm 2^\circ\text{C}$ to $\pm 5^\circ\text{C}$ and the magnitude of the sensor error is too large to achieve the improved resolution benefit of an adjustable gain circuit.

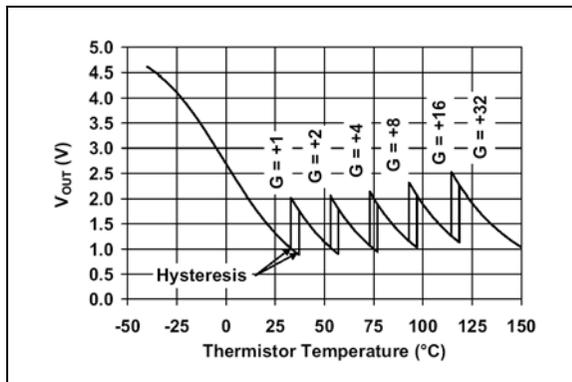


FIGURE 26: PGA V_{OUT} vs. Temperature.

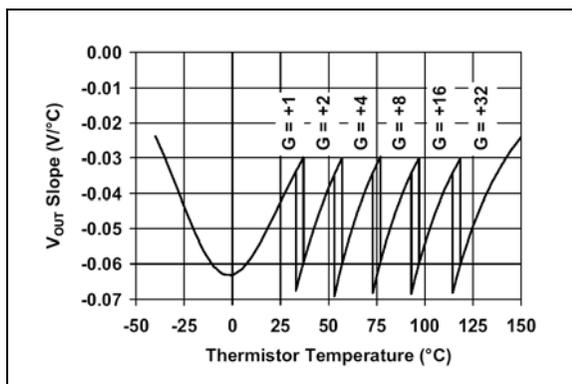


FIGURE 27: PGA ΔV_{OUT} vs. Temperature.

Silicon IC Sensors

SERIAL OUTPUT

Figure 28 shows a schematic of the TC77 serial-output sensor which integrates the temperature sensor, ADC and digital registers on a single chip that is connected to the processor through the SPI serial bus. The SPI bus uses SCK, SI/O and CS pins to transmit and receive data. Temperature is measured by monitoring the voltage of a diode with a 13-bit ADC. The temperature data is stored in the Temperature register. If a Temperature register read operation occurs while an ADC conversion is in progress, the previous completed conversion will be outputted. The Configuration register is used to select either the continuous temperature conversion or shut-down operating modes. The Shutdown mode disables the temperature-conversion circuitry to minimize the power consumption. However, the serial I/O communication port remains active. The test registers are used for offset and gain calibration by the vendor and are not available to the user.

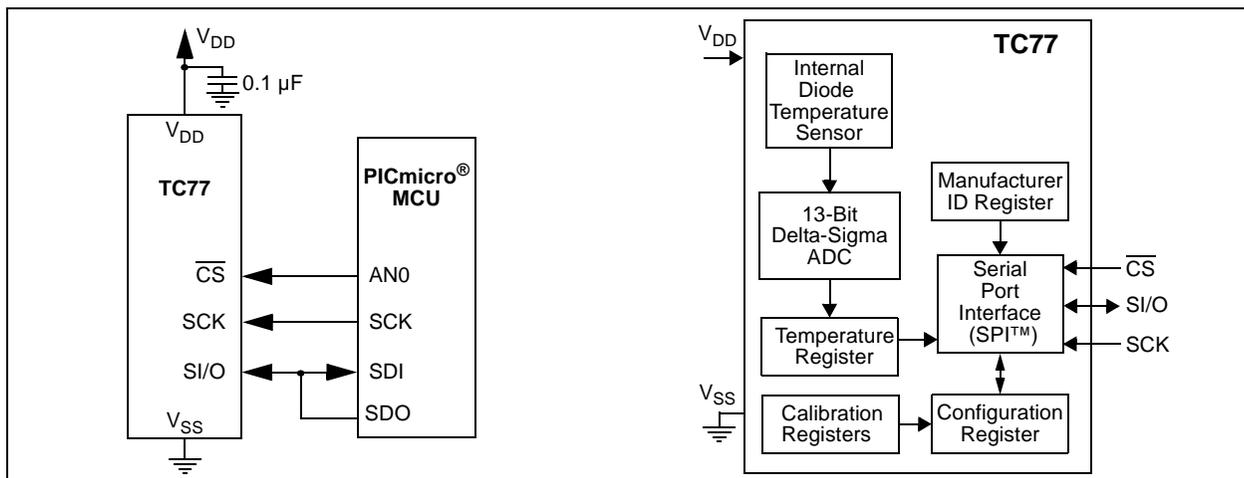


FIGURE 28: Interfacing a TC77 Silicon IC Sensor to a Microcontroller.

AN929

Serial I/O sensors can be used to monitor multiple temperatures on the same PCB and minimize the number of microcontroller interface pins. Most silicon sensors available today are designed using the SPI,

the two-wire SMBus or I²C protocols. Also, a number of temperature sensors are available that use a single I/O pin to transmit information using a pulse-width coding scheme.

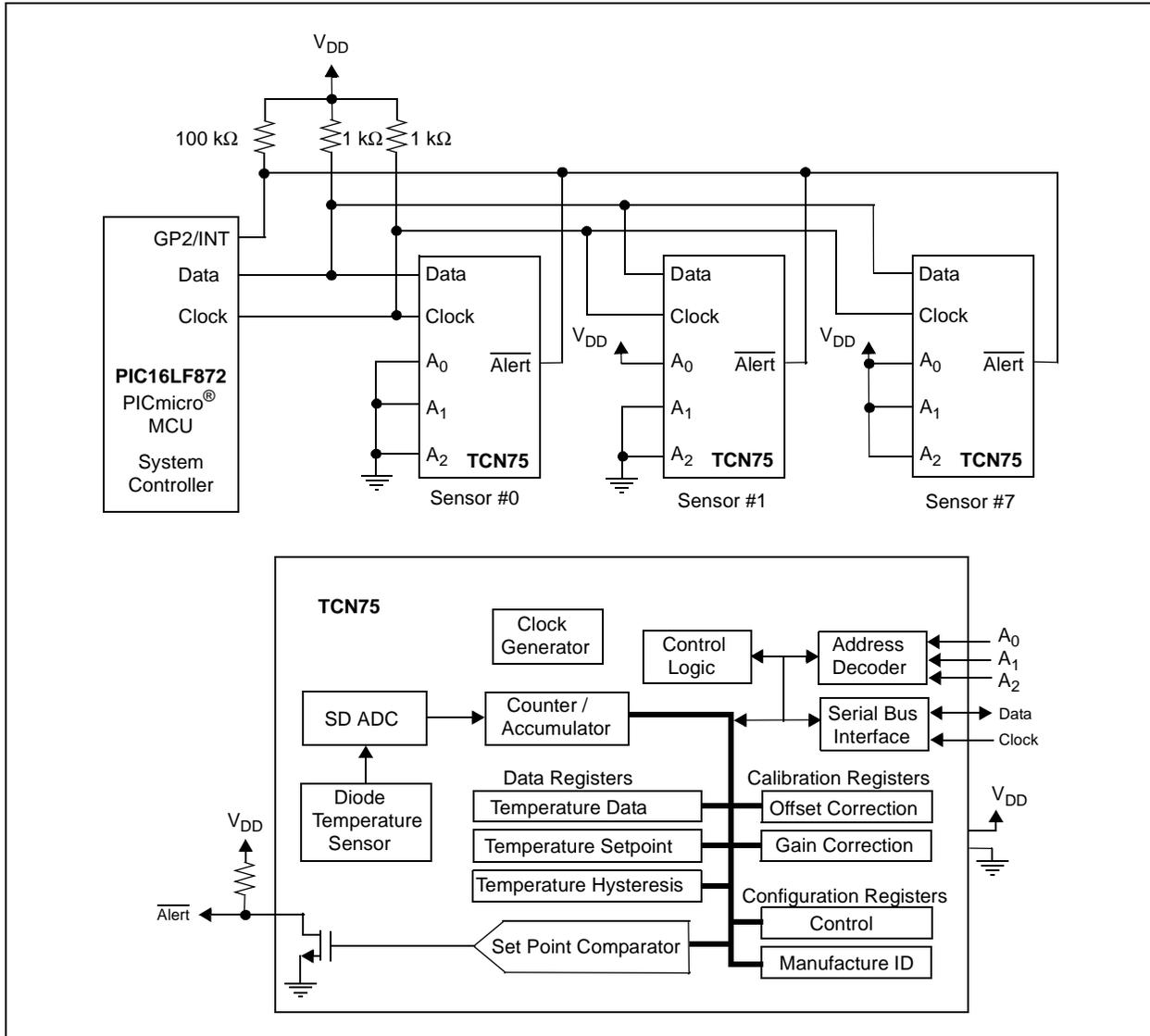


FIGURE 29: Multi-Zone Temperature Monitoring with the TCN75 Thermal Sensor.

Figure 29 provides a multi-zone temperature monitor that uses the TCN75 sensor to notify the host controller when the ambient temperature exceeds a user-programmed set point. Communication with the TCN75 sensor is accomplished via a two-wire serial bus. The microcontroller can monitor the temperature of each sensor by reading the Temperature Data register or the sensor can function as a stand-alone thermostat. The temperature threshold trip point is programmed by writing to the Set Point register. The INT pin is an open-drain output that can be connected to the microcontroller's interrupt pin to monitor up to eight sensors. Three address pins are used to identify each sensor.

ANALOG OUTPUT

Analog output silicon sensors have an output voltage in the form of the equation of a straight line. The slope of the output is equal to a constant temperature coefficient ($mV/^{\circ}C$), while the y-intercept point typically is the sensor's output voltage at $0^{\circ}C$. A simplified schematic of an analog sensor and ADC system is shown in Figure 30.

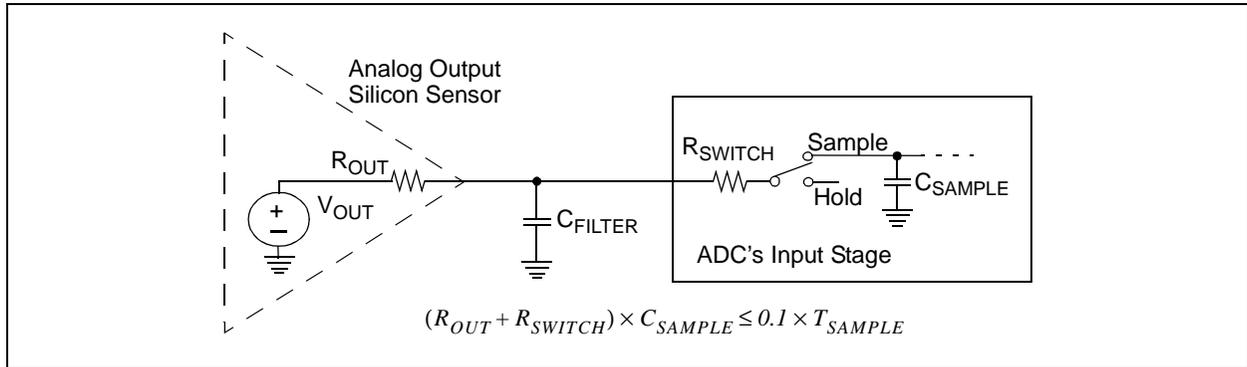


FIGURE 30: Interfacing an Analog Output Silicon Sensor to an ADC.

The sensor's output impedance can affect the ADC. The temperature sensor's output pin is typically driven by a buffer op amp, while the input of a typical ADC consists of a sample and hold circuit with a switch that connects V_{OUT} to C_{SAMPLE} . R_{OUT} , R_{SWITCH} and C_{SAMPLE} form a time constant which must be less than the sampling rate (T_{SAMPLE}) of the ADC, as illustrated by the equation in Figure 30. An external capacitor C_{FILTER} can be added to the output pin to provide additional filtering. However, this may impact the time response of the sensor. Enough time must be provided to allow C_{FILTER} to charge sufficiently between ADC conversions.

The magnitude of the C_{FILTER} capacitor should be in the range of 1 nF to 100 nF to prevent the sensor amplifier from oscillating. A small resistor of approximately 10Ω to 100Ω can be added between the output pin of the sensor and C_{FILTER} to isolate the sensor's amplifier from the capacitive load. The output impedance of the sensor R_{OUT} varies as a function of frequency. Thus, a series resistor should be added to the effective R_{OUT} resistance, if C_{FILTER} is intended to serve as the ADC's anti-aliasing filter.

CONCLUSION

Temperature sensors are used in embedded systems for both thermal monitoring and management applications. A designer must evaluate the trade-offs of the sensor, conditioning circuitry and sensor output in order to maximize the measurement accuracy while easing the interface to the microcontroller. In addition, the designer must consider system integration issues such as the location of the sensor, grounding, EMI/ESD protection and shielding in order to provide a robust temperature measurement. A sample of practical circuits and interface techniques has been provided along with design equations.

The following sensor guidelines can be used as a starting point to select a temperature sensor. If your application requires a high-temperature measurement, thermocouples are a good choice because of their wide temperature operating range. Thermocouples are typically used as remote sensors and, therefore, the circuit must provide noise immunity by using good grounding and shielding methods. If your application requires precision, RTDs set the standard with their superior repeatability and stability characteristics. For applications such as the temperature measurement on a PCB, either thermistors or silicon IC sensors should be considered. Thermistors are available in more packages, are lower in cost and have a faster thermal response time than silicon sensors. However, thermistors require additional signal-conditioning circuitry, while silicon sensors provide both the sensor and circuitry on a single IC that can be interfaced directly to the microcontroller.

The output of the sensor is selected by the available microcontroller hardware and software resources, in addition to the complexity of the sensor circuit. The sensor output can consist of an analog, frequency, ramp rate, duty cycle, serial or logic format that is proportional to temperature. Temperature measurement is a popular topic and the designer should review the literature to evaluate the many sensor and circuit options available.

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