Analog Engineer's Circuit

Ultra-Small, Low-Cost Analog Temperature Sensor Measurement Circuit With ADC

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Temperature (°C)	Resistor Voltage (mV)	TLA2024 Digital Output Code	TMP61 Voltage (mV)	TLA2024 Digital Output Code
–40	3012.5	3E1h	1987.5	5E2h
125	1781.1	649h	3218.9	37Ah

Power Supplies	
VDD	**GND**
5V	0V

Design Description

This circuit design describes a temperature measurement circuit using a linear thermistor and a 12-bit ADC. The TMP61 linear thermistor resistance changes depending on the temperature from –40°C to 125°C, and can be used as a remote measurement when placed away from the ADC. The TLA2024 ADC is used to measure the voltage across a TMP61 and a precision resistor. With the internal voltage reference of the ADC, this circuit makes a compact, low-cost, and low-power solution to measure temperature. Included in this design are ADC register settings to configure the device and pseudo code is provided to configure and read from the device. This circuit can be used in applications such as *analog input modules* for PLCs, *lab and field instrumentation*, and *factory automation and control*.
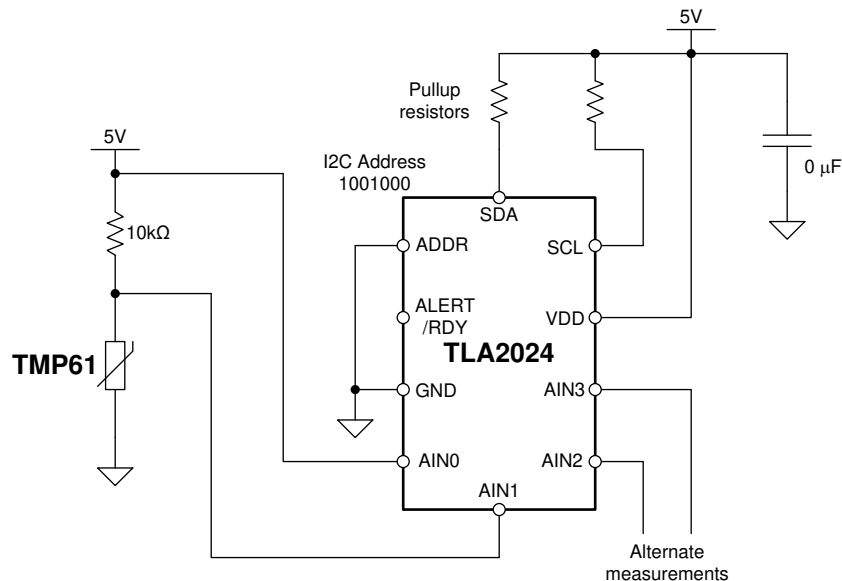
Design Notes

1. Use supply decoupling capacitors for the supply. The TLA2024 VDD must be decoupled with at least a 0.1-µF capacitor to GND. See the *TLA202x Cost-Optimized, Ultra-Small, 12-Bit, System-Monitoring ADCs Data Sheet* for details on power supply recommendations.
2. Polynomial equations or a lookup table can be used to convert the TMP61 resistance to temperature. For details, download the *Thermistor Design Tool*.
3. Temperature measurement with the TMP61 only uses two of the four analog inputs (AIN0 and AIN1) on the TLA2024. The remaining two analog inputs can be used for another differential measurement or two single-ended measurements.
4. The TLA2024 can be used to measure supply voltage with an extra measurement cycle, but not an extra analog input. AIN0 is already connected to the 5-V supply and can be measured as a single-ended setting for the multiplexer using the ±6.144V FSR setting.
5. If more resolution is needed for the ADC measurement, the ADS1115 can be substituted. The ADS1115 is similar to the TLA2024, it communicates through I^2C, and uses similar configuration registers. If SPI communication is required, the ADS1018 may be substituted.
6. For more information about the TI silicon-based linear thermistors and applications, see *TI's linear thermistors overview* and *Temperature Sensing with Thermistors*.

Component Selection

1. Identify the range of operation for the temperature sensor.

   The TMP61 has a temperature measurement range of –40°C to 125°C. With this range, the resistance of the TMP61 varies from 6537Ω to 17853Ω with a positive temperature slope. This range is used to maximize the resolution of the measurement, considering the full-scale range of the ADC.

   The following image shows the TMP61 resistance transfer function.
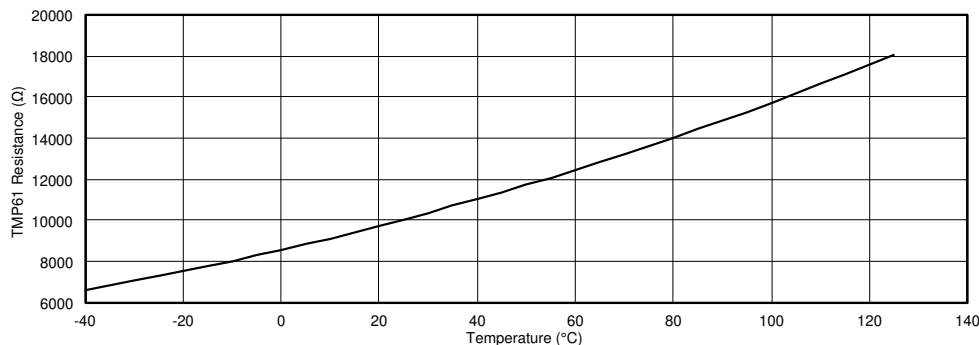
   While this transfer function is not completely linear, it is more linear that standard PTC thermistors. As mentioned previously, a lookup table or polynomial equation is required to determine the temperature based on the resistance.

   For more information about thermistor temperature conversion for the TMP61, download the *Thermistor Design Tool*. The tool contains resistance tables, example temperature conversion methods, and code examples.

2. Determine a precision resistor value for a voltage divider with the TMP61.

   To set up the measurement, a voltage divider is created from the TMP61 and a precision resistor (R1) using the supply.
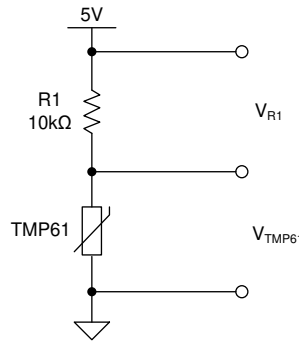
First, the ADC measures the voltage across R1 using one channel of the multiplexer of the TLA2024. This measurement of a known resistance is the first of two measurements to determine the resistance of the TMP61. Then, the ADC measures the voltage across the TMP61 with a second channel. These two measurements yield two output ADC codes.

With the known resistance of R1, the resistance of the TMP61 can be calculated from the ratio of the output codes from the two ADC measurements. Because R1 acts as a reference of comparison for the resistance of the thermistor, this resistor must be accurate. Any error in the resistance reflects as an error in the measurement of the TMP61 resistance.

The reference resistor value of R1 is chosen as 10kΩ for convenience. The room temperature resistance of the TMP61 at 25°C is roughly also 10kΩ. At this temperature, the thermistor is near the midpoint of the temperature range. If the 25°C is the midpoint, both the resistor measurement and TMP61 with be of similar voltage magnitude through the temperature range. The voltage across R1 and the TMP61 are shown against temperature in the following figure.
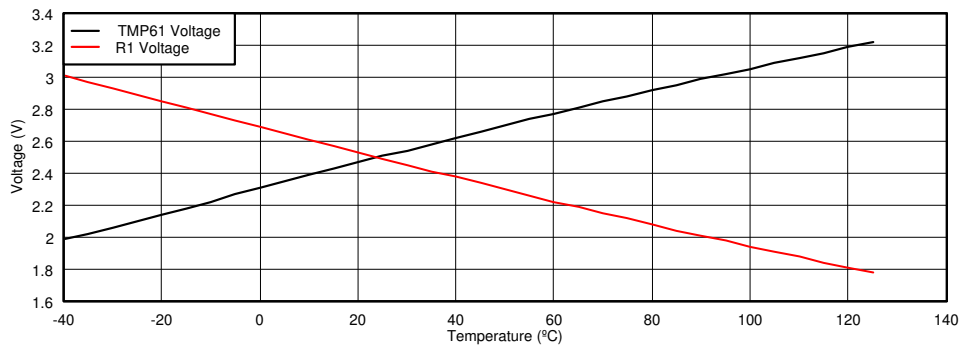
Voltages of R1 and the TMP61 vary from approximately 1.8V to 3.2V. Even as the R1 varies in voltage, the resistance is known to be a constant 10kΩ. The measurement of this voltage is compared to the measurement of the TMP61 voltage to calculate the ratio between the resistances.

3. Determine the gain and input range of the ADC.

The TLA2024 has a programmable gain amplifier (PGA) implemented through scaled capacitive sampling, not as a true amplifier. With this PGA, the input range extends to the full supply range, and can be used to set the ADC to one of six different full-scale ranges (FSR). To maximize the resolution, choose the smallest ADC full-scale range that encompasses the temperature measurement range.

Based on the temperature range from –40°C to 125°C you can determine the voltages across the two resistive elements. The first measurement of the voltage across the 10-kΩ resistor varies from 3012.5mV to 1781.1mV. The second measurement of the TMP61 voltage varies conversely from 1987.5mV to 3218.9mV. With these voltage ranges, the ±4.096V FSR can be used to measure both the resistor and the TMP61. Because both use the same ADC and FSR, the gain error difference between the measurements is very small. Using this setup, the temperature measurement range covers 616 codes for both R1 and the TMP61. This gives a basic resolution of approximately 0.27°C per code.

Because the resistors have the same current, the ADC output codes are proportional to the resistances. The output voltage does not need to be calculated and the resistance of the TMP61 can be calculated based on the ratio of the ADC codes for both measurements.

The TLA2024 reports data as a differential 16-bit ADC. Even if the ADC is used to make a single-ended measurement, the ADC reports the data as differential. A single-ended measurement is reported with 15-bits of resolution.

Configuration Register Settings

The configuration register sets the mode of operation and configuration of the ADC. Configurations include all of the settings described in the previous sections. Six fields across 16 bits are used to configure the device. Configuration register field descriptions are shown with bit names and positions, read and write usage, and reset values in the following table.

15	14	13	12	11	10	9	8
OS	MUX[2:0]			PGA[2:0]			MODE
R/W-1h	R/W-0h			R/W-2h			R/W-1h
7	**6**	**5**	**4**	**3**	**2**	**1**	**0**
DR[2:0]			RESERVED				
R/W-4h			Always write 03h				

The OS bit sets the operational status and starts a single conversion. The MUX[2:0] bits set the input multiplexer to select the analog input. The MODE bit sets the device to single-shot conversion mode. The DR[2:0] bits set the data rate of the device. See the *TLA202x Cost-Optimized, Ultra-Small, 12-Bit, System-Monitoring ADCs data sheet* for details on the configuration register.

For this application, the ADC is first set to measure the voltage across R1, using the multiplexer to measure from AIN0 to AIN1. The FSR is set to ±4.096V, with a data rate of 1600SPS. The settings for the configuration register fields in the TLA2024 are shown in the following table.

Bit	Field	Setting	Description
15	OS	1	Start conversion
14:12	MUX[2:0]	000 101	Single-ended input measurement, AINP – AINN = AIN0 – AIN1, first measurement of R1 Differential input measurement, AINP – AINN = AIN1 – GND, second measurement of TMP61
11:9	PGA[2:0]	001	FSR = ±4.096V, sets the ADC to be able to measure the full supply range of 0V to VDD
8	MODE	1	Operation in single-shot conversion mode
7:5	DR[2:0]	100	Data rate = 1600SPS
4:0	Reserved	00011	Always write 03h

Combining these bits from the field descriptions, the configuration register values are 1000 0011 1000 0011 or 8383h. This configures the first measurement of the R1 resistor.

In the second measurement, the multiplexer is then set to measure the voltage across the TMP61. For this measurement, the only change is to set the input to measure from AIN1 to GND as a single-ended measurement. The configuration register is set to 1101 0011 1000 0011 or D383h.

Channel Cycling For The TLA2024

The TLA2024 has four analog input channels from a configurable multiplexer connected to the ADC. Making the temperature measurement requires measurements only from AIN0 and AIN1 of the TLA2024 (one differential measurement and one single-ended measurement). However, the last two channels can also be included to cycle through all measurements.

To make these measurements, The ADC is programmed to cycle through the system, start each conversion, wait for the conversion to complete, and then read back the data. Then start the conversion for the next channel. Repeat each measurement for the four single-ended input channels, before moving on to the next channel.

Repeating this sequence in the system cycles through all channels. A write to the configuration register starts the conversion and configures the ADC for the proper mode of operation. The communication starts with a write to the I2C slave address of the device. The I2C write is followed by three bytes. The first byte is 01h to indicate the configuration register. The next two bytes are the data written to the configuration register. The complete communication of four bytes to setup the R1 resistor measurement is shown in the following table.

I²C Address: 1001000 Write	Address Pointer: Configuration Register	Configuration MSB: Start Conversion, Set Input, FSR, Single-Shot Mode	Configuration LSB: 128SPS, Comparator Disabled
1001 0000	0000 0001	1000 0011	1000 0011

The master then waits for the conversion to complete. For this example, the TLA2024 device is set to the default data rate of 1600SPS. Because the device uses an internal oscillator, there is some variation in the data rate. To ensure that the device is read after the ADC completes a conversion, the microcontroller waits for the maximum time required for the conversion to complete. This wait time is the nominal data period plus 10% (to compensate for the internal oscillator variation of the device). An additional 20µs is added for the wake up time of the ADC for each single-shot conversion. The total wait time is calculated in the following equation.

Wait time = nominal data period + 10% + 20µs

As an example, if the device is run at 1600SPS, the nominal data period is 625µs. The necessary wait time would be:

Wait time = (625µs × 1.1) + 20µs = 708µs

A read from the device starts with a write to the register pointer for the conversion register (00h) and then another read of two bytes from the same I²C address. The following shows the read of the R1 resistor measurement data following the first configuration of the ADC. The complete communication of five bytes is shown in the following table.

I²C Address: 1001000 Write	Address Pointer: Conversion Data Register	I²C Address: 1001000 Read	Read Conversion Data MSB	Read Conversion Data LSB
1001 0000	0000 0000	1001 0001	xxxx xxxx	xxxx xxxx

After collecting the data for R1, the TLA2024 is configured to measure the voltage across the TMP61. The communication of four bytes to setup the TMP61 measurement is shown in the following table.

I²C Address: 1001000 Write	Address Pointer: Configuration Register	Configuration MSB: Start Conversion, Set Input, FSR, Single-Shot Mode	Configuration LSB: 128SPS, Comparator Disabled
1001 0000	0000 0001	1101 0011	1000 0011

After waiting for the ADC to complete to the conversion, the same previous five byte read of the conversion data register is used to retrieve the data as shown in the previous table. The other remaining TLA2024 channels can be cycled in any order through by repeating this sequence.

Measurement Conversion

As mentioned previously, the ADC data does not need to be converted to voltage. The ratio of the ADC output codes is equivalent to the ratio of the R1 and TMP61 resistances. With OutputCode1 from the R1 measurement and OutputCode2 as the TMP61 measurement, the TMP61 resistance can be calculated from the following equation:

TMP61 resistance = 10kΩ × (OutputCode2 / OutputCode1)

Note that for the TLA2024, the data format is 12 bits with four bits zero padded on the right. A full-scale reading is 7FFh and would be read from the conversion register as 7FF0h.

Download the *Thermistor Design Tool* to make the TMP61 conversion from resistance to temperature. With the tool, the conversion can be made from calculation from a lookup table, a fourth order polynomial, or a Steinhart-Hart equation.

Pseudo Code Example

The following example shows a pseudocode sequence with the required steps to set up the device and the microcontroller that interfaces to the ADC to take subsequent readings from the TLA2024 in single-shot conversion mode. The ADC first read is for the reference resistor R1, using a differential measurement of AIN0 and AIN1. Data is taken by using the maximum data period, allowing for time to wake up the device, configure the ADC, take a single conversion, and set up other ADC measurements. A second measurement is then made with a single-ended measurement AIN1 for the TMP61 with a similar method. Other measurement channels are similarly used with a write to the configuration register and start of a conversion, wait for the conversion to complete, and a read back of the conversion.

```
Configure microcontroller for I2C communication, I2C address=1001000 (48h)
Loop
{
Send 90h 01h 83h 83h // Measure R1 voltage as Data1
// Start write to address 48h, write bit 0 (90h)
// Configuration register 01h
// Set 8383h, AIN0-AIN1, FSR=±4.096V, Single-shot conversion, DR=1600SPS, stop
Wait 708us // Wait for data period, +10% for internal oscillator variation, +20us
Send 90h 00h 91h xxh xxh // Read back ADC conversion data
// Start write to address 48h, write bit 0 (90h)
// Conversion register 00h, stop
// Start read from address 48h, read bit 1 (91h)
// Read back 2 bytes, stop
Send 90h 01h 83h 83h // Measure TMP61 voltage as Data2
// Start write to address 48h, write bit 0 (90h)
// Configuration register 01h
// Set D383h, AIN1-GND, FSR=±4.096V, Single-shot conversion, DR=1600SPS, stop
Wait 708us // Wait for data period, +10% for internal oscillator variation, +20us
Send 90h 00h 91h xxh xxh // Read back ADC conversion data
// Start write to address 48h, write bit 0 (90h)
// Conversion register 00h, stop
// Start read from address 48h, read bit 1 (91h)
// Read back 2 bytes, stop
// Calculate resistance of TMP61 as R_TMP61
Calculate R_TMP61 from 10kOhms*Data2/Data1
// Convert R_TMP61 to temperature with example code from the Thermistor Design Tool
// Measurements from AIN2 and AIN3 (optional)
Send configuration for channel 2
Wait for conversion to complete
Read channel 2
Send configuration for channel 3
Wait for conversion to complete
Read channel 3
}
```

Layout Example

The following shows an example layout of the TLA2024 device with the TMP61. Bypass capacitance is placed for the ADC using an 0402 capacitor. The resulting layout is about 200 mils by 225 mils. This measurement does not include the I^{2}C pullup resistors.
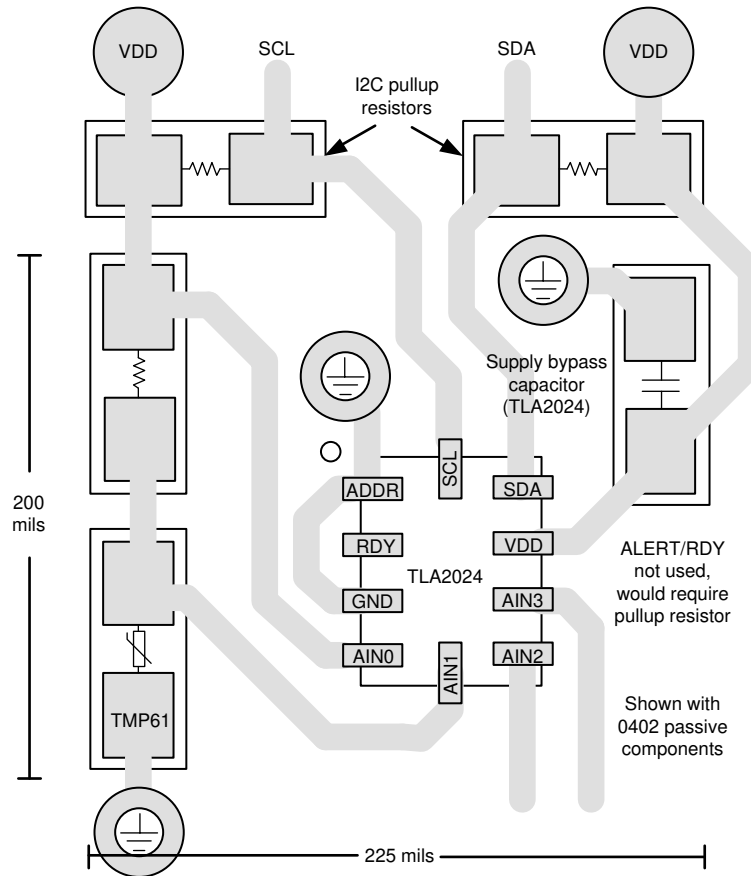
Example Layout

Design Featured Devices

Device	Key Features	Link	Other Possible Devices
TLA2024	TLA202x Cost-Optimized, Ultra-Small, 12-Bit, System-Monitoring ADCs	http://www.ti.com/product/TLA2024	Link to similar devices Link to similar SPI devices
TMP61	TMP61 ±1% 10-kΩ Linear Thermistor With 0402 and 0603 Package Options	http://www.ti.com/product/TMP61	

Design References

See the *Analog Engineer's Circuit Cookbooks* for TI's comprehensive circuit library.

Additional Resources

- Texas Instruments, *Thermistor Design Tool*
- Texas Instruments, *Temperature Sensing with Thermistors*

For direct support from TI Engineers use the E2E community:

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Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (May 2020) to Revision A (August 2021) **Page**

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