Ultra-small, precision analog temperature sensor measurement circuit with ADC

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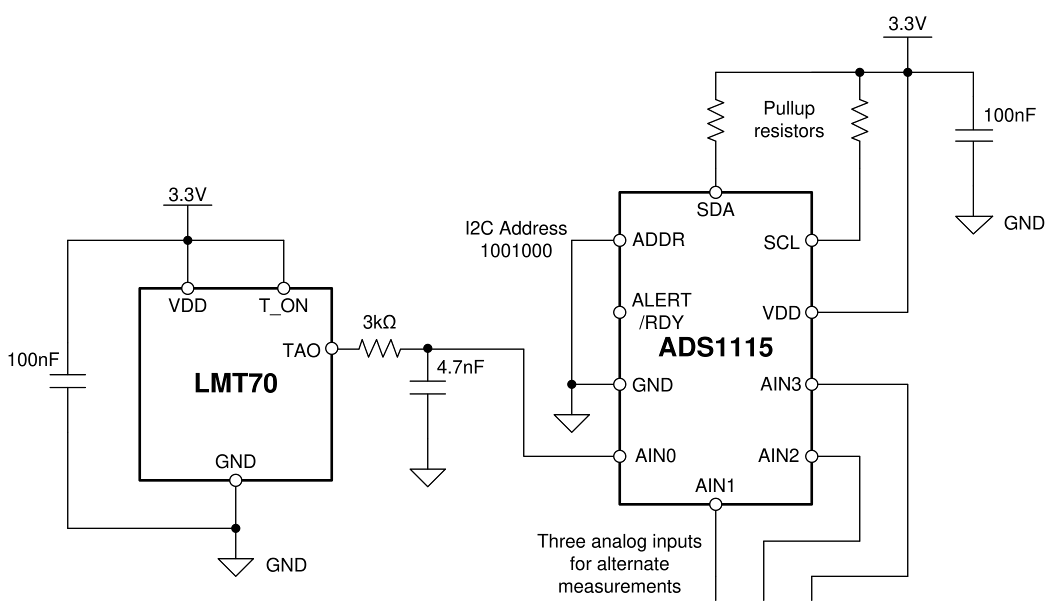
Temperature (°C)	LMT70 Output Voltage (mV)	TLA2024 Digital Output
–55	1375.219	55F4h (22004d)
125	302.785	12EDh (4845d)

Power Supplies	
VDD	GND
3.3V	0V

Design Description

This circuit design describes a temperature measurement circuit using a precision analog temperature sensor and a 16-bit ADC. The *LMT70* device temperature sensor gives an output voltage dependent on the temperature from –55°C to 150°C, and can be used as a remote measurement when placed away from the ADC. The *ADS1115* ADC is used to measure the output voltage of the LMT70. With the internal voltage reference of the ADC, this circuit makes a compact, low-power solution to accurately measure temperature. Included in this design are ADC register settings to configure the device and pseudo code 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*.



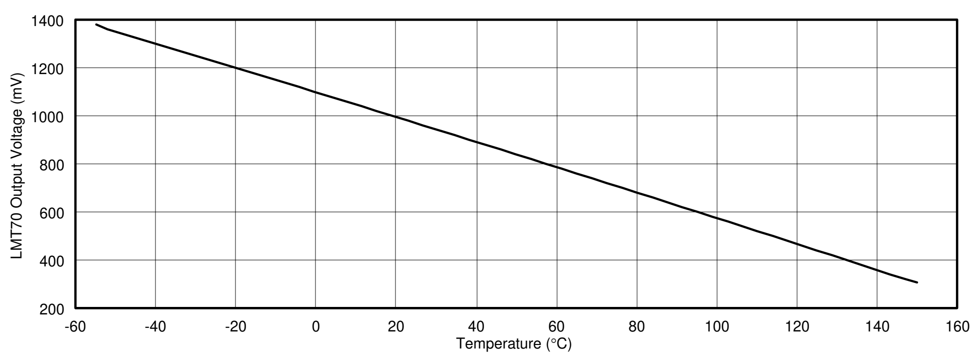
Design Notes

1. Use supply decoupling capacitors for the power supplies. VDD must be decoupled with at least a 0.1-μF capacitor to GND. See the *ADS111x Ultra-Small, Low-Power, I²C-Compatible, 860-SPS, 16-Bit ADCs With Internal Reference, Oscillator, and Programmable Comparator* and *LMT70, LMT70A ±0.05°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC* data sheets for details on power-supply recommendations.
2. When possible, use C0G (NPO) ceramic capacitors for input filtering. The dielectric used in these capacitors provides the most stable electrical properties over voltage, frequency, and temperature changes. Because of size, this may not always be practical and X7R capacitors are the next best alternative.
3. Conversion tables and temperature transfer functions for the temperature sensor shown in this application note are also found in the LMT70 data sheet in more detail.
4. While the LMT70 has a recommended operation range of –55°C to 150°C, the ADS1115 has an operating range of –40°C to 125°C. If the full operational range of the LMT70 is needed, the device should be placed remotely from the ADC.
5. This circuit design is shown with the LMT70 connected as a single-ended measurement to AIN0 of the ADS1115, while the remaining three input channels can be used for other measurements. If the temperature sensor is the only sensor measurement, then the ADS1114 can be used and AIN0 is connected to the LMT70 and AIN1 is connected to ground for the same function.
6. If less resolution can be tolerated for the ADC, the ADS1015 or the TLA2024 can be substituted. Both devices are similar to the ADS1115, communicate through I²C, and use similar configuration registers. If SPI communication is required, the ADS1118 or the ADS1018 may be substituted.
7. This application circuit may be used for thermocouple cold-junction measurement. For more information about thermocouple measurements see *A Basic Guide to Thermocouple Measurements*..

Component Selection

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

   The LMT70 has a temperature measurement range of –55°C to 150°C. With this temperature range, the output voltage of the LMT70 varies from 1375mV to 303mV with a negative temperature slope. This range is used to maximize the resolution of the measurement, considering the full-scale range of the ADC. The LMT70 output transfer function is shown in the following figure.



   Despite the appearance, the LMT70 output transfer function is not linear. Accurately determining the temperature requires interpolation from a lookup table or calculation from a polynomial equation.

2. Determine gain and input range of the ADC.

   The ADS1115 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).

   As mentioned previously, the LMT70 has an output range of 1375mV to 303mV when the temperature measurement range is –55°C to 150°C. To maximize the resolution, choose the smallest ADC full-scale range that encompasses the temperature measurement range. With this measurement range, the ADC FSR can be set to ±2.048V. At –55°C, the ADC output code would read 55F4h or 22004 in decimal and at 150°C would read 12Edh or 4845 in decimal. Using this setup, the temperature measurement would be 17159 codes. This gives a basic resolution of 0.012°C per code.

   If the temperature measurement range is limited to 15°C as the lowest temperature, then the output voltage of the LMT70 is limited to 1.024V. With this limit, the ADC FSR range can be set to ±1.024V, maximizing the resolution of the ADC.

   The ADS1115 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.

3. Select values for the input filtering for the ADC inputs.

   Often, the ADC input is filtered with basic RC filtering. If there is input filtering, the input current of the ADC reacts with any series filter resistance to create an error. For the ADS1115 device, the input current is modeled as equivalent differential and common-mode input impedance. With the negative input grounded, the equivalent input impedance can be approximated as the differential and common-mode impedance in parallel.

   Using the FSR of ±2.048V, the ADS1115 differential input impedance is 4.9MΩ and the common-mode impedance is 6MΩ. The equivalent input impedance is approximately 2.7MΩ. If the series filter resistance is much smaller than the equivalent input impedance, the gain error of the measurement is not impacted from the filtering.

   For delta-sigma type ADCs like the ADS1115, the bandwidth of the input filtering is set to be at least ten times higher than the data rate. If the ADS1115 is run at the highest data rate of 860SPS, then the input filter can be set to higher than 8.6kHz. The LMT70 can drive limited capacitance and its data sheet gives specific guidance for series resistances used with different load capacitance. For a suitable filter, use R_S = 3kΩ and C_{LOAD} = 4.7nF. This sets the input filtering bandwidth to 11.3 kHz. If a different data rate is used, or if the ADS1015 or TLA2024 is used, then this bandwidth can be recalculated for a different data rate. Regardless, follow the guidelines of the capacitive load drive for the LMT70 device as stated in the data sheet.

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. Nine 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]			COMP_MODE	COMP_POL	COMP_LAT	COMP_QUE	
R/W-4h			R/W-0h	R/W-0h	R/W-0h	R/W-3h	

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. The remaining fields are used for the ADC comparator settings which are not used in this design. See the *ADS111x Ultra-Small, Low-Power, I^{2}C-Compatible, 860-SPS, 16-Bit ADCs With Internal Reference, Oscillator, and Programmable Comparator* data sheet for more details on the configuration register.

For this application, one ADC channel is used to measure the LMT70. The multiplexer is set to measure AIN0 to GND, the FSR is set to ±2.048V, and the data rate is set to 860SPS. The settings for the configuration register fields in the ADS1115 are shown in the following table.

Bit	Field	Setting	Description
15	OS	1	Start conversion
14:12	MUX[2:0]	100	Single-ended input measurement, AINP–AINN = AIN0–GND, selection of the first channel
11:9	PGA[2:0]	010	FSR = ±2.048V, 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]	111	Data rate = 860SPS
4	COMP_MODE	0	Traditional comparator
3	COMP_POL	0	Active low
2	COMP_LAT	0	Non-latching comparator
1:0	COMP_QUE[1:0]	11	Comparator is disabled

Combining these bits from the field descriptions, the configuration register values are 1100 0101 1110 0011 or C5E3h.

Channel Cycling With the ADS1115

The ADS1115 has four analog input channels from a configurable multiplexer connected to the ADC. The LMT70 temperature measurement is made only with the ADS1115 channel connected to AIN0, leaving inputs at AIN1, AIN2, and AIN3 available for alternate measurements.

To cycle through each channel of 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. Repeating this sequence for all four inputs 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 I^2C slave address of the device. The I^2C 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 is shown in the following table.

I^2C Address: 1001000 Write	Address Pointer: Configuration Register	Configuration MSB: Start Conversion, Set Input, FSR, Single-Shot Mode	Configuration LSB: 860SPS, Comparator Disabled
1001 0000	0000 0001	1100 0101	1110 0011

The master then waits for the conversion to complete. For this example, the ADS1115 device is set to the fastest data rate of 860SPS. 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 860SPS, the nominal data period is 1.16ms. The necessary wait time would be:

Wait time = (1.16ms × 1.1) + 20µs = 1.30ms

A read from the device starts with a write to the register pointer for the conversion data register (00h) and then another read of two bytes from the same I^2C address. The following shows the read of the LMT70 measurement data following the configuration of the ADC. The complete communication of five bytes is shown in the following table.

I^2C Address: 1001000 Write	Address Pointer: Configuration Data Register	I^2C Address: 1001000 Read	Read Conversion Data MSB	Read Conversion Data LSB
1001 0000	0000 0000	1001 0001	xxxx xxxx	xxxx xxxx

Other ADS1115 channels can be cycled in any order through by repeating this sequence. Data is collected by setting the configuration register, waiting for the conversion to complete, and then reading the conversion data.

Measurement Conversion

Conversions for the output voltage of the temperature sensor are relatively straightforward based on the full-scale range of the ADC. The output voltage of the LMT70 device is calculated with the following:

Output Code = $2^{15} \times [V_{AIN0} / (2.048V)]$

LMT70 Output Voltage = V_{AIN0} = (Output Code) × (2.048) / (2^{15})

An electrical characteristics temperature lookup table follows. The voltage measurement can be converted to temperature by using interpolation with the following lookup table.

Temperature (°C)	VTAO (mV) (typical value)	Local Slope (mV/°C)
–55	1375.219	–4.958
–50	1350.441	–4.976
–40	1300.593	–5.002
–30	1250.398	–5.036
–20	1199.884	–5.066
–10	1149.070	–5.108
0	1097.987	–5.121
10	1046.647	–5.134
20	995.050	–5.171
30	943.227	–5.194
40	891.178	–5.217
50	838.882	–5.241
60	786.360	–5.264
70	733.608	–5.285
80	680.654	–5.306
90	627.490	–5.327
100	574.117	–5.347
110	520.551	–5.368
120	466.760	–5.391
130	412.739	–5.430
140	358.164	–5.498
150	302.785	–5.538

As an alternative, the output voltage of the LMT70 can be modeled with a second order transfer function. Using the least squares sum method, a best fit second order transfer function is generated using the values in the previous table. A limited temperature range of –10°C to 110°C can be used to generate an accurate transfer function with one set of coefficients. Over the full temperature range of –55°C to +150°C, a single second order transfer function has increased error at the temperature extremes and requires a different set of coefficients. The transfer function is shown in the following equation:

$T_M = a \times (VTAO)^2 + b \times (VTAO) + c$

where:

Coefficient	Best fit for –55°C to 150°C	Best fit for –10°C to 110°C
a	–8.451576E-06	–7.857923E-06
b	–1.769281E-01	–1.777501E-01
c	2.043937E+02	2.046398E+02

and VTAO is in mV and T_M is in °C. For an in-depth discussion of conversion methods, consult the LMT70 data sheet.

Pseudo Code Example

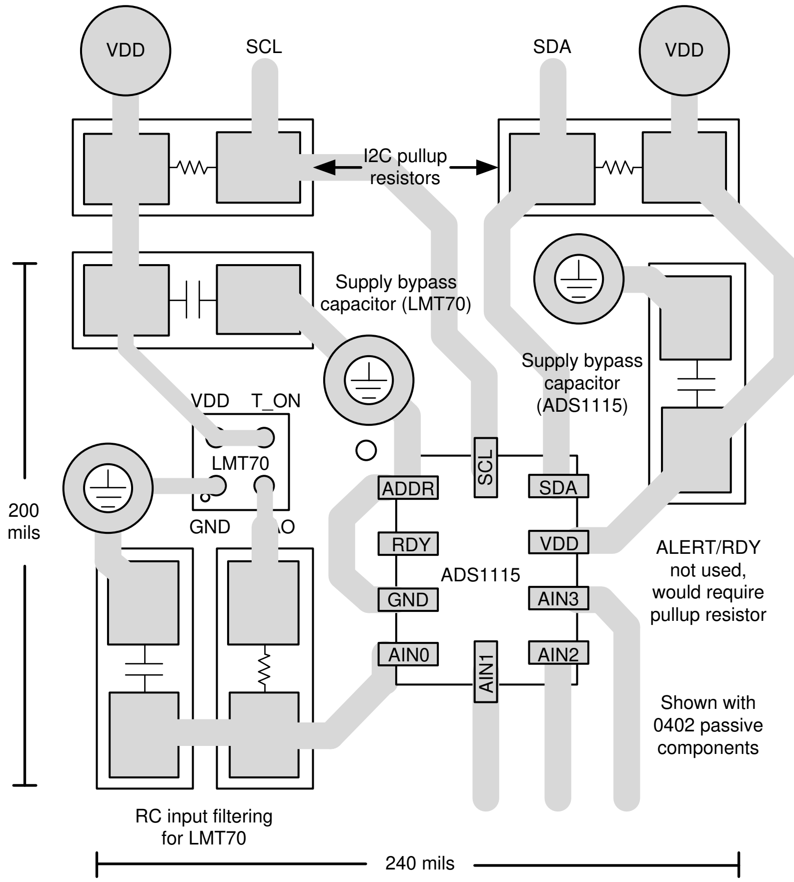
The following example shows a pseudocode sequence with the required steps to set up the device and the microcontroller that interfaces to the ADC to take subsequent readings from the ADS1115 in single-shot conversion mode. The ADC first read is for the LMT70 temperature sensor, using the AIN0 channel. 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. 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 C5h E3h //
    // Start write to address 48h, write bit 0 (90h)
    // Configuration register 01h
    // Set C1E3h, AIN0-GND, FSR=±2.048V, Single-shot conversion, DR=860SPS, stop
    Wait 1.30ms // 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
    // Measurements from AIN1, AIN2, and AIN3 (optional)
 Send configuration for channel 1
    Wait for conversion to complete
    Read channel 1
    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
}
```

For more details on the configuration of the ADS1115, see the data sheet or the *Precision measurement circuit with 16 singled-ended channels and I^2C interface circuit*.

Layout Example

The following shows an example layout with the LMT70 and ADS1115 devices. RC input filtering is added using 0402 resistors and capacitors. The resulting layout is about 200 mils by 240 mils. This measurement does not include the I^{2}C pullup resistors. A single set of these resistors are required for each system.



Example Layout

Design Featured Devices

Device	Key Features	Link	Other Possible Devices
ADS1115	ADS111x ultra-small, low-power, I^{2}C-compatible, 860-SPS, 16-bit ADCs with internal reference, oscillator, and programmable comparator	http://www.ti.com/product/ADS1115	Link to similar devices Link to similar SPI devices
LMT70	LMT70, LMT70A ±0.05°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC	http://www.ti.com/product/LMT70	

Design References

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

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