AND9037/D

Temperature Measurement using the Q32M210

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APPLICATION NOTE

Introduction

Q32M210 is a precision mixed-signal 32-bit microcontroller that contains features that are ideal for use in an automated temperature measurement system.

This application note describes three design approaches to performing temperature measurement using the Q32M210 microcontroller and Q32M210 EDK:

1. Using the on-chip temperature sensor
2. Using an external thermistor
3. Using an external transimpedance amplifier and thermistor

Applications

- Portable Medical Devices
- Personal Health and Wellness Devices
- In-Home Energy Displays
- Wireless Sensors

How to Use this Application Note

This application note is intended to be used with the Q32M210 documents shown below.

- Q32M210 Installation Guide
- Q32M210 Programmer's Guide
- Q32M210 Firmware Reference Manual
- Q32M210 Evaluation and Development Board Manual
- Q32M210 Data Sheet
- Q32M210 Engineering Tool and Quick Start Guide

The Q32M210 Evaluation and Development Kit (EDK) and Q32M210 Engineering Tool application provide a convenient way to evaluate the performance of the Q32M210 microcontroller in temperature sensing applications. Easy access is available to all Q32M210 analog resources, and an on board external thermistor allows easy prototyping with an external temperature sensor.

While the examples given in this application note can be used with any Q32M210 hardware, implementation is specifically described for the Q32M210 EDK.

Q32M210 System Overview

The following components of the Q32M210 microcontroller will be used for the three temperature measurement applications described in this note:

- Internal Temperature Sensor
- Programmable gain amplifier (PGA1) connected to ADC1
- Opamp A1, one of three low−noise opamps
- 16-bit Analog-to-Digital Converter (ADC1) with decimation filter
- ARM® Cortex™-M3 microprocessor running at 3.0 MHz

ON CHIP TEMPERATURE SENSOR

The internal temperature sensor of the Q32M210 microcontroller produces a linear analog voltage output that is proportional to temperature.

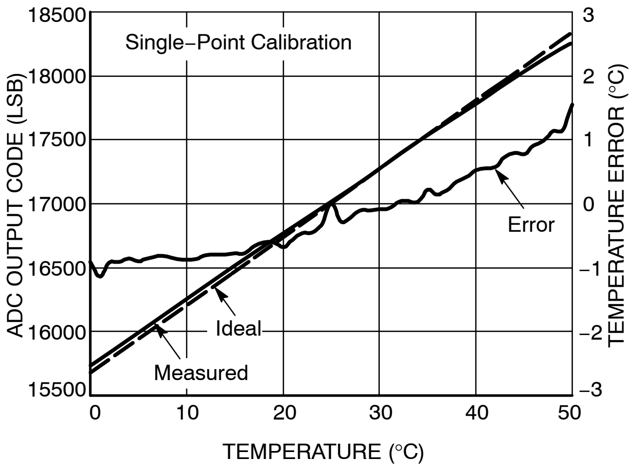

Figure 1. Q32M210 Internal Sensor Output

Note in Figure 1 above that the function of the ADC value with respect to temperature has a constant slope and a fixed offset, so linearization of the data is not necessary.

Internal Temperature Sensor Calibration

The Q32M210 temperature sensor is calibrated during production in order to determine a unique value for the offset (b value) at a single temperature.

The general slope (m value) of the temp sensor is also programmed during production, but is based on a typical value, and is not unique to each device.

To improve the accuracy of the internal temperature sensor across the entire temperature range of the device, a dual point calibration is required.

Dual temperature point calibration will account for any slope variation in addition to any offset variation; however, an extra step is required to calculate the slope. It is given by the equation:

Slope = (ADC Value1-ADC Value2) / (Caltemp1 - Caltemp2)

Internal Temperature Sensor Calibration Data Storage

The Q32M210 microcontroller uses the flash memory information page to store manufacturing and system calibration data including temperature sensor data. This data can be accessed through firmware and is write protected.

As the Q32M210 microcontroller does not have any floating point hardware, floating point calculations, especially division can be time consuming. To eliminate the need for a division the *1/Slope* value is pre-stored in memory.

The fixed value used for the slope of the internal sensor temperature curve is 54.25969102

Therefore 1/*Slope* = 1/54.25969102 ~= 0.018429887

Converting this to an IEEE 754 encoded number yields:

Sign = 0 = 1’b0 **scaleFactor** = -6

Exponent = 127 + scaleFactor = 121 = 8’b0111 1001

Mantissa = 1505862 = 23’b001 0110 1111 1010 0100 0110

Therefore:

1/Slope = 32’h3C96FA46

Compensating for DC Offset Change with Temperature

A small DC offset voltage is present in the signal path between the input to the PGA and the input to the ADC. This DC offset will affect the accuracy of the temperature measurement, and must be compensated for in the measurement procedure.

The value of the DC offset in the signal path is linear with respect to temperature, so it will be necessary to determine the value of the DC offset for each temperature measurement taken. This can be easily accomplished by connecting the PGA input to the ground reference (VSSA) and recording the value of the ADC output.

Table 1. TEMPERATURE CONSTANT DEFINES

Name of Define	Size (words)	Description	Value
Q32M210_SYS_TS_REF_SLOPE	1	Slope for the temperature sensor temperature measurement calculation C for the AFE_DOUT_VTS_CTRL setting from the calibration table (m in the y = mx + b calculation)	Q32M210_SYS_CONST_BASE + Q32M210_SYS_TS_REF_SLOPE_POS
Q32M210_SYS_TS_REF_OFFSET	1	Reference voltage offset measured by the temperature sensor at 25°C for the AFE_DOUT_VTS_CTRL setting from the calibration table (b in the y = mx + b calculation)	Q32M210_SYS_CONST_BASE + Q32M210_SYS_TS_REF_OFFSET_POS

Calculating the Temperature

The procedure for determining the temperature using the internal sensor is as follows:

- Take several measurements of the DC offset in the input signal path and determine the average value of this offset
- Take several measurements of the temperature sensor value and determine the average value
- Perform the temperature calculation using the data collected from the above steps

Several measurements of the DC offset and temperature sensor value are needed in order to average the effect of noise on the ADC measurement.

To calculate the temperature given a measurement from the internal temperature sensor, the following linear equation must be solved:

Temperature = (ADC Value – Offset) / Slope

This is simply a rearrangement of the y=mx+b equation in terms of x:

X = (y-b)/m where

m = slope of the curve

b = offset of curve (zero intercept)

The above equation can be slightly modified to include the correction for temperature dependant DC offset as shown below:

Temperature = (ADC Value – dc_offset−Offset) / Slope

An example of Q32M210 code for calculating temperature is shown below.

In this example, the value of the DC offset at the present temperature is assumed to have been previously stored in “dc_null”.

Also note that the value “zoffset” is the ADC output of the temperature sensor at 25°C minus the DC offset at the same temperature. By using an offset value at 25°C, rather than 0°C, the error is minimized in the middle of the range of temperature measurements.

```
void Get_Temp_Value()
{
  //start of temp measurement routine
    currentSample =
Sys_Analog_Get_ADC01Data();
    float zoffset = 16777-1549;
    invSlope = (float*)0x10000318;
    averageMeasurement =
(float)currentSample;
    temperature = (averageMeasurement-
dc_null - zoffset)  * (*invSlope);
}
```

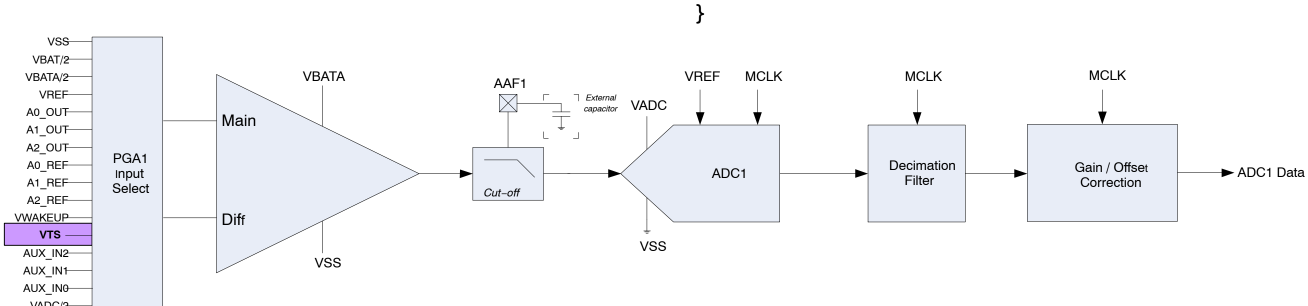

Figure 2. Q32M210 Internal Temperature Sensor Signal Path

Configuring the Temperature Sensor Signal Path

In this example, shown in Figure 2 above, the sensor output is internally routed to PGA1 for amplification and signal conditioning, and converted to a digital value using the onboard ADC1.

The Q32M210 microcontroller has two programmable gain amplifiers that allow for scaling the ADC input voltage to the full input range of the ADC. These amplifiers support differential or single ended operation, and provide a firmware controlled gain of 0 dB to 42 dB in 6 dB steps.

In this example, PGA1 is configured to perform a differential measurement on the internal temperature sensor and apply a gain of 24 dB to compensate for the relatively small voltage changes across the temperature sensor.

PGA and ADC gain errors and offsets can occur in the signal chain due to typical process variances. These gain errors and offsets result in slight inaccuracies in the values being converted by the ADC compared to the absolute voltage levels of the inputs.

As a result, before taking a measurement from the temperature sensor, ADC1 and PGA1 must be calibrated for gain and offset.

The PGA contains a configurable anti-aliasing filter that reduces the out-of-band noise into the A/D converter.

The actual cut-off frequency is determined through the control register setting as well as the external filter capacitors on the AAF0 and AAF1 pins. A cutoff frequency of 160 Hz is used to reduce noise input to the ADC.

The Q32M210 microcontroller contains two 16 bit A/D converters. The ADCs operate rail-to-rail between 0 V and V_{ADC} = 1.8 V and provide an output corresponding to this voltage range. The ADC’s are powered from a separate 1.8 V V_{ADC} regulator to minimize noise from other sections of the device.

The ADCs support two different output formats: unsigned integer and two’s complement. In this example, ADC1 is used and configured in unsigned integer mode with the output values range from 0x0000 (minimum) to 0xFFFF (maximum).

Converted outputs are provided to the ARM Cortex-M3 core via interrupt service routines or via DMA.

Temperature measurement typically requires a slow ADC sample rate due to the slow slew rate of the temperature sensor. This can be achieved by averaging the ADC output in software.

Q32M210 Analog Block Configuration for Internal Temp Sensor Measurement

The functions of the following sample code can also be performed using parameters tab of the Engineering tool as shown in Figure 3 below:

```
void Initialize_Tempsensor_Path()
{
//Enable the internal temperature sensor
block; by default the sensor is turned off
Sys_Analog_Set_TempSenseControl(TEMP_SENSE_
ENABLE);
//Enable MCLK using CLK_CTRL3 register
Sys_Clk_Config_MCLK(MCLK_CLK_ENABLE_BYTE |
MCLK_CLK_DIV_2_BYTE);
//Enable the ADC1 power supply using
AFE_OPMODE_CTRL register
Sys_Analog_Set_OpModeControl(VADC_ENABLE);

//Set ADC1 output format to unsigned
integer format
Sys_Analog_Set_ADCControl(ADC1_ENABLE |
ADC1_FORMAT_UNSIGNED_INT
|ADC1_OFFSET_DISABLE);
// Sys_Analog_Set_ADCControl(ADC1_ENABLE |
ADC1_FORMAT_TWOS_COMP|ADC1_OFFSET_DISABLE
);
//Sys_Analog_Set_ADCDataRateDecimateConfig(
DATARATE_DECIMATE_BY_4 | 468);
Sys_Analog_Set_ADCDataRateConfig(468);
//Configure the PGA to perform the
measurement on the VTS (temperature sensor)
inputs.
Sys_Analog_Set_PGA1Control(PGA1_ENABLE |
PGA1_SEL_VTS1| PGA1_DIF_SEL_VTS2);

//Set the gain and AAF cutoff frequency
using the AFE_PGA_GAIN_CTRL register
Sys_Analog_Set_PGAGainControl(PGA1_GAIN_24D
B);
}
```

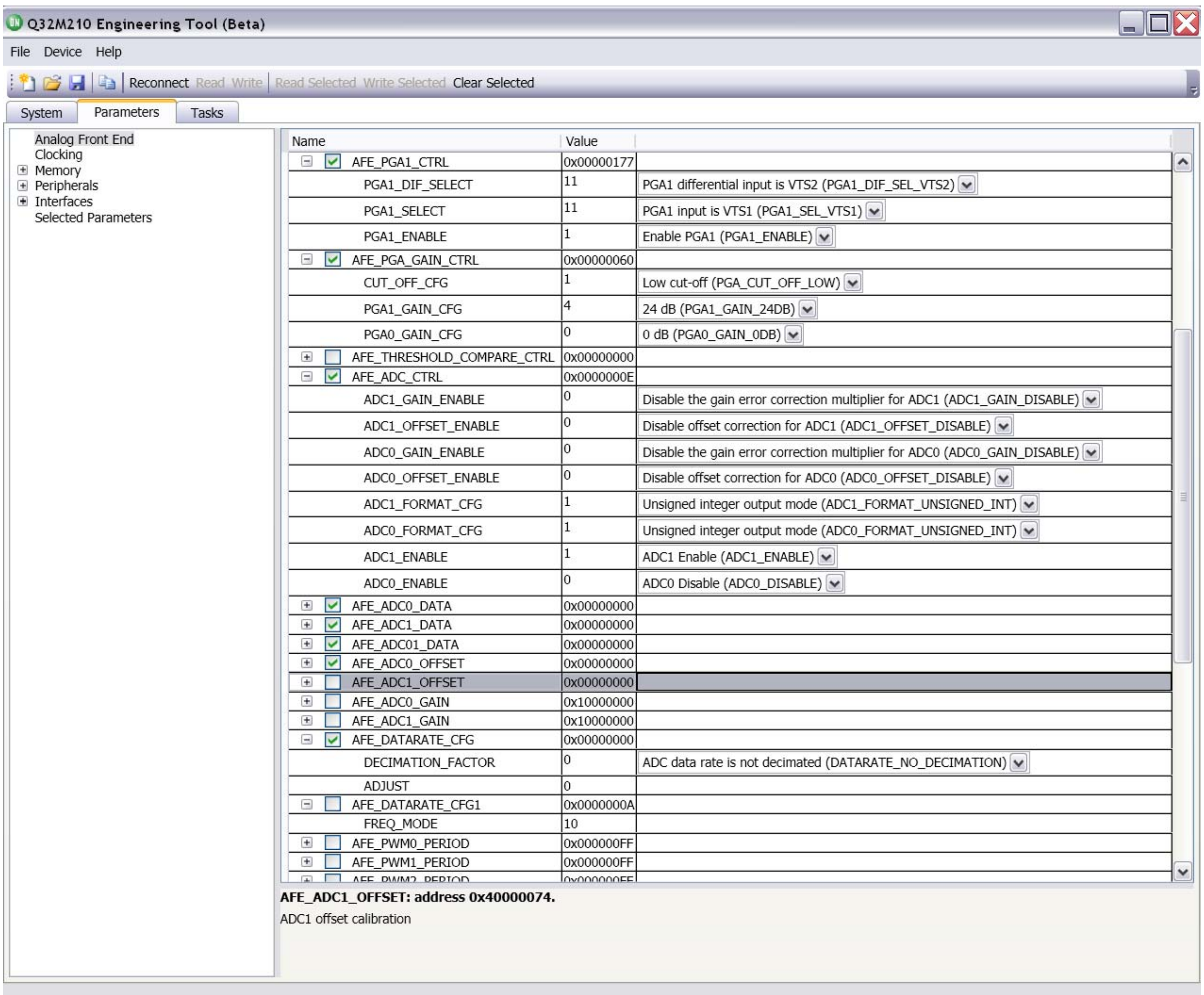

Figure 3. ADC Parameters in Q32M210 Engineering Tool

Firmware Support for Internal Temperature Sensor

The Q32M210 firmware system library contains useful functions for using the internal temperature sensor that can be called from the user application to control and configure the system hardware.

Table 2. Q32M210 INTERNAL TEMPERATURE FUNCTION DESCRIPTIONS

Function	Description
Sys_Analog_Set_TempSenseControl	Enable or disable the temperature sensor
Sys_Analog_Get_TempSenseControl	Get the current temperature sensor control setting

An example of the use of these functions is shown below:

```
// Store the previous temperature sensor
control value, so it can be
// restored later
 prevTempSenseControl =
 Sys_Analog_Get_TempSenseControl();
// Enable the internal temperature sensor
for use by the   system
Sys_Analog_Set_TempSenseControl(TEMP_SENSE_
ENABLE);
```

Sources of Error

The offset value of the internal temperature sensor has been measured and stored during production testing. Other sources of measurement error are:

- The stored value of the temperature sensor slope (m value) is an approximation resulting in approximately a +/- 2.8 C accuracy. This slope value should be replaced with a measured value for highest temperature accuracy as previously discussed
- The PGA gain coefficient is 0.008% /°C and will require individual calibration.
- The PGA is powered directly from Vbat. Noise and fluctuations of Vbat will affect overall accuracy.
- Vref temperature drift is 50 ppm/C. This corresponds to a 2.2 mV error or about 0.25% over the required 50 degree range of operation.

USING AN EXTERNAL THERMISTOR

While the internal temperature sensor is useful for very compact designs where thermistor location is not important, many applications will require the thermistor to be located a distance away from the Q32M210 microcontroller.

The Q32M210 microcontroller has provisions for multiple external sensors, including a 8:1 multiplexer for up to 8 separate temperature sensors connected to one opamp input.

The Q32M210 EDK board has an external thermistor network connected to the AUX_IN2 analog input, which can be used to measure the system temperature without the need for any additional components.

This design example makes use of the on-chip 0.9 V VREF precision voltage reference, and one auxiliary input (AUX_IN2) to measure the voltage across a thermistor in a voltage divider network.

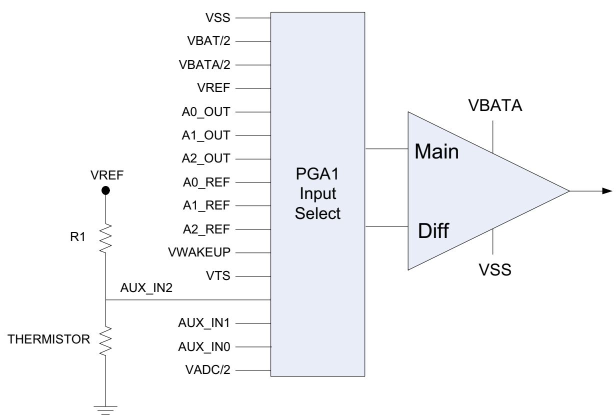

Figure 4. Q32M210 External Thermistor Signal Flow

External Thermistor Selection

There are a wide range of thermistors available with a typical 25°C rating from 1 kΩ up to 10 MΩ.

The thermistor used on the Q32M210 EDK is part number B57321V2103J60 from EPCOS AG. This thermistor has a +/- 5% resistance tolerance and a nominal impedance of 10 kΩ at 25°C as shown in Figure 5 below.

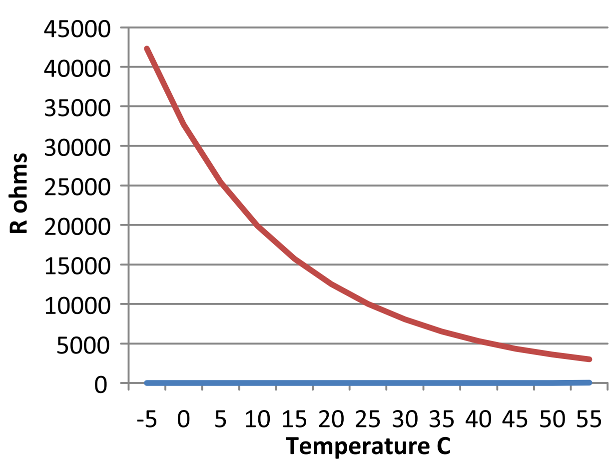

Figure 5. EPCOS B57321V2103J60 Thermistor R/T Curve

Measurement Errors with an External Thermistor

Unlike the internal temperature sensor of the Q32M210 microcontroller, use of an external thermistor results in errors due to manufacturing tolerance and a non linear R/T function.

A ±5% resistance tolerance of the thermistor will usually result in an unacceptable measurement error if uncalibrated R/T data is used. In addition, referring to Figure 5, a simple linear equation similar to y = mx + b cannot be used as the slope error increases exponentially away from the midpoint value.

Techniques for calibration and linearization of the external thermistor are given in the following sections.

Single Temperature Point Calibration of the External Thermistor

A single temperature point calibration will account for any part to part resistance variation of the external thermistor. It is still necessary to correct the error due to non linear slope variation.

Error using this method is minimized by using a mid-range temperature as the calibration point (i.e., 25°C).

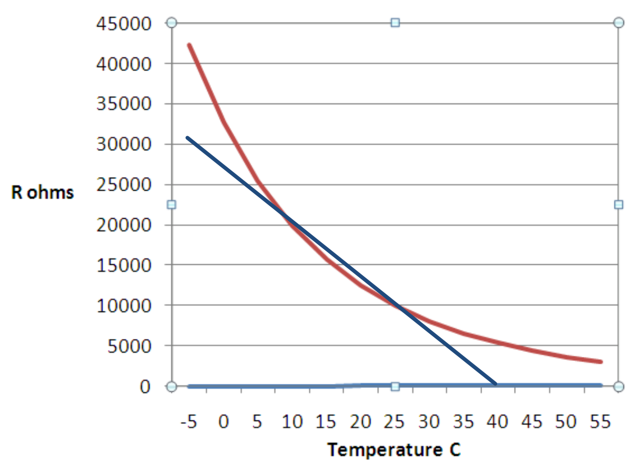

Figure 6. Error Due to Single Point Measurement

When a single temperature point calibration is used, the solution assumes a linear equation with a constant slope and a fixed resistance at a single temperature point as shown in Figure 6 above.

Linearization the Thermistor R/T Response

Once the thermistor's voltage value at 25°C has been calibrated, it is necessary to translate the raw data from the ADC to a meaningful temperature value.

The standard formula for NTC thermistor resistance as a function of temperature is given by:

$$R_T = R_{25C} e^{\left\{\beta\left[\left(\frac{1}{T+273}\right)-\left(\frac{1}{298}\right)\right]\right\}}$$

Thermistor Resistance vs Temperature Equation

Where:

R_T is the thermistor resistance at temperature, T.

R_{25C} and β are published in the manufacturer's data sheet.

For the EPCOS B57321V2103J60 thermistor, values are:

R_{25C} = 10 K

β = 4000.

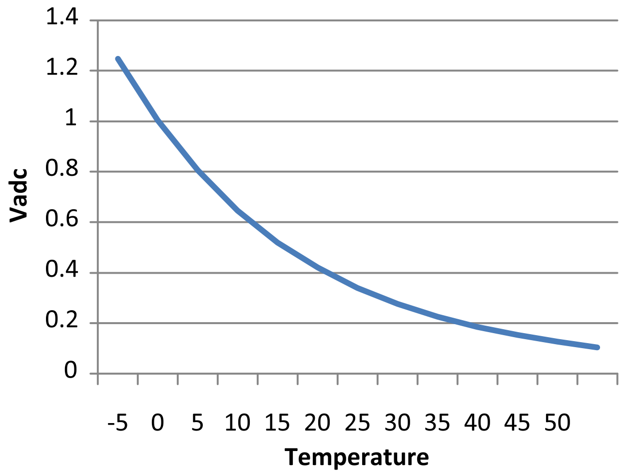

Figure 7. ADC1 Input vs Temperature for Ext Thermistor

Figure 7 above shows a non-linear response at the ADC input to the temperature as obtained from the EPCOS thermistor. As a result, the thermistor will require linearization in most applications, depending on the temperature range and accuracy required.

The non-linear response of the thermistor can be corrected using several different methods:

- linearization using an additional parallel resistor
- linearization in software using a third-order polynomial
- linearization in software by using a look-up table

Linearization Using an Additional Parallel Resistor

To use this technique, a single resistor is placed in parallel with the NTC thermistor as shown in Figure 8 below:

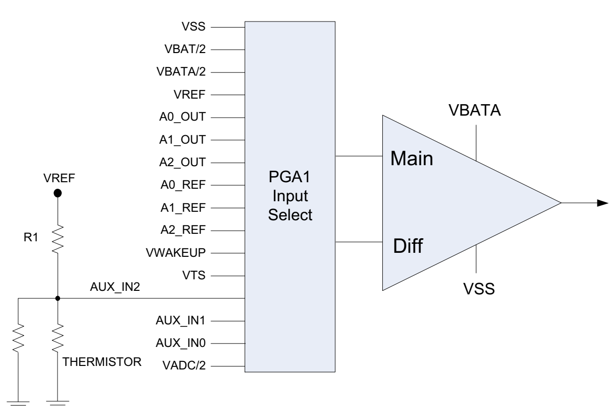

Figure 8. Parallel Resistor for R/T Linearization

The parallel addition of the resistor has the effect of improving the linearity the combined circuit's resistance.

If the resistor's value is chosen to be equal to the thermistor's resistance at room temperature (R_{25C}), then the region of relatively linear resistance will be symmetrical around 25 C, as shown in Figure 9 below.

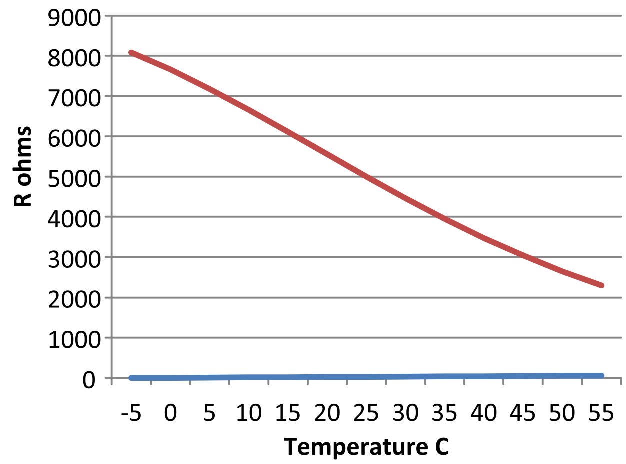

Figure 9. Linearized Temperature vs Resistance for B57321V2103J60 Thermistor

Linearization Using a Third−Order Polynomial

Steinhart and Hart developed a well known equation that is used to linearize the R/T function of a thermistor:

$$\frac{1}{T} = A + B[\ln(R)] + C[\ln(R)]^3$$

where T is temperature (in Kelvin); R is resistance (in Ω); and A, B, and C are curve−fitting coefficients that are determined by setting up three simultaneous linear equations using temperature and resistance values from three temperature points (T1, T2, T3).

For the temperature range in this application, the Steinhart-Hart equation will generate temperature values with a ±0.02°C accuracy. Once the curve-fitting coefficients are determined, this equation can be used to convert thermistor resistance values into equivalent temperature values.

Substituting the coefficients into the Steinhart-Hart equation results in:

$$\frac{1}{T} = A + B[\ln(R)] + C[\ln(R)]^3$$

where T is the temperature in Kelvin (K), R is the resistance in ohms (Ω), and T_C is the temperature in Celsius (°C).

To find the Steinhart-Hart coefficients from experimental data, a least-squares curve fitting technique is used called the Levenberg−Marquardt algorithm. Techniques for implementing this algorithm are beyond the scope of this application note.

Linearization Using a Look−up Table

The previous linearization technique showed that in order to calculate temperature you need to know the thermistor resistance as well as its Steinhart-Hart equation coefficients.

A disadvantage of the above technique is that the calculations needed are complex and consume ARM Cortex-M3 processor resources.

A lookup table conversion method is a preferred option for the Q32M210's embedded core.

A lookup table can be created to store the thermistor resistance values as a function of temperature. This eliminates the need to perform any calculation of temperature in real time.

To create the table, the thermistor resistance for a given temperature must be calculated only once prior to the table creation.

The PGA gain must also be included in the calculation so that there is a direct correlation between the ADC output and the thermistor resistance values. The final result is a table of ADC values and the corresponding temperature.

The PGA gain can be determined based on programmed settings, and the resistance-temperature function can be found by solving the Steinhart-Hart equation as previously discussed.

For most applications the temperature index is a constant step of one-half degrees Celsius, and will result in a table with length of 120 16-bit values.

External Temperature Sensor Signal Path

Please refer to ON Semiconductor Document number M-20693-002 *"Evaluation and Development Board Manual"* for detailed information on the Q32M210 EDK.

In Figure 10 below, the thermistor and series resistor R1 form a voltage divider with a voltage at AUX_IN2 that is dependent on temperature.

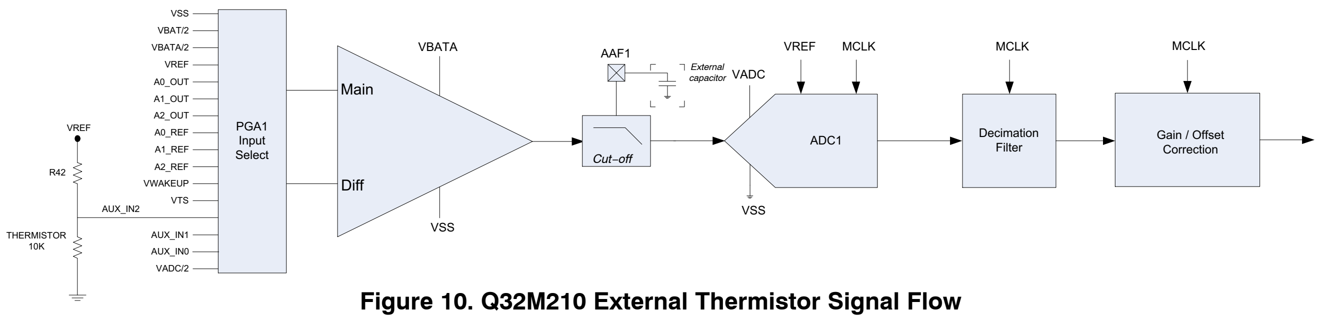

Figure 10. Q32M210 External Thermistor Signal Flow

As in the previous internal sensor example, the voltage generated by the thermistor resistor network is small in comparison to the dynamic range of the ADC. The PGA is used to introduce an 18 dB gain to the thermistor voltage resulting in an ADC input voltage shown below in Table 3.

Table 3. EPCOS TEMPERATURE VS RESISTANCE AND V_{ADC}

Temp	R_T/R_{25}	R_{therm}	V_{therm}	V_{ADC} (A=18dB)
-5	4.23	42300	0.157	1.247
0	3.27	32700	0.126	1.004
5	2.54	25400	0.101	0.805
10	1.99	19900	0.0814	0.646
15	1.57	15700	0.0655	0.520
20	1.25	12500	0.0529	0.420
25	1	10000	0.0428	0.340
30	0.805	8050	0.0348	0.276
35	0.653	6530	0.0284	0.225
40	0.532	5320	0.0233	0.185
45	0.437	4370	0.0192	0.152
50	0.36	3600	0.0159	0.126
55	0.298	2980	0.0132	0.105

Q32M210 Analog Block Configuration for External Temp Sensor Measurement

Configuration of the Q32M210 analog block for use with an external thermistor is identical to the configuration of the internal sensor described in **"Q32M210 Analog Block Configuration for Internal Temp Sensor Measurement"** with the following exception:

- Enable PGA1 and set input to AUX_IN2 using AFE_PGA1_CTRL register
- Set the gain and AAF cutoff frequency using the AFE_PGA_GAIN_CTRL register
- Set PGA1 mode to mode 0

Thermal Noise and Vreg Loading

There will be a trade off in performance between the power consumption of the thermistor network and the thermal noise associated with higher impedance thermistors.

The Vref reference is calibrated very precisely to ±0.2%, and is designed for minimal temperature dependency.

However, if it is loaded it by 100 μA, given a 2 Ω impedance, the Vref will drop to 0.8998v.

Increasing the value of the resistors connected to Vref will reduce this effect; as larger resistors are used to draw less current, the thermal noise at the input will increase.

One option for reducing average power drawn from Vref is to incorporate one of the Q32M210's on board SPST switches to act as an on/off switch for the thermistor network. This reduces the power consumption of the network to the leakage current of the SPST switch when actual measurements are not performed.

EXTERNAL THERMISTOR WITH TIA

An Improved Design

An improvement can be made in the previous design by using a transimpedance amplifier to directly convert current through the thermistor into a voltage that is input to the ADC. The advantages of this approach are a larger input signal to noise ratio, better accuracy and improved measurement dynamic range.

A transimpedance amplifier is a current to voltage converter, as shown in Figure 11 below:

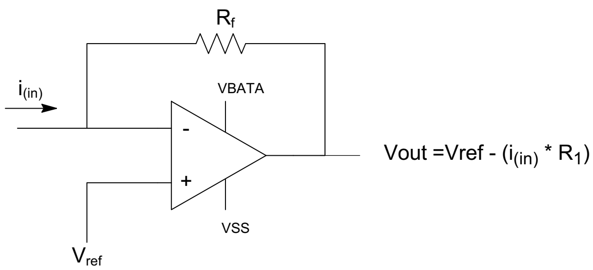

Figure 11. TransImpedance Amplifier

Three uncommitted low-noise opamps are available on the Q32M210 microcontroller. These opamps have a low GBW of approximately 30 kHz, making them a stable choice for slow varying input signals such as a thermistor R/T response.

The opamps are powered directly from the VBAT supply allowing for maximum input dynamic range of the thermistor signal. Each opamp has a dedicated input pin connected to the negative terminal v− and a dedicated input pin connected to the positive terminal v+ as shown in Figure 12 below.

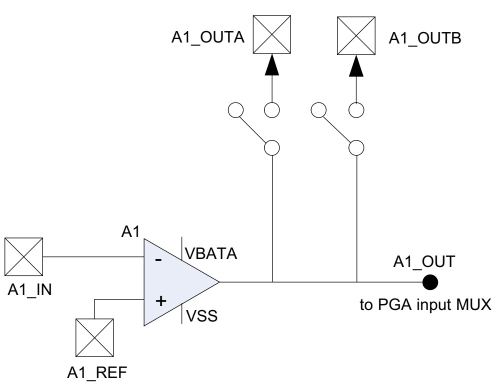

Figure 12. Q32M210 Opamp Configuration

The Q32M210 opamp A0 is connected to an 8 input multiplexer, which could be a useful component when multiple external thermistors are required to be measured in a system.

The Q32M210 opamp A1 is used for this example.

Because of the single sided power supply of the Q32M210 microcontroller, it is necessary to bias the positive input to opamp A1 with voltage equal to $V_{ref}/2$.

With a bias voltage of $V_{ref}/2$, the voltage drop across the thermistor will be:

$V_{ref}/2 = 0.45$ V

And the current through R_T :

$I_{RT} = -0.45\ V/R_T$

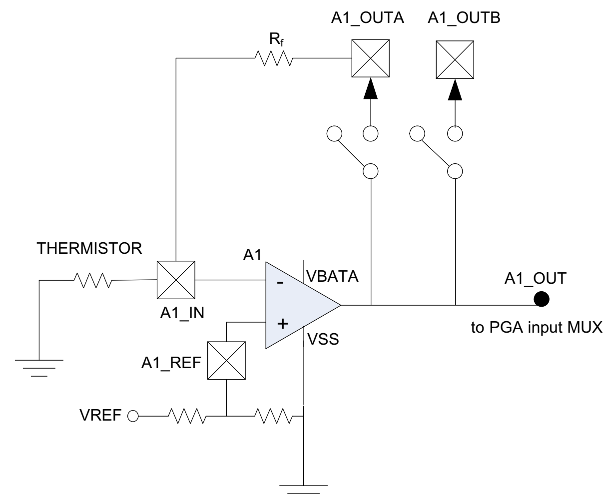

Figure 13. Q32M210 Opamp A1 in a TIA Configuration

The value of R_f can now be chosen based on the best possible range of values presented to ADC1. For a R_f value of 8.66 K, the following range of voltages are available to the input of the PGA:

Table 4. TIA VOLTAGE OUTPUT WITH Rf = 8.66 K

T	R_T	I_T	V_{out}
-5	42300	1.06E-05	0.542
0	32700	1.37E-05	0.569
5	25400	1.77E-05	0.603
10	19900	2.26E-05	0.645
15	15700	2.86E-05	0.698
20	12500	0.000036	0.761
25	10000	0.000045	0.839
30	8050	5.59E-05	0.934
35	6530	6.89E-05	1.046
40	5320	8.45E-05	1.18
45	4370	0.000102	1.34
50	3600	0.000125	1.53
55	2980	0.000151	1.75

Linearization of the TIA Thermistor Response

Once the thermistor circuit has been calibrated, it will be necessary to linearize the output the ADC using one of the methods previously described.

Temperature Measurement PCB Layout Considerations

When the Q32M210 microcontroller is used for temperature measurement with an external thermistor, care must be taken to keep the thermistor element away from digital components that can introduce noise into the thermistor output.

The PCB which contains the Q32M210 microcontroller should be designed with the analog and digital sections referenced to separate ground planes. The thermistor should be referenced to the analog ground, and digital and analog ground planes should be star connected in one place.

Avoid running digital lines under the thermistor as these traces can couple noise into the analog sections of the device.

The power supply lines to the Q32M210 microcontroller should use as large a trace as possible to provide low impedance paths and reduce the effects of noise on the power supply line.

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