Dual Channel RTD/TC Measurement System Using the MAX11410

MAXREFDES1155

Introduction

MAXREFDES1155 is a configurable two-channel resistance temperature detector (RTD)/thermocouple (TC) measurement system. Each channel can be configured for either RTD or TC input. The RTD can be either a PT100 or a PT1000 connected in a 2-wire, 3-wire, or 4-wire configuration. The MAXREFDES1155 can support all types of thermocouples, using either an on-board temperature sensor or an RTD for cold-junction compensation.

Features include the following:

- Highly accurate measurement
- Two channels
- Each channel can be configured for either RTD or TC input
- Supports 2-wire, 3-wire, and 4-wire RTD
- Supports all types of thermocouple
- Thermocouple with on-board temperature sensor for cold junction compensation
- Board-level calibration
- PMOD interface

Hardware Specification

The MAXREFDES1155 includes the following major components: analog-to-digital converter (ADC), temperature sensor, and a 1.25V voltage reference. The board is powered by an external 3.3V source. A high-precision 24-bit ADC converts the analog input to digital representation, which is then read by an external microcontroller through a serial peripheral interface (SPI). The temperature sensor is used for cold-junction compensation, and the voltage reference is used as the ADC reference during TC measurement.

Table 1. Design Specification

PARAMETER	SYMBOL	TYP
Power supply	V_{CC}	3.3V
Supply current (standby)	I_{CC}	0.448mA

Designed–Built–Tested

This document describes the hardware shown in Figure 1 as well as the firmware. This reference design has been built and tested.

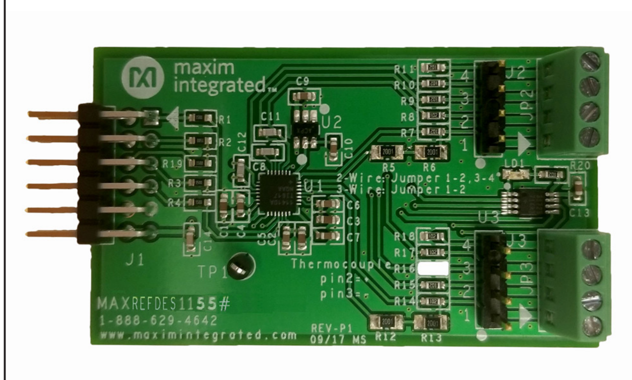

Figure 1: MAXREFDES1155 hardware.

MAX11410 Introduction

The MAX11410 is a low-power, highly integrated, multi-channel, 24-bit delta-sigma ADC. Ten analog inputs can be used for single-ended/fully differential connections in any combination. Two integrated matched current sources with 16 programmable current levels provide excitation for resistive sensors. The current source can switch to any of the analog input pins. An additional current sink and current source aids in detecting broken sensor wires. The integrated bias voltage source can be switched to one or more than one analog input. This bias voltage source is used to provide bias voltage for thermocouple measurements.

The input section between the analog input and the sigma-delta modulator input can be configured as bypass mode, buffered mode, or PGA mode. PGA can be set in steps from 1 to 128. The 24-bit delta-sigma ADC can achieve 90dB simultaneous 60Hz and 50Hz power line rejection, 3ppm INL with no missing codes. The reference source can be selected between multiple reference input pins and an analog power supply. All these features make the MAX11410 suitable for RTD/TC sensor measurement.

RTD Measurement

The following abbreviations are used throughout this section:

- i1–i2 = Current source
- R_{REF} = Reference resistor
- R_S = RTD Wire resistance
- RTD = Resistance value need to be measured
- R1–R4 = Protection resistor
- UR1–UR2 = ADC input voltage through R1 and R2

RTD is commonly used in industrial and medical applications, as it can achieve high accuracy and repeatability over a temperature range of -200°C to +800°C. The most commonly used RTDs are PT100 and PT1000, which exhibit resistance values of 100Ω and 1000Ω, respectively, at 0°C.

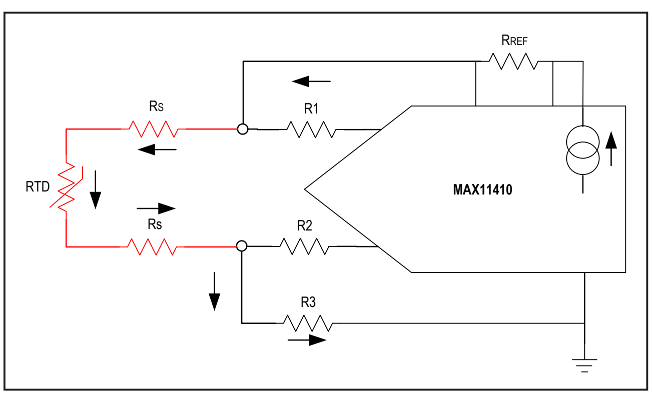

Figure 2. 2-Wire RTD measurement connection.

The most economical solution is a 2-wire connection, which is used only when the parasitic resistance is known, when the distance is short, or when high accuracy is not required. A 2-wire connection measurement circuit is illustrated in Figure 2.

In a 2-wire RTD connection, one analog port acts as the current source output. The resistors in red represent the 2-wire RTD model. As illustrated by the arrows in Figure 2, current flows through R_{REF}, the RTD wire resistance (R_S), the actual RTD resistance (RTD), followed by another R_S, and then R3. The voltage drop across R_{REF} serves as the MAX11410 reference input. As the MAX11410 ADC input is high impedance, the current flowing into R1 and R2 can be considered negligible. Therefore, the measured voltage of the ADC is as follows:

$$V_{IN} = I \text{ x } (R_S + RTD + R_S)$$

The reference voltage of ADC in this case is as follows:

$$V_{REF} = I \text{ x } R_{REF}$$

Using the two equations above, the ratio of V_{IN} to V_{REF} can be expressed as follows:

$$\frac{V_{IN}}{V_{REF}} = \frac{i \times (R_S + RTD + R_S)}{i \times R_{REF}} = \frac{(R_S + RTD + R_S)}{R_{REF}}$$

Alternatively,

$$\frac{V_{IN}}{V_{REF}} = \frac{(\text{ADC output code of } V_{IN})}{(\text{ADC output code of } V_{REF})}$$

Therefore,

$$\frac{(\text{ADC output code of } V_{IN})}{(\text{ADC output code of } V_{REF})} = \frac{(R_S + RTD + R_S)}{R_{REF}}$$

Note how the expression is independent of the current source in the expression above.

The ADC output code for V_{REF} is 224 for unipolar conversion and 223 for bipolar conversion. Because R_{REF} is selected by the designer, and the ADC output of V_{IN} would be known by reading the ADC output, the expression above can be used to calculate the (R_S + RTD + R_S) term, which is the RTD resistance for the 2-wire connection. The corresponding temperature value can then be calculated through formula or look-up table.

It is important to observe that any deviation of the R_{REF} value from the chosen value directly affects the accuracy of the RTD resistance calculation. Therefore, a low-drift resistor with accuracy of 0.1% or better is recommended. In addition, note that the RTD value calculated also includes the wire resistance. As such, a 2-wire connection is only used in short-distance temperature measurements or in cases where high accuracy is not required, so that the wire resistance can be neglected.

A 4-wire connection, which uses a Kelvin connection, is ideal for long-distance applications or those that require high accuracy. Each RTD element has two nodes, and in a 4-wire connection, two wires are connected to each RTD node. One wire from each node is connected to an ADC input. Because an ADC input exhibits high impedance, current passes through the other wire, as shown in Figure 3. As such, the impact of the wire resistance is removed, allowing a 4-wire connection to achieve highly accurate measurement. However, because of the cost of the wire, 4-wire connections are the most expensive of all the RTD connection options.

A 3-wire connection is an option that achieves highly accurate measurement with lower cost. While this type of connection removes the wire resistance in the RTD calculation, it also has one less wire compared to 4-wire connections. Therefore, 3-wire connections are the most commonly used connections in industrial applications for long-distance measurement. A 3-wire connection measurement circuit is shown in Figure 4.

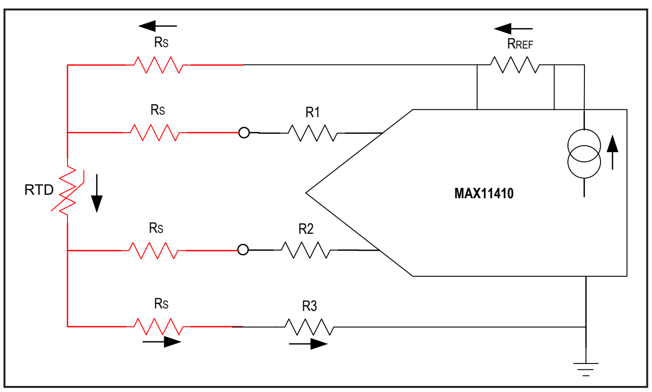

Figure 3. 4-Wire RTD measurement connection.

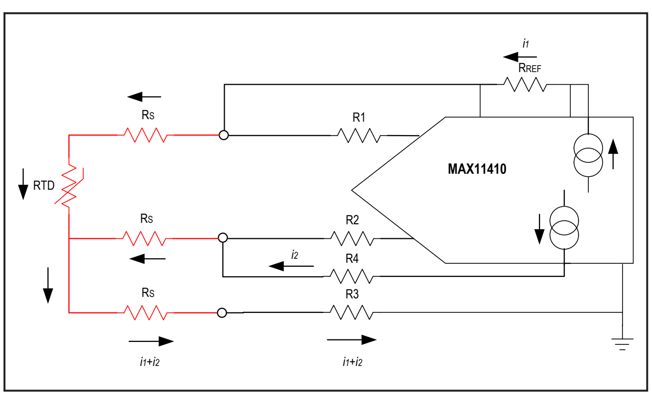

Figure 4. 3-Wire RTD measurement connection.

For 3-wire RTD connections, two analog ports act as current source outputs. The two current sources i1 and i2 are matched current sources, thus i1 = i2. R_S is the RTD wire resistance. The resistors in red represent the 3-wire RTD resistor model. The voltage across R_{REF} serves as the ADC reference.

The current source i1 flows through the reference resistor R_{REF}, R_S, RTD, R_S, and R3. The current source i2 flows through the external protection resistor R4, R_S, a second R_S, and R3. Because ADC has high input impedance, there is no current through R1 and R2, and thus no voltage drop across the resistors. Consequently, the voltage across the two nodes where R_{REF}, R1, and R_S meet and where R2, R4, and R_S meet can be directly measured at the ADC with no voltage loss.

The R1 input voltage is as follows:

$$UR1 = R_S \times i1 + RTD \times i1 + (R_S + R3) \times (i1 + i2)$$

The R2 input voltage is as follows:

$$UR2 = R_S \times i2 + (R_S + R3) \times (i1 + i2)$$

The ADC input voltage is the differential voltage between UR1 and UR2, where

$$UR1 - UR2 = R_S \times i1 + RTD \times i1 - R_S \times i2$$

Because the two current sources are matched, i1 = i2. The equation can thus be simplified as follows:

$$UR1 - UR2 = RTD \times i1$$

Note that the wire resistance is completely removed in the expression above.

Referring to the flow of current in Figure 4, the ADC reference voltage is as follows:

$$V_{REF} = i1 \times R_{REF}$$

Using the expressions for UR1 - UR2 and V_{REF}, and letting $\frac{Ur1 - Ur2}{V_{REF}} = n$, where n <= 1 if the selected R_{REF} is

the same or larger than maximum RTD value,

$$RTD = n \times R_{REF}$$

Because the value of R_{REF} is already known, n is the ratio of the ADC code of Ur1 - UR2 and full-scale voltage V_{REF}, the RTD resistor value can be calculated. The temperature for the corresponding RTD value can then be calculated using a formula or look-up table. The expression for RTD is derived under the assumption that the two current sources are matched. As such, the matching of the current sources is much more important than the absolute accuracy of the current source.

With the effect of wire resistance removed, a 3-wire connection can provide highly accurate RTD measurement.

Thermocouple Measurement

Thermocouples are also commonly used in many temperature measurement applications. Thermocouples offer a cost-effective solution for measuring a much wider range of temperatures than RTDs, and they feature ruggedness and fast response time.

A thermocouple (see Figure 5) is constructed with two wires made from dissimilar metals. One wire is predesignated as the positive side and the other as the negative side. There are many thermocouple types, including K-type, T-type, and so on. Each thermocouple type offers a unique thermoelectric characteristic over its specified temperature range.

If the measuring (hot) junction temperature is different from the reference (cold) junction temperature, a potential difference (V_{OUT}) forms across the two junctions. This voltage is a function of the difference between hot and cold junction temperatures.

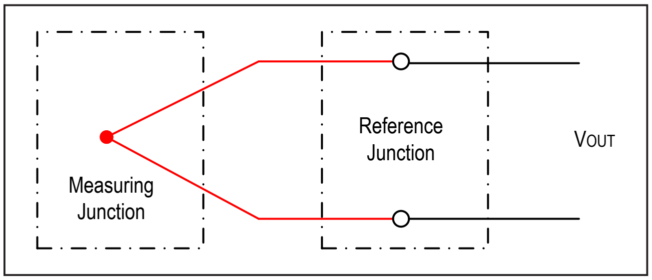

Figure 5. Basic thermocouple.

If the cold junction temperature is 0°C, the voltage measured is a direct translation of the actual hot junction temperature. Otherwise, we would need to know the cold junction temperature in addition to V_{OUT} to calculate the hot junction temperature. This is known as cold-junction compensation. Cold junction temperature can be measured using different kinds of temperature sensors. For accurate cold junction temperature measurement, RTD is the best choice, as it provides high accuracy and fast response time. Because this reference design supports both RTD and thermocouple measurements, however, it doesn't have any more channels for RTD as cold junction temperature. The reference design instead uses an alternative method: placing a temperature sensor on the board close to the reference junction of the thermocouple and using the silicon temperature on board as cold junction compensation.

The cold junction temperature measured by the RTD or on-board temperature sensor is converted to a corresponding thermocouple output voltage before being added to the thermocouple output voltage. The sum of the two voltages is the voltage generated by hot junction temperature with reference to 0°C. The corresponding temperature can be obtained by formula or look-up table.

Figure 6 illustrates the thermocouple measurement connection using an external voltage reference as the reference of the ADC. Bias voltage is applied to one end of the ADC input.

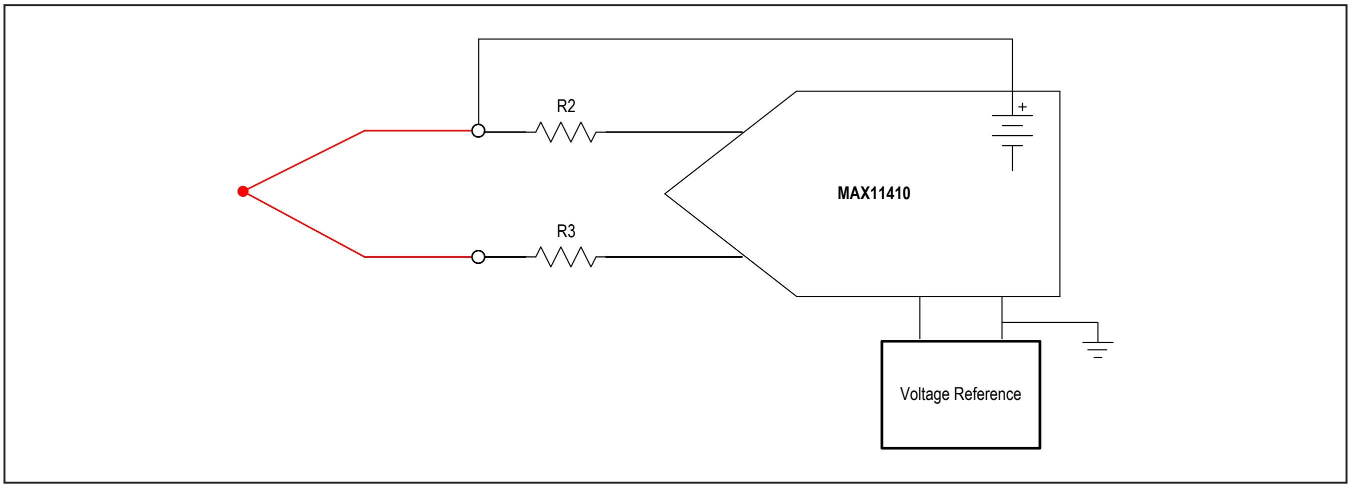

Figure 6. Thermocouple measurement connection.

Design Procedure for MAXREFDES1155

This section describes the component-selection and configuration process of the analog front end and explains the temperature-sensor selection process.

While not implemented, sensor open detection and a common-mode filter can be added to improve overall system robustness. The integrated burnout current source in the MAX11410 can be connected to the positive analog input and the current sink can be connected to the negative analog input. So, in the case of an open circuit in the sensor input path, the burnout current source and sink would pull the positive input toward AVDD and the negative input toward AGND, respectively. This would result in a full-scale reading, which means that there is an open-circuit at the sensor input.

Table 2 gives a summary of the configuration selected in step 2 through step 4 for each input type.

Step 1: Reference Resistor Selection

The reference resistor and the excitation current in combination serve as the ADC reference while performing RTD measurements. Because the maximum RTD value is slightly less than 400Ω for PT100 and 4kΩ for PT1000, to be able to support both, 4kΩ is used as the reference resistor. Reference resistors larger than 4kΩ reduce the excitation current required, which can reduce self-heating in the RTD element. However, they also reduce the signal magnitude, which reduces the overall signal-to-noise ratio of the system.

The reference resistor is placed at the high side, which reduces susceptibility to interference through the RTD inputs.

Step 2: Excitation Current and Bias Voltage Selection

The excitation current must be adjusted so that the voltage reference requirements of the ADC are met while also not causing significant self-heating to the RTD element, which would introduce additional errors to the measurement. According to the MAX11410 data sheet, the reference voltage input must be from 0.75V to AVDD, with a typical value of 2.5V. This condition sets the lower bound of the current source.

For IDAC <= 250µA, the current source output voltage compliance must be from 0V to AVDD - 0.7V. For IDAC = 1.6mA, the current source output voltage compliance must be from 0 to AVDD - 1.2V. For AVDD = 3.3V, the maximum current output voltage compliance is 2.6V when IDAC <= 250µA and 2.1V when IDAC = 1.6mA. This condition sets the upper bound of the current source. When selecting the excitation current, leaving some headroom for the current source output voltage implies that longer wires can be used, because inevitably, there is some voltage loss along the wire.

To calculate the current source output voltage, refer to Figure 2, Figure 3, and Figure 4 for visualizing the current flow through the reference resistor, RTD, and the current-limiting resistor for 2-wire, 4-wire, and 3-wire configurations. RS is ignored in the expressions below.

For 2-wire and 4-wire PT100 configurations, a minimum of 200µA is required to meet the voltage reference requirement. Current source is selected as 300µA. Because only one current source is used in 2-wire and 4-wire connections, the current source output voltage is as follows:

$$(R_{REF} + R_{\overline{RTD}} + R) \times 300\mu A = (4K + 400 + 1K) \times 300\mu A = 1.62V$$

The reference voltage is $R_{REF} \times 300\mu A = 1.2V$.

For 3-wire PT100 configurations, a minimum of 200µA is required to meet the voltage reference requirement. Current is selected as 300µA. In this case, the output current source compliance voltage is as follows:

$$(Rref + R_{\overline{RTD}}) \times 300\mu A + (R) \times 300\mu A \times 2 = 1.92V$$

where R is 1KΩ current-limiting resistor. The reference voltage is $R_{REF} \times 300\mu A = 1.2V$.

For 2-wire and 4-wire PT1000 configurations, a minimum of 200µA is required to meet the voltage reference requirement. The current source is selected as 200µA to leave sufficient headroom for current source output voltage. Because only one current source is used in 2-wire and 4-wire connections, the current source output voltage is (4K + 4K + 1K) x 200µA = 1.8V. The reference voltage is $R_{REF} \times 200\mu A = 0.8V$.

For 3-wire PT1000 configurations, a minimum of 200µA is required to meet the voltage reference requirement. The current source is selected as 200µA to leave sufficient headroom for current source output voltage. The output current voltage is (4K + 4K) x 200µA + (1K) x 200µA x 2 = 2V. The reference voltage is $R_{REF} \times 200\mu A = 0.8V$.

The bias output voltage is applied to one of the thermocouples. For the MAX11410, the bias output voltage is AVDD/2.

Table 2. Input Type vs. Current Source/Bias Voltage vs. PGA

INPUT TYPE	CURRENT/BIAS VOLTAGE	PGA	NOTE
Thermocouple	Bias Voltage	8	Current source disabled
3-wire PT100	300µA	8	Two current sources
2-wire/4-wire PT100	300µA	4	One current sources
3-wire PT1000	200µA	1	Two current sources
2-wire/4-wire PT1000	200µA	1	One current sources

Step 3: PGA Gain Selection

The value of PGA gain is selected to maximize the utilization of the ADC range while not exceeding the full-scale voltage and violating the common-mode input voltage requirement.

According to the MAX11410 data sheet, the common mode input voltage of the MAX11410 for gains of 1 to 16 is as follows:

$$100\text{mV} + \frac{V_{IN} \times GAIN}{2} \leq VCM \leq AVDD - 100\text{mV} - \frac{V_{IN} \text{ x } GAIN}{2}$$

For RTD input, because the same current flows through both the reference resistor and the actual RTD element, the ratio of the resistor sets the maximum gain possible. This gain is further limited by the common mode input voltage requirement. In the MAX11410, gain comes in powers of 2.

For PT100 configurations, because R_{REF} is 4kΩ and PT100 is 400Ω at 850ºC, the maximum possible PGA gain is 8 if the common mode requirement is not taken into account.

Taking the requirement into account, for 2-wire and 4-wire PT100 applications, the maximum V_{IN} = 300µA x 400Ω = 0.12V. In this case:

$$VCM = (300\mu A \times \text{current limiting resistor}) + \frac{0.12}{2} = 0.36V$$

To be able to stay within the bound of V_{CM}, the largest possible gain is 4.

For 3-wire PT100 applications, while V_{IN} remains as 0.12V, V_{CM} is calculated as follows:

$$VCM = (2 \times 300\mu A \times \text{current limiting resistor}) + \frac{0.12}{2} = 0.66V$$

PGA gain can be set to 8 without violating the common-mode input voltage requirement.

For 3-wire, 2-wire, and 4-wire PT1000 applications, because PT100 is 4000Ω at 850ºC, the PGA gain cannot be set larger than 1.

For thermocouples, considering that the reference voltage on board is 1.25V, the PGA gain is set to 8 to support all types of thermocouple while maximizing the utilization of the ADC output range. E type has the highest thermoelectric voltage. When the board is placed at the minimum operating temperature of -40ºC, the thermoelectric voltage is approximately 78mV. With a gain of 8, the maximum measured voltage is approximately 8 x 78mV = 0.624V. With a bias voltage of AVDD/2, or 1.65V, the common mode voltage boundary is satisfied. A gain of 16 is possible but would be too close to the nominal reference voltage.

Step 4: Temperature Sensor Selection

When the on-board temperature sensor is used for cold-junction compensation, its accuracy directly affects the accuracy of the thermocouple measurement and, thus, should be selected according to the requirements of the system. The temperature sensor should be placed as close as possible to the cold junction of the thermocouple to minimize error.

To reduce the number of necessary hardware connections and peripherals, a sensor with an SPI is selected. Only one extra slave select pin is required, and the clock and the data lines (MISO and MOSI) can be shared. On the microcontroller side, only one SPI master is necessary, leaving the rest of the peripherals for other purposes in the system.

Detailed Description of Hardware

This section describes the components of the MAXREFDES1155. Figure 7 is a block diagram of the system. The microcontroller is not included in the reference design board and is interfaced externally.

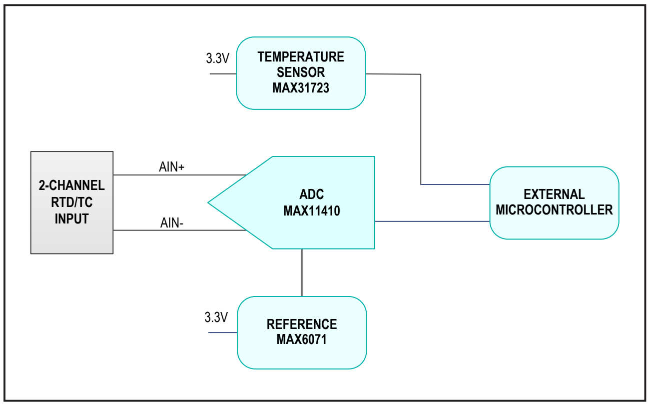

Figure 7. MAXREFDES1155 block diagram

Power Supplies

A stable 3.3V power supply must be provided externally to pin. It can be supplied by an external power supply or the output from the MAX32510 EV Kit.

Jumper Selection

Table 3 outlines the jumper configuration required to set each channel up for the desired configurations.

MAX32510 EV Kit

The MAX32510 is used as the microcontroller to configure the reference design, sample data, perform calculations to convert the ADC measurement to corresponding temperature, and communicate with the PC through UART. Table 4 lists the connections required for the EV Kit to communicate with the MAX11410 and MAX31723 on the board and supply power to the reference design. To interface with a different microcontroller, connect the SPI pins of the microcontroller to J1. Two chip select pins are required to control the MAX31723 and MAX11410 independently.

Table 3. Jumper Configuration

HEADER	SHUNT POSITION	DESCRIPTION
J2	1-2, 3-4	Setup channel 1 for 2-wire RTD configuration
	1-2	Setup channel 1 for 3-wire RTD configuration
	Open	Setup channel 1 for 4-wire RTD configuration or thermocouple
J3	1-2, 3-4	Setup channel 2 for 2-wire RTD configuratio$_n$
	1-2	Setup channel 2 for 3-wire RTD configuration
	Open	Setup channel 2 for 4-wire RTD configuration or thermocouple

Table 4. Hardware Connection Between MAX32510 EV Kit and MAXREFDES1155

MAXREFDES1155 CONNECTION (J1)	MAX32510EVKIT CONNECTION
1	P0.19
2	P0.17
3	P0.16
4	P0.18
5	Gnd Pin
6	TP3 (3V3)
9	P0.21
7, 8, 10, 11, 12	Unconnected

Detailed Description of Firmware

The MAXREFDES1155 uses the MAX32510 EV Kit as the microcontroller to communicate with the ADC and temperature sensor. The user reads the sampled data through a terminal program, allowing analysis on any third-party software. The simple process flow is shown in Figure 8. The firmware is developed in C using Keil®.

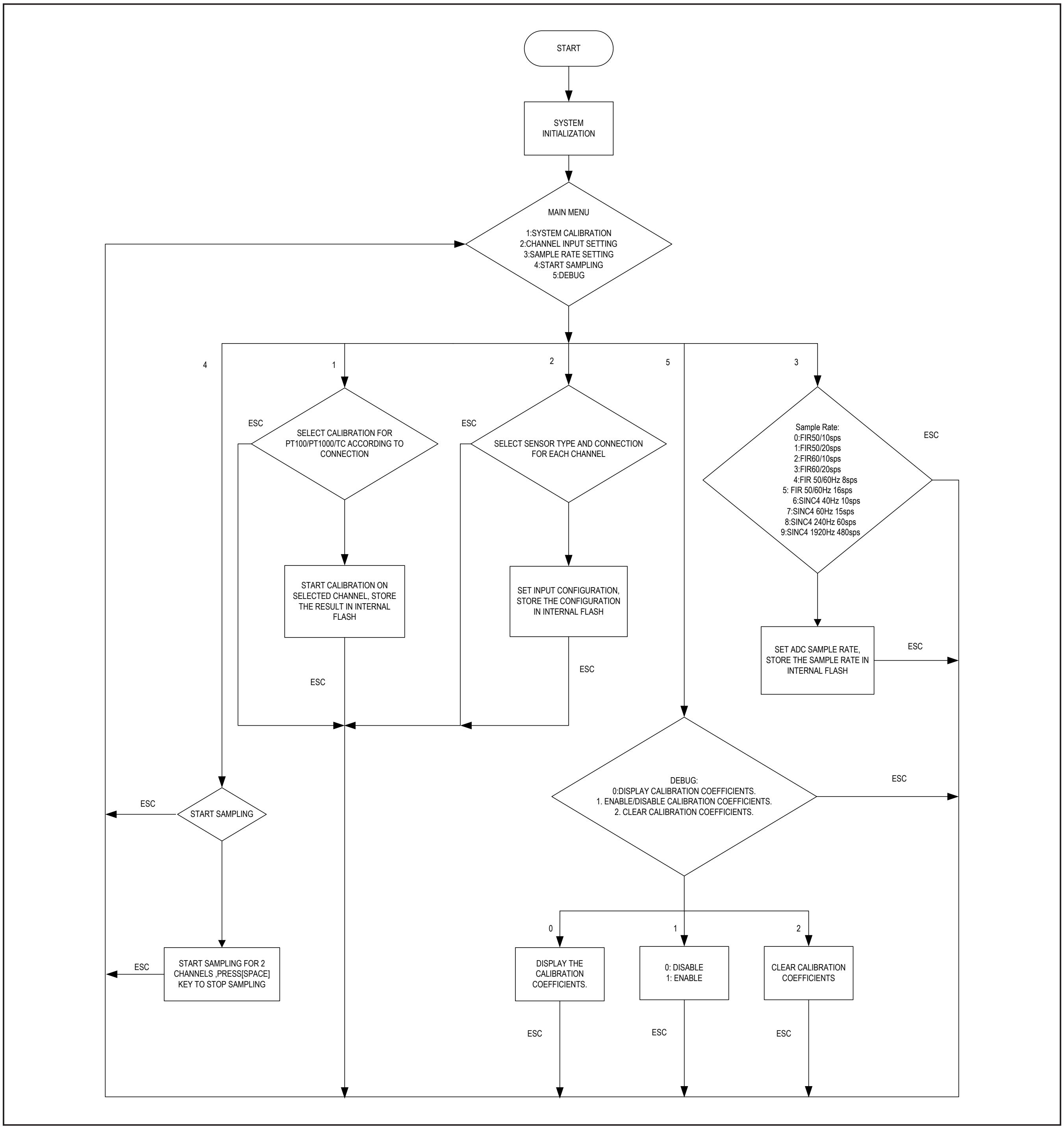

Figure 8. MAXREFDES1155 firmware flowchart.

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The firmware can perform system calibration, channel setting, sample rate setting, sampling, and accept debug commands. Calibration coefficients can be temporarily disabled to observe the contrast between using and not using the system calibration coefficients. Communication with the PC is achieved through a standard terminal program using a virtual COM port.

The provided firmware reports the thermocouple temperature for K-type thermocouples. To support other types of thermocouples, the component of the code that translates from the thermocouple voltage to temperature must be modified.

While the provided firmware only performs cold-junction compensation using on-board temperature sensor, an alternative option is to perform cold-junction compensation using RTD.

Complete source code is provided to speed up customer's system design development. Code documentation can be found in the corresponding firmware platform files.

Design Resources

Download the complete set of **Design Resources** including the schematics, bill of materials, PCB layout, and test files.

Revision History

REVISION NUMBER	REVISION DATE	DESCRIPTION	PAGES CHANGED
0	5/18	Initial release	—