ANALOG DEVICES

Circuits from the Lab™ Reference Circuits

Circuits from the Lab™ reference circuits are engineered and tested for quick and easy system integration to help solve today's analog, mixed-signal, and RF design challenges. For more information and/or support, visit www.analog.com/CN0214.

Devices Connected/Referenced	
ADuC7060/ ADuC7061	ARM7 Based Microcontroller with Dual 24-Bit Σ-Δ ADCs
ADP3333	2.5 V Low Dropout Linear Regulator
ADP7102-2.5	50 mA, High Voltage, Micropower Linear Regulator
OP193	Precision, Low Power Op Amp

USB-Based Thermocouple Temperature Measurement System Using ARM7

EVALUATION AND DESIGN SUPPORT
Circuit Evaluation Boards
   ADuC7061 Mini Kit (EVAL-ADUC7061MKZ)
Design and Integration Files
   Schematics, Layout Files, Bill of Materials

CIRCUIT FUNCTION AND BENEFITS

This circuit uses the ADuC7060/ADuC7061 precision analog microcontroller in an accurate thermocouple temperature monitoring application. The ADuC7060/ADuC7061 integrates dual 24-bit sigma-delta (Σ-Δ) analog-to-digital converters (ADCs), dual programmable current sources, a 14-bit digital-to-analog

converter (DAC), and a 1.2 V internal reference, as well as an ARM7 core, 32 kB flash, 4 kB SRAM, and various digital peripherals such as UART, timers, SPI, and I²C interfaces.

In the circuit, the ADuC7060/ADuC7061 are connected to a thermocouple and a 100 Ω platinum resistance temperature detector (RTD). The RTD is used for cold junction compensation.

In the source code, an ADC sampling rate of 4 Hz is chosen. When the ADC input programmable gain amplifier (PGA) is configured for a gain of 32, the noise-free code resolution of the ADuC7060/ADuC7061 is greater than 18 bits.

Figure 1. ADuC7060/ADuC7061 as a Temperature Monitor Controller with a Thermocouple Interface (Simplified Schematic, All Connections Not Shown)

Rev. D

CIRCUIT DESCRIPTION

The following features of the ADuC7060/ADuC7061 are used in this application:

- Primary 24-bit Σ-Δ ADC with PGA. The PGA is set for a gain of 32 in the software for this application. The primary ADC was continuously switched between sampling the thermocouple and the RTD voltages.
- Programmable excitation current sources for forcing a controlled current through the RTD. The dual current sources are configurable in 200 μA steps from 0 μA to 2 mA. For this example, a 200 μA setting was used to minimize the error introduced by the RTD self-heating.
- Internal 1.2 V reference for the ADC in the ADuC7060/ADuC7061. For measuring the thermocouple voltage, the internal voltage reference was used due to its precision.
- External voltage reference for the ADC in the ADuC7060/ADuC7061. For measuring the RTD resistance, a ratiometric setup was used where an external reference resistor (R_{REF}) was connected across the external VREF+ AND VREF– pins.
- A 14-bit DAC. The DAC was used to set the thermocouple common-mode voltage to 850 mV above ground.
- An ARM7TDMI® core. The powerful 16-/32-bit ARM7 core with integrated 32 kB flash and SRAM memory runs the user code that configures and controls the ADC, processes the ADC conversions from the RTD, and controls the communications over the UART/USB interface.
- A UART. The UART was used as the communication interface to the host PC.
- Two external switches are used to force the part into flash boot mode. By holding S1 low and toggling S2, the ADuC7060/ADuC7061 enters boot mode instead of normal user mode. In boot mode, the internal flash can be reprogrammed through the UART interface.

Both the thermocouple and the RTD generate small signals; therefore, a PGA is required to amplify those signals. As the auxiliary ADC on the ADuC7060/ADuC7061 does not have a PGA, both were connected to the primary ADC and switching between the two was done in software.

The thermocouple used in this application is a Type T (copper-constantan) that has a temperature range of −200°C to +350°C. Its sensitivity is approximately 40 μV/°C, which means that the ADC in bipolar mode, with a PGA gain of 32, can cover the entire temperature range of the thermocouple.

The RTD was used for cold junction compensation. The one used in this circuit was a platinum 100 Ω RTD, Enercorp PCS 1.1503.1. It is available in a 0805 surface-mount package. This RTD has a temperature variation of 0.385 Ω/°C.

Note that the reference resistor, R_{REF}, must be a precision 5.62 kΩ (±0.1%) resistor.

The USB interface to the ADuC7060/ADuC7061 is implemented with an FT232R UART-to-USB transceiver that converts USB signals to the UART directly.

In addition to the decoupling shown in Figure 1, the USB cable must have a ferrite bead for added electromagnetic interference (EMI)/radio frequency interference (RFI) protection. The ferrite bead used in this circuit was the Taiyo Yuden, #BK2125HS102-T, which has an impedance of 1000 Ω at 100 MHz.

The circuit must be constructed on a multilayer printed circuit board (PCB) with a large area ground plane. Proper layout, grounding, and decoupling techniques must be used to achieve optimum performance (see Tutorial MT-031, *Grounding Data Converters and Solving the Mystery of "AGND" and "DGND,"* Tutorial MT-101, *Decoupling Techniques*, the ADuC7060 Evaluation Board layout and ADuC7061 Evaluation Board layout).

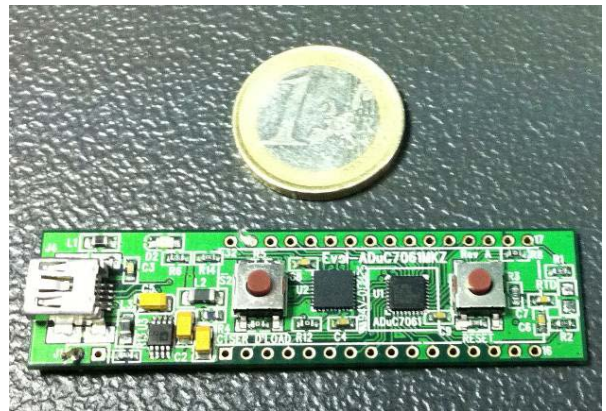The EVAL-ADuC7061MKZ PCB is shown in Figure 2.

Figure 2. EVAL-ADuC7061MKZ Board Used for this Circuit.

Code Description

The source code used to test the circuit can be downloaded as a zip file from www.analog.com/CN0214-SourceCode.

The UART is configured for a baud rate of 9600, eight data bits, no parity, and no flow control. If the circuit is connected directly to a PC, a communication port viewing application such as the Hilgraeve HyperTerminal can be used to view the results sent by the program to the UART, as shown in Figure 3.
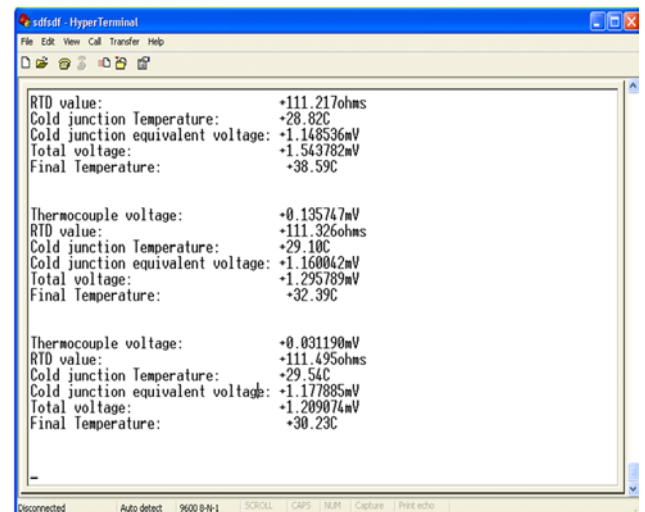

Figure 3. Output of HyperTerminal Communication Port Viewing Application

To get a temperature reading, the temperature of the thermocouple and RTD must be measured. The RTD temperature is converted to its equivalent thermocouple voltage via the lookup table provided in the source code. These two voltages are added together to give the absolute value at the thermocouple.

First, measure the voltage between the two wires of the thermocouple (V1). The RTD voltage is then measured and converted to a temperature via the lookup table. This temperature is then converted to its equivalent thermocouple voltage (V2). V1 and V2 are then added to give the overall thermocouple voltage, and this value is then converted to the final temperature measurement.

Initially, this was done using a simple linear assumption that the voltage on the thermocouple was 40 µV/°C. It can be seen from Figure 4 that this gives an acceptable error only for a small range around 0°C.
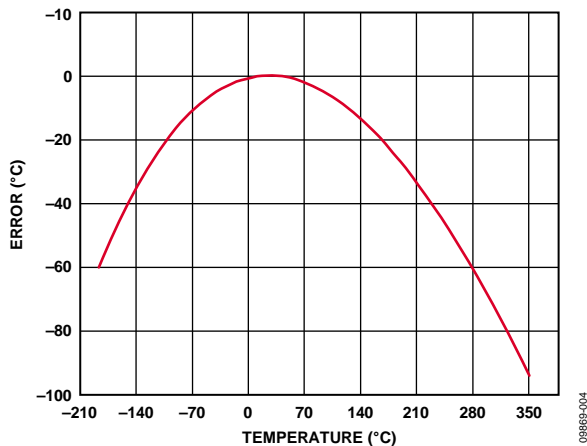
Figure 4. Error When Using Simple Linear Approximation

A better way of calculating the thermocouple temperatures is to use a sixth-order polynomial for the positive temperatures and a seventh-order polynomial for the negative temperatures. This requires mathematical operations that add to computational time and code size. A suitable compromise is to calculate the respective temperatures for a fixed number of voltages. These temperatures are stored in an array, and values in between are calculated using a linear interpolation between the adjacent points. It can be seen from Figure 5 that the error is drastically reduced using this method. Figure 5 gives the algorithm error using ideal thermocouple voltages. Figure 6 shows the error obtained when using ADC0 on the ADuC7060 to measure 52 thermocouple voltages over the full thermocouple operating range. The overall worst-case error is <1°C.
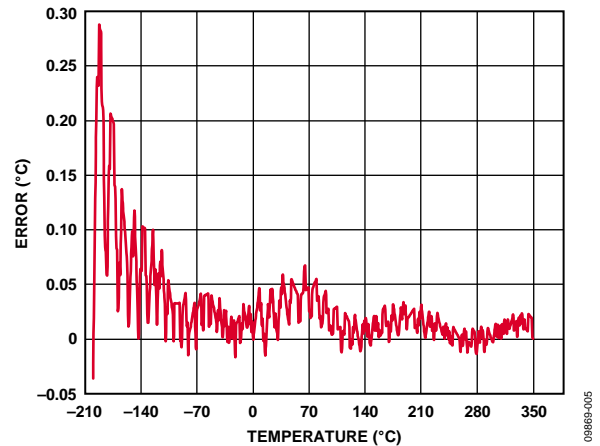
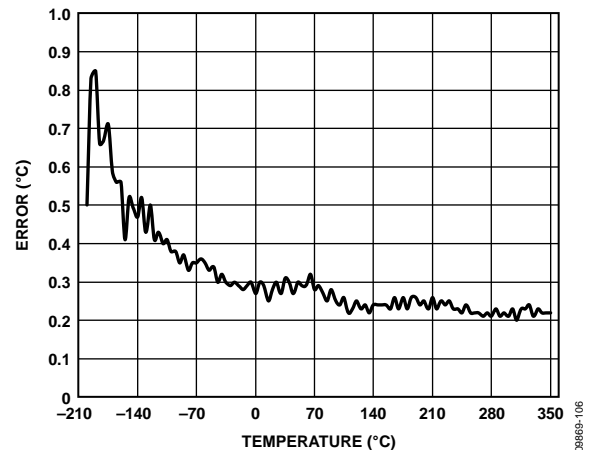Figure 5. Error When Using Piecewise Linear Approximation Using 52 Calibration Points and Ideal Measurements

Figure 6. Error When Using Piecewise Linear Approximation Using 52 Calibration Points Measured by Using ADC0 of the ADuC7060/ADuC7061

The RTD temperature is calculated using the lookup table provided in the source code and is implemented for the RTD the same way as for the thermocouple. Note that the RTD has a different polynomial describing its temperatures as a function of resistance.

For details on linearization and maximizing the performance of the RTD, refer to Application Note AN-0970, RTD Interfacing and Linearization Using an ADuC706x Microcontroller.

COMMON VARIATIONS

The ADP7102 regulator can be used as a newer alternate to the ADP3333. If more GPIO pins are required on the microcontroller, the ADuC7060, which comes in a 48-lead LFCSP or 48-lead LQFP package, is another option. Note that the ADuC7060/ADuC7061 can be programmed or debugged via a standard JTAG interface.

When using the external reference resistor as the reference source for the RTD measurement, it is recommended to buffer the input to the VREF+ pin using an op amp in unity-gain mode. This ensures that the input leakage current to the VREF+ pin does not distort the measurement accuracy. In Figure 8, an op amp, OP193, in unity-gain was used for this purpose. This input is not buffered in Figure 1; however, for best results, a buffer is required.

For a standard UART-to-RS-232 interface, the FT232R transceiver can be replaced with a device such as the ADM3202, which requires a 3 V power supply. For a wider temperature range, a different thermocouple can be used, such as a Type J. To minimize the cold junction compensation error, a thermistor can be placed in contact with the actual cold junction instead of on the PCB.

Instead of using the RTD and external reference resistor for measuring the cold junction temperature, an external digital temperature sensor can be used. For example, the ADT7410 can connect to the ADuC7060/ADuC7061 via the I²C interface.

For more details on cold junction compensation, see Sensor Signal Conditioning, Analog Devices, Chapter 7, "Temperature Sensors."

If isolation between the USB connector and this circuit is required, add the ADuM3160/ADuM4160 isolation devices.

CIRCUIT EVALUATION AND TEST

To test and evaluate the circuit, the thermocouple measurements and the RTD measurements were evaluated separately.

Thermocouple Measurement Test

The basic test setup is shown in Figure 7. Note that the thermocouple is connected to J2-8 and J2-9, and J2-5 must be connected to J2-8. The EVAL-ADuC7061MKZ board receives its power from the USB connection to the PC.
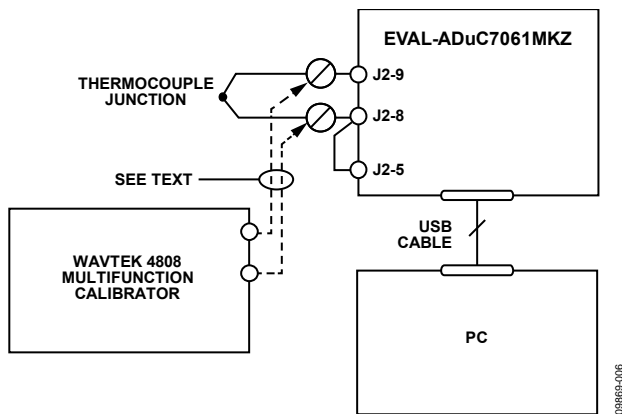
Figure 7. Test Setup Used to Calibrate and Test the Circuit Over Full Thermocouple Output Voltage Range

Two methods were used to evaluate the performance of the circuit. Initially, the circuit was tested with the thermocouple attached to the board and it was used to measure the temperature of an ice bucket, and then the temperature of boiling water.

A Wavetek 4808 multifunction calibrator was used to fully evaluate the error, as shown in Figure 4 and Figure 6. In this mode, the thermocouple was replaced with the calibrator as the voltage

source, as shown in Figure 7. To evaluate the entire range of a Type T thermocouple, the calibrator was used to set the equivalent thermocouple voltage at 11 points between −200°C to +350°C for the negative and positive ranges of the Type T thermocouple (see the ITS-90 Table for Type T Thermocouple).

To evaluate the accuracy of the lookup algorithm, 551 voltage readings, equivalent to temperatures in the range of −200°C to +350°C spaced at +1°C, were passed onto the temperature calculation functions. Errors were calculated for the linear method and the piecewise linear approximation method as can be seen in Figure 4 and Figure 5.

RTD Measurement Test

To evaluate the RTD circuit and linearization source code, the RTD on the PCB was replaced with an accurate, adjustable resistance source. The instrument used was the 1433-Z decade resistor. RTD values went from 90 Ω to 140 Ω, representing an RTD temperature range of −25°C to +114°C. The setup circuit is shown in Figure 8.
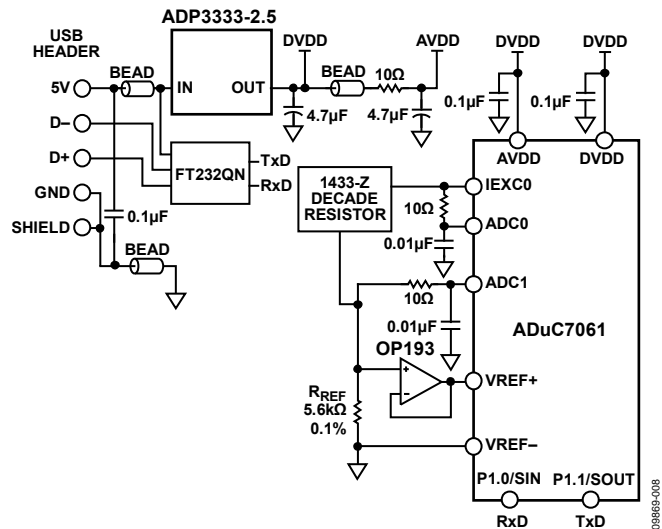

Figure 8. Test Setup Used to Calibrate and Test the RTD Output Voltage Range from −25°C to +114°C

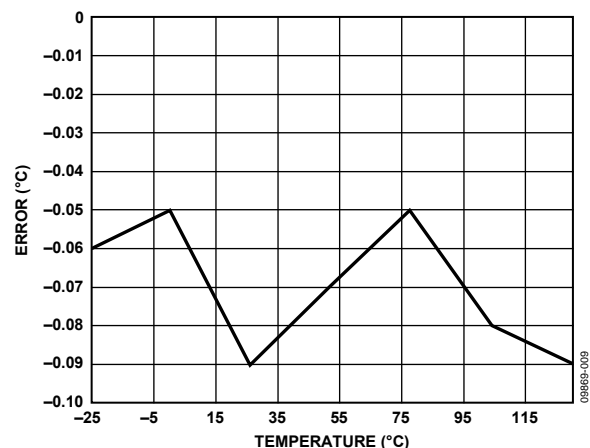The error results for the RTD tests are shown in Figure 9.

Figure 9. Error in °C of RTD Measurement Using Piecewise Linearization Code and ADC0 Measurements

LEARN MORE

CN0214 Design Support Package:
http://www.analog.com/CN0214-DesignSupport

ADIsimPower Design Tool.

Kester, Walt. 1999. *Sensor Signal Conditioning.* Analog Devices. Chapter 7, "Temperature Sensors."

Kester, Walt. 1999. S*ensor Signal Conditioning.* Analog Devices. Chapter 8, "ADCs for Signal Conditioning."

Looney, Mike. *RTD Interfacing and Linearization Using an ADuC706x Microcontroller.* AN-0970 Application Note. Analog Devices.

MT-022 Tutorial, *ADC Architectures III: Sigma-Delta ADC Basics*. Analog Devices.

MT-023 Tutorial, *ADC Architectures IV: Sigma-Delta ADC Advanced Concepts and Applications.* Analog Devices.

MT-031 Tutorial, *Grounding Data Converters and Solving the Mystery of "AGND" and "DGND."* Analog Devices.

MT-101 Tutorial, *Decoupling Techniques*. Analog Devices.

ITS-90 Table for Type T Thermocouple.

Data Sheets and Evaluation Boards

ADuC7060 Data Sheet

ADuC7061 Data Sheet

ADuC7060 Evaluation Kit

ADuC7061 Evaluation Kit

ADM3202 UART to RS-232 Transceiver Data Sheet

ADP3333 Data Sheet

ADP7102 Data Sheet

OP193 Data Sheet

REVISION HISTORY

ANALOG DEVICES