

## Thermocouple Temperature Measurement System with Less Than 500 $\mu$ A Current Drain

### EVALUATION AND DESIGN SUPPORT

#### Circuit Evaluation Boards

[CN-0206 Circuit Evaluation Board \(EVAL-CN0206-SDPZ\)](#)  
[System Demonstration Platform \(EVAL-SDP-CB1Z\)](#)

#### Design and Integration Files

[Schematics, Layout Files, Bill of Materials](#)

### CIRCUIT FUNCTION AND BENEFITS

The circuit shown in Figure 1 is a complete thermocouple system based on the AD7793 24-bit sigma-delta ( $\Sigma$ - $\Delta$ ) analog-to-digital converter (ADC). The AD7793 is a low power, low noise, complete analog front end for high precision measurement applications. The device includes a programmable gain amplifier (PGA), an internal reference, an internal clock, and excitation currents, thereby greatly simplifying the thermocouple system design.

The AD7793 consumes only 500  $\mu$ A maximum, making it suitable for any low power application, such as smart transmitters where the complete transmitter must consume less than 4 mA. The AD7793 has a power-down option. In this mode, the complete ADC, along with its auxiliary functions, is powered down so that the part consumes 1  $\mu$ A maximum.

Because the AD7793 provides an integrated solution for thermocouple design, it interfaces directly to the thermocouple. For the cold junction compensation, a thermistor along with a precision resistor is used. These are the only external components required for the cold junction measurement other than some simple RC filters for EMC considerations.

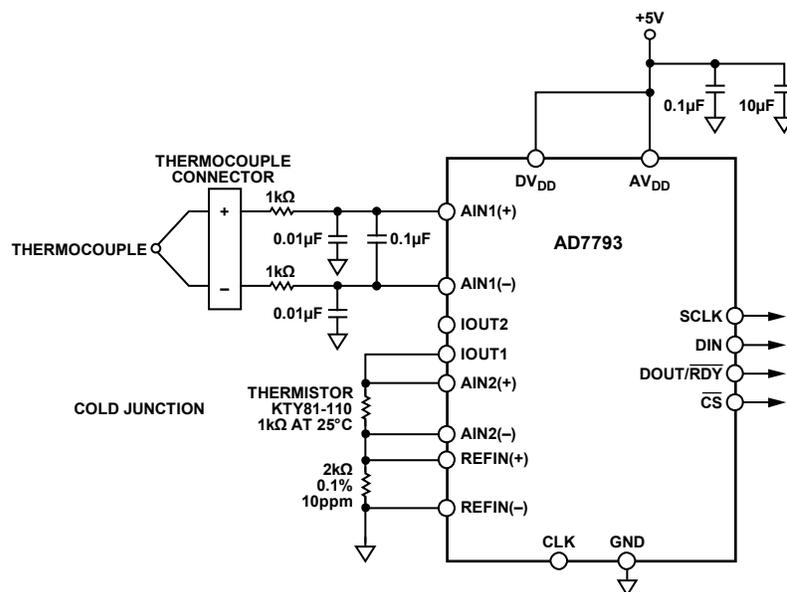


Figure 1. Thermocouple Measurement System with Cold Junction Compensation (Simplified Schematic: All Connections and Decoupling Not Shown)

#### Rev. B

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## CIRCUIT DESCRIPTION

A Type T thermocouple is used in the circuit. This thermocouple (made from copper and constantan) measures temperature from  $-200^{\circ}\text{C}$  to  $+400^{\circ}\text{C}$ . It generates a typical temperature dependent voltage of  $40\ \mu\text{V}/^{\circ}\text{C}$ .

The thermocouple response is approximately linear over a small portion of its entire temperature range, from  $0^{\circ}\text{C}$  to  $60^{\circ}\text{C}$  (see Figure 2). To allow accurate measurements over the entire temperature range, the [CN0206-SDP-0](#) evaluation software implements a linearization routine.

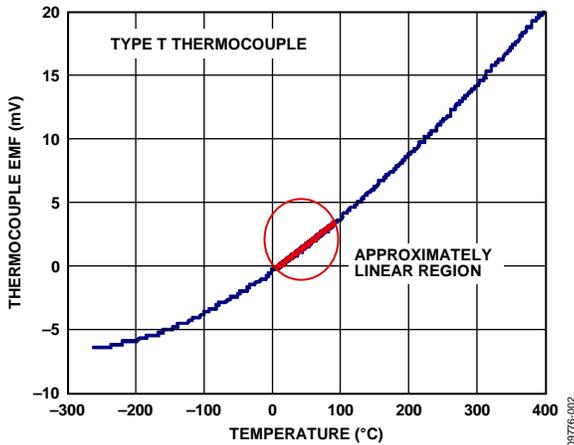


Figure 2. Thermocouple EMF vs. Temperature

### Cold Junction Compensation

Thermocouples measure the temperature difference between two points, not an absolute temperature. To measure a single temperature, maintain one of the junctions (normally the cold junction) at a known reference temperature, and the other junction at the temperature to be sensed.

Having a junction of known temperature is not convenient for most applications; therefore, a thermally sensitive device is placed on the printed circuit board (PCB). This thermistor is used to measure the temperature of the thermocouple input connection. The thermistor fits inside the metallic tab found on the thermocouple connection, minimizing any temperature gradients that may exist.

Because the voltage from a known cold junction is simulated, the appropriate correction can be applied. See the Thermocouple Linearization section for more detailed information on processing and manipulating the thermocouple and thermistor voltages to produce an accurate temperature reading.

### ADC Channel 1 Configuration, Thermocouple

The temperature range for the thermocouple is  $-200^{\circ}\text{C}$  to  $+400^{\circ}\text{C}$ . The typical temperature dependent voltage generated by the thermocouple is  $40\ \mu\text{V}/^{\circ}\text{C}$ . This voltage generates a thermocouple voltage range of  $-8\ \text{mV}$  to  $+16\ \text{mV}$ .

When reading the thermocouple voltage, the ADC uses the external  $2\ \text{V}$  reference and is configured for a gain of 64. This defines the analog input voltage range as  $\pm 31.25\ \text{mV}$  ( $\pm V_{\text{REF}}/\text{Gain}$ ). For a gain of 64, the absolute voltage on the analog inputs must be between  $\text{GND} + 300\ \text{mV}$  and  $\text{AV}_{\text{DD}} - 1.1\ \text{V}$ .

Because the [AD7793](#) operates from a single power supply, the signal generated by the thermocouple must be biased above ground so that it is within the acceptable range of the ADC. The bias voltage generator on-board the [AD7793](#) biases the thermocouple signal so that it has a common-mode voltage of  $\text{AV}_{\text{DD}}/2$ .

### ADC Channel 2 Configuration, Thermistor

The second channel of the ADC monitors the voltage generated across a thermistor being driven by one of the current output pins of the [AD7793](#). A  $1\ \text{mA}$  excitation current drives the series pair of thermistor and precision resistor ( $2\ \text{k}\Omega$ ,  $0.1\%$ ), as shown in Figure 1.

The thermistor value varies from  $0^{\circ}\text{C}$  ( $815\ \Omega$ ) to  $30^{\circ}\text{C}$  ( $1040\ \Omega$ ), producing a voltage signal range of  $815\ \text{mV}$  to  $1040\ \text{mV}$ . The precision resistor produces  $2.0\ \text{V}$  for use as an external reference. With a gain of 1, the analog input range is  $\pm 2\ \text{V}$  ( $\pm V_{\text{REF}}/\text{Gain}$ ). This architecture gives a ratiometric configuration. Any change in the value of the excitation current does not alter the accuracy of the system.

Assuming a linear transfer function between  $0^{\circ}\text{C}$  and  $30^{\circ}\text{C}$ , the relationship between the cold junction temperature and the thermistor resistance,  $R$ , is

$$\text{Cold Junction Temperature} = 30 \times (R - 815) / (1040 - 815)$$

One other consideration is the output compliance of the IOUT1 pin of the [AD7793](#). When the  $1\ \text{mA}$  excitation current is used, the output compliance equals  $\text{AV}_{\text{DD}} - 1.1\ \text{V}$ . This specification is met because the maximum voltage at IOUT1 equals the voltage across the precision resistor plus the voltage across the thermistor, which equals  $2\ \text{V} + 1.04\ \text{V} = 3.04\ \text{V}$ .

### Output Coding

The output code for an input voltage on either channel is

$$\text{Code} = 2^{N-1} \times [(AIN \times \text{Gain}/V_{\text{REF}}) + 1]$$

where:

$AIN$  is the analog input voltage.

$GAIN$  is the in-amp setting

$N = 24$ .

The [EVAL-SDP-CB1Z](#) analog microcontroller processes the conversions from the [AD7793](#).

### Thermocouple Linearization

As mentioned in the Circuit Description section, the thermocouple is only approximately linear over a small temperature range. In fact, the thermocouple is highly nonlinear over the rest of the temperature range. For this reason, a linearization procedure is implemented in the [CN0206-SDP-0](#) LabVIEW software.

The National Institute of Standards and Technology provides ITS-90 look-up tables for thermocouples. Each table contains a list of thermoelectric voltages (mV) and their corresponding temperatures.

To implement the cold junction compensation previously mentioned, the [CN0206-SDP-0](#) evaluation software takes the Type T thermocouple look-up table and searches for the thermoelectric voltage associated with the cold junction temperature. It then subtracts this thermoelectric voltage from every element in the look-up table to produce a cold junction compensated thermoelectric voltage look-up table.

The evaluation software then searches the modified look-up table for the thermocouple input voltage, as sampled by the [AD7793](#). When the [CN0206-SDP-0](#) evaluation software finds what two points this thermoelectric voltage lies between, a linear interpolation is performed to precisely calculate the thermocouple temperature.

### System Calibration

In addition to linearizing the thermocouple temperature, the evaluation software performs a two-point calibration. The user must input the lowest and highest temperature and use the [CN0206-SDP-0](#) evaluation software to produce the corresponding temperature readings.

The software takes these readings and calculates the gain and offset, and then applies these values to any future thermocouple temperature calculations.

### System Noise Considerations

For an output data rate of 16.7 Hz and a gain of 64, the rms noise of the [AD7793](#) equals 0.086  $\mu\text{V}$  (noise is referred to input). The peak-to-peak noise is

$$6.6 \times \text{RMS Noise} = 6.6 \times 0.086 \mu\text{V} = 0.5676 \mu\text{V}$$

If the thermocouple has a sensitivity of precisely 40  $\mu\text{V}/^\circ\text{C}$ , the thermocouple should measure the temperature to a resolution of

$$0.5676 \mu\text{V} \div 40 \mu\text{V} = 0.014^\circ\text{C}$$

### Test Data and Results

All data capture was performed using the [CN0206-SDP-0](#) LabVIEW evaluation software. A CL540ZA source (and appropriate Type T cable) was used to simulate the thermocouple input. The CL540ZA is capable of simulating several different types of thermocouples (J, T, E, K, R, S, B, N, and so on).

By sweeping the CL540ZA input source from  $-200^\circ\text{C}$  to  $+400^\circ\text{C}$  in  $+5^\circ\text{C}$  increments, the [CN0206-SDP-0](#) evaluation software was able to capture, linearize, and calibrate the system according to the two user-defined calibration points.

According to Figure 3, the error over the entire temperature range is less than  $1^\circ\text{C}$ . However, over most of the range, the error is less than  $0.5^\circ\text{C}$ .

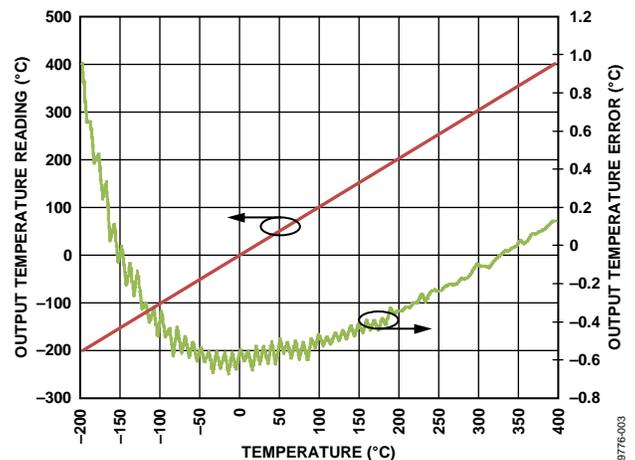


Figure 3. Linearized and Calibrated Output Temperature (with Associated Error Plot) vs. Input Temperature

The peak-to-peak noise of the [AD7793](#) was determined by shorting the input pins of the ADC together and acquiring 1000 samples. As seen in the histogram found in Figure 4, the code spread is approximately 220 codes, which translates to a temperature spread of  $0.02^\circ\text{C}$  peak-to-peak.

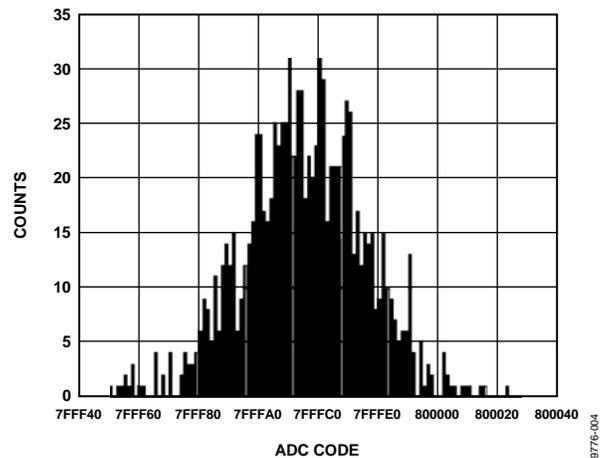


Figure 4. Histogram Showing Output Code Spread with [AD7793](#) Input Pins Shorted Together

Test data was taken using the board shown in Figure 5. Complete documentation for the system can be found in the [CN-0206 Design Support](#) package.



Figure 5. Photo of EVAL-CN0206-SDPZ Board

## COMMON VARIATIONS

The AD7793 is a low noise, low power ADC. Other suitable ADCs are the AD7792 and AD7785. Both parts have the same feature set as the AD7793. However, the AD7792 is a 16-bit ADC while the AD7785 is a 20-bit ADC.

## CIRCUIT EVALUATION AND TEST

This circuit uses the EVAL-CN0206-SDPZ circuit board and the EVAL-SDP-CB1Z System Demonstration Platform (SDP) evaluation board. The two boards have 120-pin mating connectors, allowing for the quick setup and evaluation of the circuit's performance.

The EVAL-CN0206-SDPZ board contains the circuit to be evaluated, as described in this note, and the SDP evaluation board is used with the CN0206 Evaluation Software to capture the data from the EVAL-CN0206-SDPZ circuit board.

### Equipment Needed

The following equipment is needed:

- A PC with a USB port and Windows® XP and Windows Vista® (32-bit), or Windows® 7 (32-bit)
- The EVAL-CN0206-SDPZ circuit evaluation board
- The EVAL-SDP-CB1Z SDP evaluation board
- The CN0206 Evaluation Software
- A power supply: 6 V or 6 V wall wart
- The CL540ZA thermocouple source or alternate

### Getting Started

Load the evaluation software by placing the CN0206 Evaluation Software CD in the PC. Using My Computer, locate the drive that contains the evaluation software CD and open the Readme file. Follow the instructions contained in the Readme file for installing and using the evaluation software.

## Functional Block Diagram

See Figure 1 of this circuit note for the circuit block diagram, and the EVAL-CN0206-SDPZ-SCH-RevA.pdf file for the circuit schematics. This file is contained in the CN0206 Design Support Package.

### Setup

Connect the 120-pin connector on the EVAL-CN0206-SDPZ circuit board to the CON A connector on the EVAL-SDP-CB1Z evaluation (SDP) board. Use nylon hardware to firmly secure the two boards, using the holes provided at the ends of the 120-pin connectors. With power to the supply off, connect a 6 V power supply to the +6 V and GND pins on the board. If available, a 6 V wall wart can be connected to the barrel connector on the board and used in place of the 6 V power supply. Plug the thermocouple connector into J1. Note: Do not turn on the thermocouple source at this time.

Connect the USB cable supplied with the SDP board to the USB port on the PC. Note: Do not connect the USB cable to the mini USB connector on the SDP board at this time.

### Test

Apply power to the 6 V supply (or wall wart) connected to EVAL-CN0206-SDPZ circuit board. Turn on the CL540ZA thermocouple source, connect the USB cable from the PC to the mini USB connector on the SDP board and launch the evaluation software.

When USB communications are established, the SDP board can be used to send, receive, and capture serial data from the EVAL-CN0206-SDPZ board.

Information and details regarding test setup and calibration, and how to use the evaluation software for data capture can be found in the CN-0206 User Guide.

Information regarding the SDP board can be found in the SDP User Guide.

**LEARN MORE**

CN-0206 Design Support Package:

[www.analog.com/CN0206-DesignSupport](http://www.analog.com/CN0206-DesignSupport)

Kester, Walt. 1999. *Temperature Sensors*. Section 7. Analog Devices.

MT-004 Tutorial, *The Good, the Bad, and the Ugly Aspects of ADC Input Noise—Is No Noise Good Noise?* 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.

**Data Sheets and Evaluation Boards**

AD7793 Data Sheet

AD7793 Evaluation Board

**REVISION HISTORY****8/13—Rev. A to Rev. B**

Changes to Title.....	1
Changes to Test Section.....	4

**8/12—Rev. 0 to Rev. A**

Added Circuit Evaluation Boards Section .....	1
Changes to Circuit Note Title, Circuit Function and Benefits Section and Figure 1 .....	1
Added Cold Junction Compensation Section, ADC Channel 1 Configuration, Thermocouple Section, ADC Channel 2 Configuration, Thermistor Section, Output Coding Section, and Thermocouple Linearization Section .....	2
Deleted Figure 3 and Table 1; Renumbered Sequentially .....	3
Added System Calibration Section, System Noise Considerations Section, Test Data and Results Section, Figure 3, and Figure 4 .....	3
Added Figure 5, Equipment Needed Section, Getting Started Section, Functional Block Diagram Section, Setup Section, and Test Section.....	4
Changes to Circuit Evaluation and Test Section .....	4
Changes to Data Sheets and Evaluation Boards Section .....	5

**10/11—Revision 0: Initial Version**

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