Voltage Reference Scaling Techniques: Increase the Accuracy of the Converter as Well as the Resolution

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ABSTRACT

Temperature sensing can be one of the more challenging physical entities to measure if a variety of ranges and levels of accuracy are required by one electrical system.

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1 Hardware Interface

The circuit in Figure 1 uses a low power, single-supply analog-to-digital converter, ADS7816, configured with a thermocouple and cold-junction compensation (CJC) sub-circuit to achieve the desired range of responsive- ness as well as high accuracy. The thermocouple is interfaced with a 12-bit A/D converter that allows for an adjustable input range. This range is adjusted with the voltage reference input. The range of the voltage reference input of the ADS7816 A/D converter is from the supply voltage (+5 V typically) all the way down to 0.1 V. The voltage reference range mimics a gain stage for the 12-bit converter. With this converter a suto-gain stage provides 17.6-bit virtual resolution against a 5-V scale. When this circuit is properly calibrated for the desired temperature range, the effective resolution can be increased by 50x over a system with a standard 5V full-scale range.

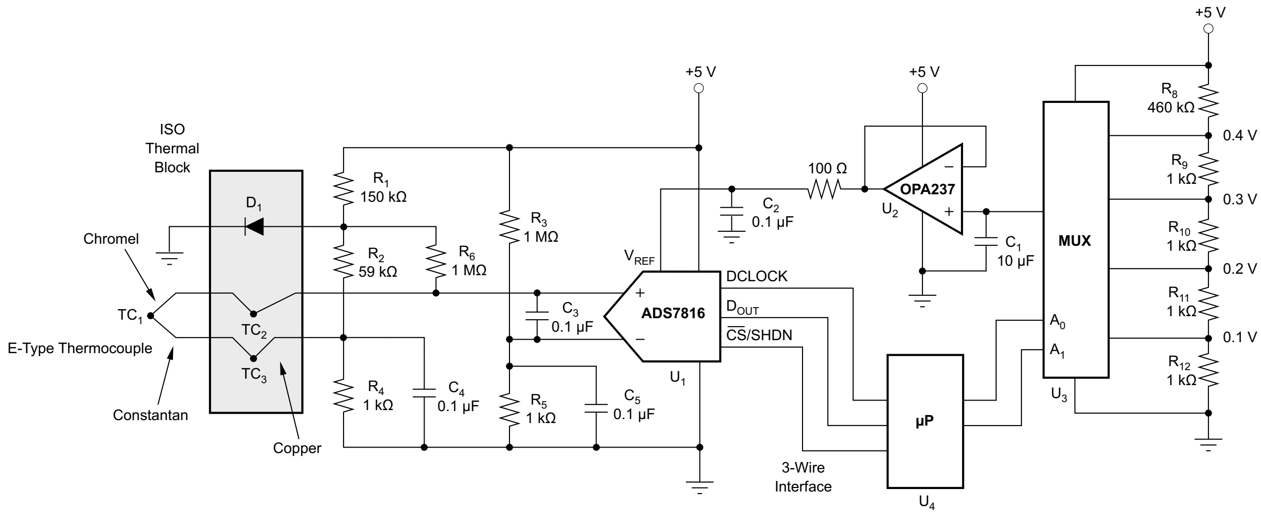

Figure 1. Thermocouple Application Using MUX to Scale Input Range of ADC to Increase Accuracy and Resolution

Other converters in the same family include the ADS1286 and ADS7817 (see Table 1). All three of these products have the unique characteristics of having a variable input range, while also being low power, low cost and available in 8-pin packages (such as PDIP, SOIC, and MSOP). This product line, also known as the fly-spec converters, is only the beginning of a new family of converters that take advantage of the versatile reference function and compact architecture. This application bulletin addresses the uniqueness of the voltage reference function to the A/D conversion process.

The thermocouple is inter- faced with a 12-bit A/D converter that allows for an adjust- able input range. This range is adjusted with the voltage reference input. The range of the voltage reference input of the ADS7816 A/D converter is from the supply voltage (+5 V typically) all the way down to 0.1 V. The voltage reference range mimics a gain stage for the 12-bit converter. With this converter a suto-gain stage provides 17.6-bit virtual resolution against a 5-V scale. When this circuit is properly calibrated for the desired temperature range, the effective resolution can be increased by 50 times over a system with a standard 5-V full-scale range.

2 A/D Converter Configurations and Applications

The key differentiating performance characteristics of these 12-bit A/D converters are summarized in Table 1. In this product line, the A/D converter input configuration is either single-ended or differential. The single-ended style input stage has a additional “sense” ($V_{IN–}$) pin. The sense pin, in conjunction with the analog input pin, rejects small signals (±200 mV) common to both pins. This allows the user of the device to extend the signal lines coming to the device over a longer distance, giving the circuit a better chance to reject undesired radiated signals. The minimum LSB size is determined by the number of bits (in all these devices, 12 bits) and the minimum voltage that is assignable to the LSB, given the input voltage range. The minimum achievable LSB size is set by the actual accuracy of the converter with the given minimum input voltage range. The accuracy of the converter is defined by the measured rms (one sigma) noise levels at the output of the device after multiple conversions. This unique use of V_{REF} adjusts the full-scale range as well as the LSB size externally.

Table 1. Flyspec 12-Bit, Single Supply Converter Product Line Capable of Achieving Very Small Actual LSB Values

PARAMETER	ADS1286	ADS7816	ADS7817
Input configuration	Single-ended with sense pin	Single-ended with sense pin	Full differential
Maximum sampling rate	20 KHz	200 KHz	200 KHz
Voltage reference range	100 mV to supply	100 mV to supply	50 mV to supply
Analog input voltage range	V_{REF}	V_{REF}	V_{REF}
Supply voltage range	4.5 V to 5.25 V	4.5 V to 5.25 V	4.75 V to 5.25 V
Minimum LSB size to 12 bits	24.4 µV	24.4 µV	24.4 µV
Minimum achievable LSB	51.79 µV	51.79 µV	51.79 µV

These converters can be used in a wide range of applications, one being thermocouple interface. A variety of thermocouples can be used for this application, such as “K”, “J” or “E” type devices. The thermocouple is constructed with two dissimilar metals that are connected together at one point. A voltage is created as a result of the temperature difference from one end of the metals to the other. The thermocouple used in this particular circuit is a type “E”. The materials used to build a type “E” thermocouple are chromel and constantan. The sensitivity of four different thermocouples is shown in the following Table 2.

Table 2. Temperature Coefficients of Various Thermocouple Types

ISA TYPE	METALS USED FOR WIRES	TEMPERATURE COEFFICIENT (µV/°C at 0°C)	USEFUL TEMPERATURE RANGE (°C)
E	Chromel/constantan	58.5	0 to +1000
J	Iron/constantan	50.2	0 to +1000
K	Chromel/alumel	39.4	0 to +1300
T	Copper/constantan	38.0	0 to +600

3 Thermocouple Specifications

Thermocouples are low impedance, voltage output devices requiring a temperature reference or compensation point. No voltage or current excitation is required, which is a plus; however, their sensitivity is very low. For example, the K-Type thermocouple has an approximate 40-μV/°C sensitivity to changes in temperature and will change approximately 50 mV for a temperature range of 0°C to 1300°C.

An application circuit that takes advantage of the unique voltage reference capability of the ADS7816 is shown in Figure 1. In this circuit, the two wires from the thermocouple are brought to an isothermal block. The isothermal block is used as a temperature reference point to eliminate the voltage errors created by the two thermocouples built with the E-Type thermocouple leads are both connected to copper traces. At the isothermal block, a diode is used in conjunction with the resistors R_1 through R_6 to zero out the undesirable effects of the thermocouples that are built into the circuit as a result of connecting chromel and constantan wires to the PCB traces. The selection of the values of the resistors R_1 through R_5 depend on the type of thermocouple used, power requirements of the diode (D_1), A/D converter input offsets and overall power consumption requirements. In this circuit, the current to the CJC circuit is designed to a nominal 35 μA.

A designed-in offset ensures that offset variation from device to device of the A/D converter does not compromise the lower temperature readings. The difference at 0°C between the two inputs of the ADS7816 is designed to have a 5-mV difference between the non-inverting and inverting inputs of the A/D converter. This 5-mV difference accounts for temperatures below 0°C as well as a possible offset voltage with the A/D converter of 1 mV (max). The ratio of the voltage divider of R_2 and R_4 is calculated to equal the drift of the “E” thermocouple (58 μV/ °C) in relation to the diode drift (–2.1 mV/ °C). The input range of the ADS7816 on the non-inverting input is equal to V_{IN+} minus V_{IN-}.

An open circuit indicator is implemented with the inclusion of R_6. To ensure that R_6 does not interface with the normal operation of the circuit, a high value is chosen, such as 1 MΩ. In the event that the lines to the thermocouple are broken, the inverting input to the A/D converter immediately becomes the voltage at the diode, approximately 0.6 V. This voltage easily exceeds any voltage that the thermocouple can generate as a result of high temperature exposure. The digital conversion of the diode voltage produces a full-scale output, which is flagged as an error condition by the μProcessor (U_4).

Typically, a thermocouple output voltage is gained by an analog front end, such as an instrumentation amplifier. The analog gain cell is set to insure that the signal full scale swing is equivalent to the A/D converter input range. The instrumentation amplifier can be eliminated by using the A/D converter with a smaller input range. This can be done by adjusting the reference voltage of the converter.

4 A/D Converter Operation

The ADS7816 is a 12-bit A/D converter with a sampling input. The input range of the ADS7816 A/D converter is equal to V_{IN+} minus V_{IN-}. The sense pin (V_{IN-}) input range is ±200 mV. The reduced V_{REF} operates in the application as a gain increase by reducing the FSR of the converter. The A/D converter's input range is decreased, while the converter continues to have a 12-bit resolution. The multiplexer (U_3) uses the voltages generated by a voltage divider across the power supply. The range and absolute values of the voltages at the input of the multiplexer are dependent on the thermocouple type and temperature range of the application.

For a temperature range of 0°C to 1000°C, the delta voltage change of the "E" type thermocouple is 58 mV. The output voltage of the multiplexer is filtered and buffered by a single supply op-amp, U_2. The affect of changing the reference voltage is summarized in Table 3 and Table 4.

Table 3. Reference Voltage Changes in ADS7816

V_{REF} INPUT	LSB VOLTAGE OF ADS7816	VIRTUAL ACCURACY TO 5-V FSR	EFFECTIVE GAIN
5.00 V	1220 µV	12 bits	1.00
3.75 V	916 µV	12.5 bits	1.33
2.50 V	610 µV	13 bits	2.00
1.25 V	305 µV	14 bits	4.00
0.50 V	122 µV	15.3 bits	10.00
0.30 V	73.2 µV	16 bits	16.67
0.20 V	48.8 µV	16.7 bits	25.00
0.10 V	24.5 µV	17.6 bits	50.00

By Decreasing V_{REF}, the input range of the ADS7816 decreases one for one. The effective resolution remains at 12 bits, however, compared to a 5-V FSR system, the virtual accuracy is improved. The virtual resolution shown in Table 3 does not account for noise in the system, which could reduce the accuracy of the device (particularly at lower values of V_{REF}).

Table 4. Reference Voltage Changes in ADS7817

V_{REF} INPUT	DIFFERENTIAL INPUT VOLTAGE RANGE	LSB VOLTAGE OF ADS7817	VIRTUAL ACCURACY TO 5-V FSR	EFFECTIVE GAIN
2.50 V	±2.50 V	1220 µV	12 bits	1.00
1.25 V	±1.25 V	612 µV	13 bits	2.00
0.50 V	±0.50 V	244 µV	14.3 bits	5.00
0.30 V	±0.30 V	146 µV	15 bits	8.33
0.20 V	±0.20 V	97.6 µV	15.7 bits	12.50
0.10 V	±0.10 V	49.0 µV	16.3 bits	25.00
0.05 V	±0.05 V	24.5 µV	17.6 bits	50.00

The Input Range of the ADS7817 is equal to twice of the reference voltage. By decreasing V_{REF}, the input range of the ADS7817 decreases proportionally. The effective resolution remains at 12 bits. Compared to a 5-V FSR system the virtual accuracy is improved. The virtual resolution shown in Table 4 does not account for noise in the system, which could reduce the accuracy of the device (particularly at lower values of V_{REF}).

Although a thermocouple was used to illustrate the function of this circuit, other sensing devices can also be used making the multiplexer more useful. With this simple circuit the digital control can vary the gain coefficient from 1 to 50X.