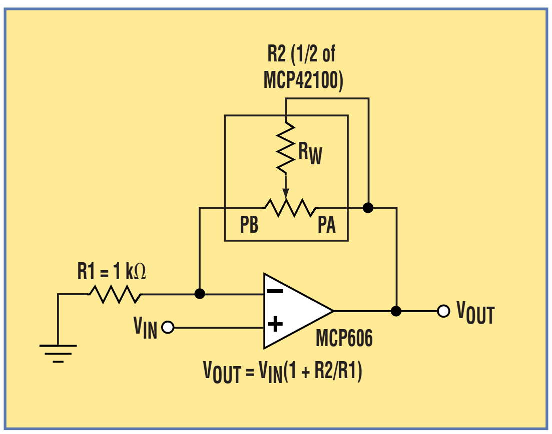
# Overcome Analog-Circuit Temperature Sensitivity

*Using a digital potentiometer with greatly enhanced "out-of-box" accuracy and temperature performance is the best solution.*

**BY BONNIE C. BAKER**
*Microchip Technology Inc.*

Digital potentiometers enable system designers to program resistive values in an analog circuit during its initial calibration, or normal operation. This advantage lets circuit conditions be dynamically changed, creating a "smart" analog system that can respond to the surrounding environment. Because this programmable feature seems all too promising, the suspicious analog engineer will correctly anticipate that it doesn't come for free. The temperature performance of today's digital potentiometers shows that they perform with much less accuracy than standard mechanical potentiometers or discrete resistor combinations. But a clever designer can take advantage of secondary temperature behavior by utilizing the matching characteristics of these digital devices.




***1. The thermal performance of this simple gain circuit using a digital potentiometer is typically 800 ppm/°C.***

Most engineers think that digital potentiometers are far superior to their mechanical cousins. In terms of their programmability and reliability, this is absolutely true. It's far more accurate and less expensive to have programming code sent out from the controller to the digital potentiometer than to twist a wiper in the mechanical potentiometer with a screwdriver. But without enhancements, the "out-of-box" accuracy and temperature performance of a digital potentiometer won't be superior to those of a mechanical potentiometer. However, by using a few simple techniques, you can change the temperature performance of these potentiometers 500 to 800 ppm/°C, thus achieving an improvement of 100 times over other solutions.

***Simple Programmable Gain Circuit:*** The resistive material of most of today's digital potentiometers is fabricated with the poly diffusions of CMOS processes. Because these resistors are fabricated using poly diffusions, the resistive elements aren't trimmed to precision. Consequently, the initial accuracy of most digital potentiometers from part to part at room temperature is ±30% (maximum). The thermal drift specifications are either 800 ppm/°C or 500 ppm/°C, depending on which poly diffusion is used to fabricate the resistive element. If this type of resistor element is employed in a simple amplifier gain configuration and the basic specifications of the digital potentiometer are ignored, the nominal error and overtemperature error may bring an unexpected, unpleasant surprise *(Fig. 1, Table 1)*.

As the example in Figure 1 shows, the amplifier circuit's gain using the MCP606 CMOS single-supply op amp is equal to:

$$V_{OUT} = V_{IN} (1 + R2 / R1)$$

This simple circuit is designed to

**TABLE 1: PROGRAMMABLE GAIN RANGE**

| Digital code | R2 value* (Ω) | Gain* (V/V) | Initial error*(%) | Temperature error (ppm/°C) |
|---|---|---|---|---|
| 3 | 1.7k | 2.7 | ±30 | 800 |
| 127 | 49.6k | 50.6 | ±30 | 800 |
| 255 | 99.6k | 100.6 | ±30 | 800 |

*assuming RW = 0 Ω

**TABLE 2: PROGRAMMABLE GAIN RANGE**

| Digital code | R2 value* (Ω) | Gain* (V/V) | Initial error*(%) | Temperature error (ppm/°C) |
|---|---|---|---|---|
| 3 | 1.17k | 2.00 | ±1 | 1 |
| 127 | 49.6k | 43.4 | ±1 | 1 |
| 255 | 99.6k | 86.1 | ±1 | 1 |

*assuming RW = 0 Ω

have an adjustable, programmable gain by placing a digital potentiometer across the amplifier's feedback loop. A circuit with this type of flexibility can't be easily implemented by using discrete resistors. But the nominal gain and temperature stability of the discrete design are superior to those of the circuit using the digital potentiometer.

**TABLE 3: VOLTAGE REFERENCE ERRORS**

| | Room temperature | Over −40°C to 85°C range |
|---|---|---|
| R1 (±0.25 LSB typical error) | ±0.019 mV | ±0.003 mV |
| R2 (±0.25 LSB typical error) | ±0.019 mV | ±0.003 mV |
| R3 (±0.25 LSB typical error) | ±0.019 mV | ±0.003 mV |
| Total typical error at V3 | ±0.057 mV | ±0.009 mV |

With a discrete design, the nominal value of resistors R1 and R2 could easily and inexpensively be chosen to have a 1% tolerance. Also, if an attempt were made to ensure that these two resistors were manufactured using the same material, they would have fairly consistent temperature tracking.

In contrast, a digital potentiometer could be implemented in the feedback loop with different results. The digital potentiometer selected for this example is a dual digital potentiometer with a 100-kΩ nominal typical resistance from terminal PA to PB. The out-of-box nominal resistance of the digital potentiometer selected for the circuit in Figure 1 could vary up to ±30% from the typical specified resistance, or 100 kΩ ±30 kΩ. Placing the digital potentiometer in the feedback loop of the circuit ratioed against the input discrete resistance could, in a worst-case scenario, result in part-to-part variation with a gain of ±30%.

This potentially large margin of error would be widened further over temperature variations. The typical temperature change of the digital potentiometer's resistive element is 800 ppm/°C. For instance, if the temperature excursion for a 10-kΩ resistive element were from 25°C to 75°C, the resistive element would change by 400 Ω, or 4%. The circuit configuration in Figure 1 may not seem like a good solution, but it's easy to fix with just a few design tricks.

An alternative circuit that addresses both the accuracy and overtemperature issues of the circuit in Figure 1 employs a dual digital potentiometer to fill both resistor positions in the circuit *(Fig. 2, Table 2)*. Because both resistor elements are on one chip, their nominal matching and temperature drift characteristics are closely matched.

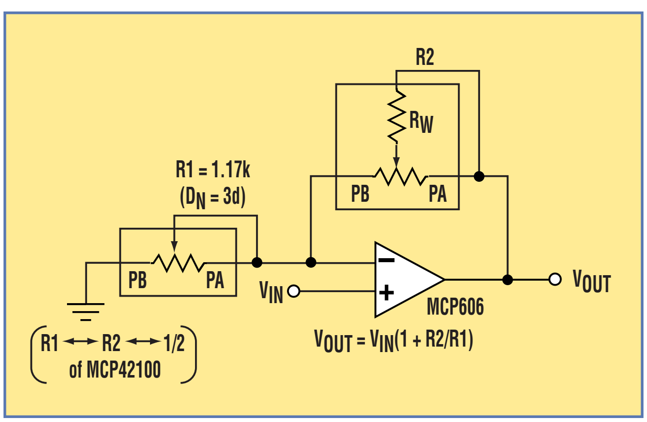
This design strategy provides great returns in the circuit design by changing the gain of the circuit from a ±30% potential error down to ±1%, creating an improvement of 30 times. In addition, the circuit's overtemperature performance has been improved from the poor performance of 800 ppm/°C down to 1 ppm/°C. This constitutes a significant improvement of 800 times. But the largest benefit gained from this approach is that this circuit retains its wide range of programmable gains.

***Good Temperature Matching:*** A single digital potentiometer can be used in circuits effectively if the two sides of the potentiometer are placed so that the resistive elements in the transfer function are ratioed. For instance, this can be done with an adjustable voltage reference by employing the power supply as the voltage source at the top of the potentiometer *(Fig. 3)*.

The output voltage of the adjustable reference in Figure 3 is equal to:

$$V_{REF} = V_{DD} \times R_{POT-B} / R_{POT-AB}$$

This potentiometer configuration is typically called the voltage divider mode.



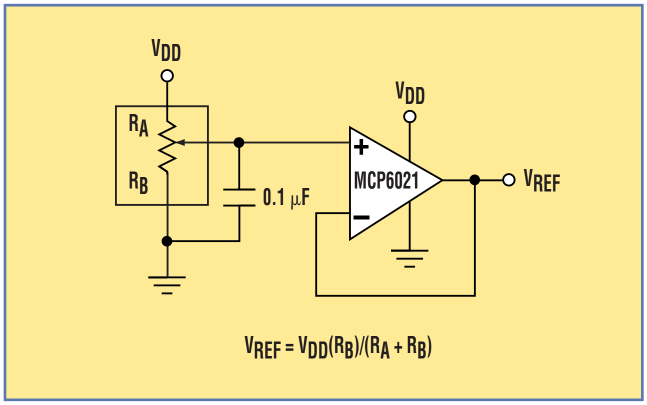

***2. The intrinsic matching of a dual digital potentiometer is used to benefit this gain circuit to achieve initial gain accuracy of ±1% (maximum) and a typical temperature coefficient of 1 ppm/°C.***

The resolution and accuracy of this reference circuit depend mainly on the number of programmable bits of the digital potentiometer and the voltage at $V_{DD}$. When using any of Microchip's 8-bit digital potentiometers and a 5-V supply, the nominal LSB size would be 19.53 mV. The absolute accuracy and overtemperature performance of the voltage presented at the input of the amplifier don't depend on the absolute nominal resistance of the digital potentiometer. Rather, the performance of this programmable voltage reference depends primarily on the stability of the power supply, then on the matching of the digital potentiometer's resistive elements.

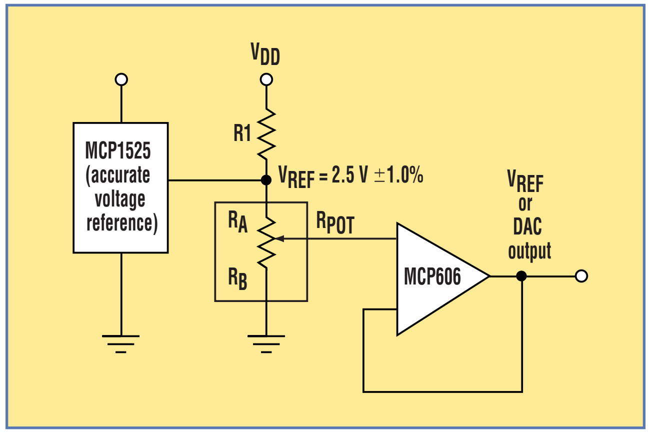
Consider the following example of the effects of the digital potentiometer errors: The MCP4x010 (10-kΩ digital potentiometer) would perform with an absolute accuracy of less than ±0.25 LSB (typical), or ±4.8825 mV in this circuit at 25°C. Over temperature (−40°C to 85°C), the output voltage would typically vary 1 ppm/°C due to resistance matching. This translates into a worst-case variance over temperature of 0.5 mV, or ±0.25mV. Adding this to the error at room temperature, the total possible error becomes ±5.3825 mV, or ±0.28 LSB. (Calculations for this example assume the power supply is stable at 5 V.)

If power-supply errors are considered, the variance in the power supply directly affects the accuracy of the digital potentiometer's output. For instance, if a supply provides the voltage with a ±5% variance, the error contribution to the voltage divider can be substantial.

The digital potentiometer in this circuit can be selected with current consumption across the element or noise as the main concern. The current through a 10-kΩ potentiometer with a 5-V supply is 500 µA. Compare this with the 50-µA current through a 100-kΩ potentiometer. In contrast, the output noise of the 10-kΩ potentiometer programmed to a 127d (half-scale) setting is 6.36 $nV/\sqrt{Hz}$ at 1 kHz (rms). In the case of the 100-kΩ poten-




**3. Using the matching top and bottom sides of a single-silicon digital potentiometer in a voltage-divider configuration will enhance the temperature performance of this circuit.**




**4. A voltage reference will stabilize the errors from the power supply shown in Figure 3. In this circuit, the MCP1525 is a 2.5-V device with an accuracy of ±1% over –40°C to 85°C.**

tiometer, the output noise would be 20.5 nV/√Hz at 1 kHz (rms). This would be compared to the op amp noise of 8.7 nV/√Hz at 10 kHz (rms). In this circuit, the op amp is used to isolate, or buffer, the digital potentiometer resistance from ensuing stages.

Figure 4 shows another technique for designing a precision adjustable voltage reference. In this circuit, the power supply's variability is stabilized with a precision voltage reference. Because the digital potentiometer is again configured as a voltage divider, the errors at the amplifier's output are similar to the errors discussed in the previous example. The only difference between the circuit in Figure 3 and the circuit in Figure 4 is that the power supply in the latter has been replaced with a precision reference.

As illustrated in Figure 3, the errors contributed by the digital potentiometer are less significant than the errors created by the power supply. The errors caused by any power-supply variations have been minimized in the circuit in Figure 4. This configuration is often used when the digital potentiometer is employed in a digital-to-analog converter (DAC) function.

***A Stable 16-Bit Converter:*** Finally, a 16-bit voltage reference, or DAC, can be designed using three digital potentiometers and three op amps *(Fig. 5)*. In this configuration, R1 and R2 are implemented by using a dual MCP42010 digital potentiometer. Because these potentiometers are in the same package and used in a voltage-divider configuration, efficient tracking in terms of nominal value and overtemperature performance is possible.

The two potentiometers can be programmed to have a 1-bit difference without losing monotonicity. The third potentiometer, R3, is employed to divide the difference between the voltage at the output of op amps A1 and A2. The configuration in Figure 5 provides a theoretical output resolution of 16 bits. When $V_{DD}$ is equal to 5 V, the LSB size is 76.29 mV.

In this circuit, the voltage at $V_{DD}$ can be divided into 256 different segments with the two digital potentiometers, R1 and R2. The LSB size for this portion of the circuit is:

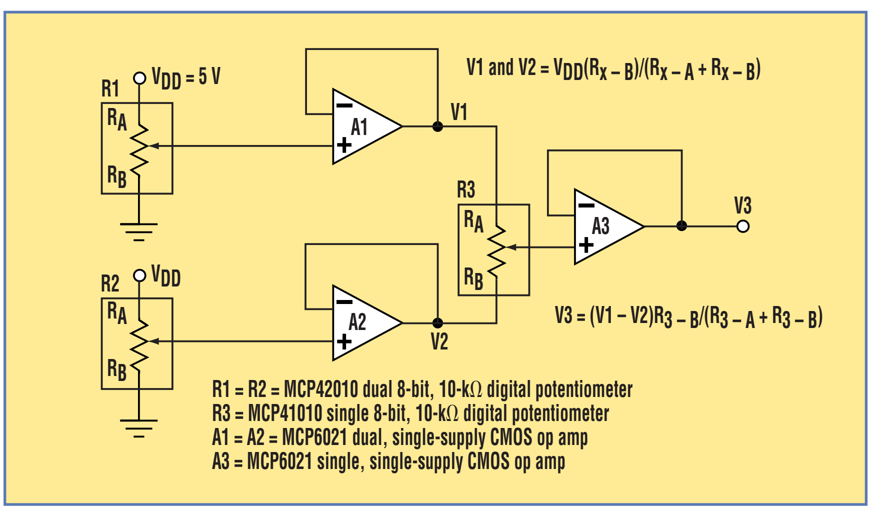
$$V_{1-LSB} = V_{DD} / 2^n = 5\ V / 256 = 19.53\ mV$$

$$V_{2-LSB} = V_{DD} / 2^n = 5\ V / 256 = 19.53\ mV$$

where n = 8 for the 8-bit digital potentiometer.

The actual digital potentiometers making up R1 and R2 have no missing codes in their transfer function. So feasibly, one digital potentiometer could be programmed with a code of 100d (for R1) and the other with a code of 101d (for R2). With this programming, the output voltage at V1 and V2 would be:

$$V1\ (100d) = V_{DD} \times R_{1-B} / (R_{1-B} + R_{1-A})$$




**5. A 16-bit DAC is created with three digital potentiometers and three operational amplifiers. Because the R1 and R2 potentiometers are in the same package and used in a voltage-divider configuration, efficient tracking is possible in terms of nominal value and overtemperature performance.**

$= 5\ V \times (3.906\ k\Omega / 10\ k\Omega)$
$= 1.9531\ V$

V2 (101d)
$= V_{DD} \times R_{2-B} / (R_{2-B} + R_{2-A})$
$= 5\ V \times (3.906\ k\Omega / 10\ k\Omega)$
$= 1.9727\ V$

The voltage difference of V1and V2 is applied across the digital potentiometer, R3. The difference of these two voltages is then divided again by this third digital potentiometer, which is configured as a voltage divider. The LSB size of R3 is equal to:

$$V_{3-LSB} = (V_{DD} / 2^n) / 2^n = V_{DD} / 2^{2n} = V_{DD} / 2^{16}$$

where n = 8 for the 8-bit digital potentiometer. The LSB size of the system at V3 is 76.29 µV, given $V_{DD}$ = 5 V.

In the error analysis of this circuit, it can quickly be found that at 25°C, the nominal errors of the digital potentiometer have the highest potential to create the largest errors. Table 3 lists the nominal and temperature errors affecting the adjustable voltage reference shown in Figure 5. Calculations assume that A1, A2, and A3 are ideal amplifiers; that the MCP4X010 digital potentiometers are used; and that $V_{DD}$ = 5 V. All values are referred to the output, V3.

Although the circuit in Figure 5 is designed as a DAC with 16-bit resolution, the errors of the first stage, including the amplifiers, are divided down by the second stage. Given this error analysis, the circuit in Figure 5 is accurate to 12.3 bits or ±0.114 mV. This analysis doesn't take into account variations in $V_{DD}$ over temperature.

The digital potentiometer has entered the market with clear advantages over the mechanical potentiometer. These include reliability and repeatability. But at first glance, its overtemperature behavior can limit its usefulness. Fortunately, the initial resistance and overtemperature shortcomings can be minimized with a few simple design tricks. If the digital potentiometer is used in circuits so that the resistive elements, either in a dual or single device, are configured in a ratiometric fashion, the nominal absolute resistance value and temperature coefficients of the individual elements are cancelled. This leaves a resistive element that's programmable and equivalent in performance to the mechanical potentiometer.

**Bonnie C. Baker,** currently the analog/interface applications engineering manager at Microchip Technology Inc., earned an MSEE from the University of Arizona, Tucson. Baker can be reached by phone at (602) 612-5051, or via e-mail at bonnie.baker@microchip.com.