Digital Potentiometers – Selection Guides Don't Tell the Whole Story

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Since the appearance of digital potentiometers about 20 years ago, these ICs have grown technologically to become system ICs, incorporating many system support functions in addition to the digitally-controlled potentiometer. However, not all of the features found in the latest digital potentiometers can be listed in selection tables, so this article will shed some light into some of these features while also providing a supplementary look at the system selection guidelines for these products.

In contrast to their mechanical counterparts, digital potentiometers offer significant advantages like greater reliability, accuracy, as well as simple control and remote adjustability via a digital interface. Through their various packaging options, they can also be conveniently assembled anywhere on a printed circuit board. Additionally, there might seem to be little difference between a digital potentiometer and a digital-to-analog converter (DAC). However there are some significant differences between the two devices and its important to understand those differences to select the best solution for your application.

DACs, in general, offer higher resolution when compared to digital potentiometers. In many applications, however, this resolution is only needed over a very narrow adjustment range, as for example in a power supply whose output voltage needs to be adjusted from say 4.95 to 5.05V. A 6-bit digital potentiometer, for example, offers the same resolution as a 10-bit DAC over one-sixteenth of the DAC's range. Thus, a digital potentiometer allows you to place all your resolution bits right where you need them.

Digital potentiometers can be thought of as digitally-controlled resistors, they are more suitable for use where impedance networks are required. The voltage across them can float with respect to ground and the current can flow through them in either direction. DACs, on the other hand, behave like controlled voltage or current sources.

As the original objective of digital potentiometers was to replace mechanical ones, the advantages of digital potentiometers were viewed in conjunction with this main function. Towards that end, the use of EEPROM has made it possible to permanently store the value of a digital potentiometer, equivalent to the shaft rotation/wiper position of its mechanical counterpart. The DS1809 digital potentiometer, for example, offers two ways of storing the value, namely "on demand" (the system commands the chip to store the value) or via an "autostore" feature in which the part stores its value when the voltage applied to it falls below a certain threshold (Fig. 1).

A very useful feature, typically found in laser driver applications, is the ability to protect the non-volatile value of a digital potentiometer with a password. This function can be found in the DS3902. If, however, the safety requirements call for simply avoiding accidentally modifying the programmed value in the digital potentiometer, then a write-protect function may offer a more effective solution. This function can be found in the DS1845 and digital potentiometers from a few vendors.

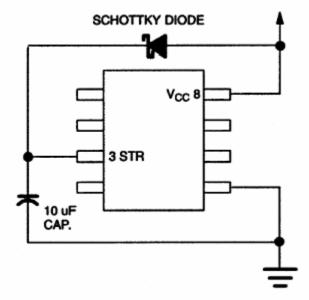


Fig 1. When Vcc falls below a voltage threshold, the DS1809 automatically stores its last setting.

Another function found in digital potentiometers with non-volatile memory is called *one-time programmability* (OTP). One can also accomplish a pseudo OTP function simply by making the digital potentiometer inaccessible to the end user. Both of the above mentioned protection mechanisms are in fact preferred by equipment manufacturers who want the flexibility of being able to reprogram a digital potentiometer which was incorrectly programmed at the factory. Additionally, this feature serves well in applications in which a final adjustment must be made just before the product is shipped – setting the final range or threshold, for example.

When applications demand more than just a stand-alone digital potentiometer, the DS3904, a triple digital pot with integrated analog switches allows the system to digitally switch in or out the potentiometers. Such a capability is handy in applications such as when dual comparator threshold settings are required, or different range settings are needed.

An often overlooked applicability of digital potentiometers and variable resistors is that they can be used in applications where the end-to-end resistance needs to be low, e.g. 100Ω . The DS3906 was conceived precisely to address this type of application. The variable resistors in the chip have pseudo-logarithmic characteristics that make them exhibit a linear characteristic when connected in parallel with lower-value external

resistors as illustrated in Fig. 2. Note that the smaller the external resistance, the greater the resolution.

The output impedance of a digital potentiometer is code-dependent. Their wiper also contains a typical resistance which is in the hundreds of ohms. Both of these characteristics play, however, a secondary role in an application as long as the wiper output is connected to a high-impedance input like that of a buffer op amp. The DS3908 is a dual digital potentiometer which in fact integrates buffer amplifiers. These buffers are programmable gain amplifiers that not only buffer the signal but can amplify its value as well (see Fig. 3). A simple I²C serial control interface and three address pins allows designers to cascade up to eight of these chips to create an array with a total of 16 digital potentiometers.

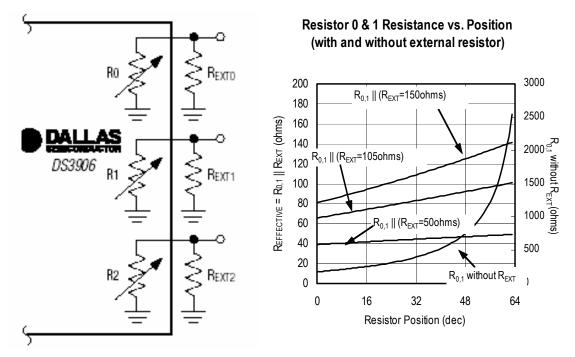


Fig. 2 By connecting resistors in parallel with the DS3606's variable resistors, low-value variable resistors can be obtained.

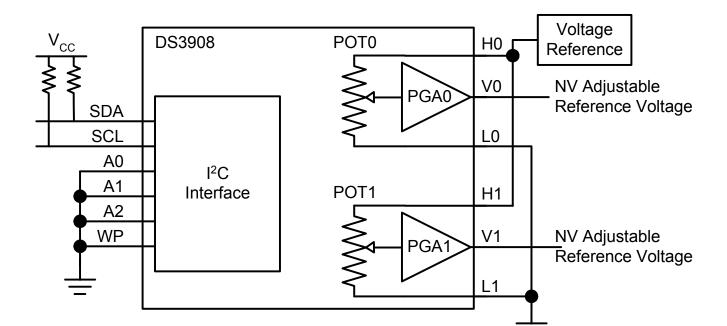


Fig. 3 Dual digital potentiometer with programmable-gain buffers.

If 8 bits of signal resolution is not enough for an application, one can obtain 9 bits via the DS1868, a dual 256-step potentiometer whose potentiometers can be connected in series as shown in Fig. 4. This is referred to as a stacked configuration and it allows the user to double the total end-to-end resistance of the part. The resolution of the combined potentiometers will remain the same as a single potentiometer, but with a total of 512 wiper positions (e.g. 9 bits). Inside the chip, the stack multiplexer block combines the two wipers into one. The chip is controlled via a 3-wire serial interface that allows multiple devices to be cascaded into a daisy-chain configuration.

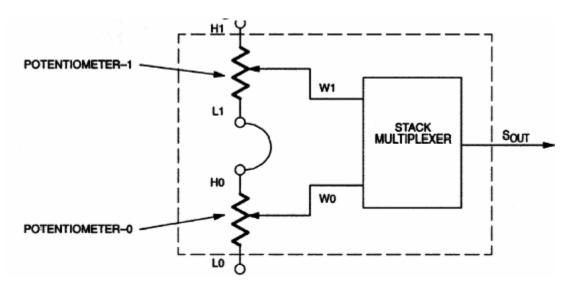


Fig. 4 The signal resolution can be doubled by connecting the two digital potentiometers in the DS1868 as shown.

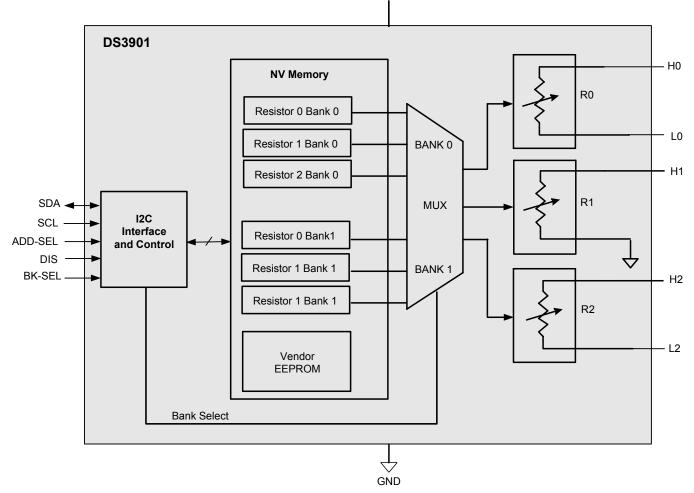
In addition to storing the wiper value, some digital potentiometers, like the DS1845, pack extra EEPROM that can be used to store user data like serial number, manufacturing date, etc. In such devices, the memory can be read by the host system, and thus even the wiper setting values can be read back.

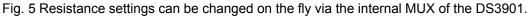
As mentioned earlier, a useful feature is the ability to switch between two resistance values on the fly. Applications requiring this feature include voltage margining, range setting, current-limit threshold selection, and others. Designed for such applications, the DS3901, a triple variable resistor device, also allows the three resistors to be switched

into a high-impedance state (i.e. three resistance states). Additionally, the chip also provides data protection via a two-level password scheme, thus preventing competitors from copying the settings.

Digital potentiometers and digital variable resistors are fabricated in a process that typically limits their absolute tolerance to about $\pm 20\%$. Although this tolerance is relatively wide, it is of minor relevance if the digital potentiometer is used in ratiometric applications. Also, once the digital potentiometer is set, its temperature coefficient is typically around 4ppm/°C. With the aid of on-board EEPROM, the digital potentiometer can be automatically adjusted such that it is virtually invariant to temperature variations. The DS3501, for example, contains a look-up table which gets indexed by a temperature sensor. Each resistance value is referenced to a programmed value at 4°C intervals.

Vcc





Applications Examples

The calculation of the digital value of a digital potentiometer can be easily explained by way of example (see Fig. 6). Suppose that the total digital potentiometer resistance, R_{P_i} is 100k and its number of taps is n = 256. The digital value that must be loaded to set the low side of the wiper, R_{L_i} to 20k Ω would be

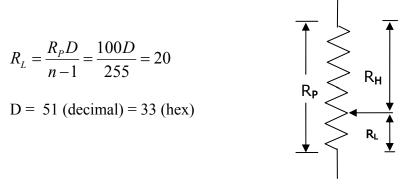
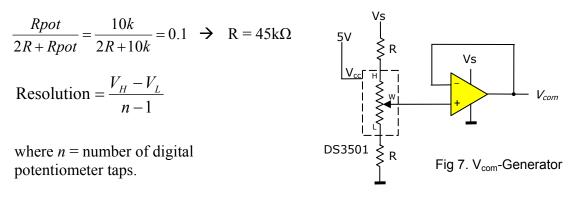


Fig. 6 Digital potentiometer

Normally digital potentiometers can be used at any voltage which lies within their supply voltage rails. The DS3501, however, allows the voltage across its end-to-end resistance to go up to 15.5V although its control section runs off a 5V supply (See Fig. 7). A typical application for this part is the generation of V_{COM} . This voltage serves as a virtual ground for driving the pixels on an LCD. The voltage available is $V_S = 15V$, and for this example it is desired to generate a V_{COM} of 7.5V with a ±10% total adjustment range.

Since V_{COM} was selected to be $V_S/2$, the upper and lower fixed resistors in the voltage divider are chosen to be of equal value. The DS3501 has a total resistance value of $10k\Omega$. Then,



Now

$$V_H - V_L = V_S \left(\frac{R_{POT}}{2R + R_{POT}}\right)$$

Substituting $V_H - V_L$ into the equation for resolution, we obtain

Resolution =
$$\frac{V_s}{n-1} \left(\frac{R_{POT}}{2R + R_{POT}} \right) = 11.8 \text{mV/tap}$$

The maximum voltage the potentiometer sees is

$$V_{H} = V_{S} \left(\frac{R + R_{POT}}{2R + R_{POT}} \right) = 8.25 \text{V}$$

Example 2: Digital potentiometers are very often used in power supplies. As previously mentioned, the wiper resistance plays a minor role if it is connected to a high-impedance network. The following example shows the case where the digital potentiometer is not connected to a high impedance circuit, but rather to a feedback network where the wiper resistance does need to be considered. See Fig. 8a.

Suppose that it is desired to trim the output voltage of a power supply from 4.95 to 5.05V. The circuit in Fig. 8a shows a basic configuration of the error amplifier. The amplifier compares the divided-down equivalent of the output voltage to a given reference and amplifies the difference. For this example, it is desired to attenuate the error by at least 20dB.

To keep the feedback resistor from being impractically large and also to minimize errors due to the amplifier's bias current, it is best to use a digital potentiometer with the lowest end-to-end resistance possible. A look at the available choices reveals that the lowest end-to-end resistance available is $10k\Omega$. To leverage the entire resolution of the digital potentiometer to the power supply output's adjustment range we connect a low value resistor in parallel with the potentiometer (again Fig. 8a). For simplicity we chose this parallel resistor to be 100Ω . Note that this resistor is two orders of magnitude lower than the end-to-end resistance of the digital potentiometer so that the latter can be considered as being connected across a low-output-impedance voltage source.

To determine the values of R_1 and R_2 , the voltage divider calculation can be simplified by removing the potentiometer. In reference to Fig. 8b, when the op amp is connected as shown by the solid lines, it will steer the output voltage, V_o , to 5.05V. When the op amp is connected as depicted by the broken line, it will steer V_o to 4.95V. In both cases the voltage at the inverting input of the amplifier is assumed to be equal to 1.2V. By equating the resulting two voltage-divider equations, we obtain

 $5.05R_2 = 4.95(R + R_2)$

Since $R = 100\Omega$, R_2 becomes 4.95k Ω . Then, by arbitrarily choosing the case where the op amp is connected as shown by the solid lines in Fig. 8b, we can write:

$$\frac{5.05R_2}{R_1 + R_2 + R} = 1.2$$

Substituting the values for R and R_2 into the above equation, R_1 becomes 15.78k Ω .

The total ladder resistance adds up to $20.83k\Omega$. So, if V_o is 5V the current flowing through the resistance ladder becomes 240μ A. This current is at least two orders of magnitude higher than the worst-case bias current of a typical general-purpose amplifier (e.g. the MAX4493). It is also adequate enough to prevent noise from getting picked up by the amplifier which could result in the power supply becoming unstable.

For this example we select the DS1804-10 digital potentiometer. Its wiper resistance is 400Ω typical and 1000Ω maximum. As shown in Fig. 8c, we can represent the network looking into the ladder resistance by a Thevenin resistance, R_{TH}, connected in series with the wiper resistance. This Thevenin resistance is given by

$$R_{TH} = \frac{(R_1 + R/2)(R_2 + R/2)}{R_1 + R_2 + R}$$

Substituting the values calculated previously, $R_{TH} = 3.8k\Omega$. Adding the maximum wiper resistance, R_W , of 1000 Ω , the amplifier sees an input resistance of 4.8k Ω . A 20dB of gain is equivalent to a gain of 10, so the feedback resistor, R_F , required becomes 48k Ω . Repeating this calculation but now using the typical value of R_W yields a gain of 21dB, not a significant deviation from the desired gain.

The maximum wiper capacitance of 7pf in conjunction with the R_{TH} and R_W produce a pole at 5.4MHz. This is acceptable since this pole lies well above the feedback loop's 0dB crossover frequency therefore posing no negative effect on power supply's dynamic behavior.

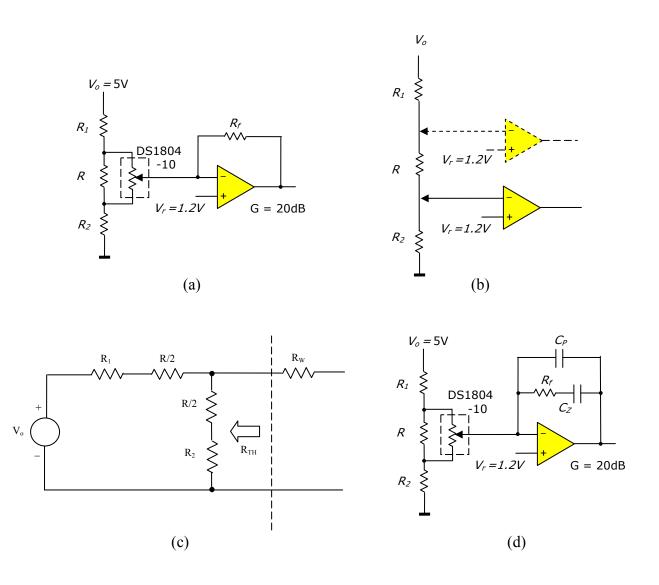


Fig 8. Error amplifier compensation

The error amplifier's feedback loop is typically tailored so that amplifier's open loop gain is applied at dc. This implies having a pole at the origin, which comes about as a result of the two capacitors in the amplifier's feedback path being in parallel with an infinite impedance (see Fig. 8d). In a current-mode-controlled power supply a zero can be placed slightly ahead of the moving pole caused by the power supply's output capacitor and the load. The zero's corner frequency is given by:

$$f_Z = \frac{1}{2\pi R_F C_Z}$$

A pole can placed at least one decade above the zero in order to roll off any parasitic effects like the output capacitor's equivalent series resistance. This pole's frequency is given by:

$$f_P = \frac{1}{2\pi R_F C_P}$$
 where $C_P >> C_Z$

If the pole and the zero mentioned above are less than a decade apart, then C_P in the pole frequency equation needs to be substituted by $C_P || C_Z$. In voltage-mode power supplies, two zeros at equal frequencies are typically required in order to offset the large phase shift caused by the output inductor and capacitor. If the LC resonant frequency is very high, the feedback configuration of Fig 8d can still be used, however making sure that the 0dB crossover point occurs before this resonant frequency and the high-frequency pole in the amplifier's feedback loop is placed at least a decade above the LC resonant frequency.

The details of loop compensation go beyond the scope of this article, and the interested reader can contact Maxim at the eMail address given at the end of this article for further information.

Finally, the 1.2V reference voltage for the non-inverting input of the error amplifier can be obtained by using a DS4303, a precise electronically adjustable reference which can be programmed to within 300mV of its supply rails.

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