AN1080

Understanding Digital Potentiometer Resistor Variations

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INTRODUCTION

All semiconductor devices have variations over process. In the case of digital potentiometer devices, this process variation affects the device resistive elements (R_{AB} -> R_S and R_W). These resistive elements also have variations with respect to voltage and temperature, which will also be discussed.

This application note will discuss how process, voltage, and temperature affect the Resistor Network's characteristics and specifications. Also, application techniques will be covered that can assist in optimizing the operation of the device to improve performance in the application.

The process technology used also affects the operational characteristics. We will focus on the characteristics for devices fabricated in CMOS.

TERMINOLOGY

To assist with the discussions in this application note, the following terminology will be used. Figure 1 illustrates several of these terms.

Resolution - The number of unique wiper positions that can be selected between Terminal B and Terminal A.

Wiper Value - The value in the wiper register which selects the one wiper switch to close so that the Wiper Terminal is connected to the Resistor Network.

R_{AB} - The total resistance between the A Terminal and the B Terminal.

R_S - The Step resistance. This is the change in resistance that occurs between two adjacent wiper register values. It is also the R_{AB} resistance divided by the number of R_S resistors (resolution) in the Resistor Ladder.

R_W - The resistance of the analog switch that connects the Wiper Terminal to the Resistor Ladder. Each analog switch will have slightly different resistive characteristics.

Resistor Ladder - Is the serial string of R_S resistors between Terminal B and Terminal A. The total resistance of this string equals R_{AB}.

Resistor Network - Is the combination of R_S resistors and R_W resistor that create the voltage levels and current paths between the A Terminal, B Terminal, and Wiper Terminal.

R_{BW} - The total resistance from Terminal B to the Wiper Terminal. This resistance equals:

R_S * (Wiper Register value) + R_W.

R_{AW} - The total resistance from Terminal A to the Wiper Terminal. This resistance equals:

R_S * (Full Scale value - Wiper Register value) + R_W.

Full Scale - When the Wiper is connected to the closest tap point to Terminal A.

Zero Scale - When the Wiper is connected to the closest tap point to Terminal B.

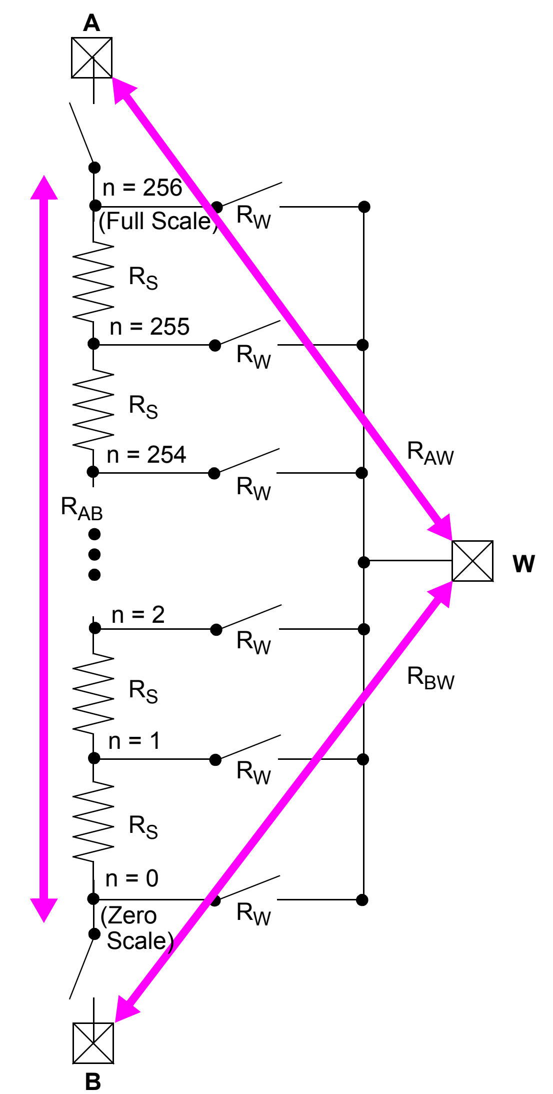

FIGURE 1: *8-Bit Resistor Network.*

THE R_{AB} RESISTANCE

The R_{AB} resistance is the total resistance between Terminal A and Terminal B. The R_{AB} resistance is really a resistor string of R_S resistors. The R_S resistors are designed to be uniform, so they have minimal variation with respect to each other. The R_S resistors, and the R_{AB} resistance, will track each other over voltage, temperature, and process.

Many manufacturers specify the devices R_{AB} resistance to be ±20% from the targeted (typical) value. This specification is to indicate that from “device-to-device” the resistance could range ±20% from the typical value. This specification is NOT meant that a given devices resistance will vary ±20% over voltage and temperature.

So, when the R_{AB} resistance is +10% from the typical value, then each R_S resistor is also +10% from the typical value.

The “device-to-device” R_{AB} resistance could be off by up to 40% of the typical value. This occurs if one device has a resistance (R_{AB}) that is -20% and the other device is +20%.

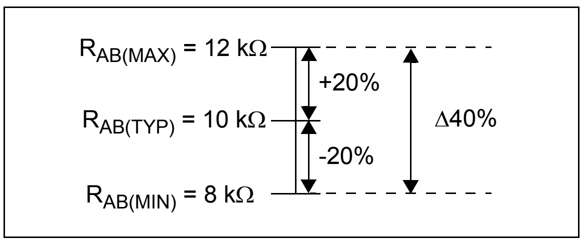

FIGURE 2: *R_{AB} Variations.*

So, naturally the R_{AB} resistance may have some effect in a Potentiometer configuration (voltage divider), but this variation can have a real effect in a Rheostat configuration (variable resistor).

In the Potentiometer configuration, if the A and B terminals are connected to a fixed voltage, then this variation should not effect the system. But, if either (or both) the A or/and B terminals are connected through resistors to the fixed voltage source, then the change in R_{AB} value could effect the voltage at the W terminal (for a given wiper code value).

In the Rheostat configuration, the R_{BW} resistance value will vary as R_S varies. So, at full scale R_{BW} approximately equals R_{AB}, and will have the same ±20% from the typical value.

The Step Resistance (R_S)

Microchip offers Digital Potentiometer devices with typical R_{AB} resistances of 2.1 kΩ, 5 kΩ, 10 kΩ, 50 kΩ and 100 kΩ. These devices will either offer 6-bits or 8-bits of resolution. The step resistance (R_S) is the R_{AB} resistances divided by the number of wiper steps.

The step resistance is important to understand when you are using the device in a rheostat mode, or the potentiometer is being windowed by resistors on the Terminal A and/or on the Terminal B. Table 1 shows the step resistances available for the different R_{AB} values available.

TABLE 1: STEP RESISTANCE

R_{AB} Resistance (kΩ - typ.)	Step Resistance (R_S) (Ω - typ.)		Comment
	6-Bit Device (63 R_S)	8-Bit Device (256 R_S)	
2.1	33.33	—	Smallest Step resistance available
5.0	79.37	—	
10.0	158.73	39.06	Can trade off between cost and Step Resistance (resolution)
50.0	793.65	195.31	Can trade off between cost and Step Resistance (resolution)
100.0	—	390.63	Largest R_{AB} resistance

On a semiconductor device, a resistor can be made with metal/poly/contact components. Designing a structure from these components can be used to form a resistive element (R_S). Repeating this resistive element into a string of resistors (R_S) creates the R_{AB} resistance. The node between each R_S resistor is a contact point (source or drain) for the wiper switch.

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Devices with Multiple Potentiometers

Some devices are offered that have two or more independent potentiometers. Each potentiometer will exhibit similar characteristics given similar conditions (terminal voltages, wiper settings, …).

The R_{AB} variation between potentiometers on the same silicon is relatively small. In dual potentiometer devices, the variation is typically specified as a maximum variation (R_{AB1}-R_{AB2}/R_{AB1} or R_{AB1}-R_{AB2}/ R_{AB2}) of 1%. This is true even though from device-to-device, the R_{AB} variation can be ±20% over process.

The R_{AB} of both potentiometers (and therefore the R_Ss) will track each other as the device conditions change. It is assumed that the terminals of each potentiometer are at the same voltages (and wiper value). If not, then they may not track each other to the same degree.

R_{AB} vs. R_{BW} Resistance

The R_{AB} resistance is "constant" in that it is independent of the value in the wiper register. While the R_{BW} (or R_{AW}) resistance is directly related to the value in the wiper register. When the wiper register is loaded with it's maximum value, the R_{BW} resistance is close to R_{AB} resistance. The "closeness" depends on the Resistor Network implementation (see Figure 4), the R_S resistance, and the wiper resistance (R_W).

THE R_W RESISTANCE

Figure 4 show the common way to illustrate the block diagram. In this figure, the wiper resistance is represented as a resistor. In actuality, the wiper is connected to each R_S node with an analog switch (see Figure 3). Each of these analog switches has a resistive property to them and will vary from switch to switch. Also, the resistive nature of these analog switches is more susceptible to process variations, voltage, and temperature than the step resistors (R_S) in the resistor ladder.

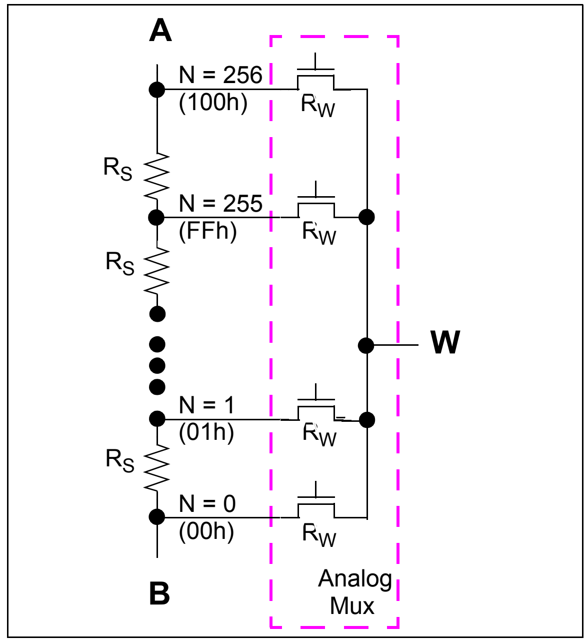

FIGURE 3: *R_W Implementation.*

The characteristics of the analog switch depends on the voltages on the switch nodes (source, drain, and gate). The characterization graphs shown in Figure 10 through Figure 13 had Terminal B to V_{SS} and Terminal A to V_{DD}.

Within a voltage range, the change in resistance will be linear relative to the device voltage. At some point as the voltage decreases, the resistive characteristics of the switches will become non-linear at increase exponentially. This is related to the operational characteristics of the switch devices at the lower voltage.

All the wiper switches will start to increase non-linearly at about the same voltage.

Temperature also effects the resistive nature of the wiper switches greater than the R_{AB} (R_S) resistance.

The wiper resistance increases as the voltage delta between the resistor network node and the voltage on the analog mux switch becomes "small", so that the switch is not fully turned on. The wiper resistance curve would look different if Terminal A was at V_{DD}/2 while Terminal B is at V_{SS}. In this case, the higher value wiper codes would have the higher wiper resistance (R_W).

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The Resistor Network

Figure 4 shows three possible Resistor Network implementations for an 8-bit resistor network. Each has an advantage and a disadvantage. The system designer needs to understand which implementation the device uses to ensure the circuit meets the system requirements.

Implementation A has 256 steps (2^8 steps) and 256 Step Resistors (R_S), but the wiper register must be 9-bits wide to allow the selection of N = 256 (Full Scale). This increases the complexity of the wiper decode logic (increases cost), but this implementation allows the Wiper (W) to be connected to Terminal A.

Implementation B has 255 steps (2^8 - 1 steps) but 256 Step Resistors (R_S). This allows the wiper register to be 8-bits wide, but now the Wiper (W) can no longer connect to Terminal A, since there is one R_S resistor between the maximum wiper tap position and the Terminal A connection.

Implementation C has 255 steps (2^8 - 1 steps) and 255 Step Resistors (R_S). This allows the wiper register to be 8-bits wide, and to allow the selection of N = 255 (Full Scale).

> **Note:** The possible nodes that the wiper can connect to on the resistor ladder will depend on the digital potentiometer device.

TABLE 2: IMPLEMENTATION DIFFERENCES

Implementation	"True" Full Scale	Wiper Register	R_{AB} =	R_{BW} =	Comment
A	Yes	9-bits	256 R_S	256 R_S + R_W	Wiper can connect to the full range of taps from Terminal A and Terminal B, but firmware must take into account the extra addressing bit. The increased complexity of the addressing decode adds cost to the device.
B	No	8-bits	256 R_S	255 R_S + R_W	Wiper can not connect to the Terminal A tap. The application design or the controller firmware may be required to take this into account.
C	Yes	8-bits	255 R_S	255 R_S + R_W	Wiper can connect to the full range of taps from Terminal A and Terminal B, but the controller firmware would need to ensure it addressed that there are 255 R_S resistors and not 256 R_S resistors.

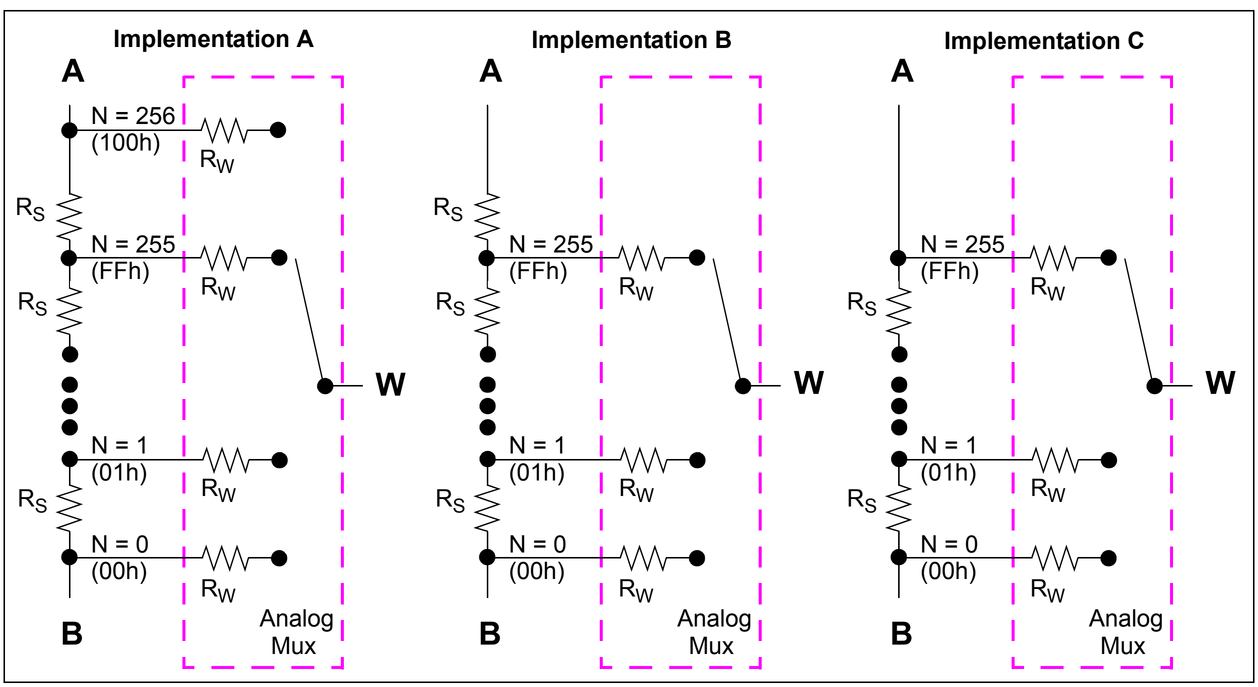

FIGURE 4: *Possible 8-Bit Resistor Network Implementations.*

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THE R_{BW} OR R_{AW} RESISTANCE

When using a Digital Potentiometer device in a Rheostat configuration, should the variable resistor be created from the Wiper to Terminal B (R_{BW}) or from the Wiper to Terminal A (R_{AW})?

This question really depends on which Terminal (A or B) that the Wiper connects to when the wiper register is loaded with 0h (Zero Scale). For this discussion, we will assume that the Wiper will connect to Terminal B.

In either case, you can load the wiper register to get the desired resistance value, but if you recall Terminal B is at Zero-Scale. So, that means when using the R_{BW} configuration, as the wiper register is incremented, the resistance increases. Conversely, when using the R_{AW} configuration, as the wiper register is incremented, the resistance decreases. Which configuration is used depends more on any advantages that may occur in the applications firmware algorithm for the control of the resistance.

The Floating Terminal, What to do?

When the Digital Potentiometer device is used in a Rheostat configuration, the third terminal (let's say Terminal A) is "floating". So what should be done with it?

There are two possibilities:

1. "Tie" it to the W Terminal.
2. Leave it floating.

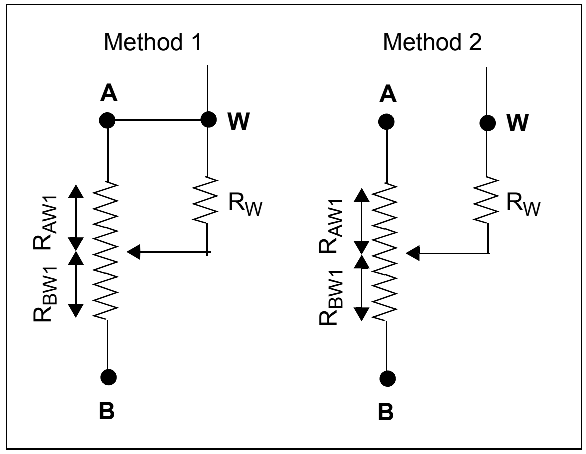

FIGURE 5: *Rheostat Configurations.*

Method 1: "Tie" it to the W Terminal

In this case, the effective resistance of the wiper resistance (R_{WEFF}) will be $R_W \| R_{AB1}$. This resistance will always be less than R_W, but it will vary over the selected tap position. The R_{WEFF} resistance can be calibrated out of the system, but it becomes a much more complicated controller firmware task.

Method 2: Leave it floating

This way, the wiper resistance remains "constant" over the selected tap position. This becomes much easier for the controller firmware to calibrate out of the system.

VARIATIONS OVER VOLTAGE AND TEMPERATURE

There are two variations that occur over voltage and temperature that we will look at. These are the variations of the R_{AB} resistance and the R_W resistance. The characterization graphs also show how these variations effect the INL and DNL error of the device.

R_{AB} Variation

For this discussion, we will look at the characterization graphs from the MCP402X Data Sheet (DS21945D). These graphs are shown in Figure 6 through Figure 9. These graphs are used to illustrate several points, but the general characteristics will be seen on all digital potentiometers.

Note 1:	The MCP401X and MCP402X devices have 6-bits of resolution (R_{AB} = 63 R_S).
2:	For this characterization, Terminal A = V_{DD} and Terminal B = V_{SS}.

Depending on the silicon implementation of the R_S resistors will determine the characteristic shape of the resistance over temperature. For these devices, the R_S resistor was designed so that one part of the resistor has a negative temperature coefficient and another part of the resistor has a positive coefficient. That is the reason why the resistance bows over the temperature range. This is done to minimize the end-to-end change in resistance, and in effect reduces the worst-case delta resistance over temperature.

Table 3 shows the R_{AB} data from the MCP402X Data Sheet (DS21945D) Characterization Graphs at 5.5V and 2.7V, and over temperature (@ -40°C, +25°C and +125°C). The minimum and maximum resistance values are also captured. This data was then analyzed over this characterization range.

Note:	The R_S value can be calculated by: R_{AB} / (# R_S resistors in R_{AB})

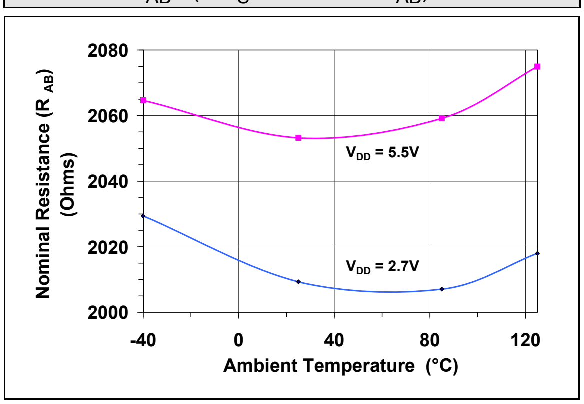

FIGURE 6: *MCP402X 2.1 kΩ – Nominal Resistance (Ω) vs. Ambient Temperature and V_{DD}.*

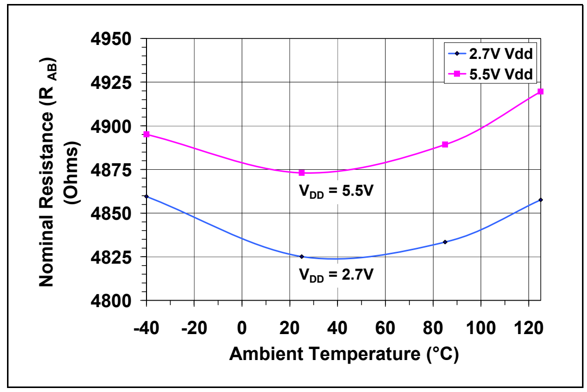

FIGURE 7: *MCP402X 5 kΩ – Nominal Resistance (Ω) vs. Ambient Temperature and V_{DD}.*

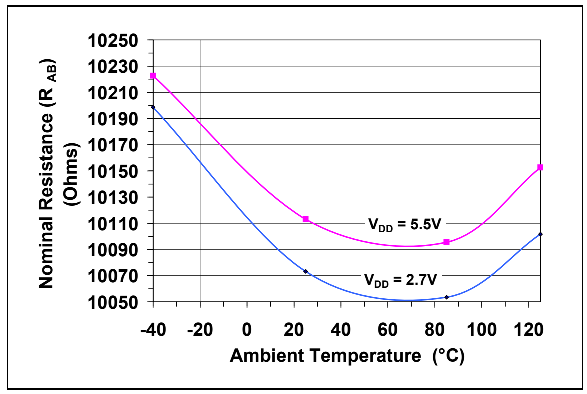

FIGURE 8: *MCP402X 10 kΩ – Nominal Resistance (Ω) vs. Ambient Temperature and V_{DD}.*

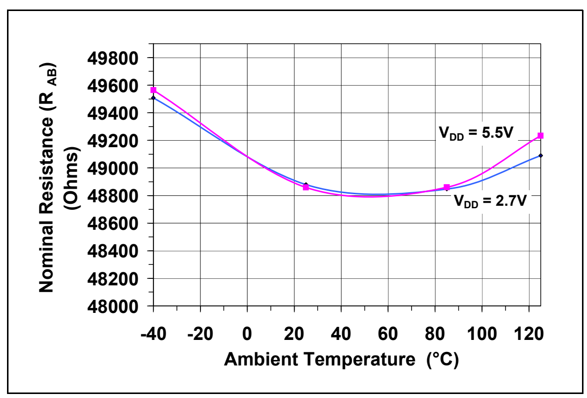

FIGURE 9: *MCP402X 50 kΩ – Nominal Resistance (Ω) vs. Ambient Temperature and V_{DD}.*

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From the analysis, it can be determined that the smaller the R_{AB} resistance, the greater the effect that voltage and temperature has as a percentage of the target resistance.

Also, if the application is operating at a narrower voltage or temperature window, the R_{AB} variation will be less than across the entire voltage/temperature range.

It is interesting to note that depending on the devices target R_{AB} value, either limiting the voltage of operation or limiting the temperature range will lead to minimizing the variation. In the case of the 2.1 kΩ device, if the voltage is held constant, the variation is about 1%, while the variation over temperature is about 2.2%. On the 5.0 kΩ device, variation over temperature is about the same as the variation over voltage. for the 10.0 kΩ and 50.0 kΩ devices, the variation over voltage is much larger than the variation over temperature.

TABLE 3: R_{AB} VALUES AND VARIATION OVER VOLTAGE AND TEMPERATURE

Device RAB	Voltage	Characterization R_{AB} Value								
		-40°C	+25°C	+125°C	Min.	Max.	Delta	% (of Target Resistance)	Lowest Min.[1] to Highest Max.[1]	% (of Target Resistance)
2.1 kΩ	5.5V	2065	2053	2075	2052	2075	22	0.95%	68	3.24%
	2.7V	2030	2010	2018	2007	2030	23	1.10%		
Delta Resistance over Voltage		35	43	57	48	45				
% (of Target Resistance: 2.1 kΩ)		1.67%	2.05%	2.71%	2.29%	2.14%				
5.0 kΩ	5.5V	4895	4873	4920	4873	4920	47	0.94%	96	1.92%
	2.7V	4860	4825	4860	4824	4860	36	0.72%		
Delta Resistance over Voltage		35	48	60	49	60				
% (of Target Resistance: 5.0 kΩ)		0.70%	0.96%	1.20%	0.98%	1.20%				
10.0 kΩ	5.5V	10223	10113	10152	10092	10223	131	1.31%	173	1.73%
	2.7V	10200	10073	10102	10050	10200	150	1.50%		
Delta Resistance over Voltage		23	50	40	42	23				
% (of Target Resistance: 10.0 kΩ)		0.23%	0.50%	0.40%	0.42%	0.23%				
50.0 kΩ	5.5V	49590	48880	49220	48810	49590	780	1.56%	800	1.6%
	2.7V	49510	48880	49080	48790	49510	720	1.44%		
Delta Resistance over Voltage		80	0	140	20	80				
% (of Target Resistance: 50.0 kΩ)		0.16%	0.00%	0.28%	0.04%	0.16%				

Note 1: The lowest Minimum is typically found at 2.7V and the highest Maximum is typically found at 5.5V. See shaded cells.

R_W Variation

For this discussion, we will look at the characterization graphs from the MCP402X Data Sheet (DS21945D). These graphs are shown in Figure 10 through Figure 13. These graphs are used to illustrate several points, but the general characteristics will be seen on all digital potentiometers.

Note 1:	The MCP401X and MCP402X devices have 6-bits of resolution (R_{AB} = 63 R_S).
2:	For this characterization, Terminal A = V_{DD} and Terminal B = V_{SS}.

When the device is at 5.5V, the wiper resistance is relatively stable over the wiper code settings. As the device voltage drops, the wiper resistance increases. Then, at some threshold voltage, the middle codes of the wiper will start to have the highest resistance (see Figure 11). This is due to the resistive characteristics of the analog switch with respect to the voltages on the switch nodes (source, drain, and gate).

The variation of the wiper resistance is also influenced by the wiper code selected and the voltages on Terminal A and Terminal B.

Depending on the configuration of the digital potentiometer in the application (V_{DD}, V_A, V_B, and wiper code), the wiper resistance may show waveform over wiper code.

This change in wiper resistance (R_W) effects the INL of the device much greater for devices with the smaller R_{AB} (and therefore R_S) resistance value. This can be seen in comparing the wiper resistance and INL error in the graphs of Figure 11 and Figure 13.

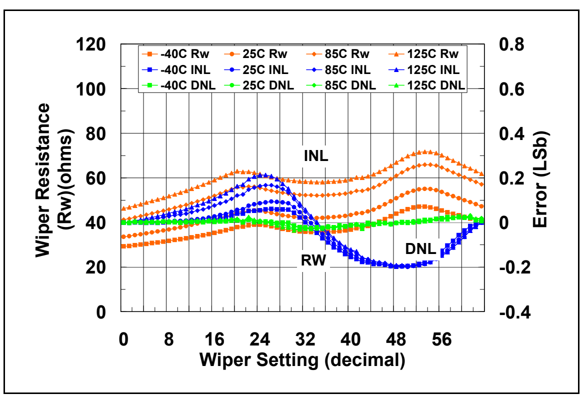

FIGURE 10: *MCP402X 2.1 kΩ Rheo Mode – R_W (Ω), INL (LSb), DNL (LSb) vs. Wiper Setting and Ambient Temperature (**V_{DD} = 5.5V**).*

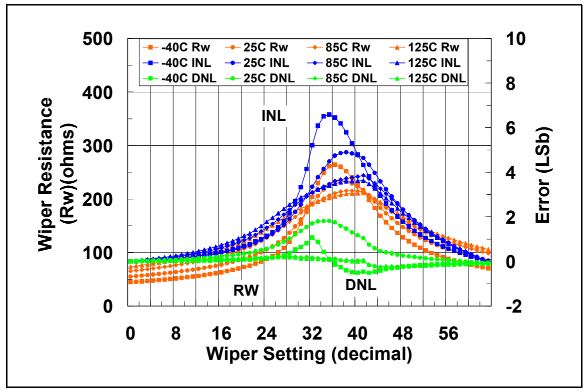

FIGURE 11: *MCP402X 2.1 kΩ Rheo Mode – R_W (Ω), INL (LSb), DNL (LSb) vs. Wiper Setting and Ambient Temperature (**V_{DD} = 2.7V**).*

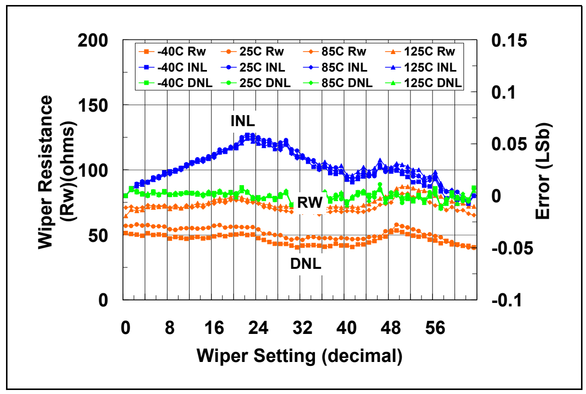

FIGURE 12: *MCP402X 50 kΩ Rheo Mode – R_W (Ω), INL (LSb), DNL (LSb) vs. Wiper Setting and Ambient Temperature (**V_{DD} = 5.5V**).*

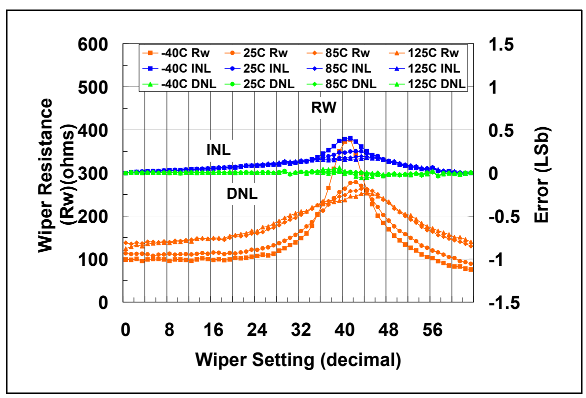

FIGURE 13: *MCP402X 50 kΩ Rheo Mode – R_W (Ω), INL (LSb), DNL (LSb) vs. Wiper Setting and Ambient Temperature (**V_{DD} = 2.7V**).*

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Table 4 shows the relationship of the Step resistance (R_S) to the Wiper Resistance. This is important to understand when the resistor network is being used in a Rheostat configuration, since the variation of the wiper resistance (R_W) has a direct effect on the R_{BW} (or R_{AW}) resistance. The system can be designed to calibrate these variations as long as the system is capable of measuring the digital potentiometer device voltage and the system temperature.

TABLE 4: TYPICAL STEP RESISTANCES AND RELATIONSHIP TO WIPER RESISTANCE

Resistance (Ω): Typical: Total (R_{AB})	Resistance (Ω): Typical: Step (R_S): 6-bit Device (63 resistors)	Resistance (Ω): Typical: Step (R_S): 8-bit Device (256 resistors) (4)	Resistance (Ω): Wiper (R_W) (3): Typical	Resistance (Ω): Wiper (R_W) (3): Max @ 5.5V	Resistance (Ω): Wiper (R_W) (3): Max @ 2.7V	R_W / R_S (%) (1): R_W = Typical	R_W / R_S (%) (1): R_W = Max @ 5.5V	R_W / R_S (%) (1): R_W = Max @ 2.7V	R_W / R_{AB} (%) (2): R_W = Typical	R_W / R_{AB} (%) (2): R_W = Max @ 5.5V	R_W / R_{AB} (%) (2): R_W = Max @ 2.7V
2100	33.33	—	75	125	325	225.0%	375.0%	975.0%	3.57%	5.95%	15.48%
5000	79.37	—	75	125	325	94.5%	157.5%	409.5%	1.5%	2.50%	6.50%
10000	158.73	—	75	125	325	47.25%	78.75%	204.75%	0.75%	1.25%	3.25%
	—	39.06	75	100	125	192.0%	256.0%	320.0%	0.75%	1.0%	1.25%
50000	793.65	—	75	125	325	9.45%	15.75%	40.95%	0.15%	0.25%	0.65%
	—	195.31	75	100	125	38.4%	51.2%	64.0%	0.15%	0.20%	0.25%
100000	—	390.63	75	100	125	19.2%	25.6%%	32.0%	0.08%	0.10%	0.13%

Note 1: R_S is the typical value. The variation of this resistance is minimal over voltage.

2: R_{AB} is the typical value. The variation of this resistance is minimal over voltage.

3: R_W values are taken from the MCP402X Data Sheet (6-bit devices) and the MCP41XXX/MCP42XXX Data Sheet (8-bit devices).

4: MCP41XXX and MCP42XXX devices.

THE A AND B TERMINALS

The voltage on the A and B terminals (V_A and V_B) can be any voltage within the devices power supply rails (V_{SS} and V_{DD}). Lets call the voltages at these nodes, V_A and V_B.

The voltage across the resistor R_{AB} (V_{AB}) is | V_A - V_B |. In the circuit shown in Figure 14, as the V_{AB} voltage becomes smaller relative to the voltage range, the effective resolution of the device increase, though the resolution is limited to between the V_A and V_B voltages.

This means that the potentiometer can be used to trim a voltage set point within a defined voltage window (see Figure 14). So, if the digital potentiometer is 8-bits (256 steps) and the delta voltage between V_A and V_B is 1V, then each step of the digital potentiometer results in a change of 1/256 V, or 3.9 mV. If the device needed to have this resolution over an entire 5V range, then the digital potentiometer would require 1280 steps, which is over 10-bits of accuracy.

This allows a less precise (lower cost) device to be used for more precise circuit tuning over a narrower voltage range. Table 5 shows the effective resolution of the digital potentiometer relative to the system voltage and the V_A - V_B voltage.

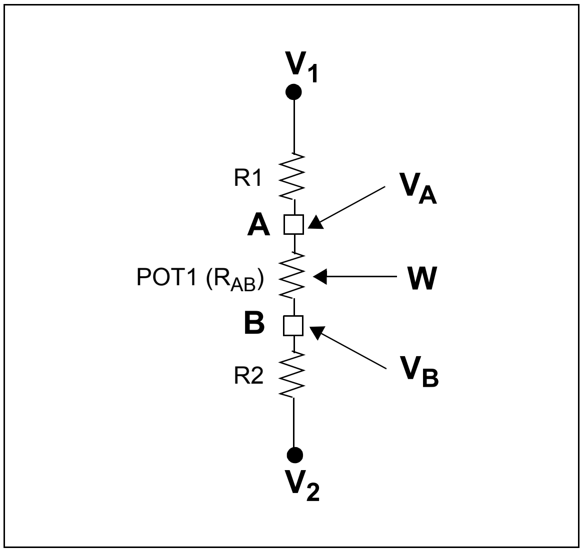

FIGURE 14: *Windowed Trimming.*

There is no requirement for a voltage polarity between Terminal A and Terminal B. This means that V_A can be higher or lower then V_B.

TABLE 5: HOW THE V_{AB} VOLTAGE EFFECTS THE EFFECTIVE RESOLUTION

V_{AB} (V)	Step Voltage (V_S) (mV)		Effective Resolution		Comment
	6-bit Device (63 R_S)	8-bit Device (256 R_S)	6-bit Device (63 R_S)	8-bit Device (256 R_S)	
5.0	79.4	19.5	6-bits	8-bits	V_{AB} = V_{DD}
2.5	39.7	9.8	7-bits	9-bits	V_{DD} = 5.0V, V_{AB} = V_{DD}/2
1.25	1.98	4.9	8-bits	10-bits	V_{DD} = 5.0V, V_{AB} = V_{DD}/4

Shutdown Mode

Some devices support a "shutdown" mode. The purpose of this mode is to reduce system current. A common implementation is to disconnect either Terminal A or Terminal B from the internal resistor ladder. This creates an open circuit and eliminates the current from Terminal A (or Terminal B) through the R_S resistors to Terminal B (or Terminal A). The current to/from the wiper depends on what the device does with the W Terminal in shutdown. The MCP42XXX device forces the W Terminal to connect to Terminal B (Zero Scale).

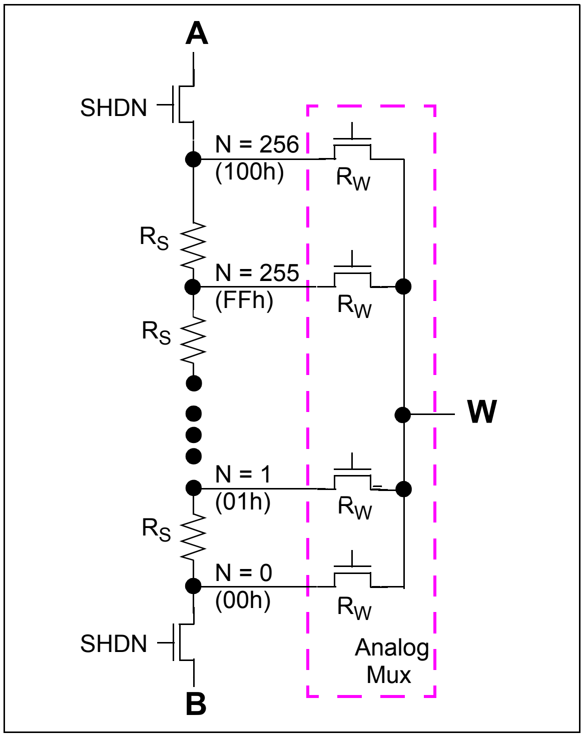

FIGURE 15: *Disconnecting Terminal A (or Terminal B) from the Resistor Ladder.*

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IMPLEMENTING A MORE PRECISE RHEOSTAT

The R_{AB} (R_S) value of a typical digital potentiometer can vary as much as ±20% from device to device. This variation can have a great effect on a circuit that is using the R_{BW} resistance for tuning and this variation for the rheostat value may not be desirable.

If you want to make your variable resistor more precise for system calibration and tuning, the following technique may be useful.

To create a circuit with greater accuracy, the system needs to be able to calibrate the digital potentiometer to make a precise rheostat. This is at a cost of the resolution of the digital potentiometer.

At the system manufacturing test, a method needs to be present to measure the resistance of the R_{AB} value. This could be done by measuring the current through R_{AB}. This value ($R_{AB(CAL)}$) would be saved on the embedded systems non-volatile memory. The embedded systems controller could use this information to calibrate the rheostat value (R_{BW}), where:

$$R_{BW} = ((R_{AB(CAL)}/\text{Resolution}) * \text{Wiper Value}) + R_W$$

For this discussion, we will use a digital potentiometer with a typical R_{AB} resistance of 10 kΩ. That means that the R_{AB} resistance could be as small as 8 kΩ ($R_{AB(MIN)}$) or as large as 12 kΩ ($R_{AB(MAX)}$). Figure 16 a graphic representation of the variations of R_{AB} resistance by showing the minimum and maximum resistances verses the wiper code value.

Table 6 shows the actual calculations for each step for the typical R_{AB} resistance (10 kΩ) and worst-case R_{AB} resistances (8 kΩ and 12 kΩ). When the R_{AB} (R_{BW}) resistance is 12 kΩ, the R_{BW} = 8 kΩ crossover occurs at wiper value 171 (decimal).

Very few devices will actually be the 8 kΩ value, but every device will have a wiper register value that will be close to this 8 kΩ resistance. The circuit should assume that the resistance is the minimum. That is because all devices can have a wiper value which “creates” this resistance value.

The embedded systems controller firmware would take the calibration value and ensure that the digital potentiometer wiper value did not exceed the desired resistance (8 kΩ). For a system that had a “typical” device (10 kΩ), that would mean the wiper value would not exceed 205 (decimal), while for a “+20% “device (12 kΩ) the wiper value would not exceed 171 (decimal). These values give the closest resistance value to the desired rheostat target value of 8 kΩ.

The calibration information could be represented as the maximum wiper value code or as the actual R_{AB} or R_S value. The embedded systems controller firmware then would calculate the appropriate wiper values for the desired R_{BW} resistance. Voltage and temperature calibration information could also be stored.

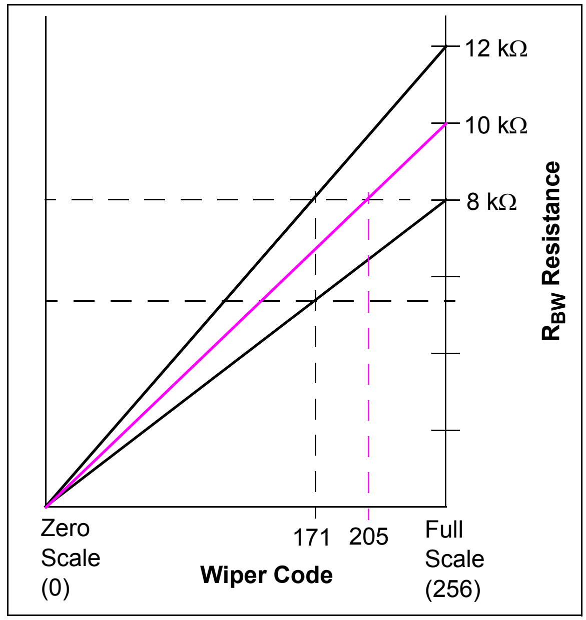

FIGURE 16: *R_{AB} Variation.*

Here we have designed the application circuit where this rheostat only operates from 0Ω to 8 kΩ and all digital potentiometer devices (over process) will meet this requirement. This means that we have reduced the resolution of the digital potentiometer since we no longer have the full 256 steps. Looking at the worst-case resistance (+20%), there are a maximum of 171 steps. This means that the worst-case step accuracy is 1/171 (~0.58%). This represents a resolution of approximately 7.4-bits. We have a trade-off between a precise variable resistor and the resolution (number of steps) that the variable resistor can support.

The error from the 8 kΩ target will be no greater than $\pm R_{S(MAX)}/2$ (or ± 23.5Ω) which is ≤ 0.29%. Where:

$$R_{S(MAX)} = R_{AB(MAX)}/\text{Resolution} = 12000/256 = 46.875\Omega.$$

Any R_{BW} resistance ≤ 8 kΩ can be selected for the variable resistor range. Choosing a lower resistance does not necessarily affect the accuracy, but does affect the number of steps available for the resistor. Let’s say that we select a 5 kΩ resistance, the wiper values would range from 107 (+20%) to 160 (-20%). The worst-case (minimum) number of steps is 107, which gives an step accuracy of 1/107 (~0.93%) and an error from target resistance ≤ 0.47%. This is still in line with systems designed using 1% resistors, but still requires a fixed voltage and temperature. Additional calibration values can be used to correct for the change of the wiper resistance (R_W) over temperature and voltage.

Additional embedded systems controller firmware calibration can be done to take into account the change in R_S and R_W resistance over temperature and voltage.

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Referring to Table 3, for the 10 kΩ (typical) device, the R_{AB} variation over the specified voltage range is ~0.4%. The R_{AB} variation for a given device over temperature is ~1.4%. Other system techniques could be used to calibrate out the effect of these variations.

A precise variable resistor can be implemented in a system, if each system's digital potentiometer is calibrated.

Table 6 shows the calculations for a 10 kΩ device, over process. The calculation is based on an 8-bit device that has 256 step resistors (R_S) and 257 steps. When the Wiper code value is "01", that shows the step resistance (R_S).

SUMMARY

We have discussed how the components of the resistor network (R_{AB}, R_S, and R_W) can vary over process, voltage, temperature, and wiper code. Understanding these variations allows you to understand the implications in your application and if required use techniques to compensate or calibrate for these variations to optimize the application operation.

Using some of these calibration techniques, it was shown how a precise rheostat (variable resistor) can be implemented in a system.

TABLE 6: R_{BW} RESISTANCE AT WIPER CODE - 10 kΩ (TYPICAL) 8-BIT (256 R_S'S) DEVICE

Wiper Code	R_{BW} Resistance (Ω) (1)			Comment
	Min. (-20%)	Typical	Max (+20%)	
00	0.00	0.00	0.00	
01	31.25	39.0625	46.875	This indicates the R_S resistance value
02	62.50	78.125	93.75	
:	:	:	:	
106	3312.50	4140.625	4868.75	
107	3343.75	4179.6875	5015.625	This Wiper Code makes a +20% device have the closest resistance to the 5 kΩ target.
108	3375.00	4218.75	5062.50	
:	:	:	:	
159	4968.75	6210.9375	7453.125	
160	5000.00	6250.00	7500.00	This Wiper Code makes a -20% device have the closest resistance to the 5 kΩ target.
161	5031.25	6289.0625	7546.875	
:	:	:	:	
170	5312.50	6640.625	7968.75	
171	5343.75	6679.6875	8015.625	This Wiper Code makes a +20% device have the closest resistance to the 8 kΩ target.
172	5375.00	6718.75	8062.50	
:	:	:	:	
204	6375.00	7968.75	9562.50	
205	6406.25	8007.8125	9609.375	This Wiper Code makes a typical device have the closest resistance to the 8 kΩ target.
206	6437.50	8046.875	9656.25	
:	:	:	:	
254	7937.50	9921.875	11906.25	
255	7968.75	9960.9375	11953.125	
256	8000.00	10000.00	12000.00	8 kΩ resistance is the maximum resistance that is supported by ALL 10 kΩ (typical) devices (over process)

Note 1: R_{BW} resistance assume a wiper resistance (R_W) of 0Ω.

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