AN682

Using Single Supply Operational Amplifiers in Embedded Systems

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INTRODUCTION

Beyond the primitive transistor, the operational amplifier is the most basic building block for analog applications. Fundamental functions such as gain, load isolation, signal inversion, level shifting, adding and/or subtracting signals are easily implemented with this building block. More complex circuits can also be implemented, such as the instrumentation amplifier, a current to voltage converter, and filters, to name only a few. Regardless of the level of complexity of the operational amplifier circuit, knowing the fundamental operation and behavior of this building block will save a considerable amount of upfront design time.

Formal classes on this subject can be very comprehensive and useful. However, many times they fall short in terms of experience or common sense. For instance, a common mistake that is made when designing with operational amplifiers is to neglect to include the bypass capacitors in the circuit. Operational amplifier theory often overlooks this practical detail. If the bypass capacitor is missing, the amplifier circuit could oscillate at a frequency that "theoretically" doesn't make sense. If text book solutions are used, this is a difficult problem to solve.

This application note is divided into three sections. The first section will list fundamental amplifier applications with the design equations included. These amplifier circuits where selected with embedded system integration in mind.

The second section will use these fundamental circuits to build useful amplifier functions in embedded control applications.

The third section will identify the most common single supply operational amplifier (op amp) circuit design mistakes. This list of mistakes has been gathered over many years of trouble shooting circuits with numerous designers in the industry. The most common design pitfalls can easily be avoided if the check list from this short tutorial is used.

FUNDAMENTAL OPERATIONAL AMPLIFIER CIRCUITS

The op amp is the analog building block that is analogous to the digital gate. By using the op amp in the design, circuits can be configured to modify the signal in the same fundamental way that the inverter, AND, and OR gates do in digital circuits. In this section, fundamental building blocks such as the voltage follower, non-inverting gain and inverting gain circuits will be discussed. This will be followed by a rail splitter, difference amplifier, summing amplifier and current to voltage converter.

Voltage Follower Amplifier

Starting with the most basic op amp circuit, the buffer amplifier (shown in Figure 1) is used to drive heavy loads, solve impedance matching problems, or isolate high power circuits from sensitive, precise circuitry.
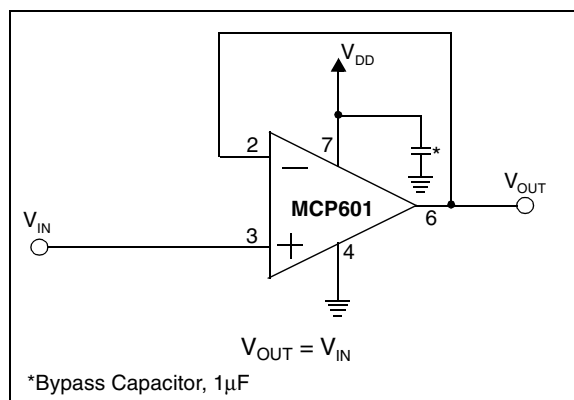

$$V_{OUT} = V_{IN}$$

*Bypass Capacitor, 1µF

Figure 1: *Buffer Amplifier; also called a voltage follower.*

The buffer amplifier, shown in Figure 1, can be implemented with any single supply, unity gain stable amplifier. In this circuit as with all amplifier circuits, the op amp must be bypassed with a capacitor. For single supply amplifiers that operate in bandwidths from DC to megahertz, a 1µF capacitor is usually appropriate. Sometimes a smaller bypass capacitor is required for amplifiers that have bandwidths up to the 10s of megahertz. In these cases a 0.1µF capacitor would be appropriate. If the op amp does not have a bypass capacitor or the wrong value is selected, it may oscillate.

The analog gain of the circuit in Figure 1 is +1 V/V. Notice that this circuit has a positive overall gain but the feedback loop is tied from the output of the amplifier to

the inverting input. An all too common error is to assume that an op amp circuit that has a positive gain requires positive feedback. If positive feedback is used, the amplifier will most likely drive to either rail at the output.

This amplifier circuit will give good linear performance across the bandwidth of the amplifier. The only restrictions on the signal will occur as a result of a violation of the input common-mode and output swing limits. These limitations will be discussed in the third section of this application note ("Amplifier Design Pitfalls").

If this circuit is used to drive heavy loads, the amplifier that is actually selected must be specified to provide the required output currents. Another application where this circuit may be used is to drive capacitive loads. Not every amplifier is capable of driving capacitors without becoming unstable. If an amplifier can drive capacitive loads, the product data sheet will highlight this feature. However, if an amplifier can't drive capacitive loads, the product data sheets will not explicitly say.

Another use for the buffer amplifier is to solve impedance matching problems. This would be applicable in a circuit where the analog signal source has a relatively high impedance as compared to the impedance of the following circuitry. If this occurs, there will be a voltage loss with the signal as a consequence of the voltage divider between the source's impedance and the following circuitry's impedance. The buffer amplifier is a perfect solution to the problem. The input impedance of the non-inverting input of an amplifier can be as high as 10^{13} Ω for CMOS amplifiers. In addition, the output impedance of this amplifier configuration is usually less than 10 Ω.
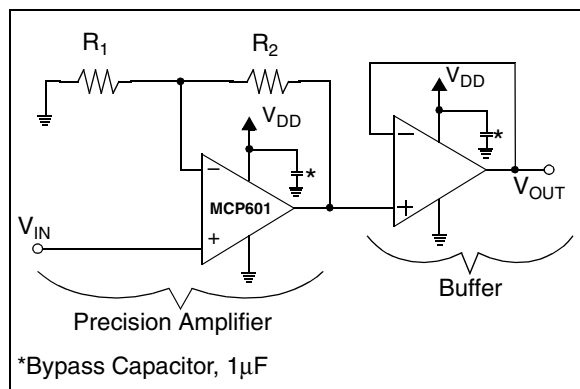

Figure 2: *Load isolation is achieved using a buffer amplifier.*

Yet another use of this configuration is to separate a heat source from sensitive precision circuitry, as shown in Figure 2. Imagine that the input circuitry to this buffer amplifier is amplifying a 100µV signal. This type of amplification is difficult to do with any level of accuracy in the best of situations. This precision measurement can easily be disrupted by changing the output current drive of the device that is doing the amplification work. An increase in current drive will cause self heating of the chip which will induce an offset change. An analog

buffer can be used to perform the function of driving heavy loads while the front end circuitry can be used to make precision measurements.

Gaining Analog Signals

The buffer solves a lot of analog signal problems, however, there are instances in circuits where a signal needs to be gained. Two fundamental types of amplifier circuits can be used. With the first type, the signal is not inverted as shown in Figure 3. This type of circuit is useful in single supply[1] amplifier applications where negative voltages are usually not possible.
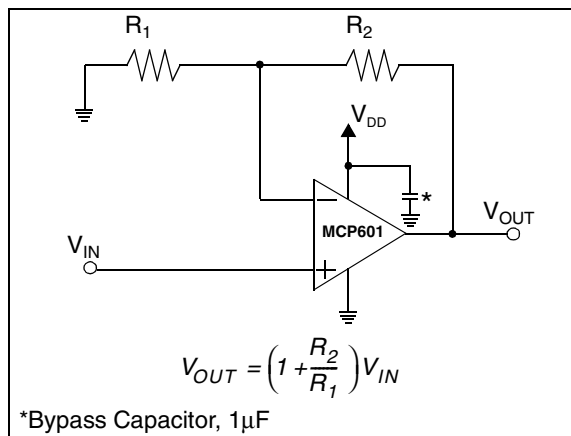

$$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right)V_{IN}$$

*Bypass Capacitor, 1µF

Figure 3: *Operational amplifier configured in a non-inverting gain circuit.*

The input signal to this circuit is presented to the high impedance, non-inverting input of the op amp. The gain that the amplifier circuit applies to the signal is equal to:

$$V_{OUT} = \left(1 + \frac{R_2}{R_1}\right)V_{IN}$$

Typical values for these resistors in single supply circuits are above 2kΩ for R_2. The resistor, R_1, restrictions are dependent on the amount of gain desired versus the amount of amplifier noise and input offset voltage as specified in the product data sheet of the op amp.

Once again, this circuit has some restrictions in terms of the input and output range. The non-inverting input is restricted by the common-mode range of the amplifier. The output swing of the amplifier is also restricted as stated in the product data sheet of the individual amplifier. Most typically, the larger signal at the output of the amplifier causes more signal clipping errors than the smaller signal at the input. If undesirable clipping occurs at the output of the amplifier, the gain should be reduced.

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1. For this discussion, single supply implies that the negative supply pin of the operational amplifier is tied to ground and the positive supply pin is tied to +5V. All discussion in this application note can be extrapolated to other supply voltages where the single supply exceeds 5V or dual supplies are used.

An inverting amplifier configuration is shown in Figure 4. With this circuit, the signal at the input resistor, R_1, is gained and inverted to the output of the amplifier. The gain equation for this circuit is:

$$V_{OUT} = -\left(\frac{R_2}{R_1}\right) V_{IN} + \left(1 + \frac{R_2}{R_1}\right) V_{BIAS}$$

The ranges for R_1 and R_2 are the same as in the non-inverting circuit shown in Figure 3.

$$V_{OUT} = -\left(\frac{R_2}{R_1}\right) V_{IN} + \left(1 + \frac{R_2}{R_1}\right) V_{BIAS}$$
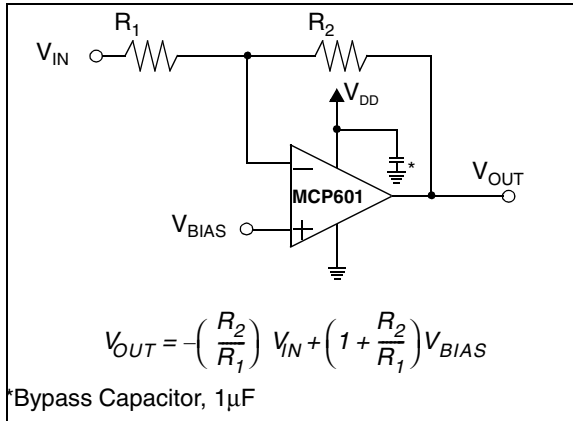
*Bypass Capacitor, 1µF

Figure 4: *Operational amplifier configured in an inverting gain circuit. In single supply environments a V_{BIAS} is required to insure the output stays above ground.*

In single supply applications, this circuit can easily be misused. For example, let R_2 equal 10kΩ, R_1 equal 1kΩ, V_{BIAS} equal 0V, and the voltage at the input resistor, R_1, equal to 100mV. With this configuration, the output voltage would be −1V. This would violate the output swing range of the operational amplifier. In reality, the output of the amplifier would go as near to ground as possible.

The inclusion of a DC voltage at V_{BIAS} in this circuit solves this problem. In the previous example, a voltage of 225mV applied to V_{BIAS} would level shift the output signal up 2.475V. This would make the output signal equal to (2.475V − 1V) or 1.475V at the output of the amplifier. Typically, the average output voltage should be designed to be equal to VDD/2.

Single Supply Circuits and Supply Splitters

As was shown in the inverting gain circuit (Figure 4), single supply circuits often need a level shift to keep the signal between negative (usually ground) and positive supply pins. This level shift can be designed with a single amplifier and a combination of resistors and capacitors as shown in Figure 5. Many times a simple buffer amplifier without compensation capacitors will accomplish this task. In other cases the level shift circuit will see dynamic or transient load changes, like the reference to an Analog-to-Digital (A/D) converter. In these applications, the level shift circuit must hold its voltage constant. If it does change, a conversion error might be observed.
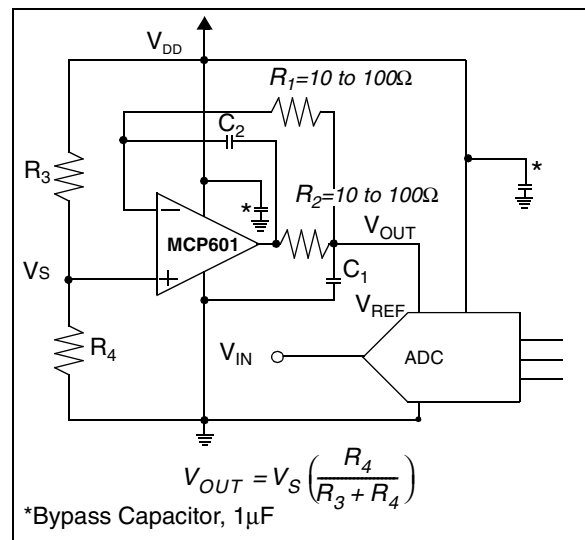

$$V_{OUT} = V_S \left(\frac{R_4}{R_3 + R_4}\right)$$

*Bypass Capacitor, 1µF

Figure 5: *A supply splitter is constructed using one operational amplifier. This type of function is particularly useful in single supply circuits.*

A solid level shift voltage can easily be implemented using a voltage divider (R_3 and R_4) or a reference voltage source buffered by the amplifier. The transfer function for this circuit is:

$$V_{OUT} = V_{DD} \left(\frac{R_4}{R_3 + R_4}\right)$$

The circuit in Figure 5 has an elaborate compensation scheme to allow for the heavy capacitive load, C_1. The benefit of this big capacitor is that it presents a very low AC resistance to the reference pin of the A/D converter. In the AC domain, the capacitor serves as a charge reservoir that absorbs any momentary current surges which are characteristic of sampling A/D converter reference pins.

The Difference Amplifier

The difference amplifier combines the non-inverting amplifier and inverting amplifier circuits of Figure 3 and Figure 4 into a signal block that subtracts two signals. The implementation of this circuit is shown in Figure 6.
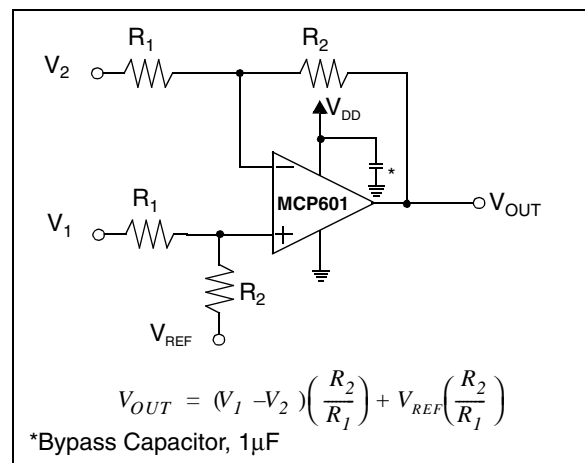

$$V_{OUT} = (V_1 - V_2)\left(\frac{R_2}{R_1}\right) + V_{REF}\left(\frac{R_2}{R_1}\right)$$

*Bypass Capacitor, 1µF

Figure 6: *Operational amplifier configured in a difference amplifier circuit.*

The transfer function for this amplifier circuit is:

$$V_{OUT} = (V_1 - V_2)\left(\frac{R_2}{R_1}\right) + V_{REF}\left(\frac{R_2}{R_1}\right)$$

This circuit configuration will reliably take the difference of two signals as long as the signal source impedances are low. If the signal source impedances are high with respect to R_1, there will be a signal loss due to the voltage divider action between the source and the input resistors to the difference amplifier. Additionally, errors can occur if the two signal source impedances are mismatched. With this circuit it is possible to have gains equal to or higher than one.

Summing Amplifier

Summing amplifiers are used when multiple signals need to be combined by addition or subtraction. Since the difference amplifier can only process two signals, it is a subset of the summing amplifier.
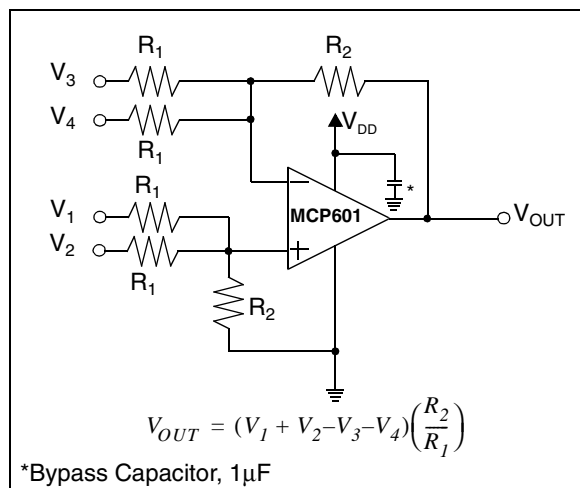

$$V_{OUT} = (V_1 + V_2 - V_3 - V_4)\left(\frac{R_2}{R_1}\right)$$

*Bypass Capacitor, 1µF

Figure 7: *Operational amplifier configured in a sum- ming amplifier circuit.*

The transfer function of this circuit is:

$$V_{OUT} = (V_1 + V_2 - V_3 - V_4)\left(\frac{R_2}{R_1}\right)$$

Any number of inputs can be used on either the inverting or non-inverting input sides as long as there are an equal number of both with equivalent resistors.

Current to Voltage Conversion

An operational amplifier can be used to easily convert the signal from a sensor that produces an output current, such as a photodetector, into a voltage. This is implemented with a single resistor and an optional capacitor in the feedback loop of the amplifier as shown in Figure 8.
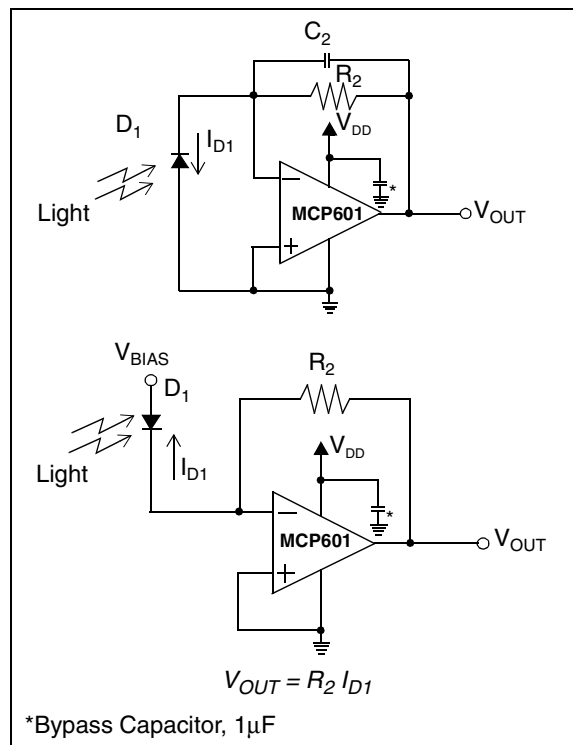

$$V_{OUT} = R_2 I_{D1}$$

*Bypass Capacitor, 1µF

Figure 8: *Current to voltage converter using an amplifier and one resistor. The top light scanning circuit is appropriate for precision applications. The bottom circuit is appropriate for high speed applications.*

As light impinges on the photo diode, charge is generated, causing a current to flow in the reverse bias direction of the photodetector. If a CMOS op amp is used, the high input impedance of the op amp causes the current from the detector (I_{D1}) to go through the path of lower resistance, R_2. Additionally, the op amp input bias current error is low because it is CMOS (typically <200 pA). The non-inverting input of the op amp is referenced to ground which keeps the entire circuit biased to ground. These two circuits will only work if the common mode range of the amplifier includes zero.

Two circuits are shown in Figure 8. The top circuit is designed to provide precision sensing from the photodetector. In this circuit the voltage across the detector is nearly zero and equal to the offset voltage of the amplifier. With this configuration, current that appears across the resistor, R_2, is primarily a result of the light excitation on the photodetector.

The photosensing circuit on the bottom of Figure 8 is designed for higher speed sensing. This is done by reverse biasing the photodetector, which reduces the parasitic capacitance of the diode. There is more leakage through the diode which causes a higher DC error.

USING THE FUNDAMENTALS

Instrumentation Amplifier

Instrumentation amplifiers are found in a large variety of applications from medical instrumentation to process control. The instrumentation amplifier is similar to the difference amplifier in that it subtracts one analog signal from another, but it differs in terms of the quality of the input stage. A classic, three op amp instrumentation amplifier is illustrated in Figure 9.
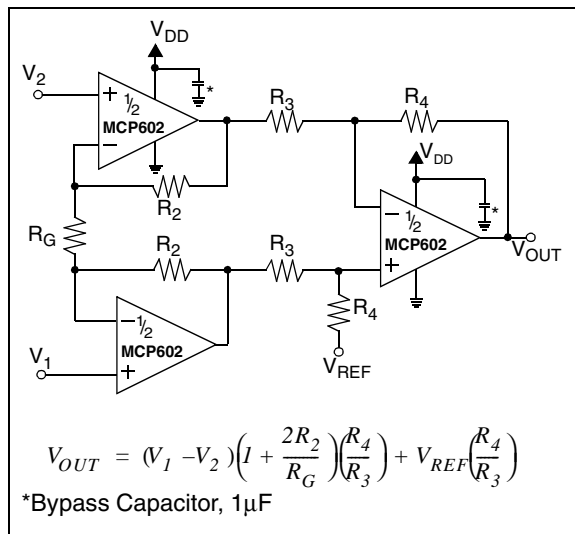
$$V_{OUT} = (V_1 - V_2)\left(1 + \frac{2R_2}{R_G}\right)\left(\frac{R_4}{R_3}\right) + V_{REF}\left(\frac{R_4}{R_3}\right)$$

*Bypass Capacitor, 1µF

Figure 9: *An instrumentation amplifier can be designed using three amplifiers. The input operational amplifiers provide signal gain. The output operational amplifier converts the signal from two inputs to a single ended output with a difference amplifier.*

With this circuit the two input signals are presented to the high impedance non-inverting inputs of the amplifiers. This is a distinct advantage over the difference amplifier configuration when source impedances are high or mismatched. The first stage also gains the two incoming signals. This gain is simply adjusted with one resistor, R_G.

Following the first stage of this circuit is a difference amplifier. The function of this portion of the circuit is to reject the common mode voltage of the two input signals as well as differentiate them. The source impedances of the signals into the input of the difference amplifier are low, equivalent and well controlled.

The reference voltage of the difference stage of this instrumentation amplifier is capable of spanning a wide range. Most typically this node is referenced to half of the supply voltage in a signal supply application. A supply splitter such as the circuit in Figure 5 can be used for this purpose. The transfer function of this circuit is:

$$V_{OUT} = (V_1 - V_2)\left(1 + \frac{2R_2}{R_G}\right)\left(\frac{R_4}{R_3}\right) + V_{REF}\left(\frac{R_4}{R_3}\right)$$

A second instrumentation amplifier is shown in Figure 10. In this circuit, the two amplifiers serve the functions of load isolation, and signal gain. The second amplifier also differentiates the two signals.
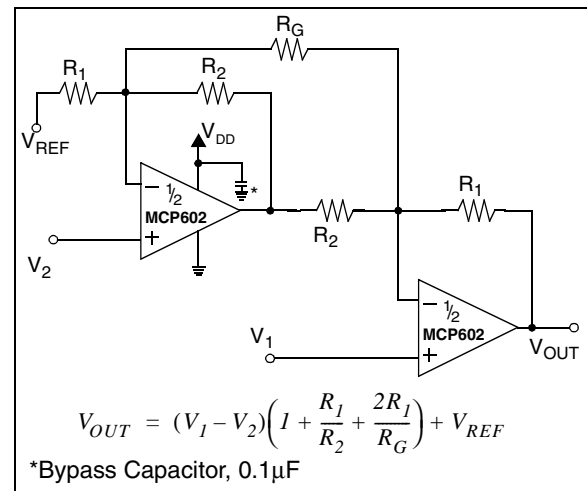
$$V_{OUT} = (V_1 - V_2)\left(1 + \frac{R_1}{R_2} + \frac{2R_1}{R_G}\right) + V_{REF}$$

*Bypass Capacitor, 0.1µF

Figure 10: *An instrumentation amplifier can be designed using two amplifiers. This configuration is best suited for higher gains. (gain > 3 V/V)*

The circuit reference voltage is supplied to the first op amp in the signal chain. Typically, this voltage is half of the supply voltage in a single supply environment.

The transfer function of this circuit is:

$$V_{OUT} = (V_1 - V_2)\left(1 + \frac{R_1}{R_2} + \frac{2R_1}{R_G}\right) + V_{REF}$$

Floating Current Source

A floating current source can come in handy when driving a variable resistance, like an Resistive Temperature Device (RTD). This particular configuration produces an appropriate 1mA source for an RTD type sensor, however, it can be tuned to any current.
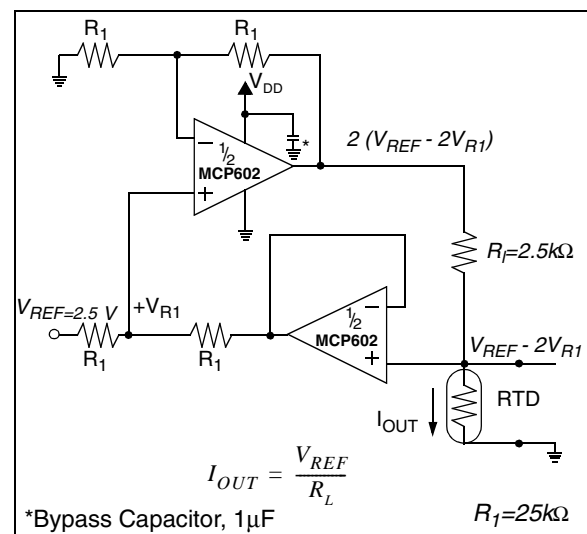
$$I_{OUT} = \frac{V_{REF}}{R_L}$$

*Bypass Capacitor, 1µF

Figure 11: *A floating current source can be constructed using two operational amplifiers and a precision voltage reference.*

With this configuration, the voltage of V_{REF} is reduced via the first resistor, R_1, by the voltage V_{R1}. The voltage applied to the non-inverting input of the top op amp is $V_{REF} - V_{R1}$. This voltage is gained to the amplifier's output by two to equal $2(V_{REF} - V_{R1})$. Meanwhile, the output for the bottom op amp is presented with the voltage $V_{REF} - 2V_{R1}$. Subtracting the voltage at the output of the top amplifier from the non-inverting input of the bottom amplifier gives $2(V_{REF} - V_{R1}) - (V_{REF} - 2V_{R1})$ which equals V_{REF}.

The transfer function of the circuit is:

$$I_{OUT} = \frac{V_{REF}}{R_L}$$

Filters

Bandpass and low pass filters are very useful in eliminating unwanted signals prior to the input of an A/D converter. The low pass filter shown in Figure 12 has two poles that can be configured for a Butterworth filter response. Butterworth filters have a flat magnitude response in the pass-band with good all-around performance.
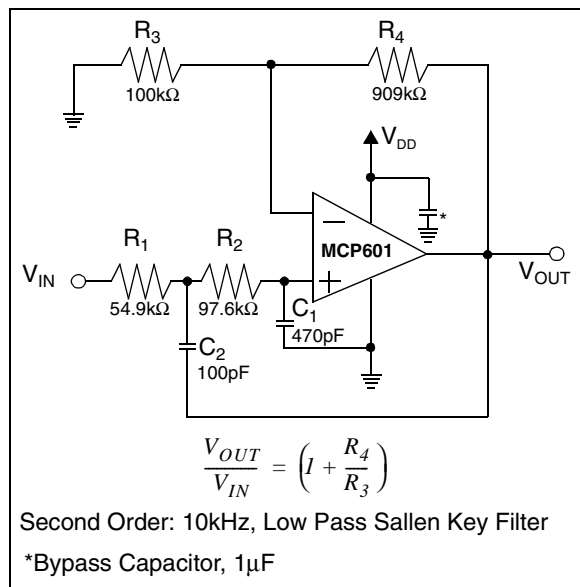

$$\frac{V_{OUT}}{V_{IN}} = \left(1 + \frac{R_4}{R_3}\right)$$

Second Order: 10kHz, Low Pass Sallen Key Filter

*Bypass Capacitor, 1μF

Figure 12: *Low pass, 2-pole, active filters are easily designed with one operational amplifier. The resistors and capacitors can be adjusted to implement other filter types, such as Bessel and Chebyshev.*

On the down side, there is some overshoot and ringing with a step response through this filter. This may or may not be an issue, depending on the application circuit requirements. The gain of this filter is adjustable with R_3 and R_4.

Notice the similarities in this gain equation and the non-inverting amplifier shown in Figure 3.

This type of filter is also referred to as an anti-aliasing filter, which is used to eliminate circuit noise in the frequency band above half of nyquist of the sampling system. In this manner, these high frequency noises, that would typically alias back into the signal path, are removed.

The DC gain of the circuit in Figure 12 is:

$$\frac{V_{OUT}}{V_{IN}} = \left(1 + \frac{R_4}{R_3}\right)$$

The bandpass filter shown in Figure 13 is configured with a zero and two poles to accommodate speech applications. The single zero high pass filter portion of this circuit is constructed with C_1 and R_1 in parallel with R_2. Notice that R_1 and R_2 also creates a supply splitter voltage at the non-inverting inputs of both of the amplifiers. This insures that both operational amplifiers operate in their linear region. The second amplifier, U_2, in conjunction with the components R_3, R_4, C_3, and C_4 set a two pole corner frequency. This filter eliminates high frequency noise that may be aliased back into the signal path.

The signal gain of this circuit is:

$$V_{OUT} = V_{IN}\left(\frac{R_3}{R_4}\right)\left(\frac{R_2}{R_1 + R_2}\right)$$

For more details about low pass filters refer to *AN699 "Anti-aliasing Analog Filters for Data Acquisitions Systems"*.
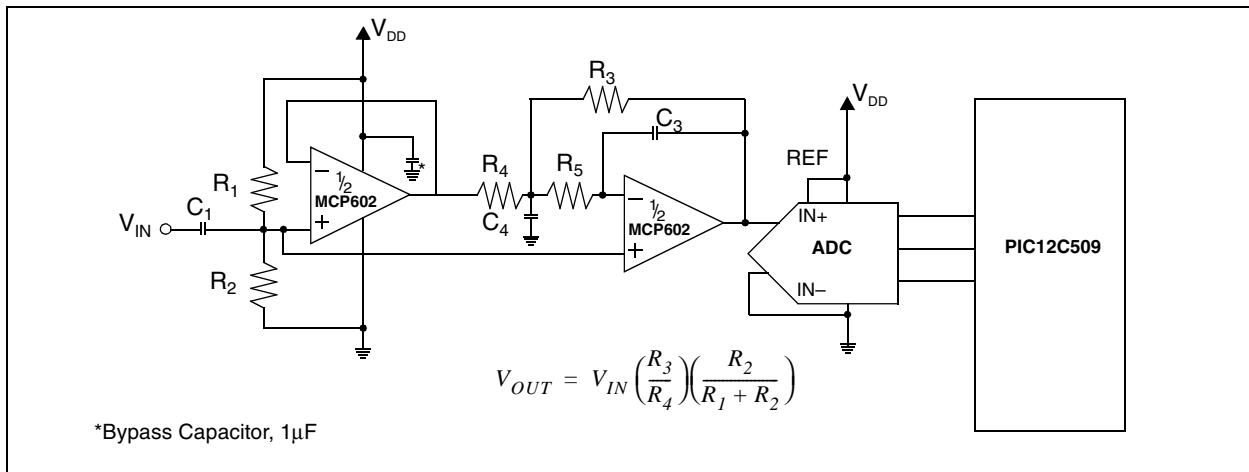
Figure 13: *Band pass filters can be implemented with one operational amplifier designed to perform the high pass function and a second amplifier to perform the low pass function.*
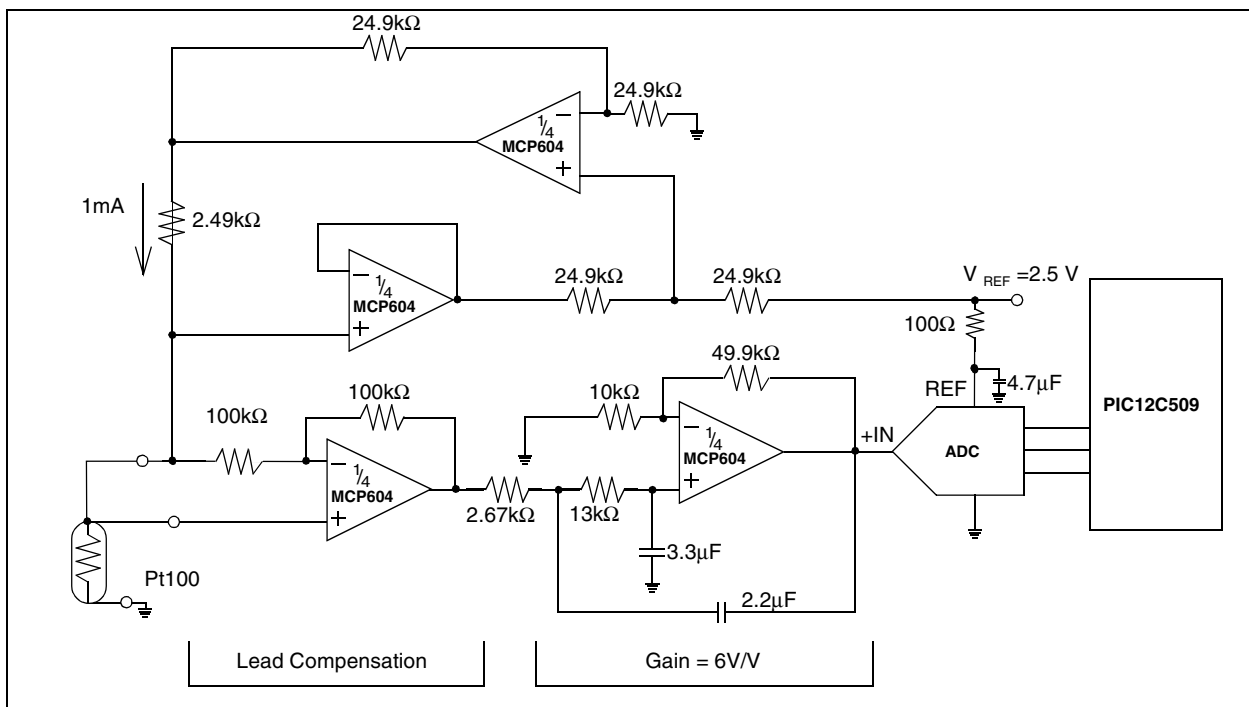
$$V_{OUT} = V_{IN} \left(\frac{R_3}{R_4} \right) \left(\frac{R_2}{R_1 + R_2} \right)$$

Figure 14: *Complete single supply temperature measurement circuit.*

Putting it Together

The circuit shown in Figure 14 utilizes four operational amplifiers along with a 12-bit A/D converter to implement a complete single supply temperature measurement circuit. The temperature sensor is an RTD which requires current excitation. The current excitation is supplied by the circuit described in Figure 11. The gain and anti-aliasing filter is implemented with the circuit shown in Figure 13.

The voltage signal from the RTD is sensed by an amplifier that is used in a combination of a non-inverting configuration and inverting configuration.

The output of this amplifier is then sent to an amplifier that is configured as a two pole, low pass filter in a gain of +6V/V. A gain of six was chosen in order to comply with the input range of A/D converter. Assuming the sampling frequency of the A/D converter is 75kHz, which is also know as the nyquist frequency, the cut-off frequency of the anti-aliasing filter (U4) is set to 10kHz. This allows plenty of bandwidth for the filter to attenuate the signal prior to 1/2 of nyquist. The A/D converter is a 12-bit Successive Approximation Register (SAR) converter that is interfaced to the PIC12C509 microcontroller.

AMPLIFIER DESIGN PITFALLS

Theoretically, the circuits within this application note work. Beyond the theory, however, there are few tips that will help get the circuit right the first time. This section, "Amplifier Design Pitfalls", lists common problems associated with using an op amp with a power supply and an input signal on a PC Board. It is divided into four categories: General Suggestions, Input State Problems, Bandwidth Issues, and Single Supply Pitfalls. Hopefully, the most common problems with op amp implementation have been addressed within this application note, however, if you have any other inputs from experience, please e-mail your suggests to bonnie.baker@microchip.com.

In General

1. Be careful of the supply pins. Don't make them too high per the amplifier specification sheet and don't make them too low. High supplies will damage the part. In contrast, low supplies won't bias the internal transistors and the amplifier won't work or it may not operate properly.

2. Make sure the negative supply (usually ground) is in fact tied to a low impedance potential. Additionally, make sure the positive supply is the voltage you expect when it is referenced to the negative supply pin of the op amp. Placing a volt meter across the negative and positive supply pins will verify that you have the right relationship between the pins.

3. Ground can't be trusted, especially in digital circuits. Plan your grounding scheme carefully. If the circuit has a lot of digital circuitry, consider separate ground and power planes. It is very difficult, if not impossible, to remove digital switching noise from an analog signal.

4. Decouple the amplifier power supplies with by-pass capacitors as close to the amplifier as possible. For CMOS amplifiers, a $0.1\mu F$ capacitor is usually recommended. Also decouple the power supply with a $10\mu F$ capacitor.

5. Use short lead lengths to the inputs of the amplifier. If you have a tendency to use the white perf boards for prototyping, be aware that they can cause noise and oscillation. There is a good chance that these problems won't be a problem with the PCB implementation of the circuit.

6. Amplifiers are static sensitive! If they are damaged, they may fail immediately or exhibit a soft error (like offset voltage or input bias current changes) that will get worse over time.

Input Stage Problems

1. Know what input range is required from your amplifier. If either inputs of the amplifier go beyond the specified input range, the output will typically be driven to one of the power supply rails.

2. If you have a high gain circuit, be aware of the offset voltage of the amplifier. That offset is gained with the rest of your signal and it might dominate the results at the output of the amplifier.

3. Don't use rail-to-rail input stage amplifiers unless it is necessary. By the way, they are only needed when a buffer amplifier circuit is used or possibly an instrumentation amplifier configuration. Any circuit with gain will drive the output of the amplifier into the rail before the input has a problem.

Do You Have the Bandwidth?

1. Account for the bandwidth of the amplifier when sending signals through the circuit. You may have designed an amplifier for a gain of 10 and find that the AC output signal is much lower than expected. If this is the case, you may have to look for an amplifier with a wider bandwidth.

2. Instability problems can usually be solved by adding a capacitor in parallel with the feedback resistor around the amplifier. This does mean typically and not always. If an amplifier circuit is unstable, a quick stability analysis will show the problem and probably the solution.

Single Supply Rail-to-Rail

1. Operational Amplifier output drivers are capable of driving a limited amount of current to the load.

2. Capacitive loading an amplifier is risky business. Make sure the amplifier is specified to handle any loads that you may have.

3. It is very rare that a single supply amplifier will truly swing rail-to-rail. In reality, the output of most of these amplifiers can only come within 50 to 200mV from each rail. Check the product data sheets of your amplifier.

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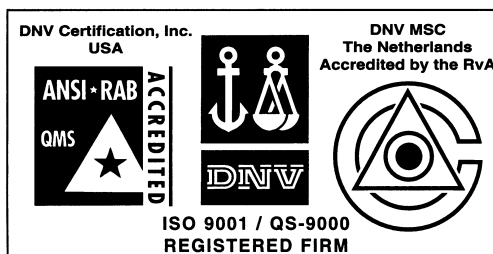Tel: 49-89-627-144 0 Fax: 49-89-627-144-44

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