
Optimizing Internal Operational Amplifiers for Analog Signal Conditioning

Introduction

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The Operational Amplifier (OPA) module of PIC16 and PIC18 devices is a versatile peripheral that can be used in analog signal acquisition applications, such as in low-side current amplifiers, voltage regulators or multimeters. When using an analog component such as an operational amplifier that is embedded in a microcontroller, some precautions must be taken to ensure proper analog signal conditioning. This document highlights techniques to properly condition analog signals for embedded operational amplifiers. While this document covers the specific features for PIC18-Q41, most of the advice is relevant to older devices and other variations of the OPA module.

For more information about setting up the OPA module, refer to the device data sheet or TB3280, *"Using the Operational Amplifier Module on PIC16 and PIC18"*.

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1. Operational Amplifier (OPA) Module

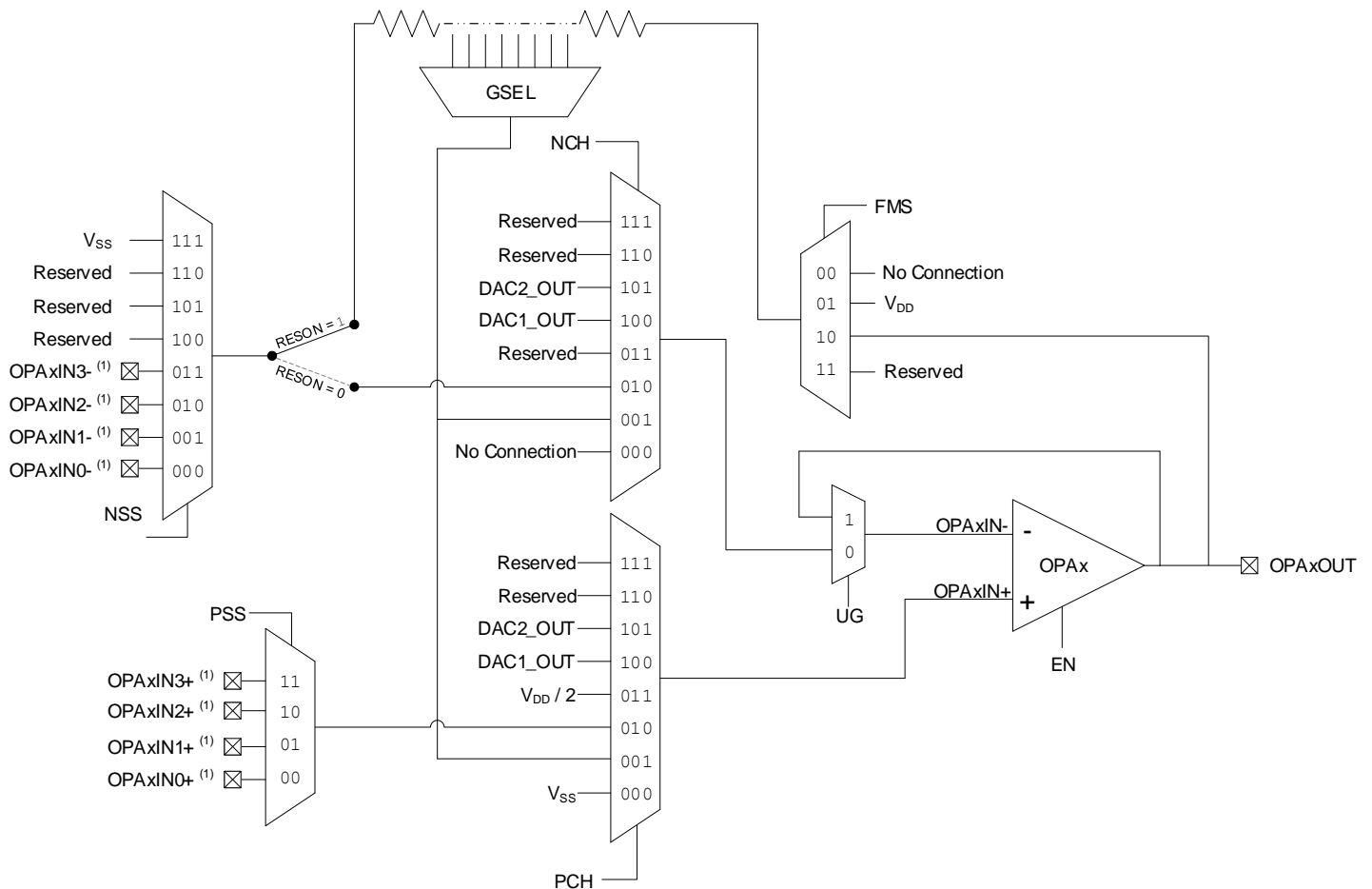
The Operational Amplifier (OPA) module is a general-purpose operational amplifier that can be used as a signal buffer or as a programmable gain amplifier (PGA). The PGA functionality of the OPA module can be used to amplify analog signals that would ordinarily not be measurable with the on-board ADC. Using the OPA module allows users to simplify their designs, reducing PCB area and material costs. Some of the intelligent analog features of the OPA module in the new PIC18-Q41 family are shown in Figure 1-1.

The Operational Amplifier (OPA) module contains features that reduce the number of external components needed and saves on board space that is required to implement a practical operational amplifier design. The following list contains key features of the OPA module:

- Multiple Non-Inverting and Inverting Input Pins Available
- Configurable Positive and Negative Source Selections
- Hardware Controlled Drive with Override Controls
 - Forced Unity Gain Mode
 - Forced Rail Drive Mode
- Programmable Input Offset Voltage Calibration
- Programmable Gain Options

Refer to [Figure 1-1](#) for a detailed block diagram of the OPA module.

Figure 1-1. OPA Module Block Diagram (PIC18-Q41 family)



Note:

1. Refer to the **"Pin Allocation Table"** section of the device data sheet for details about OPAXIN- and OPAXIN+ availability per port.

2. Operational Amplifier Input and Output Ranges

Embedded operational amplifiers are single supply, meaning that the operational amplifier can only use the same V_{DD} and V_{SS} as the microcontroller. In some cases, dedicated inputs may allow for separate analog V_{DD} (AV_{DD}) and analog ground (AV_{SS}) supplies. The voltage of the analog supply should be identical to the digital supply. The inputs of the operational amplifier must be kept within the power supply limits. Some embedded operational amplifiers have internal charge pumps, which can be enabled in software. The charge pump allows for rail-to-rail outputs, but doing so increases the quiescent current draw of the peripheral.



Important: The OPA module has the same limitations as general purpose I/O's. All I/Os must be kept within the absolute maximum ratings for the expected performance and device operation. Refer to the device data sheet for more information.

3. Integration with Other Peripherals

The embedded operational amplifier has internal connections to other analog peripherals that are available on the device. Such peripherals include the Analog-to-Digital Converter (ADC) and the Digital-to-Analog Converter (DAC), both of which can leverage the operational amplifier to improve their analog performance.

The ADC on the microcontroller can sample the output of the operational amplifier directly, without the need of external connections. The operational amplifier can be used as a buffer or programmable gain amplifier (PGA) for an analog input, which may reduce the acquisition time for high-impedance signals and improve the signal resolution for small signals.

The DAC(s) on the microcontroller can use the OPA module as a buffer. This enables additional functionalities, such as buffering unbuffered DACs, tracking (or mirroring) a DAC output, or creating an output from an internal DAC that is normally inaccessible.

4. Input Offset Voltage Trimming

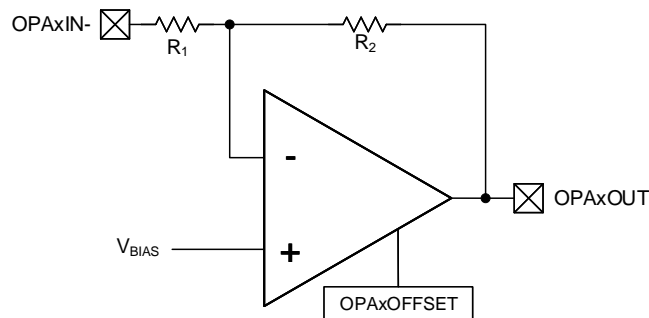
The OPA module is factory calibrated to the offset tolerance stated in the device data sheet. Operating the device at non-ambient or extreme temperatures can cause errors beyond the specification. The provided example simulates the input offset voltage drift by constantly writing to the offset register, and then periodically running the calibration routine to return the offset register to the correct value.



Important: The self-calibration is unlikely to be as accurate or precise as a calibration in a controlled lab. It will be dependent on the conditions and setup during the process.

In the non-calibration (starting configuration) state, the OPA module is configured as an inverting amplifier with a bias voltage of $V_{DD}/2$, as shown in Figure 4-1. Other operational amplifier configurations are possible, but would require more extensive changes to the electrical configuration before running the routine.

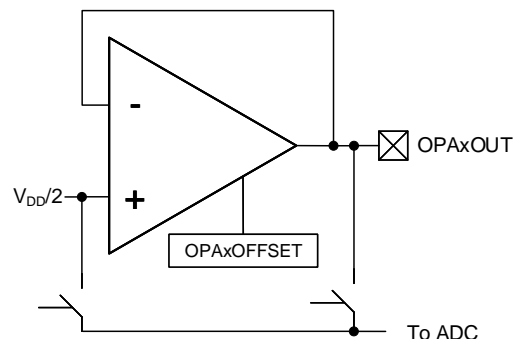
Figure 4-1. Starting Configuration



To avoid excessive calibration time in the system, it is recommended that calibration is done based on a trigger. The trigger used will vary based on the application requirements. Some possibilities for the calibration trigger include: a button for the user, a measured temperature change on die, or a time-based period. For this example, the program recalibrates itself every 10 seconds. To simulate temperature error during the calibration process, a 10 ms timer writes to the offset register constantly (when not calibrating), causing the offset to go up and down. This is a much more extreme case than the subtle changes caused by temperature, but it is intended to showcase the algorithm.

During calibration, the microcontroller reconfigures the OPA module as a unity gain buffer. The program uses the internal reference signal of $V_{DD}/2$ as the reference level. The specific value of the reference level is not important, so long as it is within the ADC sampling range, relatively stable, and has a sufficient range for offset adjustment. After the calibration has been completed, the module returns to the starting (user) configuration, which in this case is an inverting amplifier. Figure 4-2 shows the configuration used during calibration.

Figure 4-2. Calibration Mode Schematic



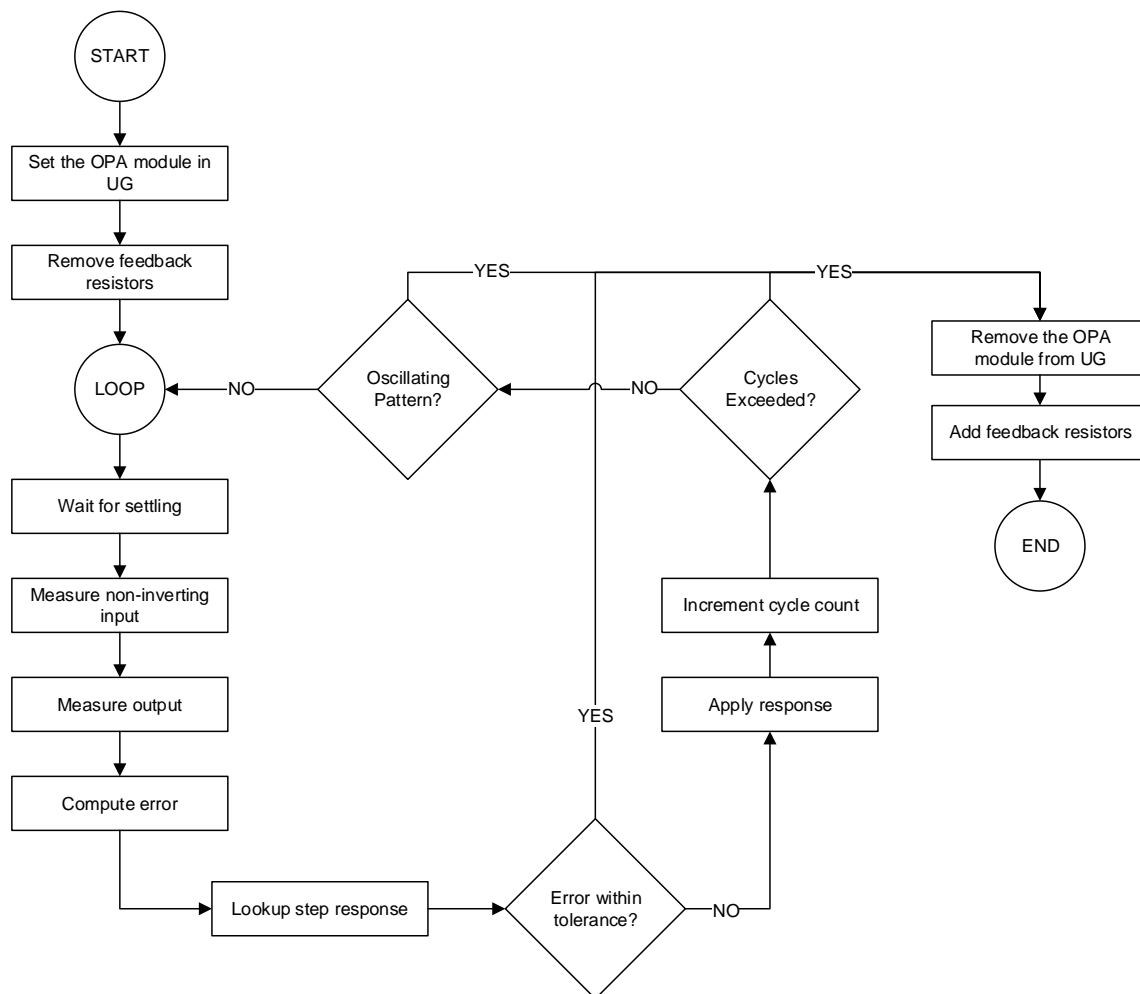
4.1 Calibration Algorithm

When calibrating the input offset voltage, as many variables as possible need to be removed, the first of which is gain error. Gain error complicates the calculation to find the step response and the calibration point. The simplest way to minimize gain error is to switch to a unity gain configuration. In unity gain, the operational amplifier is extremely close to the ideal gain of one, which negates the need to compensate for the error.

The next setup needed for calibration is the reference signal, which is applied to the non-inverting input of the operational amplifier. It is important that the reference signal is a stable DC level. If the reference signal varies with time, the delay between sampling the reference signal and the output could cause errors.

The calibration process (as shown [Figure 4-3](#)) is an iterative algorithm that modifies the offset register (OPAxOFFSET) of the device until the difference between the reference level and the output is within a specific number of bits. A simple Look-Up Table (LUT) is used to convert the magnitude of the error to a step response to be added (or subtracted) to the OPAxOFFSET register. The error tolerance in bits can be converted to the equivalent voltage error by multiplying by the voltage per step resolution of the ADC.

Figure 4-3. Calibration Flowchart



View Code Examples on GitHub

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5. Internal and External Feedback Networks

5.1 Internal Gain Accuracy

The internal resistor ladder on the device is built from a strip of resistive material with taps to a multiplexer at specific positions on the strip. Due to process variations, each microcontroller has a different resistance per unit on the internal resistor ladder. While the resistivity of the material varies from device to device, the ratio of resistance on the ladder remains relatively stable, thus providing similar gains across multiple devices. For applications that require a high degree of gain accuracy, it is advised to use external resistors for the feedback network.



Inadvertent use of the internal resistor ladder or the internal feedback multiplexer in a configuration with external gain resistors may cause a gain error due to parallel resistance from the internal ladder. It is recommended to keep both the internal resistor ladder and the internal feedback multiplexer disabled when not in use to avoid this issue.

5.2 Improved Analog Layout Using Internal Pin Multiplexers

The internal pin selection multiplexers for the OPA module can be used to move the inputs of the operational amplifier to a different pin for improved PCB layout. External components used with the operational amplifier should be placed as close as possible to the pins to reduce errors and noise.

6. Isolating Analog and Digital Signals

I/O's that switch frequently, such as Pulse Width Modulated (PWM) or clock signals, are more likely to introduce crosstalk into the operational amplifier. The best way to reduce crosstalk from these signals is to keep them as far away from the analog inputs and outputs as possible.

Internally, the OPA module has a multiplexer for selecting the inverting and non-inverting input pins, which can help move the analog inputs to more convenient locations. Additionally, Peripheral Pin Select (PPS) can be used to move some digital peripheral signals to other pins on the device which may increase the separation.

For applications that further require reduced crosstalk and noise, there are two more options. One option is to reduce the operating frequency of the part, and the other is to put the part in Sleep during crucial analog operations. These steps are only recommended if absolutely necessary, due to the significant drawbacks associated with them.

7. Analog Signal Filtering

7.1 Signal Grounding and Power

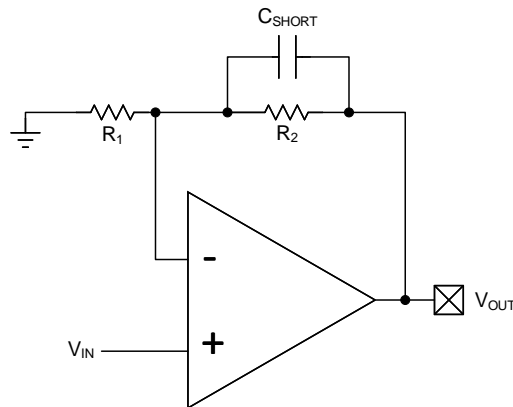
To ensure maximum analog signal integrity, careful considerations must be taken in regards to signal impedance, noise sources and PCB trace routing distance. The recommendations below discuss a few possible methods to ensure signal integrity:

- Low power sensors may share a power and ground line with the microcontroller to turn ground and power offsets into common-mode errors, which significantly reduces the impact of these errors. Both the sensor and the microcontroller should have decoupling capacitors as close as possible to the power pins.
- Off-board or distant sensors should not share power and ground with the microcontroller, as an exception to the above recommendation. In this case, using an instrumentation amplifier (such as the MCP6N11 or MCP6N16) to convert the difference between the signal and the signal's ground to the reference ground of the device is recommended.
- High impedance sensors, such as resistor dividers, should be buffered at the source to reduce the impact of noise on the signal.

7.2 Feedback Capacitance

By inserting a capacitor (C_{SHORT}) in parallel with the feedback resistor (R_2), the noise from the output of the operational amplifier can be reduced. [Figure 7-1](#) shows this configuration with a non-inverting amplifier, although it may also be used for other operational amplifier configurations.

Figure 7-1. Non-Inverting Amplifier with Feedback Capacitor



C_{SHORT} appears as a short circuit to the higher frequencies, which reduces the gain for those frequencies. Consider the gain equation for this configuration in terms of complex impedance ([Equation 7-1](#)).

Equation 7-1. Gain and Impedance of a Non-Inverting Amplifier

$$V_{OUT} = \left(1 + \frac{Z_2}{R_1}\right) V_{IN}$$

C_{SHORT} is in parallel with R_2 , where the reactance of the capacitor is in parallel with resistance of R_2 . By applying the superposition theorem, the output of the operational amplifier becomes the sum of the DC and AC components separately ([Equation 7-2](#)). This reduces High Frequency (HF) noise on the output at the cost of AC gain of the amplifier. To ensure the filter works properly, the chosen cutoff frequency should be much higher than the -3dB point of the RC network, where the low-impedance of the capacitor creates the short circuit. The capacitor used in the network should be low Equivalent Series Resistance (ESR) and Equivalent Series Inductance (ESL). Capacitors with high ESR and ESL will complicate the analysis.

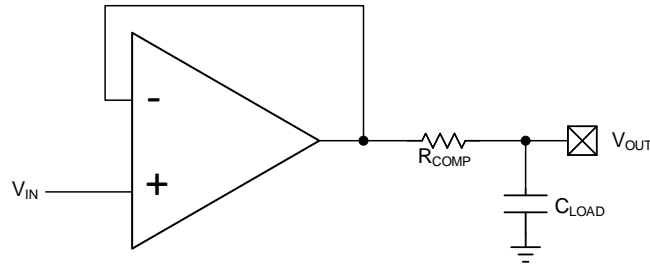
Equation 7-2. Combined Gain of a Non-Inverting Amplifier (when $X_C \ll R_2$)

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

8. Output Drive Precautions

For an operational amplifier driving a capacitive load, the output may become unstable and oscillate due to the phase shift of the capacitor (C_{LOAD}). To reduce this effect, the operational amplifier can be configured to remove the capacitor from the feedback loop, which allows the operational amplifier to remain stable, while continuing to drive the capacitor. [Figure 8-1](#) shows a method that can be used to compensate for the loading capacitor C_{LOAD} .

Figure 8-1. Driving a Capacitive Load



The value of R_{COMP} is dependent upon the size of C_{LOAD} . R_{COMP} should be rated to handle the peak output power and be large enough to keep the operational amplifier from exceeding the maximum output current during the current spike from the charging capacitor.



Important: A sufficiently large C_{LOAD} and small R_{COMP} can cause permanent damage to the device. It is recommended to choose a R_{COMP} that is large enough to prevent significant current flow through the ESD diodes when the device is powered off.

9. Power Supply Recommendations

For embedded operational amplifiers, the power supply to the device is crucial in maximizing its performance. The list below contains recommendations for reducing power supply noise.

- The decoupling capacitors should be placed as close as possible to each power pin. It is recommended to use ceramic, low ESR capacitors for decoupling. The recommended capacitor values are 0.1 μF and 1 nF, with the 1 nF capacitor being closer to the device.
- On devices with separate analog and digital power lines, the power supplies should be separate. Separate bipolar linear regulators for each power input is recommended.
- In some cases, ferrite beads may improve power supply noise. However, this option should be evaluated per application.
- The power supply for the device should be filtered through a dedicated bipolar⁽¹⁾ linear regulator to reduce the effects of noise from other devices in the system.

Note:

1. Bipolar linear regulators generally have lower noise than CMOS based regulators.

10. PCB Layout Recommendations

The performance of an operational amplifier is affected by the parasitic elements that are around the device. A proper layout is required to ensure optimum performance. In some cases, there are tradeoffs that may improve performance in one aspect at the cost of another. Listed below are a few tips to consider when designing a mixed signal PCB:

- Good grounds are crucial for the performance of the device. While digital signals are tolerant of ground bounce and voltage offsets, analog performance will be significantly impacted by these effects.
 - For devices with a shared ground pin, the ground return should be kept away from other digital signals to avoid ground bounce and coupling.
 - For devices with separate analog and digital grounds, star grounding patterns are recommended.
 - In all cases, the ground return for the device should be uninterrupted, wide and as short as possible. It is recommended to connect the ground return into a plane, if possible.
- Digital signals, such as clocks, PWMs or any other switching signal, should be shielded⁽¹⁾ and routed away from analog signals.
 - Keeping these traces as short as possible helps reduce and prevent interference from entering the analog signals.
- Using a guard^(1,2) with analog signals and nodes⁽³⁾ can reduce the amount of noise coupled.
 - Guarding increases the capacitance of the signal. Oscillations may occur if the output of the operational amplifier has too much capacitance present⁽⁴⁾. Reference the [Output Drive Precautions](#) section for more information.



Tip:

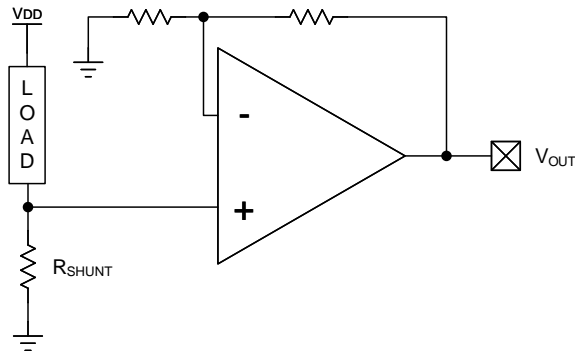
1. Stitching the guard or shield to ground will lower the parasitic inductance and is recommended.
2. The ground line used for guarding analog signals should be kept away from digital signals and the digital return paths to avoid noise.
3. The feedback node of the operational amplifier, usually on the inverting pin, is extremely sensitive to noise.
4. Generally, the limit on output capacitance for operational amplifiers is in the range of 10s of pF.

11. Example Use Cases

11.1 Low-side Current Sense Amplifier

For monitoring motors or power supplies, small shunt resistors are frequently used to monitor the current through the circuit. The smaller the shunt resistor, the lower the loss from the shunt resistance. However, this makes it harder to measure the current. To make the signal from the current shunt more usable, a non-inverting amplifier (as shown in [Figure 11-1](#)) can be used to convert the shunt voltage to a much larger signal for use with other peripherals or devices.

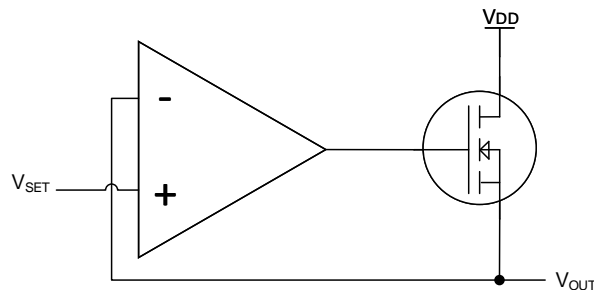
Figure 11-1. Low-side Current Amplifier



11.2 Linear Voltage Regulator

The operational amplifier can be connected where the non-inverting input has a voltage applied (V_{SET}), and the inverting input is connected to the source of an N-type MOSFET (V_{OUT}). The output of the amplifier is connected to the gate. If V_{OUT} is lower than V_{SET} , then the operational amplifier pushes charge into the gate of the transistor. If V_{OUT} is higher than V_{SET} , then the operational amplifier pulls charge from the gate, lowering the gate voltage. [Figure 11-2](#) shows a basic diagram of a linear voltage regulator.

Figure 11-2. Linear Voltage Regulator Schematic



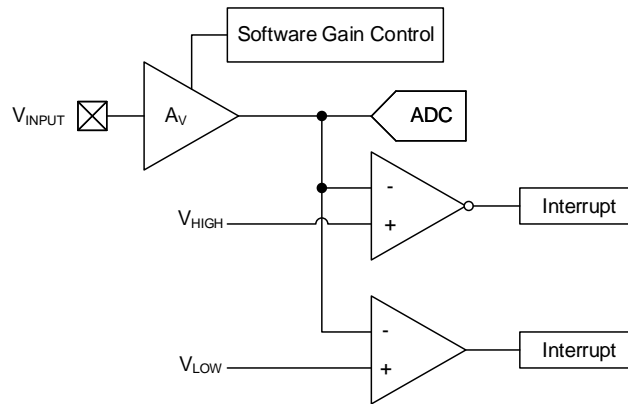
When using the OPA module in a configuration such as this, ensure that the voltage applied to the inputs does not exceed the “**Absolute Maximum Ratings**” listed in the device data sheet, or permanent damage may occur.

11.3 Automatic Gain Control

For a device such a multimeter, where the input signal has a wide range, it is critical that the system has a method for automatically scaling a signal to keep it within the ADC's range. The OPA module's internal resistor ladder allows for quickly changing the gain of the non-inverting amplifier. To properly implement automatic gain control, a comparator can be used to determine when a gain switch is necessary.

Figure 11-3 shows a block diagram of such a setup. The input signal is buffered and multiplied by the gain (A_V) for sampling by the ADC. The two comparators generate an interrupt if the signal reaches the set levels V_{HIGH} or V_{LOW} . V_{HIGH} might be set to the Fixed Voltage Reference (FVR) of the ADC, while V_{LOW} could be set above the low output range of the operational amplifier. One possible source for V_{LOW} is an on-board Digital-to-Analog Converter (DAC), whose level can be varied, depending on the next gain available in the ladder.

Figure 11-3. Automatic Gain Control (AGC) Example



12. Conclusion

Embedded operational amplifiers are a powerful resource that can enhance the analog performance of microcontrollers. Careful considerations, ranging from the power supply to the signal source, must be taken when using these operational amplifiers in applications. These considerations must be taken into account to maximize the analog performance of the peripheral. The recommendations in this document are intended to be a starting point for analog design when working with embedded operational amplifiers.

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