
Analog Applications in 8-bit PIC® and AVR® Microcontrollers

Introduction

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One of the best benefits of a microcontroller are the Core Independent Peripherals (CIPs), which improve the performance of the CPU, reduce power consumption and/or add new capabilities to the device. Advances in CIPs have allowed microcontrollers to integrate in the analog domain with on-board operational amplifiers (OPA/OPAMP), Analog-to-Digital Converters (ADCs) and Digital-to-Analog Converters (DACs). While discrete devices may offer higher analog performance, the integrated analog CIPs offer run-time configuration, reduced BOMs and smaller design areas. This document will show a few possible ways to utilize or generate analog signals on microcontrollers.

Table of Contents

Introduction.....	1
1. Buffering and Scaling Signals with an Operational Amplifier (OPA/OPAMP).....	3
1.1. Example: Signal Scaling with the OPAMP.....	3
2. Powering Multi-Voltage I/O (MVIO).....	5
2.1. Demo: Pulse Amplitude Modulation.....	5
2.2. Example: Signal Scaling with the OPAMP.....	6
3. Generating Analog Signals with Pulse Width Modulation (PWM).....	7
4. Measure V_{DD} without External Components.....	8
5. Measure Power Supplies and Batteries.....	9
6. Revision History.....	11
The Microchip Website.....	12
Product Change Notification Service.....	12
Customer Support.....	12
Microchip Devices Code Protection Feature.....	12
Legal Notice.....	12
Trademarks.....	13
Quality Management System.....	14
Worldwide Sales and Service.....	15

1. Buffering and Scaling Signals with an Operational Amplifier (OPA/OPAMP)

One of the most common use-cases for the internal operational amplifier peripheral is to buffer or scale an input signal to improve signal resolution and/or ADC acquisition time. (This assumes the impedance of the input signal is higher than that of the OPAMP's output impedance.) Signal resolution can be improved by using an operational amplifier (OPA/OPAMP) with an internal resistor ladder to dynamically scale the input signal to the measurement range of the ADC. In this configuration, the OPAMP acts like a Programmable Gain Amplifier (PGA) for the ADC.

Note: The internal resistor ladder is available on select PIC and AVR microcontrollers.

The OPAMP can also be used to reduce the acquisition time required to measure the input signal. Without an OPAMP, a high impedance input signal would have to directly charge the sample and hold (S/H) capacitor inside of the ADC. This increases the required signal acquisition time and loads down the signal. But with an OPAMP buffer, the S/H capacitor is charged quickly while also isolating the input from the capacitive load. The OPAMP buffer's inputs are high impedance, which keeps the input signal from being loaded, while the output is low impedance to quickly charge the S/H capacitor.

Note: There are configurations of the OPAMP where the input impedance of the OPAMP's circuit is much lower than the input impedance of the OPAMP itself (e.g., inverting amplifier configurations) which may load the signal. This does not occur in unity gain or non-inverting amplifier configurations.

1.1 Example: Signal Scaling with the OPAMP

Device Support: PIC18F16Q41, AVR128DB48

In these two code examples, one of the integrated OPAMP(s) is used to implement a PGA for the ADC. The microcontroller acquires a sample from the ADC while in Sleep mode.

The gain of the PGA is set by the user. Each time the button on the Curiosity Nano is pressed, the gain is increased, up-to a maximum of 16. Once the maximum gain has been reached, the gain is reset to 1 (unity gain).

Periodically, the microcontroller wakes up from sleep, samples the ADC, then prints the current gain of the PGA and the measured value to a serial terminal, like [MPLAB® Data Visualizer](#).

Figure 1-1. UART Output from Demo

```
Current Gain: 1
Measured: 0.200V

New Gain: 1.07

Current Gain: 1.07
Measured: 0.213V

New Gain: 1.14

Current Gain: 1.14
Measured: 0.228V

New Gain: 1.33

Current Gain: 1.33
Measured: 0.265V

New Gain: 2

Current Gain: 2
Measured: 0.399V

New Gain: 2.67

Current Gain: 2.67
Measured: 0.531V
```

1.1.1 Source Code

- PIC18F16Q41: <https://github.com/microchip-pic-avr-examples/pic18f16q41-analog-demo-mplab-mcc>
- AVR128DB48: <https://github.com/microchip-pic-avr-examples/avr128db48-analog-demo-mplab-mcc>

2. Powering Multi-Voltage I/O (MVIO)

Multi-Voltage I/O (MVIO) is a feature on some devices that allows an I/O port to operate at a different voltage level than the rest of the microcontroller. As an example, this allows a 3.3V microcontroller to interface with 1.8V logic, or for a 3.3V microcontroller to interface with 5V devices.

One of the requirements to use MVIO is that the MVIO port must be supplied with the voltage level used by the port. This can come from a dedicated power rail, or alternatively, it can be generated internally using an OPAMP in the microcontroller.

Note: It is more power efficient to power the MVIO through a dedicated power supply. However, a built in OPAMP requires no extra design area or components.

The maximum output current on the MVIO port will be limited by the OPAMP's maximum output current; this also requires the operating voltage of the microcontroller to be higher than or equal to that of the MVIO supply. However, it is suitable for many applications.

There are three ways to set the output of the OPAMP:

- Digital to Analog Converter (DAC)
- Internal Resistor Ladder (available on select devices)
- External Reference Level

The first method is to use the on-board DAC. The DAC peripheral can be set to the voltage level needed. The on-board voltage references can be used to improve the accuracy of the DAC.

The second method is to generate the output level with the internal resistor ladder. Normally, the internal resistor ladder is used as a part of the feedback network of the OPAMP. However, this ladder can also be used as a voltage divider to set the output level. The OPAMP would be setup to operate in unity gain mode to buffer the output of the resistor ladder.

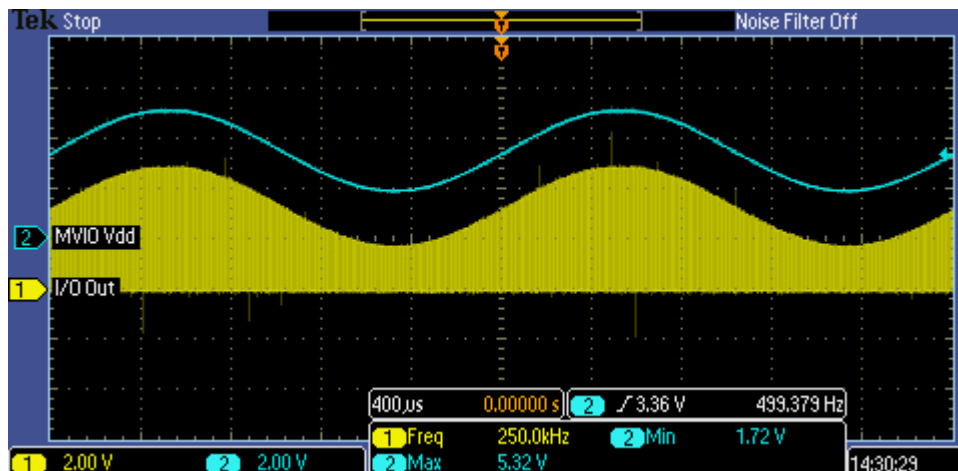
The final method is to use an external reference. Since the OPAMP has a high input impedance, the reference level can be from a simple resistor voltage divider or an external DAC outside of the microcontroller.

2.1 Demo: Pulse Amplitude Modulation

Device Support: AVR128DB48

This demonstration shows the wide operating range of the MVIO by creating Pulse Amplitude Modulated (PAM) waveforms on the MVIO port. The DAC on the AVR DB is used to synthesize varying waveforms, while the integrated OPAMP buffers and supplies the MVIO rail. This results in digital waveforms with analog modulation. For demonstration purposes, the digital waveform shown is a 250 kHz PWM output (at 50% duty cycle) mixed with a sine wave.

Figure 2-1. PAM Output on MVIO Port



2.1.1 Source Code

- AVR128DB48: <https://github.com/microchip-pic-avr-examples/avr128db48-pam-generator-mplab>

2.2 Example: Signal Scaling with the OPAMP

Device Support: AVR128DB48

This example shows three ways to set the voltage output of the OPAMP and how to monitor/measure the MVIO supply with the ADC.

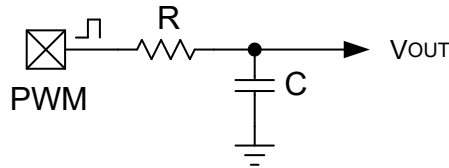
2.2.1 Source Code

- AVR128DB48: <https://github.com/microchip-pic-avr-examples/avr128db48-using-opamp-as-a-regulated-power-supply>

3. Generating Analog Signals with Pulse Width Modulation (PWM)

In most microcontrollers, the number of internal DACs in the device are limited. An alternative way to generate analog signals in the microcontroller is to use an RC filter with a PWM output. Most microcontrollers have some form of dedicated hardware that can generate PWM. The output voltage of the RC filter is proportional to the duty cycle of the PWM. [Figure 3-1](#) shows the RC filter connections from the I/O pin:

Figure 3-1. RC Low Pass Filter



Note: This assumes the load on the output of the filter is negligible. If loaded, then a more complex analysis is required. For a sharper response, cascading multiple stages of the filter will improve performance.

To generate an analog output, there are four variables to consider:

- Frequency (of PWM)
- Duty Cycle (of PWM)
- Resistance
- Capacitance

Each of these variables influences the response and performance of the analog output. Frequency, for instance, influences ripple. If the frequency is too low, then the capacitor will have a high output ripple due to over-charging and -discharging. But, if the frequency is too high, then the resolution of the PWM is degraded.

To start, select a resistor and capacitor for the filter. The capacitor used in the filter should be kept small for two reasons. Firstly, larger capacitors take up more PCB area than smaller capacitors. Secondly, a large, charged capacitor can power-up a microcontroller through the ESD diodes in the I/O pins, causing unusual reset behavior or damage. We recommend using a high stability dielectric, such as X7R or C0G, to ensure the filter capacitance is stable with changes in output voltage.

This example uses $R = 10\text{k}\Omega$ and $C = 0.1\mu\text{F}$ to implement the filter:

$$f_{-3dB} = \frac{1}{2\pi RC}$$

To reduce the amount of output ripple, the frequency of the PWM should be much higher than the -3 dB point. As a general guideline, this means at least 10x higher in frequency. With the example values ($R = 10\text{ k}\Omega$ and $C = 0.1\text{ }\mu\text{F}$), the -3 dB point works out to be about 159 Hz. Creating a PWM output at 1.6 kHz would fulfill the basic requirements, but the ripple reduces significantly with frequency. If a higher frequency output is available, or more optimal for generation, then the higher frequency option should be used instead.

The final variable to consider is the duty cycle (DC), which proportionally relates the desired output voltage to the power supply to the microcontroller, as shown below.

$$V_{OUT} = DC * V_{DD}$$

Where V_{OUT} is the output of the filter, DC is the duty cycle (in %), and V_{DD} is the power supply to the microcontroller.

4. Measure V_{DD} without External Components

Using the Device Information Area (DIA) fields on some PIC[®] MCUs, it is possible to measure the operating voltage of the microcontroller without using any external components.

Note: For AVR[®] MCUs or devices without DIA fields, see [5. Measure Power Supplies and Batteries](#) for an alternative method.

Inside of the DIA fields are the measured values of the Fixed Voltage Reference (FVR) from the factory. By using the power supply (V_{DD}) as the voltage reference and measuring the FVR with the ADC, it is possible to compute the value of V_{DD}.

To do so:

1. Set the ADC to use V_{DD} as a reference
2. Select the FVR for the ADC input
3. Acquire a sample
4. Read the DIA field that correlates with FVR settings
5. Solve for V_{DD} with the following expression:

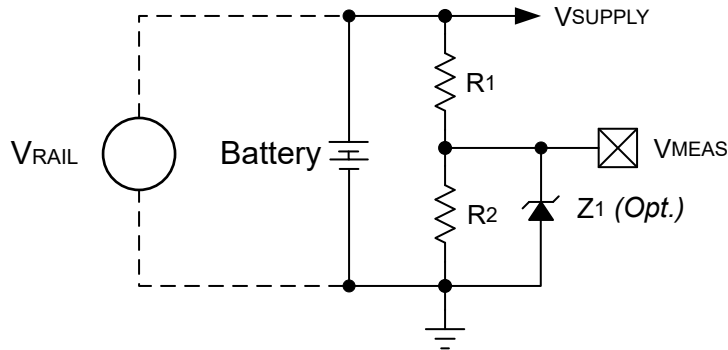
$$\frac{DIA < N}{MEASURED} = V_{DD}(\text{in } mV)$$

Where: DIA is the value from the look-up tables, N is the resolution of the ADC and MEASURED is the result from the ADC.

5. Measure Power Supplies and Batteries

Another way to measure power supplies and batteries is to use a voltage divider. The simplest method is to use two resistors to divide the supply to a value within the ADC's measurement range, as shown in [Figure 5-1](#).

Figure 5-1. Simple Voltage Divider Circuit

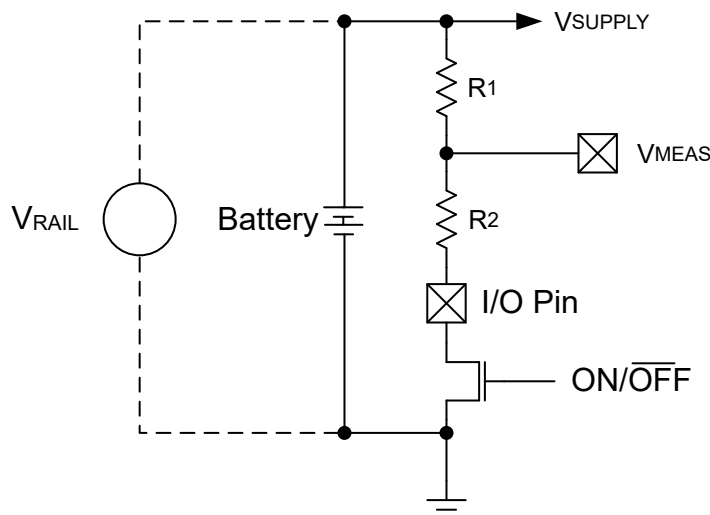


Note: If measuring a supply that exceeds the absolute maximum ratings, a fail-safe shunt regulator (such as a Zener diode) and/or a fusible resistor (R_1) can provide some protection. The protection networks must be evaluated for each application and tested before use in production.

One way to improve the circuit shown in [Figure 5-1](#) is to add a capacitor across R_2 . If the capacitor is sized correctly, then the signal acquisition time can be reduced significantly. However, this limits the sample rate, as the capacitor requires time to charge/discharge between conversions. This technique is further discussed in Microchip Application Note AN4225, "[Maximizing the Signal: Tips and Tricks to Properly Acquiring Analog Signals](#)" (DS00004225A).

A slightly more advanced version of the voltage divider incorporates a small NMOS transistor into the divider to shutdown the division network when not needed. However, the NMOS can be replaced with an open-drain I/O pin instead. This circuit can be used for faster acquisition times by using lower-valued resistor divider networks, which reduce source impedance for the ADC. A small amount of error is added due to the resistance of the NMOS or I/O pin.

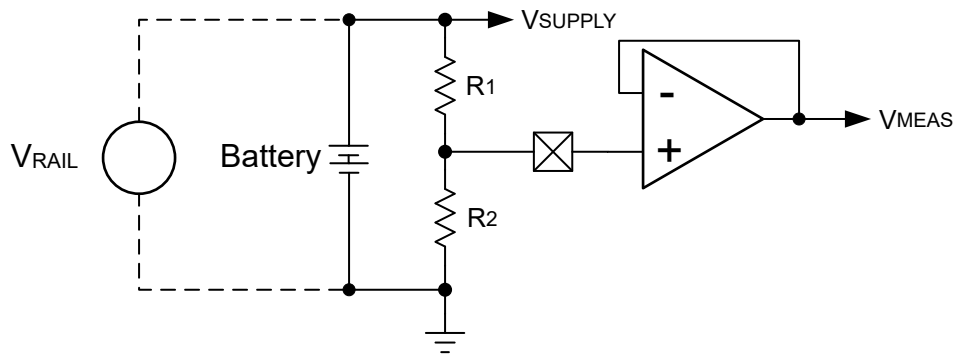
Figure 5-2. Voltage Divider with On and Off



Note: This circuit can only be used with power supplies at or less than the supply of the microcontroller.

To improve acquisition time for high-impedance divider networks, an OPAMP (see [1. Buffering and Scaling Signals with an Operational Amplifier \(OPA/OPAMP\)](#)) can be used to buffer the output.

Figure 5-3. Voltage Divider with an OPAMP Buffer



6. Revision History

Document Revision	Date	Comments
A	02/2022	Initial document release.

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