



# Hardware Conditioning of Sensor Signals

Priyabrata Sinha  
Microchip Technology Inc.

Common Sensing Elements

© 2008 Microchip Technology Incorporated. All Rights Reserved.

Slide 1

I'm Priyabrata Sinha from Microchip Technology, and welcome to the **Hardware Conditioning of Sensor Signals** web seminar. This webinar explains the analog hardware conditioning we require for sensor signals before they can be digitally processed by an embedded processor such as the Digital Signal Controllers from Microchip Technology.

## Seminar Overview

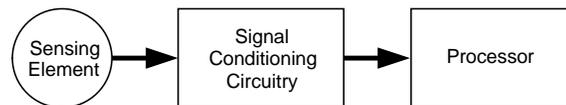
- **Overview of Analog Signal Conditioning**
- **Anti-Aliasing Filters: Benefits and Design**
- **Amplifiers: Types and Characteristics**
- **ADC Interfacing Considerations**

We will begin this seminar with an introduction to the various aspects of the signal conditioning that is typically needed to bring the analog signals generated by a sensor into a form that can be processed by an embedded processor such as a DSC or microcontroller. Through most of the presentation, we will discuss some key signal conditioning components used for sensor signal processing applications.

First, we will look at a type of analog filters called Anti-Aliasing Filters, understand the benefits of using these filters and how to design them. We will then move on to the broad subject of how to suitably amplify the sensor signals using various techniques and classes of amplifiers. Finally, we will explore some signal conditioning considerations that come into play when we need to interface the filtered and amplified sensor signals with an Analog-to-Digital Converter, or ADC, which is often an on-chip peripheral module within the DSC or MCU device.

## Basic Sensor Signal Chain

- Sensing element outputs can be either voltage, current, or frequency-based
- Basic signal path consists of the sensing element, signal conditioning circuitry, and a processor such as a Digital Signal Controller (DSC)



In all of the intelligent sensing applications discussed in this series of seminars, we use a common sensor signal path, which consists of the sensing element, signal conditioning circuitry to map the sensing element's output signal into a range that the remaining electronic circuitry can process, and then filtering circuitry to reduce or eliminate electronic noise. In this presentation, it is the Signal Conditioning block that we are primarily interested in. This signal conditioning circuitry conditions the signals coming from the sensor, and since a majority of sensors generate analog output signals, this circuitry is essentially analog rather than digital.

## Signal Conditioning Overview

- **Analog signal conditioning needs vary by sensor**
- **Signals must be clean and band-limited**
  - Anti-Aliasing Filter needed
- **Sensor signals are often weak in amplitude**
- **Some conditioning may be needed for interfacing with ADC**
  - Amplification needed
  - Level-shifter may be needed
  - ADC power supply and voltage reference considerations

The specific signal conditioning circuits that are needed in a sensor application depend on the type of sensor employed. For example, a sensor that generates output voltages according to the magnitude of the physical parameter being measured would require different signal conditioning from a sensor that produces variable resistance. But essentially, there are certain typical signal conditioning requirements in sensor applications.

First, the signals generated by the sensor must be as free of noise as possible. Moreover, the frequency content of the signal, in other words its bandwidth, must be limited to a certain range, based on some constraints about which we will learn shortly. This often makes it necessary to use what is referred to as an Anti-Aliasing Filter.

Secondly, the signals generated by sensors, whether voltages, currents or electrical properties, usually have weak amplitudes. In order to process the signal accurately, and also to make the system more robust to the effect of noise, the signal needs to be amplified.

In addition to filtering and amplification, the need to convert the signal into digital form using an Analog-to-Digital Converter, or ADC, adds some more signal conditioning needs. Besides amplifying the signal, the signal might also need to be translated to suit different ADC voltage references. Also, many ADCs, especially those contained inside an MCU or DSC, only operate on unipolar inputs; that is, the input voltage can not alternate between positive and negative levels with respect to the Ground. In such cases, a Level Shifter is required.

## Anti-Aliasing Filters

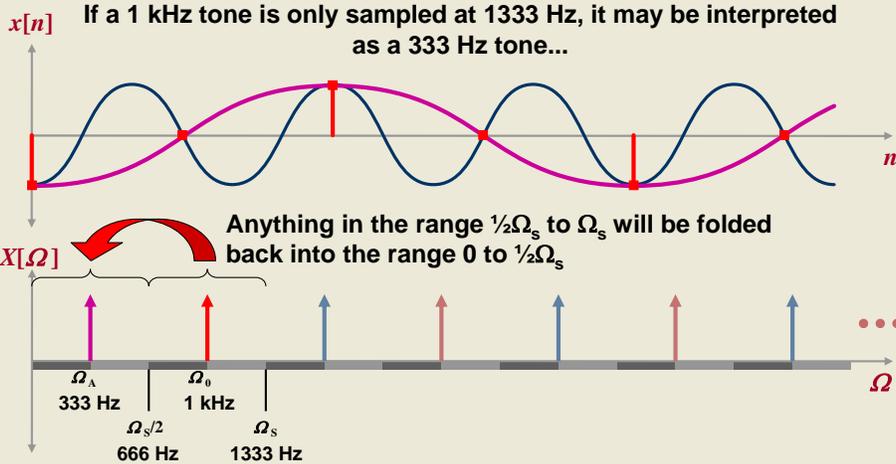
- **Anti-Aliasing Filter is an analog filter that band-limits the sensor output signal to satisfy the Nyquist-Shannon Sampling Theorem**
  - Sampling rate used to convert an analog signal to digital must be greater than twice the highest frequency of the input signal in order to be able to reconstruct the original perfectly from the sampled version
- **Filter cut-off frequency should be chosen based on useful signal content of sensor output signal**
- **Anti-Aliasing Filters prevent irreversible signal corruption, as shown in following slides**

The Nyquist-Shannon Sampling Theorem is a fundamental concept that imposes a constraint on the minimum rate at which an analog signal must be sampled for conversion into digital form, such that the original signal can later be reconstructed perfectly. Essentially, it states that this sampling rate must be at least twice the maximum frequency component present in the signal; in other words, the sample rate must be twice the overall bandwidth of the original signal, in our case produced by a sensor. This is a key requirement for effective signal processing in the digital domain.

In reality, sampling at a higher rate increases the computational bandwidth and memory required by an embedded processor. While the presence of advanced features like Direct Memory Access may reduce the processor load somewhat, in real-time and space-constrained sensor applications, the higher sampling rate may still not be feasible in many cases. Therefore, the system developer needs to constrain the bandwidth of the original signal, rather than simply increasing the sampling rate. An analog filter that restricts the signal bandwidth to half the sampling rate, or preferably even less, is called an Anti-Aliasing Filter. Of course, the cut-off frequency of this hardware filter must be chosen in such a way that the useful information present in the sensor output signal is preserved.

Now that we have seen the basic objective of an Anti-Aliasing Filter, let us look at an example that illustrates the effect of aliasing if an Anti-Aliasing Filter were not implemented.

## Anti-Aliasing Filters



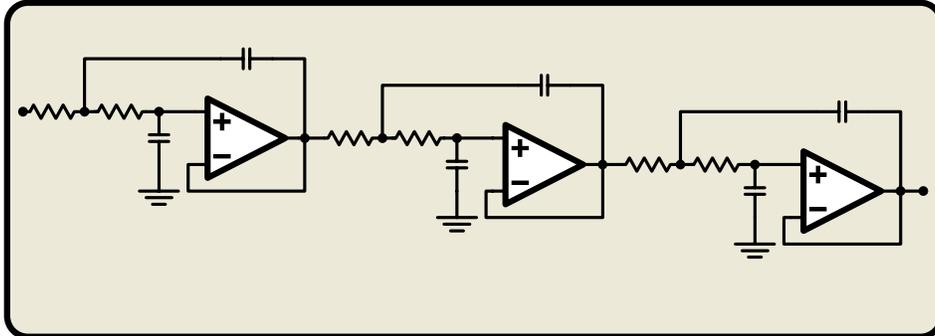
The 1 kHz signal now goes under the *alias* of 333 Hz! Which one is the real signal? There is no way to tell once it has been sampled!

Let us consider a simplistic scenario: a 1 kHz tone is being sampled at a sampling rate of 1.333 kHz; that is, a waveform with one thousand cycles in a second is sampled one thousand three-hundred thirty-three times during each second. It is apparent that this example does not satisfy the Nyquist-Shannon Sampling Theorem because the minimum sampling rate according to that rule is 2 kHz. In other words, the signal has a frequency content greater than half of the actual sampling rate of 1.333 kHz.

As can be seen from the timing diagram, some of the variations of the signal waveform are effectively being missed by the sampling process. If you try to reconstruct the original signal from its samples, it ends up looking like a 333 Hz sinusoidal waveform rather than 1 kHz. The insufficient number of samples used in this example has essentially created an incorrect lower frequency of 333 Hz, which is commonly referred to as an “alias”. While this was a simplified example, the same phenomenon occurs even with complex waveforms, whenever the input signal is not band-limited to satisfy Nyquist-Shannon Sampling Theorem.

Can this adverse effect be eliminated through digital filtering in software after the signal itself has been sampled and converted by the ADC? Unfortunately not, as the frequency content of the original has already been altered irreversibly. There is simply no way for the application software to determine if anti-aliasing had indeed occurred or not.

## Anti-Aliasing Filter Design

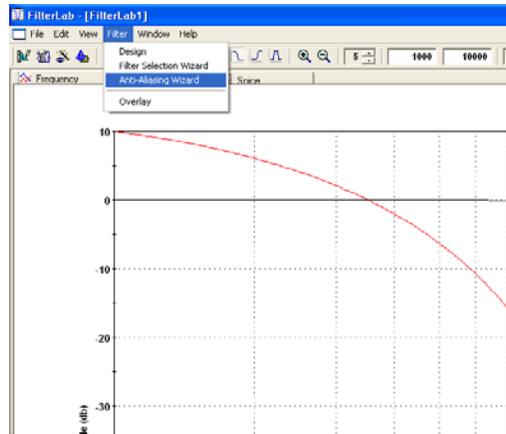


- **An ordinary analog low-pass filter**
  - Most popular filter implementation used is Sallen-Key
- **Designed using traditional analog design methods**
  - Much easier or to use the Microchip FilterLab<sup>®</sup> analog filtering software tool

It must be clear by now that an Anti-Aliasing Filter has to be an analog filter, implemented in hardware even before the sensor signal reaches the ADC. Also, by its very nature, an Anti-Aliasing Filter is a low-pass filter. There are several techniques used to design an analog low-pass filter; one of the most popular filter structures used is the Sallen-Key Filter. A Sallen-Key Filter is basically a cascade of RC filter stages, with each stage having a non-inverting amplifier configuration.

The Sallen-Key, and indeed all techniques that can be used to design Anti-aliasing Filters for sensor applications, utilize traditional analog design methods, which can involve a lot of manual mathematical computations and can therefore be prone to design errors. Fortunately, the Microchip FilterLab<sup>®</sup> analog filter design software makes designing such filters a trivial task, as we will see in the following slides.

## Anti-Aliasing Filter Design



- **Step 1: Open the FilterLab<sup>®</sup> analog filtering software tool and select “Anti-Aliasing Wizard” option from the Filter Menu**

The first step in designing an Anti-Aliasing Filter circuit using the FilterLab<sup>®</sup> analog filtering software tool is to open the FilterLab<sup>®</sup> analog filtering software tool application. Then, select the “Anti-aliasing Wizard”, which is a step-by-step tool that walks the user through the simple steps involved in designing the filter.

 **Anti-Aliasing Filter Design**



- **Step 2: Enter passband cut-off frequency (Hz)**
- **Step 3: Enter ADC sampling frequency (Hz)**
- **Step 4: Enter ADC resolution (number of bits)**
- **Step 5: Enter desired Signal-to-Noise Ratio (dB)**

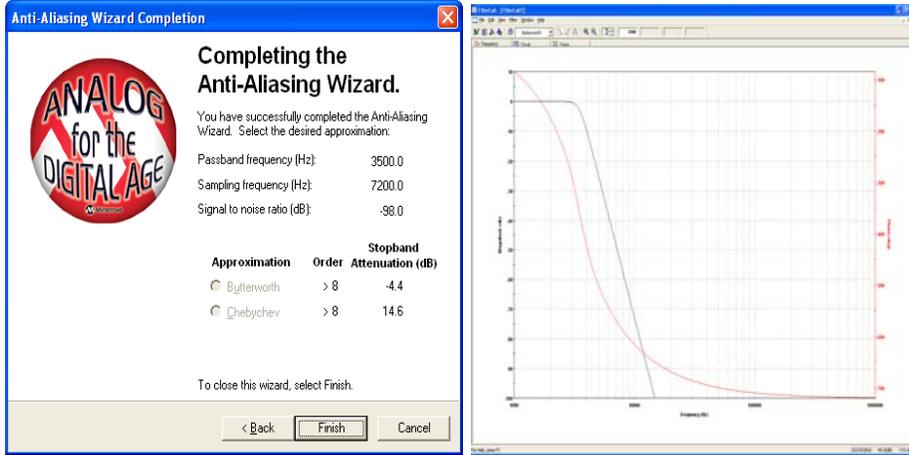
Common Sensing Elements      © 2008 Microchip Technology Incorporated. All Rights Reserved.      Slide 9

Once the Anti-aliasing Wizard is executed, it prompts the user to enter various essential parameters that specify the limits under which the filter must be designed to operate.

The first such specification is the filter cut-off frequency, which defines the passband of the filter. This parameter should be carefully selected, primarily based on the highest frequency at which the sensor signal contains any relevant information. This is often directly related to the response time of the sensor. Then, enter the sampling frequency of the ADC, which defines the rate at which the signal would be sampled by the embedded system. This frequency must be selected to be as high as is practically feasible on the ADC and processor. At a minimum, this must be more than twice the passband cut-off frequency.

The next parameter, the ADC resolution, is directly tied to the number of bits in the ADC conversion results. Finally, enter the desired Signal-to-Noise Ratio, or SNR, of the filter. This is what decides how much the input waveform is suppressed beyond the cut-off frequency; the greater the attenuation, the greater the complexity of the filter circuit in terms of number of components. Thus, in practice there may be some trade-off between the filter SNR obtained and the cost of the system hardware.

## Anti-Aliasing Filter Design



The screenshot shows the 'Anti-Aliasing Wizard Completion' dialog box on the left and a plot of filter characteristics on the right. The dialog box contains the following information:

**Completing the Anti-Aliasing Wizard.**  
You have successfully completed the Anti-Aliasing Wizard. Select the desired approximation:

Passband frequency (Hz): 3500.0  
Sampling frequency (Hz): 7200.0  
Signal to noise ratio (dB): -98.0

Approximation	Order	Stopband Attenuation (dB)
<input type="radio"/> Butterworth	> 8	-4.4
<input type="radio"/> Chebyshev	> 8	14.6

To close this wizard, select Finish.

Buttons: < Back, Finish, Cancel

The plot on the right shows the magnitude response of the filter. The x-axis is Frequency (Hz) on a logarithmic scale from 1000 to 10000. The y-axis is Magnitude (dB) from 0 to -100. A solid black line represents the ideal filter response, and a red line represents the actual filter response. The actual response shows a roll-off that is slightly less steep than the ideal response, especially at higher frequencies.

- **Step 6: Verify results and click “Finish” to see design**

Finally, the Anti-aliasing Filter draws a plot of the actual filter characteristics obtained relative to the desired characteristics. Once you have verified the results and are satisfied with the filter performance indicated by the plot, click Finish to complete the filter design process. Alternatively, you can go back to previous steps and adjust some parameters to see if that gets you the desired results.

It should be obvious that this process really did not require the user to know anything about the filter design methodology or make any calculations. The software tool automatically generates a circuit diagram such as the Sallen-Key filter structure we had seen earlier. The diagram will show the number of filter stages, as well as all the resistor and capacitor values used.

## Amplifiers

- **Sensor outputs are often weak and must be amplified to occupy as much of the ADC's dynamic range as possible**
- **Proper Op-Amp selection is critical to amplified sensor data accuracy**
  - **Gain-Bandwidth Product (GBWP)**
  - **Input Offset Voltage and Input Bias Current**
  - **Gain Linearity**
  - **Op-amp Noise**
  - **Common Mode Rejection Ratio (CMRR)**
  - **Power Supply Rejection Ratio (PSRR)**

The signals generated by most sensor elements are very small in magnitude, and must therefore be amplified. For example, the voltage produced at the leads of a thermocouple for a single degree Centigrade rise in temperature, could be as low as 49 microvolts, which can be easily drowned by system noise sources or device imperfections. If a gain factor of 249 is applied, the resultant voltage per degree Centigrade is 10 millivolts per degree Centigrade; for a 3.3V system, one would still be able to measure temperatures up to 330 degree Centigrade, at the same time utilizing the dynamic range of the ADC to a large extent. Moreover, after amplification the signal becomes less susceptible to the effect of low-level additive noise sources. The most critical element of an amplifier circuit is usually an operational amplifier, or Op-Amp. It is essential to perform due diligence in selecting the right op-amp for a particular application. Let us briefly discuss some key electrical characteristics of op-amps and what effect they have on system performance.

Firstly, the Gain-Bandwidth Product, or GBWP, is crucial. This parameter defines how the op-amp gain factor would decrease as the signal frequency increases. Obviously, an op-amp with higher GBWP would be able to handle signals over a wider frequency range without compromising on amplification. The Input Offset Voltage is perhaps the single most critical error source in an op-amp, especially in a differential configuration. Input Offset Voltage refers to the voltage produced at the output of an op-amp when the input is zero; ideally, the offset should be zero. Offsets are typically compensated using either trimming potentiometers or in software. A related error is the Input Bias Current, which is the current flowing into the inputs of the op-amp. Another amplification error is non-linearity, which is defined as the maximum deviation from a straight line on the plot of output versus input. Often, the process imperfections in the op-amp can add some amount of random noise to the measurements. This noise needs to be filtered out either using hardware or software.

Finally, two other key quality metrics of an op-amp are its Common Mode Rejection Ratio, or CMRR, and Power Supply Rejection Ratio, or PSRR. Let us look at CMRR first. "Common mode gain" is a term used to describe how much the op-amp output would change if the same input signal were to be fed into both inputs and this common signal were to be changed by 1 volt. On the other hand, "Differential mode gain" is the change in output when a differential input is changed by 1 volt, that is: an amplifier gain as we understand it. The CMRR is defined as the ratio of this common mode gain and differential mode gain. It may be noted that CMRR has an adverse effect only in a non-inverting amplifier configuration. The PSRR is computed in a similar manner, but this metric relates to the change in output voltage with a change in power supply voltage.

## Single-ended Amplifiers

- **When signal conditioning and processing blocks are located close to actual sensor, system is less susceptible to noise**
  - **Classic single-ended Gain Amplifiers are used**
  - **Minimal discrete components used**
  - **Key requirements: rail-to-rail voltages, high GBWP**
  - **Example systems: PIR Detectors, Hall Effect Sensors, Thermistors, Smoke Detectors, Humidity Sensors**

Local sensor systems are those in which the sensors are located relatively close to their respective signal conditioning circuits; in such cases, the noise environment is not severe. Single-ended non-inverting amplifiers are a good choice for amplifying the sensors' output because they require a minimal amount of discrete components.

Single-ended amplifiers are essentially op-amps in which one input is connected to the sensing element, and the other input is tied to a resistive voltage circuit that determines the gain of the amplifier. Some typical features of such single-ended amplifiers are rail-to-rail input and output voltages and a high Gain Bandwidth Product.

As listed here, some common examples of sensor subsystems using single-ended amplifiers are Passive Infra-Red sensors, Hall Effect motion sensors, Thermistors, Smoke Detectors and Humidity Sensors. As you can infer, most of these applications require the sensor and processing circuit to be very localized.

## Differential Amplifiers

- **When signal conditioning and processing blocks are remotely located, or placed in a noisy environment, single-ended amps are not so accurate**
  - **Differential Amplifiers are used**
  - **Also used for Wheatstone Bridge sensors**
  - **More discrete components used**
  - **Key requirements: large CMRR, small offset**
  - **Example systems: Pressure sensors, Thermocouples**

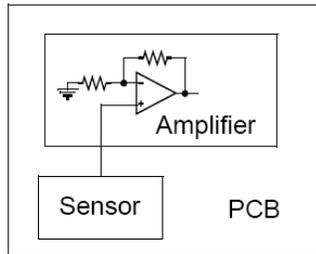
Systems in which the sensors are not located in close proximity to the signal conditioning circuitry are referred to as Remote Sensor systems. The signal conditioning considerations that apply to such remote sensors also apply to systems in which the sensor is local but placed in a high-noise environment; for example, a Thermocouple interface. In such applications, single-ended amplifiers are very susceptible to transmission noise. Instead, transmission of sensor outputs as a pair of differential signals is far more robust. To amplify differential signals, one needs differential amplifiers, that is: amplifiers in which the two inputs are driven into the two inputs of an op-amp.

An application scenario in which differential amplifiers are essential irrespective of whether the sensor is local or remote, is when the sensor is used in a Wheatstone's Bridge configuration: pressure sensors such as strain gauges are a classic example.

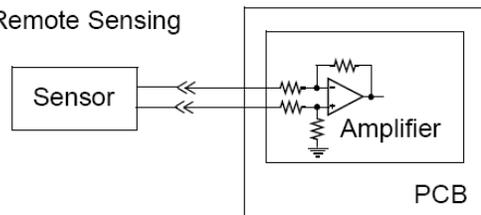
Some notable features of a Differential Amplifier are a large Common Mode Rejection Ratio and a small offset voltage.

## Single-Ended and Differential Amplifiers

Local Sensing



Remote Sensing



The two classes of amplifiers we just discussed are illustrated here. In the first example, the sensor and the amplifier are located on the same PCB, thereby allowing the usage of a non-inverting single-ended amplifier. In the second example, the sensor is located away from the amplifier circuit and the sensor outputs are a pair of differential signals; this makes a differential amplifier configuration necessary. In both cases, note that the values of the resistors used in the input resistive networks are what determine the gain applied to the signals.

## Instrumentation Amplifiers

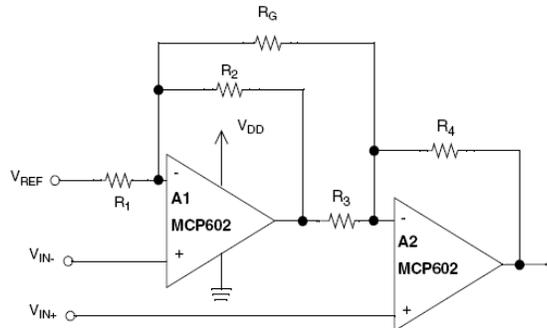
- **Type of differential amplifier with desired characteristics for measurement systems**
  - Can be designed using op amps, or specialized Instrumentation Amplifier ICs can be used
  - Very low offset, drift and noise
  - Very high gain, input impedance
  - High CMRR across frequency, to reject supply noise
- **Several possible configurations**
  - Two op-amp or three op-amp
  - Single power-supply or dual power-supply

An instrumentation amplifier, or in-amp, is a special class of closed-loop amplifiers with differential inputs and high-impedance, balanced inputs. As such, the characteristics of such amplifiers make them very suitable for using in instrumentation systems, and in general, any kind of measurement-oriented applications such as sensor signal processing. Instrumentation amplifiers can be implemented using multiple op-amps, with a suitable choice of discrete components such as resistors and potentiometers to control the gain. However, many self-contained Instrumentation Amplifier chips are also available; such ICs contain an internal resistive network, thereby eliminating or minimizing external components.

Instrumentation amplifiers have certain characteristics that are very desirable in sensor signal conditioning. For example, their offset voltage, drift of characteristics over time, and noise generated, are very low. Moreover, they provide a very high gain factor, high CMRR over their entire operating frequency range, and as mentioned earlier, high input impedance.

When Instrumentation Amplifiers are implemented using op-amps, several alternative configurations are possible, and I will mention a few of them. In-amps most commonly employ either two or three op-amps, and either a single power supply or a dual power supply.

## Two Op-Amp Instrumentation Amplifiers

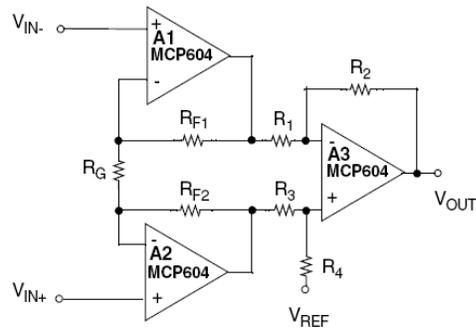


$$V_{OUT} = \left(1 + \frac{R_1}{R_2} + \frac{2R_1}{R_G}\right)(V_{IN+} - V_{IN-}) + V_{REF} = \left(\frac{4 + 60k\Omega}{R_G}\right)(V_{IN+} - V_{IN-}) + V_{REF}$$

Where  $R_1 = 30k\Omega$  and  $R_2 = 10k\Omega$

A differential amplifier based on a single op-amp does not provide the high performance and precision needed by an Instrumentation Amplifier. Therefore, many in-amps use two op-amps, ideally two op-amps located in the same IC which provides better matching. The configuration shown here results in a high input impedance, which permits the two sensor sources to be high-impedance and even unbalanced. The CMRR is limited by how closely the R2-to-R1 ratio and the R4-to-R3 ratio match each other, and is CMRR is higher as a result of the gain applied to the signal. The resistor  $R_G$  can be used as a trimming resistor to adjust the amplifier gain.

## Three Op-Amp Instrumentation Amplifiers

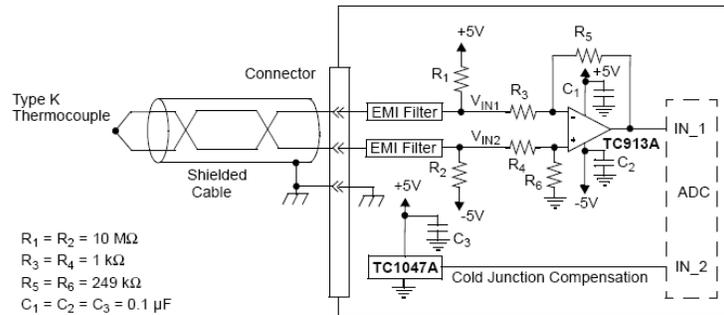


Where  $R_{F1} = R_{F2}$  and  $R_1 = R_2 = R_3 = R_4$

$$V_{OUT} = \left(1 + \frac{2R_F}{R_G}\right)(V_{IN+} - V_{IN-}) + V_{REF}$$

In order to obtain even more closely balanced high-impedance inputs, three op-amps need to be utilized as shown in this figure, instead of the two op-amp configuration we have already seen. Again, the resistor  $R_G$  is used to control the gain of the amplifier. A powerful feature of a three op-amp instrumentation amplifier is that there is no common mode gain at all, as no common mode voltage can appear across  $R_G$ . This essentially means that the CMRR is directly proportional to the gain. Moreover, any common mode errors in the two input stages are effectively canceled out in the output differential amplifier stage due to the inherent symmetry of this configuration; this is especially true when the op-amps are located in the same IC. Due to these advantages, the three op-amp setup is widely used in dedicated In-Amp ICs.

## Example #1: Dual Power Supply Thermocouple Interface



$$V_{OUT} = (V_{IN2} - V_{IN1}) \left( \frac{R_5}{R_3} \right) + V_{REF} = (\Delta V_{IN}) \left( \frac{249k}{1k} \right)$$

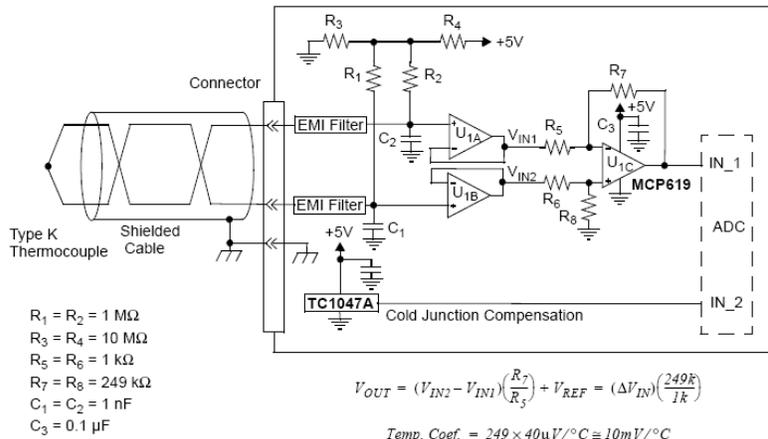
$$\text{Temp. Coef.} = 249 \times 40 \mu\text{V}/^\circ\text{C} \cong 10 \text{ mV}/^\circ\text{C}$$

This example shows a thermocouple interface to the Analog-to-Digital Converter input pins of a DSC or MCU device. The two open leads of the thermocouple are connected to the two inputs of a differential amplifier through a resistive feedback network. A TC913A auto-zeroed op-amp was selected for the differential amplifier, primarily because of its low maximum offset voltage of 15 millivolts and high CMRR of 116 decibels. The thermocouple inputs are tied to separate positive and negative supplies through 10 megaohm resistors, so that the circuit can detect a failed open-circuit thermocouple. The gain of the amplifier was selected to the 249, which provides a temperature coefficient of 10 millivolts per degree centigrade. EMI filters are employed on both inputs to the amplifier, in order to reduce the effect of Electromagnetic Interference on the system.

The DSC or MCU computes the actual temperature by subtracting the cold junction temperature from the temperature determined from the thermocouple amplifier. The cold junction temperature is measured with a TC1047A silicon IC analog output sensor, and provides an output voltage of 10 millivolts per degree centigrade with an offset of 500 millivolts. Therefore, two ADC inputs of the DSC or MCU are being used in this application example.

Note that the system illustrated here requires two different power supplies: one for +5V and another for -5V. When dual supplies are used, the reference voltage Vref is directly connected to Ground. The dual supply configuration allows for measuring the parameter of interest over a wide range, as a result of the increased signal range.

## Example #2: Single Power Supply Thermocouple Interface



This diagram depicts the same thermocouple interface system, except that this configuration uses a low-cost, single power-supply amplifier circuit using a quad op-amp. The buffered input differential amplifier topology is similar to an instrumentation amplifier and offers the feature of equal and high input impedance in the amplifier inputs. An instrumentation amplifier with integrated gain resistors can also be used to implement this circuit. As in the previous example, the gain of the amplifier was selected to be 249, providing a temperature coefficient of 10 millivolts per degree centigrade. The thermocouple inputs are biased to half the power supply voltage instead of being connected to ground.

A disadvantage of a single power-supply amplifier system is that the dynamic range of the signal is reduced to half of what it would be for a dual power-supply circuit. However, single power-supply systems require a lower system cost, power consumption and physical space; therefore, this configuration is becoming increasingly popular in embedded systems, especially in applications requiring compactness or portability.

## Programmable Gain Amplifiers

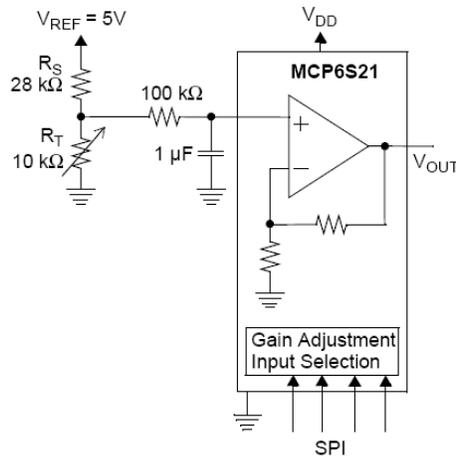
- **A specialized amplifier IC with multiplexed multiple inputs and programmable gain**
- **Ideal for interfacing with multiple sensors**
- **Ideal for non-linear sensors, e.g. thermistor**
  - Gain can be adjusted for non-linearities
- **Example: MCP6SX2**
  - Digital control of gain (1x - 32x) using SPI
  - Up to 8 inputs, multiplexed using SPI
  - External  $V_{REF}$  pin centers amplified signal

In many intelligent sensing applications, a single DSC is used to process the inputs from several sensors, often sensors of different types, which would require applying different gains to each sensor output signal. Moreover, the gain applied to each sensor output might need to be adjusted during run-time, for example: to compensate for a Thermistor producing non-linear outputs across the temperature range. Adjustable gains are impossible in a conventional amplifier designed using fixed discrete components.

Both of the above objectives are accomplished quite easily by using a special type of amplifier called a Programmable Gain Amplifier, or PGA. PGA devices provide varied capabilities for multiplexing sensor output signals and adjusting the gains applied to them.

For instance, the MCP6SX2 PGA from Microchip provides the ability to control the amplifier gain in linear multiples from 1 to 32. The gain setting is determined by the software application running on the DSC or MCU, and is communicated to the PGA using a Serial Peripheral Interface, or SPI, communication channel. This PGA supports up to 8 input signals, with the selection controlled by the DSC or MCU, again using the SPI channel. In addition, an external voltage reference pin can be used to set the voltage mid-point of the amplified sensor signal.

## Example #3: Thermistor Interface



$$V_{OUT} = \left( \frac{R_T}{R_S + R_T} \right) (V_{REF}) \text{ (Amplifier Gain)}$$

This example illustrates the use of a PGA to amplify the output from a Thermistor. The Thermistor, labeled  $R_T$ , is placed in a voltage divider arrangement, with the voltage across the Thermistor fed to an input of the PGA. Only one input signal is shown here for clarity; remember that up to 8 signals can be interfaced. The fixed resistor  $R_S$  determines the overall voltage swing, or dynamic range, of the PGA input signal.

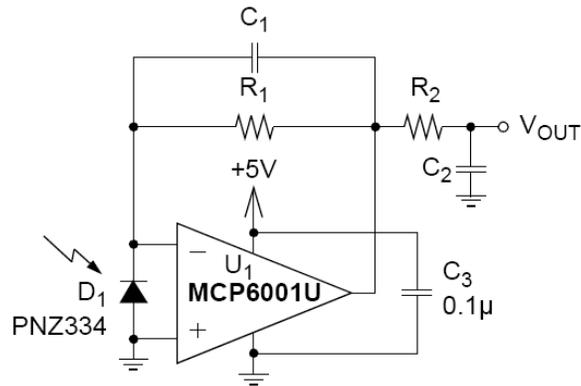
## Other Amplifier Types

- **Transimpedance Amplifier**
  - **Converts current to voltage**
  - **Used for high-impedance sensors that generate current outputs, e.g. Photodiode or CCD**
  - **Constant voltage bias due to “virtual short”**
- **Isolation Amplifier**
  - **Avoids direct electrical connection between a high-voltage sensor and rest of the system**
  - **Avoids high voltages in rest of the system from entering sensor, e.g. in an ECG or EEG**

We have seen a number of types of amplifier devices and circuits that are widely used in sensor applications. There are also some other special classes of amplifiers that do not perform the classical task of amplifying an input voltage by a gain factor. One such example is a Transimpedance Amplifier, which is commonly used to amplify the signals from high impedance current sensors, such as a Photodiode or CCD. A Transconductance Amplifier takes as its input a sensor output current that varies according to a physical parameter such as light intensity, and converts it into a proportionally varying voltage waveform. The sensor element is placed between the two inputs of an op-amp, resulting in a virtual short between the inputs and therefore produces a voltage proportional to the current through the sensor element.

An Isolation Amplifier, as the name suggests, electrically isolates two circuits from each other. This can be useful in two ways. In an application where the sensor could sometimes generate very high voltage outputs or voltage transients, the rest of the circuit needs to be protected from such high voltages. Conversely, there are applications, especially in medical equipment such as an Electro-Cardiogram or Electro-Encephalograph, in which the body must be protected from any momentary high-voltage spikes or short-circuits occurring in the rest of the sensor processing system. In both circumstances, an Isolation Amplifier prevents direct transfer of electrical energy between different parts of the overall circuit.

## Example #4: Photodiode Interface



This diagram shows an example of how a Transconductance Amplifier may be implemented using an op-amp and an external RC network. As explained before, the sensor element, in this case a Photodiode D<sub>1</sub>, is connected across the two inputs of the op-amp, and the resultant output voltage, labeled V<sub>out</sub>, is directly proportional to the current through D<sub>1</sub>, which is in turn proportional to the light intensity being measured.

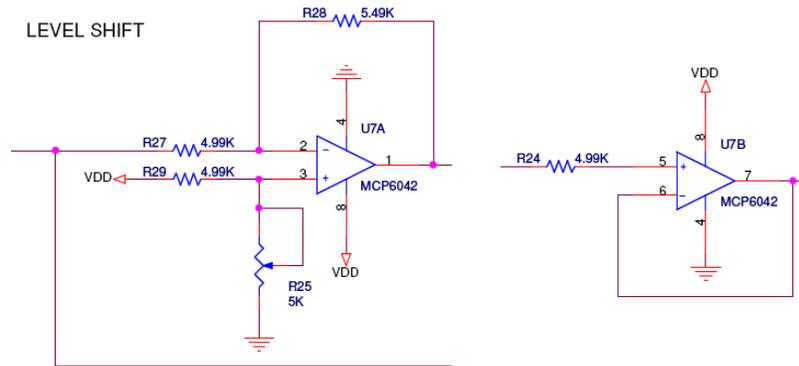
## ADC Interfacing Considerations

- **Proper decoupling of voltage rails using capacitors improves accuracy**
- **Amplified sensor output might contain offset that must be subtracted from ADC conversions in software**
- **Using external voltage references often yields higher conversion accuracy**
  - Reference identical to supply provides best results
- **If ADC is unipolar, level of signal must be shifted up to be all-positive**
  - e.g. from [-1.65V, +1.65V] range to [0V, 3.3V] range
- **Current output may not be enough for ADC input**
  - Need buffer amplifier to increase drive strength

The varying characteristics and capabilities of the Analog-to-Digital Converter used to convert the analog sensor signals to digital form, also places some unique requirements on the signal conditioning circuitry. Some of these are simply good circuit design practices: for example, adding a decoupling capacitor between every pair of positive voltage supply and ground pins on the DSC or MCU device helps to enhance ADC accuracy by keeping the voltage rails stable during the conversion process. In some cases, the sensor element may produce a fixed voltage offset: for example, the TC1047A temperature sensor IC has an offset of 500 millivolts. In such cases, the only recourse is to compensate for this offset during processing in software. Sometimes, the configuration in which the ADC is used can play a major role in determining the data conversion accuracy of the ADC: for example, using an external voltage reference pin to provide the ADC voltage rails generally produces better ADC performance compared to using the processor's own analog power supply as reference. In addition, having the reference voltage rails identical to the device power supply levels produces the best results.

If the ADC is contained within the DSC or MCU device, which is desirable in embedded applications, it is very common for the on-chip ADC to be unipolar. This means that the ADC can only sample positive voltage levels, as opposed to a bipolar ADC that can sample signals that take both positive and negative values over time. For example, the ADC input might accept voltages in the 0 to 3.3 volts range, but not voltages in the -1.65 to + 1.65 volts range. However, sensor output signals are typically bipolar. Therefore, a special type of inverting op-amp circuit called a Level Shifter is required in such cases. Another special signal conditioning circuit that may be required is a Buffer Amplifier, which is an op-amp circuit that is used to transfer a voltage from a circuit with high output impedance to a circuit with low input impedance.

## Level Shifter and Buffer Amplifier



Classic circuits for a Level Shifter and a Buffer are shown here. The Level Shifter is essentially an inverting differential amplifier, with the non-inverting input derived from the positive voltage rail. Note that a potentiometer is used to adjust the mid-point voltage of the Level Shifter output. The Buffer Amplifier is essentially a non-inverting amplifier with unity gain, and prevents the output circuit from loading the input circuit and distorting the signals as a result. There are many other types of signal conditioning circuits that may be required depending on the specifics of the sensor and processor; we have only discussed some of the most common ones here.

## Summary

- **Basic sensor signal path consists of the sensing element, signal conditioning circuitry and a data processing and control device like the dsPIC® DSC**
- **Outputs of a wide variety of sensors can be effectively processed by a dsPIC DSC**
- **Using a combination of amplifiers, anti-aliasing filters and other circuits such as level-shifters, sensor output can be converted to a form that can be converted by an on-chip ADC**
- **Several analog devices from Microchip can be utilized for these signal conditioning functions**

In summary, the choice of sensing element is critical because it determines what we can and can't observe. When selecting the sensing element, we want to be sure that we identify and address all of the system requirements either through the sensing element itself or through additional electronic circuitry and software algorithms that overcome any deficiencies in the element.

The basic sensor signal path in our framework consists of the sensing element, signal conditioning circuitry, and filtering circuitry before entering the dsPIC® DSC for additional processing. With its wide array of specialized hardware resources, the dsPIC DSC interfaces easily to all three types of sensing element output signals (voltage, current, and frequency). Its onboard support of high-speed sampling and efficient digital signal processing algorithms makes the Microchip dsPIC DSC an ideal platform for intelligent sensor applications.

## What do you do next?

- **Learn at University of Microchip Regional Training Center Hands-On Courses**
  - *DSP Curriculum*
  - *16-bit PIC24 & dsPIC Products Curriculum*
- **Purchase 16-bit 28-pin Starter Demo Board (DM300027)**
  - *Several Intelligent Sensor Interface Boards available*
- **Download Software Development Tools**
  - *MPLAB IDE (Free)*
  - *MPLAB C30 (Free Student Edition available) with DSP & Fractional Math Libraries*
  - *REAL ICE or MPLAB ICD 2*
  - *dsPIC Filter Design tool and FilterLab Analog Filter Design tool*
  - *dsPICworks Data Analysis & DSP Software*
- **Several Application Notes on sensors and analog devices on Microchip website: [www.microchip.com](http://www.microchip.com)**
- ***"Intelligent Sensor Design using the Microchip dsPIC" by Creed Huddleston***

With this we come to the end of this seminar.

The primary source of additional information is the Microchip website, which is a treasure trove of free and low-cost software and hardware development tools, extensive application notes and data sheets, web seminars, online discussion groups, and much more. The site also contains extensive documentation specifically for the dsPIC<sup>®</sup> digital signal controllers family, including family overviews, user guides, and data sheets for individual devices. Microchip also provides several hands-on workshops and seminars on 16-bit DSC and Microcontroller products, including classes designed especially in the area of DSP for sensor processing. I would also like to draw your attention towards the low-cost 16-bit 28-pin Starter Demo Board, which can be used in conjunction with a set of Intelligent Sensor Interface Boards that we are developing.

Finally, for developers with an understanding of the C programming language, the book *Intelligent Sensor Design Using the Microchip dsPIC<sup>®</sup>* offers a detailed exploration of the use of the dsPIC DSC in intelligent sensing products and includes source code illustrating temperature sensing, pressure sensing, and flow meter applications.

On behalf of Microchip, I thank you for watching this web seminar and for considering Microchip's products for your next design.