Why Precision Signal Chains Need to Be Discrete
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Overview of a Signal Chain
A signal chain filters, amplifies, and converts a low amplitude analog signal to a digital value where it can be useful to the target system. Since the measured signal can be on the order of millivolts, constructing a signal chain requires selecting the correct components by a careful examination of the important specifications and tolerances needed to achieve the desired accuracy. Under ideal conditions, a signal chain would just need an ADC. However, the real world contains less-than-ideal conditions, demanding quality op amps and precision resistors. While finding these components might seem straightforward, in truth the overall accuracy of any signal chain circuit over operating conditions is directly related to knowing exactly how to choose the proper precision components.

A signal chain circuit takes a weak signal that needs to be measured, buffers it, amplifies it to a useful level, and converts it into a digital value. The weak signal is first interfaced to an op-amp which buffers and amplifies the signal, then sends it to an analog to digital converter (ADC) which makes the digital value of the parameter available to a microcontroller, usually by a serial interface such as an SPI.

Under ideal conditions, a signal chain would just consist of an ADC. The input to the ADC might require analog signal conditioning which can include filtering, converting current to voltage, and amplifying or reducing the signal. However, except in engineering textbooks, the real world contains less than ideal conditions including noise and drift, requiring op amps and precision resistors. And once again, except in engineering textbooks ideal op-amps and perfect precision resistors do not exist either.

While selecting the op-amps, amplifiers, and analog to digital converters can sometimes seem straightforward, the overall accuracy of the design depends upon the selection of high precision resistors and capacitors.

Devices Used in a Signal Chain
A very basic overview of a signal chain segments it into three blocks: first the sensor interface to the signal being sensed; second is an amplifier to boost the signal to a usable level for the third block, the analog to digital converter. Often blocks one and two are combined into a single block.

The most common sensor interface is an op-amp, which is then fed to another op-amp that amplifies the signal. While the multi-pin semiconductors do the work, it’s the discrete components like resistors and capacitors that make sure the work is done correctly. The accuracy of a signal chain circuit over operating conditions is directly related to the selection of precision discrete components.”
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Figure 1: The different stages of a typical signal chain

The suitability of a circuit for its application can be made or broken based on if the resistors are as wide as 5.0% or as tight as 0.01%. The situation is even more critical in harsh environments, such as monitoring of sensors in industrial environments.

Critical Parameters When Selecting Components for a Signal chain

Not all op-amps are created equal and it’s important to understand the key parameters and how they can affect a circuit. The most important is probably the input offset voltage. This is the voltage measured at the output of the op-amp when the voltage difference between the two inputs equals zero. Ideally the input offset voltage should be zero, but in reality it is a very small number, as low as hundreds of millivolts. Another important parameter is the input impedance, also called the input resistance. This is the resistance that a voltage across the input pins sees. For an ideal op-amp the resistance would be infinite, as this means the input voltage is not affected. In reality this is on the order of mega-ohms to prevent sensing errors. Another parameter related to error is the input bias current, which is the current draw of the inputs of the op-amp.

When measuring extremely small signals that can vary by 1% of full scale, it’s necessary to use precision resistors. Of course the correct resistance of the resistor in ohms needs to be determined. The most important parameter related to the resistance is the resistor tolerance, which can vary from a wide 10% to as low as a narrow 0.01%. In some cases temperature variations across the resistor can produce a very small voltage in the microvolt range. The susceptibility of a resistor to these induced voltages caused by temperature is called Thermal EMF. While this small voltage is normally inconsequential, in signal chains amplifying weak
voltages, thermal EMF can introduce significant errors in the result which can be almost impossible to diagnose if thermal EMF is not considered when selecting components.

The analog to digital converter (ADC) is the final block of the signal chain. The most important parameter of an ADC is how many bits of resolution it has. 16-bit ADCs have been very common, but 24-bit ADCs are increasingly popular in precision signal chains. Integral Nonlinearity (INL), expressed as a percentage of full scale or as LSB, is another parameter critical to ADC accuracy. It represents the deviation of the ADC from an ideal output. This parameter is crucial because it represents an unrecoverable inaccuracy that cannot be compensated for. It is also important to understand the Sampling Rate of the ADC, representing the speed in samples per second that the ADC can perform individual sample captures and conversions.

Sensing DC Voltages with a Signal Chain

The most common analog sensors present the sensor data as a weak electrical signal. These signals are represented in a number of ways, but the most common signal chain amplifies a weak DC voltage and converts it into a digital format. Almost all analog environmental sensors – magnetic, temperature, weight, vibration, etc. – are available with sensor outputs that provide a voltage representative of the parameter being measured. The simplest circuit for measuring a voltage is a classic gain amplifier as seen in Figure 2.

![Figure 2: Non-inverting Amplifier (source: Analog Devices)](image)

To achieve optimal precision, the resistors $R_G$ and $R_F$ should be matched. The Vishay MPM matched pair of resistors provides 2 PPM/C accuracy over temperature and ratio tolerances as tight as 0.01%. The 3mm long SOT-23 packages offer exceptional stability over voltage and temperature.
While simple and easy to build, the gain circuit in Figure 2 does not compensate for op-amp real world imperfections such as input bias currents or input impedances. Although an amplifier circuit based on a single op-amp may be easy to use, it also may not have the performance and accuracy needed for amplifying very small signals. That’s why a dual op-amp configuration is more common, providing precise amplification, minimizing distortion, and compensating for op-amp real world imperfections. Figure 2 is a dual amplifier circuit using two matched op-amps. The circuit is arranged so that there is one op-amp for each input, maximizing the input impedance.

The Analog Devices ADA4522-2 Dual Channel Ultra-low Noise Precision Op-Amp used seen in Figure 4 is excellent for amplifying small signals and boasts low noise with zero drift. The input bias current is 50pA (typical) and the input offset voltage is 0.7µV (typical) which minimizes the impact on measuring very weak voltages, resulting in high accuracy measurements. As there is one op-amp for each input, the input impedance is the common mode input impedance, which is an extremely high 100GΩ.
The ADA4522-2 contains two matched op-amps in one package, which cancels any errors due to non-ideal op-amp conditions when matched op-amps are required. The two matching op-amps provide on-chip electromagnetic interference (EMI) filtering and does not require an external calibration circuit. It targets both voltage and current sensing circuits for signal chain applications. It can operate over a very wide supply voltage range, from 4.5V to as high as 55.0V.

For the circuit in Figure 2, the circuit equation is:

\[
V_{OUT} = \left(1 + \frac{R_1}{R_2} + \frac{2R_1}{R_G}\right)(V_{IN+} - V_{IN-}) + V_{REF}
\]

Where \(R_1 = R_3\) and \(R_2 = R_4\).

When looking at the above circuit, it becomes obvious that precision resistors are needed. If \(R_1=R_2=1\,\Omega\) and \(R_G = 2\,\Omega\), assuming perfect resistors will give the circuit a gain \((G)\) of 3. If common off-the-shelf 5% carbon resistors are used, the circuit would have a worst-case gain that fluctuates ±5.24%, varying from \(G=2.84\) to 3.16. This error is greater than the error of many sensors, rendering the circuit inappropriate for signal chain circuits. Even worse, as these inaccuracies are introduced at the beginning of the signal chain, the errors are further amplified and multiplied down the chain. A developer can waste days frantically debugging a circuit that fails to provide accurate readings because of an improper choice of resistors.

Luckily, Vishay Thin Film offers their AORN series of AEC-200 qualified resistors, providing four matched resistors in an SOIC-8 package. Drift is a mere ±5 PPM/°C with a 0.05% ratio tolerance and a thermal EMF of 0.08µV/°C. Using these resistors, gain would vary from 2.998 to 3.002, a variation of about 0.01%, well below the error tolerances of voltage based sensors.

![Figure 5: Vishay AORN Thin Film Resistors in an SOIC Package (Source: Vishay)](image-url)
The Analog to Digital Converter

The Analog to Digital Converter is the heart of most signal chain circuits. Even with a perfect buffer and amplifier circuit, the signal chain is only as accurate as the resolution and accuracy of the ADC.

The Analog Devices (ADI) AD7175-2 is a high resolution, 24-bit Sigma-Delta (Σ-Δ) ADC incorporating a true rail-to-rail input buffer. It boasts an accuracy (INL) of ±7.8ppm full scale, leading-edge noise performance, and a sampling rate of up to 250ksps. This ADC can be configured as two fully differential, or four single-ended, analog inputs with a channel scan rate of 50ksps per channel. It is designed to operate as a fast settling, high resolution, multiplexed ADC with high levels of configurability.

![ANALOG DEVICES AD7175-2 FUNCTIONAL BLOCK DIAGRAM](image)

*Figure 6: Analog to Digital converters such as the AD7175-2 from Analog Devices feature rail to rail inputs, fast scan rates, and fast settling time for the accurate measurement of fast signals.*

For a 24-bit ADC with a dynamic range of 0 to +5V rail-to-rail, and if the unamplified sensor output has a voltage range of 0 to +3VDC, then assuming the ADC design has an error of ±1 LSB the result will only be reading 60% of the AD7175-2's dynamic range.

\[
2^{24} = 0xFFFF (16,777,215)
\]

\[
2^{24} \times 60\% = 10,066,329, \text{ converting to hex } = 0x999999.
\]

This will result in an accuracy of only ±4 LSB, effectively making the 24-bit ADC a 20-bit ADC.
In a signal chain, if the amplifier circuit in Figure 4 has a gain of 1.66, amplifying a 0 to 3VDC signal without noise or distortion to a range of 0 to +5.0VDC, allowing for the full dynamic range of the ADC, results in a significantly more accurate measurement.

**Conclusions**

While the construction of modern signal chains can appear straightforward, the use of common off the shelf components can result in a design project similar to software development: 20% of the time can be spent developing the signal chain while 80% is spent debugging it. Valuable time is saved by the use of precision components, most notably the selection of highly accurate resistors that optimize the accuracy of the circuit over operating conditions.