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# 2.6 - AIN [U3 Datasheet]



## AIN Overview

The LabJack U3 has up to 16 analog inputs available on the flexible I/O lines (FIO0-FIO7 and EIO0-EIO7). Single-ended measurements can be taken of any line compared to ground, or differential measurements can be taken of any line to any other line.

Analog input resolution is 12-bits. The range of single-ended analog inputs is normally about 0-2.44, and there is a “special” 0-3.6 volt range available. The range of differential analog inputs is typically ± 2.4 volts, but is pseudobipolar, not true bipolar. The difference (positive channel minus negative channel) can be -2.4 volts, but neither input can have a voltage less than -0.3 volts to ground. For valid measurements, the voltage on every low-voltage analog input pin, with respect to ground, must be within -0.3 to +3.6 volts. See Appendix A for voltage limits to avoid damage.

On the U3-HV, compared to the -LV, the first four flexible I/O are fixed as analog inputs (AIN0-AIN3), and have scaling such that the input range is a true bipolar ±10 volts normally, and -10 to +20 volts when using the “special” range. The input impedance of these four lines is roughly 1 MΩ, which is good, but less than the normal low voltage analog inputs. Analog/digital configuration and all other digital operations on these pins are ignored. FIO4-EIO7 are still available as flexible I/O, same as the U3-LV.

To get the special 0-3.6 volt or -10/+20 volt range, you do a differential reading with the negative channel set to 32, although the reading is actually single-ended.

Because the scaling on the high-voltage inputs on the U3-HV (AIN0-AIN3) is inherently single-ended, a factory calibration is not possible for differential readings. If a differential reading is requested where either channel is a high-voltage channel, the driver will return the raw binary reading and the user must handle calibration/conversion. Note that 0 counts is about -20V and 65520 counts is about +20V, and no high-voltage channel can be less than -12.8V or more than +20.1V.

The analog inputs have a QuickSample option where each conversion is done faster at the expense of increased noise. This is enabled by passing a nonzero value for put_config special channel *LJ_chAIN_RESOLUTION*. There is also a LongSettling option where additional settling time is added between the internal multiplexer configuration and the analog to digital conversion.

This allows signals with more source impedance, and is enabled by passing a nonzero value for put_config special channel *LJ_chAIN_SETTLING_TIME*. Both of these options are disabled by default. This applies to command/response mode only, and the resulting typical data rates are discussed in Section 3.1. For stream mode, see Section 3.2.

Note that sinking excessive current into digital outputs can cause substantial errors in analog input readings. See Section 2.8.1.4 for more info.

# 2.6.1 - Channel Numbers [U3 Datasheet]

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The LabJack U3 has up to 16 external analog inputs, plus a few internal channels. The low-level functions specify a positive and negative channel for each analog input conversion. With the LabJackUD driver, the IOType LJ_ioGET_AIN is used for single-ended channels only, and thus the negative channel is internally set to 31. There is an additional IOType called LJ_ioGET_AIN_DIFF that allows the user to specify the positive and negative channel.

**Table 2.6.1-1.** Positive Channel Numbers

| Positive Channel # | |
|---|---|
| 0-7 | AIN0-AIN7 (FIO0-FIO7) |
| 8-15 | AIN8-AIN15 (EIO0-EIO7) |
| 30 | Temp Sensor |
| 31 | Vreg |

**Table 2.6.1-2.** Negative Channel Numbers

| Negative Channel # | |
|---|---|
| 0-7 | AIN0-AIN7 (FIO0-FIO7) |
| 8-15 | AIN8-AIN15 (EIO0-EIO7) |
| 30 | Vref |
| 31 or 199 | Single-Ended |
| 32 | Special 0-3.6 or -10/+20 (UD Only) |

Positive channel 31 puts the internal Vreg (~3.3 volts) on the positive input of the ADC. See Section 2.6.4 for information about the internal temperature sensor.

If the negative channel is set to anything besides 31/199, the U3 does a differential conversion and returns a pseudobipolar value. If the negative channel is set to 31/199, the U3 does a single-ended conversion and returns a unipolar value. Channel 30 puts the internal voltage reference Vref (~2.44 volts) on the negative input of the ADC.

Channel 32 is a special negative channel supported by the LabJack UD driver. When used, the driver will actually pass 30 as the negative channel to the U3, and when the result is returned the driver adds Vref to the value. For a low-voltage analog input this results in a full span on the positive channel of about 0 to 4.88 volts (versus ground), but since the voltage on any analog input cannot exceed 3.6 volts, only 75% of the converter's range is used and the span is about 0 to 3.6 volts. For a high-voltage analog input, channel 32 (special range) results in a span of about -10 to +20 volts.

In the U3 examples that accompany the Exodriver, u3.c also supports channel 32 in calls to eAIN().

Channel 32 is also supported in LabJackPython:

```
# On the U3, wire a jumper from DAC0 to FIO0, then run:
>>> import u3
>>> d = u3.U3()
>>> d.configIO(FIOAnalog = 1) # Set FIO0 to analog
>>> d.writeRegister(5000, 3) # Set DAC0 to 3 V
>>> d.getAIN(0, 32)
3.0141140941996127
```

For the four high-voltage channels on the U3-HV, the special channel negative channel also puts Vref on the negative. This results in an overall range of about -10 to +20 volts on the positive input.

# 2.6.2 - Converting Binary Readings to Voltages [U3 Datasheet]

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## Converting Binary Readings to Voltages Overview

This information is only needed when using low-level functions and other ways of getting binary readings. Readings in volts already have the calibration constants applied. The UD driver, for example, normally returns voltage readings unless binary readings are specifically requested.

Following are the nominal input voltage ranges for the low-voltage analog inputs. This is all analog inputs on the U3-LV, and AIN4-AIN15 on the U3-HV.

**Table 2.6.2-1.** Nominal Analog Input Voltage Ranges for Low-Voltage Channels

| | Max V | Min V |
|---|---|---|
| Single-Ended | 2.44 | 0 |
| Differential | 2.44 | -2.44 |
| Special 0-3.6 | 3.6 | 0 |

**Table 2.6.2-2.** Nominal Analog Input Voltage Ranges for High-Voltage Channels

| | Max V | Min V |
|---|---|---|
| Single-Ended | 10.3 | -10.3 |
| Differential | N/A | N/A |
| Special -10/+20 | 20.1 | -10.3 |

Note that the minimum differential input voltage of -2.44 volts means that the positive channel can be as much as 2.44 volts less than the negative channel, not that a channel can measure 2.44 volts less than ground. The voltage of any low-voltage analog input pin, compared to ground, must be in the range -0.3 to +3.6 volts.

The “special” range (0-3.6 on low-voltage channels and -10/+20 volts on high-voltage channels) is obtained by doing a differential measurement where the negative channel is set to the internal Vref (2.44 volts). For low-voltage channels, simply do the low-voltage differential conversion as described below, then add the stored Vref value. For high-voltage channels, do the same thing, then multiply by the proper high-voltage slope, divide by the single-ended low-voltage slope, and add the proper high-voltage offset. The UD driver handles these conversions automatically.

Although the binary readings have 12-bit resolution, they are returned justified as 16-bit values, so the approximate nominal conversion from binary to voltage is:

Volts(uncalibrated) = (Bits/65536)*Span (Single-Ended)

Volts(uncalibrated) = (Bits/65536)*Span – Span/2 (Differential)

Binary readings are always unsigned integers.

Where span is the maximum voltage minus the minimum voltage from the tables above. The actual nominal conversions are provided in the tables below, and should be used if the actual calibration constants are not read for some reason. Most applications will use the actual calibrations constants (Slope and Offset) stored in the internal flash.

Volts = (Slope * Bits) + Offset

Since the U3 uses multiplexed channels connected to a single analog-to-digital converter (ADC), all low-voltage channels have the same calibration for a given configuration. High-voltage channels have individual scaling circuitry out front, and thus the calibration is unique for each channel.

See Section 5.4 for detail about the location of the U3 calibration constants.

# 2.6.2.1 - Analog Inputs With DAC1 Enabled (Hardware Revisions 1.20 & 1.21 only) [U3 Datasheet]



This Section only applies to the older hardware revisions 1.20 and 1.21. Starting with hardware revision 1.30, DAC1 is always enabled and does not affect the analog inputs.

The previous information assumed that DAC1 is disabled. If DAC1 is enabled, then the internal reference (Vref = 2.44 volts) is not available for the ADC, and instead the internal regulator voltage (Vreg = 3.3 volts) is used as the reference for the ADC. Vreg is not as stable as Vref, but more stable than Vs (5 volt power supply). Following are the nominal input voltage ranges for the analog inputs, assuming that DAC1 is enabled.

**Table 2.6.2.1-1.** Nominal Analog Input Voltage Ranges (DAC1 Enabled)

| | Max V | Min V |
|---|---|---|
| Single-Ended | 3.3 | 0 |
| Differential | 3.3 | -3.3 |
| Special -10/+20 | N/A | N/A |

Note that the minimum differential input voltage of -3.3 volts means that the positive channel can be as much as 3.3 volts less than the negative channel, not that a channel can measure 3.3 volts less than ground. The voltage of any analog input pin, compared to ground, must be in the range -0.3 to +3.6 volts, for specified performance. See Appendix A for voltage limits to avoid damage.

Negative channel numbers 30 and 32 are not valid with DAC1 enabled.

When DAC1 is enabled, the slope/offset calibration constants are not used to convert raw readings to voltages. Rather, the Vreg value is retrieved from the Mem area, and used with the approximate single-ended or differential conversion equations above, where Span is Vreg (single-ended) or 2Vreg (differential).

# 2.6.3 - Typical Analog Input Connections [U3 Datasheet]



## Typical Analog Input Connections Overview

A common question is “can this sensor/signal be measured with the U3”. Unless the signal has a voltage (referred to U3 ground) beyond the limits in Appendix A, it can be connected without damaging the U3, but more thought is required to determine what is necessary to make useful measurements with the U3 or any measurement device.

Voltage (versus ground): The single-ended analog inputs on the U3 measure a voltage with respect to U3 ground. The differential inputs measure the voltage difference between two channels, but the voltage on each channel with respect to ground must still be within the common mode limits specified in Appendix A. When measuring parameters other than voltage, or voltages too big or too small for the U3, some sort of sensor or transducer is required to produce the proper voltage signal. Examples are a temperature sensor, amplifier, resistive voltage divider, or perhaps a combination of such things.

Impedance: When connecting the U3, or any measuring device, to a signal source, it must be considered what impact the measuring device will have on the signal. The main consideration is whether the currents going into or out of the U3 analog input will cause noticeable voltage errors due to the impedance of the source. To maintain consistent 12-bit results, it is recommended to keep the source impedance within the limits specified in Appendix A.

Resolution (and Accuracy): Based on the measurement type and resolution of the U3, the resolution can be determined in terms of voltage or engineering units. For example, assume some temperature sensor provides a 0-10 mV signal, corresponding to 0-100 degrees C. Samples are then acquired with the U3 using the 0-2.44 volt single-ended input range, resulting in a voltage resolution of about 2.44/4096 = 596 µV. That means there will be about 17 discrete steps across the 10 mV span of the signal, and the temperature resolution is about 6 degrees C. If this experiment required a resolution of 1 degrees C, this configuration would not be sufficient. Accuracy will also need to be considered. Appendix A places some boundaries on expected accuracy, but an in-system calibration can generally be done to provide absolute accuracy down to the linearity (INL) limits of the U3.

Speed: How fast does the signal need to be sampled? For instance, if the signal is a waveform, what information is needed: peak, average, RMS, shape, frequency, … ? Answers to these questions will help decide how many points are needed per waveform cycle, and thus what sampling rate is required. In the case of multiple channels, the scan rate is also considered. See Sections 3.1 and 3.2.

# 2.6.3.1 - Signal from the LabJack [U3 Datasheet]

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One example of measuring a signal from the U3 itself, is with an analog output. All I/O on the U3 share a common ground, so the voltage on an analog output (DAC) can be measured by simply connecting a single wire from that terminal to an AIN terminal (FIO/EIO). The analog output must be set to a voltage within the range of the analog input.

# 2.6.3.2 - Unpowered Isolated Signal [U3 Datasheet]

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An example of an unpowered isolated signal would be a photocell where the sensor leads are not shorted to any external voltages. Such a sensor typically has two leads, where the positive lead connects to an AIN terminal and the negative lead connects to a GND terminal.

# 2.6.3.3 - Signal Powered By the LabJack [U3 Datasheet]

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A typical example of this type of signal is a 3-wire temperature sensor. The sensor has a power and ground wire that connect to Vs and GND on the LabJack, and then has a signal wire that simply connects to an AIN terminal.

Another variation is a 4-wire sensor where there are two signal wires (positive and negative) rather than one. If the negative signal is the same as power ground, or can be shorted ground, then the positive signal can be connected to AIN and a single-ended measurement can be made. A typical example where this does not work is a bridge type sensor, such as pressure sensor, providing the raw bridge output (and no amplifier). In this case the signal voltage is the difference between the positive and negative signal, and the negative signal cannot be shorted to ground. Such a signal could be measured using a differential input on the U3.

# 2.6.3.4 - Signal Powered Externally [U3 Datasheet]

An example is a box with a wire coming out that is defined as a 0-2 volt analog signal and a second wire labeled as ground. The signal is known to have 0-2 volts compared to the ground wire, but the complication is what is the voltage of the box ground compared to the LabJack ground.

If the box is known to be electrically isolated from the LabJack, the box ground can simply be connected to LabJack GND. An example would be if the box was plastic, powered by an internal battery, and does not have any wires besides the signal and ground which are connected to AINx and GND on the LabJack.

If the box ground is known to be the same as the LabJackGND, then perhaps only the one signal wire needs to be connected to the LabJack, but it generally does not hurt to go ahead and connect the ground wire to LabJack GND with a 100 Ω resistor. You definitely do not want to connect the grounds without a resistor.

If little is known about the box ground, aDMM can be used to measure the voltage of box ground compared to LabJack GND. As long as an extreme voltage is not measured, it is generally OK to connect the box ground to LabJack GND, but it is a good idea to put in a 100 Ω series resistor to prevent large currents from flowing on the ground. Use a small wattage resistor (typically 1/8 or 1/4 watt) so that it blows if too much current does flow. The only current that should flow on the ground is the return of the analog input bias current, which is only microamps.

The SGND terminals (on the same terminal block asSPC) can be used instead of GND for externally powered signals. A series resistor is not needed as SGND is fused to prevent overcurrent, but a resistor will eliminate confusion that can be caused if the fuse is tripping and resetting.

In general, if there is uncertainty, a good approach is to use aDMM to measure the voltage on each signal/ground wire without any connections to the U3. If no large voltages are noted, connect the ground to U3 SGND with a 100 Ω series resistor. Then again use the DMM to measure the voltage of each signal wire before connecting to the U3.

Another good general rule is to use the minimum number of ground connections. For instance, if connecting 8 sensors powered by the same external supply, or otherwise referred to the same external ground, only a single ground connection is needed to the U3. Perhaps the ground leads from the 8 sensors would be twisted together, and then a single wire would be connected to a 100 Ω resistor which is connected to U3 ground.

# 2.6.3.5 - Amplifying Small Signal Voltages [U3 Datasheet]

The best results are generally obtained when a signal voltage spans the full analog input range of the LabJack. If the signal is too small it can be amplified before connecting to the LabJack. One good way to handle low-level signals such as thermocouples is the LJTick-InAmp, which is a 2-channel instrumentation amplifier module that plugs into the U3 screw-terminals.

For a do-it-yourself solution, the following figure shows an operational amplifier (op-amp) configured as non-inverting:

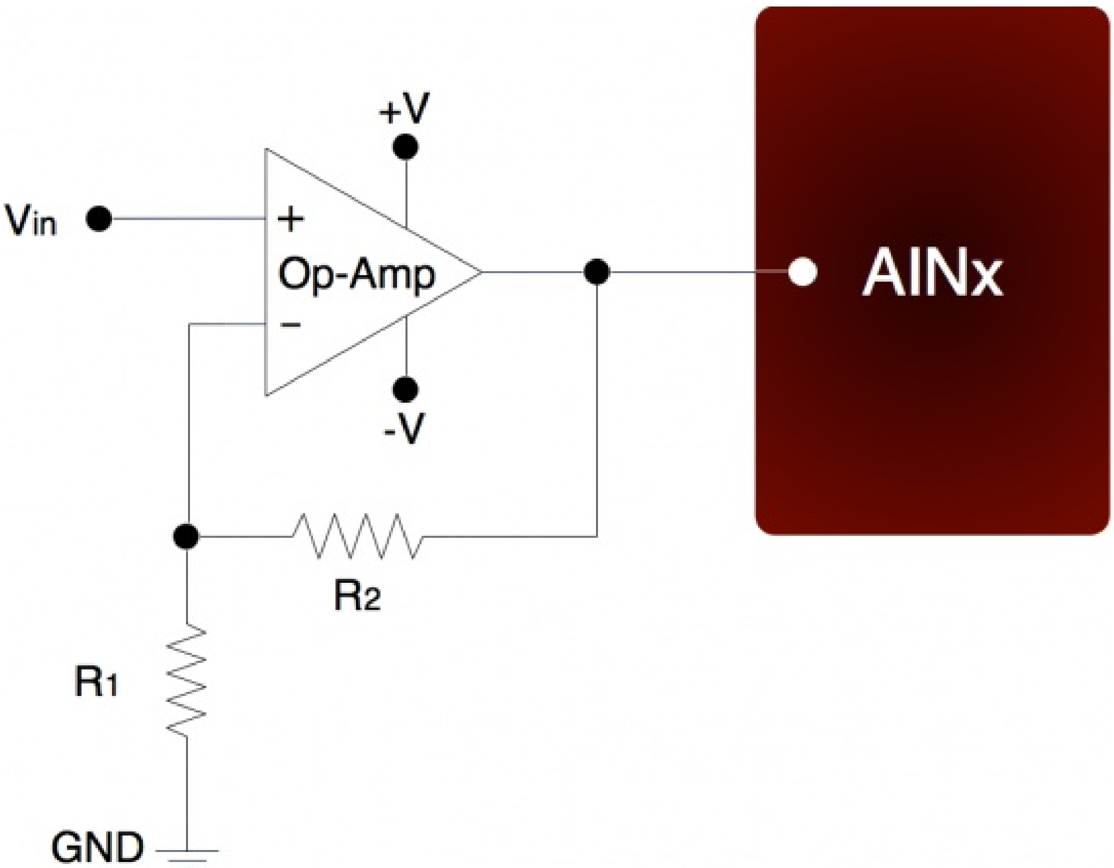


**Figure 2.6.3.5-1.** Non-Inverting Op-Amp Configuration

The gain of this configuration is:

Vout = Vin * (1 + (R2/R1))

100 kΩ is a typical value for R2. Note that if R2=0 (short-circuit) and R1=inf (not installed), a simple buffer with a gain equal to 1 is the result.

There are numerous criteria used to choose an op-amp from the thousands that are available. One of the main criteria is that the op-amp can handle the input and output signal range. Often, a single-supply rail-to-rail input and output (RIRO) is used as it can be powered from Vs andGND and pass signals within the range 0-Vs. The OPA344 from Texas Instruments (ti.com) is good for many 5 volt applications.

The op-amp is used to amplify (and buffer) a signal that is referred to the same ground as the LabJack (single-ended). If instead the signal is differential (i.e. there is a positive and negative signal both of which are different than ground), an instrumentation amplifier (in-amp) should be used. An in-amp converts a differential signal to single-ended, and generally has a simple method to set gain.

# 2.6.3.6 - Signal Voltages Beyond 0-2.44 Volts (and Resistance Measurement) [U3 Datasheet]

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The normal input range for a low voltage analog input channel (FIO/EIO) on the U3 is about 0-2.44 volts. There is also a Special 0-3.6V range available on those inputs. The easiest way to handle larger voltages is often by using the LJTick-Divider, which is a two channel buffered divider module that plugs into the U3 screw-terminals.

The basic way to handle higher unipolar voltages is with a resistive voltage divider. The following figure shows the resistive voltage divider assuming that the source voltage (Vin) is referred to the same ground as the U3 (GND).

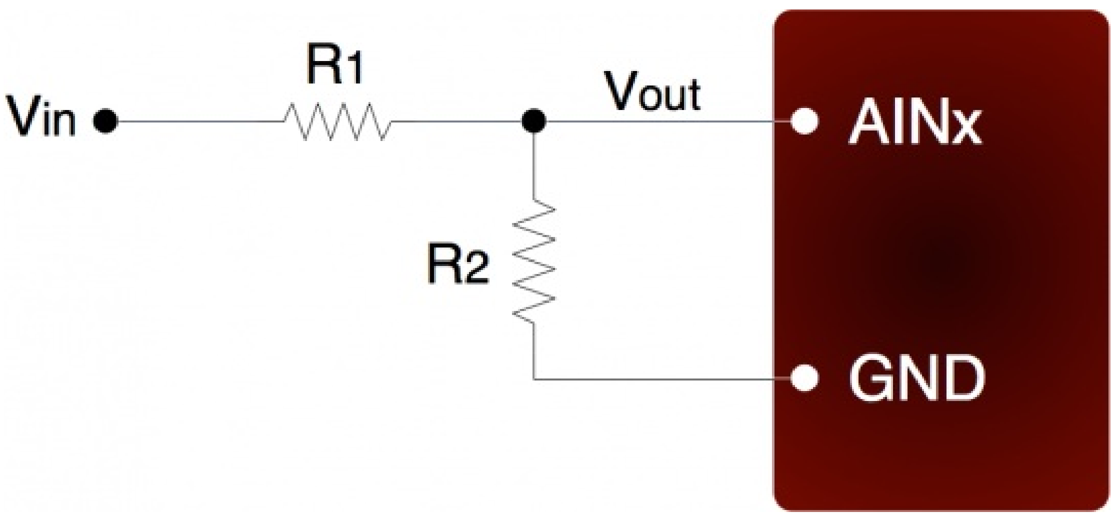


**Figure 2.6.3.6-1.** Voltage Divider Circuit

The attenuation of this circuit is determined by the equation:

Vout = Vin * ( R2 / (R1+R2))

This divider is easily implemented by putting a resistor (R1) in series with the signal wire, and placing a second resistor (R2) from the AIN terminal to a GND terminal. To maintain specified analog input performance, R1 should not exceed the values specified in Appendix A, so R1 can generally be fixed at the max recommended value and R2 can be adjusted for the desired attenuation.

The divide by 2 configuration where R1 = R2 = 10 kΩ (max source impedance limit for low-voltage channels), presents a 20 kΩ load to the source, meaning that a 5 volt signal will have to be able to source/sink up to +250 µA. Some signal sources might require a load with higher resistance, in which case a buffer should be used. The following figure shows a resistive voltage divider followed by an op-amp configured as non-inverting unity-gain (i.e. a buffer).

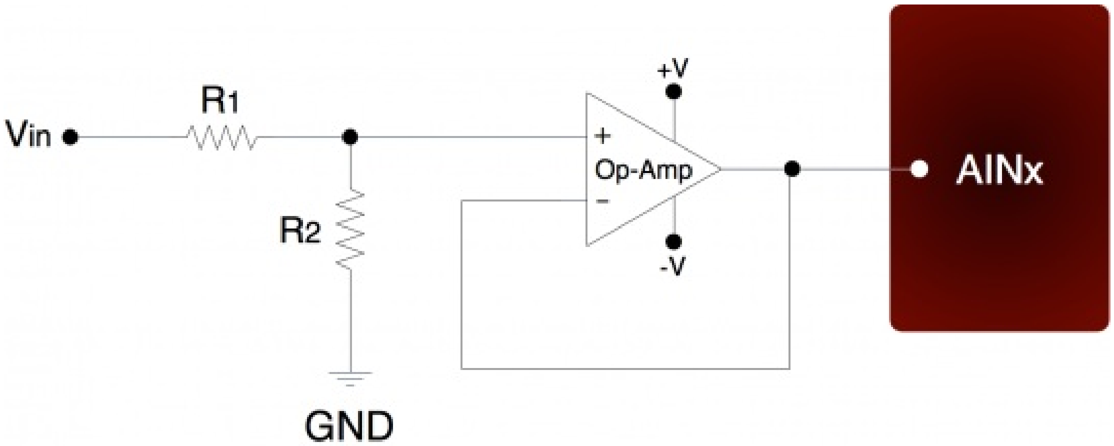


**Figure 2.6.3.6-2.** Buffered Voltage Divider Circuit

The op-amp is chosen to have low input bias currents so that large resistors can be used in the voltage divider. For 0-5 volt applications, where the amp will be powered from Vs and GND, a good choice would be the OPA344 from Texas Instruments (ti.com). The OPA344 has a very small bias current that changes little across the entire voltage range. Note that when powering the amp from Vs and GND, the input and output to the op-amp is limited to that range, so if Vs is 4.8 volts your signal range will be 0-4.8 volts.

To handle bipolar voltages, you also need offset or level-shifting. Refer to application note SLOA097 from ti.com for more information.

The information above also applies to resistance measurement. A common way to measure resistance is to build a voltage divider as shown in Figure 2.6.3.6-1, where one of the resistors is known and the other is the unknown. If Vin is known and Vout is measured, the voltage divider equation can be rearranged to solve for the unknown resistance.

# 2.6.3.7 - Measuring Current (Including 4-20 mA) with a Resistive Shunt [U3 Datasheet]



The best way to handle 4-20 mA signals is with theLJTick-CurrentShunt, which is a two channel active current to voltage converter module that plugs into the UE9 screw-terminals.

The following figure shows a typical method to measure the current through a load, or to measure the 4-20 mA signal produced by a 2-wire (loop-powered) current loop sensor. The current shunt shown in the figure is simply a resistor.

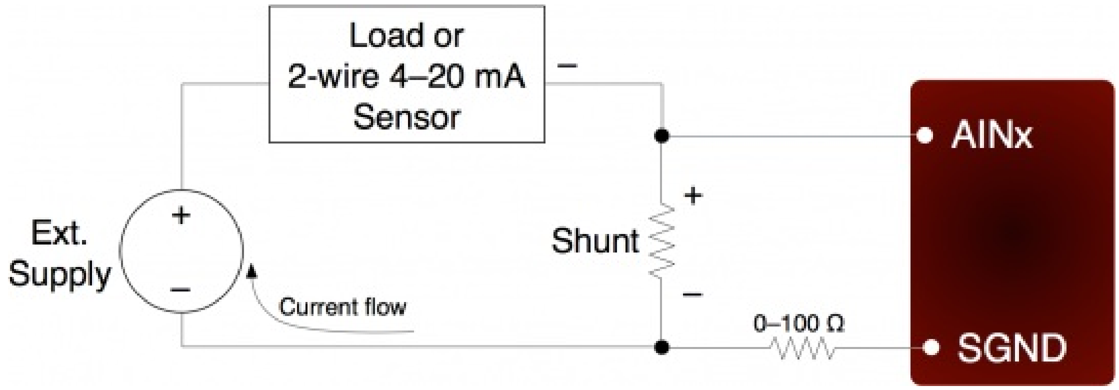


**Figure 2.6.3.7-1.** Current Measurement With Arbitrary Load or 2-Wire 4-20 mA Sensor

When measuring a 4-20 mA signal, a typical value for the shunt would be 120 Ω. This results in a 0.48 to 2.40 volt signal corresponding to 4-20 mA. The external supply must provide enough voltage for the sensor and the shunt, so if the sensor requires 5 volts the supply must provide at least 7.4 volts.

For applications besides 4-20 mA, the shunt is chosen based on the maximum current and how much voltage drop can be tolerated across the shunt. For instance, if the maximum current is 1.0 amp, and 1.0 volts of drop is the most that can be tolerated without affecting the load, a 1.0 Ω resistor could be used. That equates to 1.0 watts, though, which would require a special high wattage resistor. A better solution would be to use a 0.1 Ω shunt, and then use an amplifier to increase the small voltage produced by that shunt. If the maximum current to measure is too high (e.g. 100 amps), it will be difficult to find a small enough resistor and a Hall effect sensor should be considered instead of a shunt.

The following figure shows typical connections for a 3-wire 4-20 mA sensor. A typical value for the shunt would be 120 Ω which results in 0.48 to 2.40 volts.

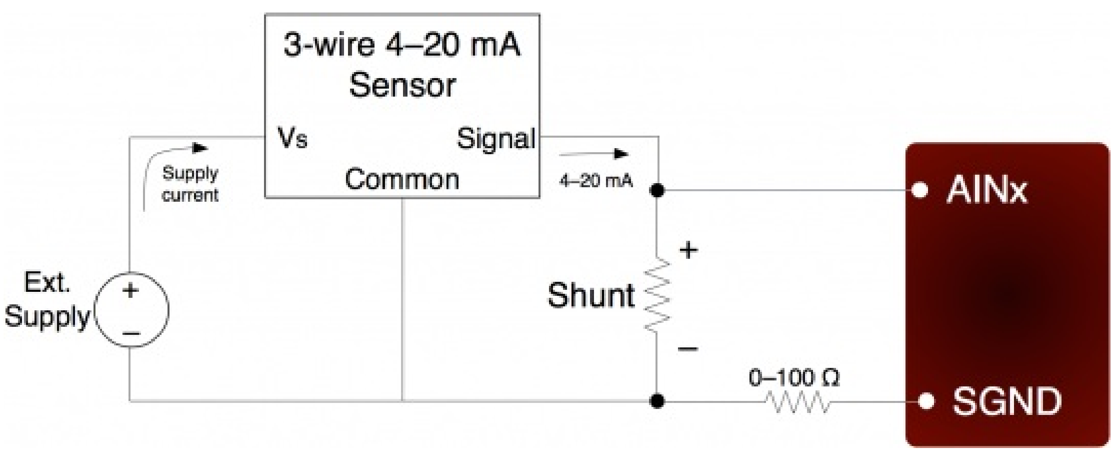


**Figure 2.6.3.7-2.** Current Measurement With 3-Wire 4-20 mA (Sourcing) Sensor

The sensor shown in the above figure is a sourcing type, where the signal sources the 4-20 mA current which is then sent through the shunt resistor and sunk into ground. Another type of 3-wire sensor is the sinking type, where the 4-20 mA current is sourced from the positive supply, sent through the shunt resistor, and then sunk into the signal wire. If sensor ground is connected to U3 ground, the sinking type of sensor presents a problem, as at least one side of the resistor has a high common mode voltage (equal to the positive sensor supply). If the sensor is isolated, a possible solution is to connect the sensor signal or positive sensor supply to U3 ground (instead of sensor ground). This requires a good understanding of grounding and isolation in the system. The LJTick-CurrentShunt is often a simple solution.

Both figures show a 0-100 Ω resistor in series withSGND, which is discussed in general in Section 2.6.3.4. In this case, if SGND is used (rather than GND), a direct connection (0 Ω) should be good.

The best way to handle 4-20 mA signals is with theLJTick-CurrentShunt, which is a two channel active current to voltage converter module that plugs into the U3 screw-terminals.

# 2.6.3.8 - Floating/Unconnected Inputs [U3 Datasheet]

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The reading from a floating (no external connection) analog input channel can be tough to predict and is likely to vary with sample timing and adjacent sampled channels.  Keep in mind that a floating channel is not at 0 volts, but rather is at an undefined voltage.  In order to see 0 volts, a 0 volt signal (such as GND) should be connected to the input.

Some data acquisition devices use a resistor, from the input to ground, to bias an unconnected input to read 0.  This is often just for “cosmetic” reasons so that the input reads close to 0 with floating inputs, and a reason not to do that is that this resistor can degrade the input impedance of the analog input.

In a situation where it is desired that a floating channel read a particular voltage, say to detect a broken wire, a resistor (pull-down or pull-up) can be placed from the AINx screw terminal to the desired voltage (GND, VS, DACx, …).  A 100 kΩ resistor should pull the analog input readings to within 50 mV of any desired voltage, but obviously degrades the input impedance to 100 kΩ. For the specific case of pulling a floating channel to 0 volts, a 1 MΩ resistor to GND can typically be used to provide analog input readings of less than 50 mV. This information is for a low-voltage analog input channel on a U3.

Note that the four high-voltage channels on the U3-HV do sit at a predictable 1.4 volts. You can use a pull-down or pull-up resistor with the high-voltage inputs, but because their input impedance is lower the resistor must be lower (~1k might be typical) and thus the signal is going to have to drive substantial current.

# 2.6.3.9 - Signal Voltages Near Ground [U3 Datasheet]

The nominal input range of a low-voltage single-ended analog input is 0-2.44 volts.  So the nominal minimum voltage is 0.0 volts, but the variation in that minimum can be about +/-40 mV, and thus the actual minimum voltage could be 0.04 volts.

This is not an offset error, but just a minimum limit.  Assume the minimum limit of your U3 happens to be 10 mV.  If you apply a voltage of 0.02 volts it will read 0.02 volts.  If you apply a voltage of 0.01 volts it will read 0.01 volts.  If you apply a voltage less than 0.01 volts, however, it will still read the minimum limit of 0.01 volts in this case.

One impact of this, is that a short to GND is usually not a good test for noise and accuracy.  We often use a 1.5 volt battery for simple tests.

If performance all the way to 0.0 is needed, use a differential reading (which is pseudobipolar).  Connect some other channel to GND with a small jumper, and then take a differential reading of your channel compared to that grounded channel.

The nominal input range of a high-voltage single-ended analog input is +/-10 volts, so readings around 0.0 are right in the middle of the range and not an issue.

# 2.6.4 - Internal Temperature Sensor [U3 Datasheet]



The U3 has an internal temperature sensor. Although this sensor measures the temperature inside the U3, which is warmer than ambient, it has been calibrated to read actual ambient temperature, although should only be expected to be accurate to within a few degrees C. For best results the temperature of the entire U3 must stabilize relative to the ambient temperature, which can take on the order of 1 hour. Best results will be obtained in still air in an environment with slowly changing ambient temperatures.

With the UD driver, the internal temperature sensor is read by acquiring single-ended analog input channel 30, and returns degrees K. Use channel 30 anywhere you would use an analog input channel (e.g. with eAIN).

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