Summary:

Students will learn to use operational amplifier circuits to prepare transducer output signals for input to analog-to-digital converters.

Materials:

This activity will be done by the team as a whole. The team should have available the following materials, equipment, and supplies (*indicates supplied by LaACES):

1. Four AD-820 operational amplifier integrated circuits in DIP-8 package*
2. Solderless breadboard
3. Two-cell battery holder* and selection of AA batteries
4. Potentiometer*
5. Capacitors and resistors as shown on schematic diagrams below*
6. Small hookup wire, clip leads, and soldering tools
7. Multimeter
8. Arduino Mega
9. Bench power supply
10. Arduino programming cable

The laboratory should also be equipped with the following:

1. Flat work tables sufficient to seat all students with plenty of work space

Introduction:

The analog-to-digital converter (ADC) included on the Arduino has an input signal range which is selectable as either 0 to 5.00 volts. Most sensors or transducers used to measure physical variables will have output signals which do not match that ADC input range. One task of a signal conditioning circuit is to transform the available transducer signal so that its minimum value (the *base*) is 0 volts, and so that its range of values (the *span*) does not exceed either 5.00 volts.

Adjustment of *span* will require either amplification or attenuation, while adjustment of *base* will require adding or subtracting an *offset voltage*.

Example 1 – Base is correct, but Span is too small.

Suppose the ACD were set up for 0 to 5.00 volt input, but a sensor provided a signal in the range 0 to 600 mV. If the sensor were connected directly to the ADC, only 12% of the ADC's available range would be used.

The operational amplifier circuit shown in **Figure 1** below can be used to provide the needed amplification (also called *voltage gain*, or simply, *gain*) to increase the sensor signal so that its span covers the full range of the ADC input.

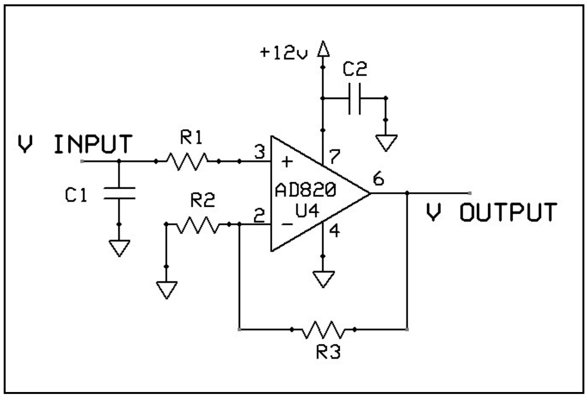

Figure 1. Non-inverting amplifier

The amplification factor, hereafter to be called simply the *gain*, is determined by the values of the resistors according to the following relation:

$$V_{out} = \left(1 + \frac{R_3}{R_2}\right) V_{in} \qquad \text{Amplification Factor, } A_V = \left(1 + \frac{R_3}{R_2}\right)$$

In the example under consideration, it is desired that a 600 mV input voltage would result in a 5.00 volt output, so the gain should be set to 8, requiring that R_3 be seven times larger than R_2. It's common practice to choose the smaller of the resistors to be in the range of a few thousand ohms, so, using standard 5% tolerance resistors, R_3=75 K and R_2=10 K will be a good approximation.

The value of R_1 is non-critical, and does not significantly affect the circuit gain. Good design practice is to select R_1 to be approximately equivalent to the parallel combination of R_2 and R_3, in this case either 8.2 K or 9.1 K would be a good choice.

Example 2 – Base is not zero and Span is too small

Now presume a sensor provides a signal whose minimum value is 450 mV and maximum value is 800 mV. Such a range is typical for PN junction diodes used as temperature sensors.

The base is 450 mV and the span are just 350 mV. Try visualizing the transformation needed as a graph of output voltage (0 to 5 volts) versus input voltage (0.45 V to 0.80 V) Such a graph is plotted below:

The graph in **Figure 2** represents a transfer function between the output and the input of the signal conditioning circuit, given by the equation of the straight line

$$V_{OUT} = 14.286V_{IN} - 6.4286$$

Or, in terms of the **Figure 3** circuit parameters

$$V_{OUT} = V_{IN}\left[1 + R_3\left(\frac{1}{R_2} + \frac{1}{R_4}\right)\right] - V_{REF}\left[\frac{R_3}{R_2}\right]$$

The gain is recognizable as the coefficient of V_{IN} (14.286), and the constant term (-6.4286) represents an offset voltage which must be subtracted.

In other words, the input signal is multiplied by a factor of 14.286 (the gain) and then 6.4286 volts (the offset) are subtracted in order to produce an output voltage that varies from 0 to 5.0 volts.

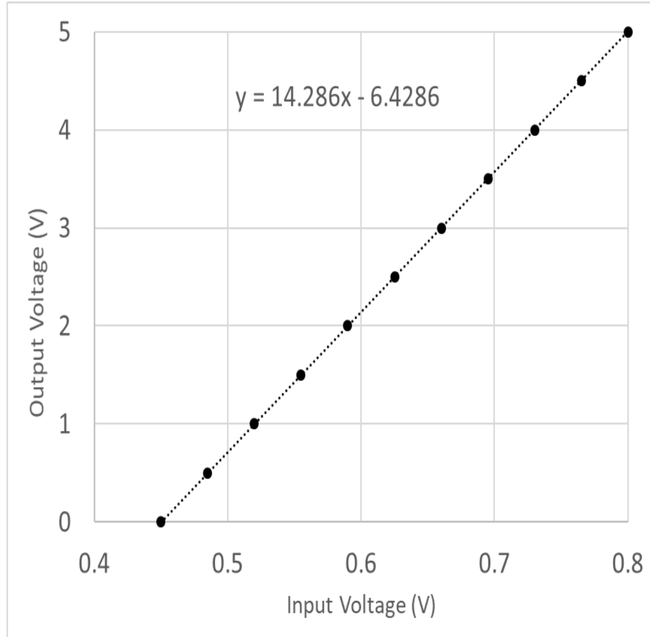

Figure 2. Signal conditioning transfer function

A variation of the non-inverting amplifier circuit, shown in **Figure 3**, can accomplish the desired result.

Since an offset of -6.4286 V and a gain of 14.286 are required, V_{REF}, R_2, R_3, and R_4 are selected so that

$$R_3\left(\frac{1}{R_2} + \frac{1}{R_4}\right) = 13.286$$

and

$$V_{REF}\left[\frac{R_3}{R_2}\right] = 6.4286$$

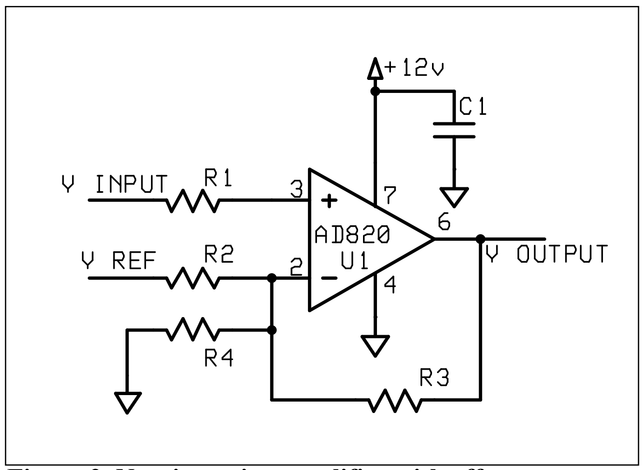

Figure 2. Non-inverting amplifier with offset

The two equations above must be solved simultaneously. But unfortunately, there are four unknown quantities. This is where design choices must be made. In practice, V_{REF} and R_4 will be selected to be conveniently obtainable values, and the equations will be solved for R_2 and R_3. Values of 10 K for R_4 and 3.0 V for V_{REF} would be one appropriate choice. An Excel worksheet can be created to perform the remaining calculations.

Here it is found that R_2 should be 51.9 K, R_3 should be 111.4 K, and R_1 should be 7.8 K. These obviously are not "off-the-shelf" component values. The value of R_1 is not critical, since it does not appear in either the gain or offset calculations, so a standard value of either 7.5 K or 8.2 K may be used.

R_2 and R_3, however, must be very close to the calculated values if the gain and offset are to be correct. In practice, these resistors will be implemented as the series combination of a fixed and a variable resistor (*potentiometer*), as shown in **Figure 4**.

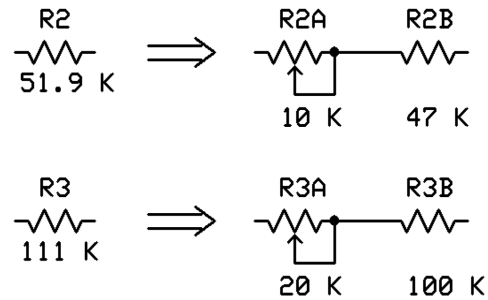

Figure 4. Implementing precise resistances

Example 3 – Amplifying the difference between two voltages

Frequently transducers are employed which represent the physical quantity being measured as the difference between a pair of output voltages. A typical example is a line of inexpensive pressure sensors which incorporate a Wheatstone Bridge circuit. The ambient pressure is directly proportional to the difference of the voltages at either side of the bridge circuit.

An *instrumentation amplifier* is the usual method employed to condition such *differential mode* signals. **Figure 5** illustrates a simple version that can be built using three ordinary operational amplifiers.

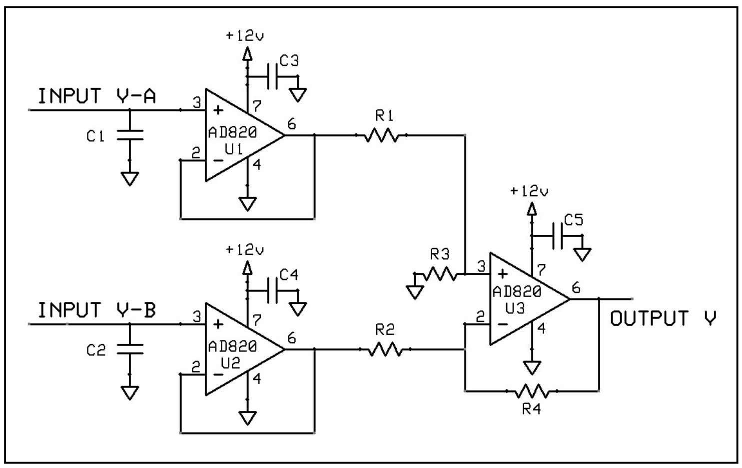

Figure 5. Instrumentation amplifier

This circuit includes a special version of the non-inverting amplifier. Both U1 and U2 are configured as *unity gain voltage followers*, or simply termed, *voltage followers*. In place of the usual feedback resistor (R_3 in **Figures 1 and 3**) a direct connection (zero resistance) is used. The result is that the voltages at the output pins of U_1 and U_2 (pins 6) will *follow*, that is, always be equal to, the input voltages at pins 3.

U3 now acts as a differential amplifier whose output, at pin 6, will be

$$V_{\text{OUT}} = \left(1 + \frac{R_4}{R_2}\right)\left(\frac{R_3}{R_1 + R_3}\right)(V_{\text{A}}) - \left(\frac{R_4}{R_2}\right)V_{\text{B}}$$

Now, if R_3 is made equal to R_4, and R_1 equal to R_2, the above expression can be simplified and expressed as

$$V_{OUT} = \left(\frac{R_4}{R_2}\right)(V_A - V_B)$$

In other words, the output of the circuit will be a voltage equal to the difference between the two input voltages but multiplied by the gain factor set by the ratio of the resistors R_4/R_2 and R_3/R_1. It is very important that the resistors be matched so that the two ratios are as nearly equal as possible. Often precision resistors (1% or even smaller tolerance) will have to be used, or combinations of fixed and variable resistance (as in **Figure 4**) are employed.

Procedure:

Construct and test the circuits discussed, using solderless breadboard prototyping methods.

You should prototype the circuits described in Examples 1, 2 and 3 above. Use the circuit of **example 2 to implement a temperature sensor using a 1N457 diode as the sensor**. Use the **circuit of Example 3 to readout an ICS1210 type pressure sensor**.

Then combine the circuits with the Arduino Mega and the GPS logger shield you should construct a data logging system that reads the outputs of the sensors are records them. You will need to perform a calibration of the sensors so that you record the data temperature and pressure units rather than just ADC units or voltage.

Your data acquisition system should read, display and store to the SD card the temperature and pressure data with timestamps from the GPS. Each data record should indicate if the GPS has received a lock, the number of satellites connected, the latitude, and the longitude. The data record should also be in comma delimited ASCII characters and saved to a .csv file for exporting to Excel.

Be sure to take pictures and notes in your lab notebook as you will be writing a report documenting circuits, your calibrations procedures, and your data logging software for A16.02 – Capstone Report : Sensors Interface and Calibration Report

The report should include narrative descriptions where applicable, tables of measured data, electronic circuit diagram(s), and a flow chart of the software needed to read and store the data.

References:

R16.03 ICS1210 series Data Sheet
R16.04 AD820A Data Sheet
R16.05 AD822 Data Sheet
R16.01 – Excel Sheet: *Sensors and Signal Conditioning Computations*