Signal Processing Circuits
For Analog to Digital Converters

One of the limitations of many low cost, single supply, analog to digital converter ICs today is that they have a limited input voltage range. This note discusses various ways of implementing input processing to allow these devices to operate in the "real world." The ADS7870 is used as the example A/D but the equations and samples are generic enough so that you can configure the circuits for other devices.

The ADS7870 has three possible internal voltage reference values. This note assumes that the 2.048 volt reference has been selected and that its Programmable Gain Amplifier is set to a gain of 1. When used in its single ended mode the A/D then has a useful input voltage range of 0 volts to Vref – 1 LSB and has 11 bit resolution.

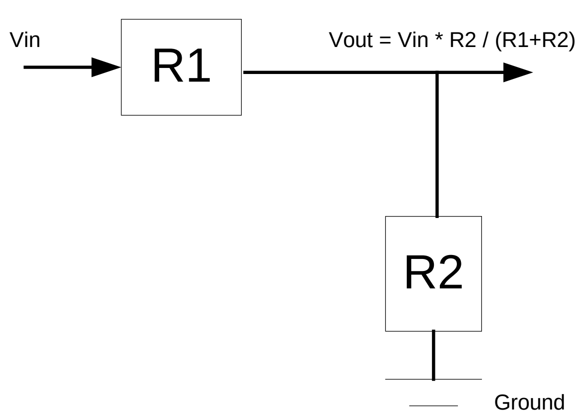
When used in its differential mode the useful input voltage range of -Vref to Vref – 1 LSB (relative to the + input) and has 12 bit resolution. The MSB becomes the sign bit. However, the input voltage must always be >= 0.

Some A/Ds have an input voltage limit of 2*Vref, so be sure to keep that in mind when determining the maximum input voltage.

For Circuits 1 and 2 the value of R2 should be adjusted based on the input resistance of the A/D. However, if the calculated value is much greater than the A/D resistance then simple calibration should be all that is required.

Circuit 1

The simplest form of scaling only works for uni-polar inputs which is a voltage divider as shown below.



If your system only needs to measure between 0 volts and some positive voltage greater than the reference then a simple voltage divider might be adequate. By rearranging the equation in Circuit 1 and specifying the required input resistance you can determine the value for R2:

R2 = Vout * R1 / (Vin - Vout)

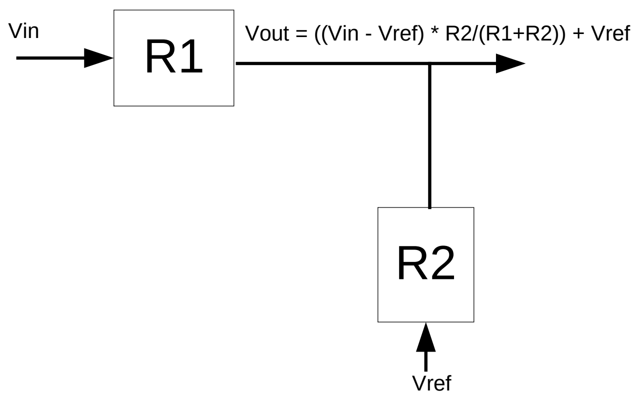
If R1 = 100Kohms and Vin = 10V when Vout = 2.048 then R2 = 25.7Kohms

Just as a practical matter it would be a good idea to use a slightly higher value as the maximum for Vin just to insure that you have some "headroom." If we use 10 volts as the actual maximum Vin the scale factor for converting from A/D counts to volts is 10/2047 = 4.8851 millivolts /count. (2047 is the maximum count value for an 11 bit device.) This can be used but is somewhat awkward. It also does not allow for "headroom." A better solution is to round up the value calculated above to 5millivolts. This yields a maximum input voltage value of 10.235 volts.

The applied voltage can be calculated from the count value as measured by the A/D: Vin = Count * .005

Circuit 2

The figure below is similar to Circuit 1 except that it allows you to measure bi-polar voltages.



You can see that if Vref = 0 the equation reduces to the same as in Circuit 1. Solving the equation for the reference voltage yields:

Vref = Vout(R1+R2)/R1 – Vin*R2/R1.

"Now what?" you may ask. The next step is to set Vout = 0 (because the minimum input voltage to the A/D must be 0v) and see what happens: Vref = -Vin*R2/R1. If we assume that the largest negative input voltage will yield Vout = 0, then Vref must be positive. Substituting -10 in the above equation yields: Vref = 10*R2/R1.

Now lets set Vout = 2.0v, a little below the maximum allowed by the A/D converter. This will be achieved when Vin = 10v. The equation becomes: Vref = 2*(R1+R2)/R1 – 10*R2/R1.

We now have two equations with three unknowns. Now we should pick a value for R1 since it is the major contributor to the input resistance. As in the previous example lets make it 100Kohms. The two equations become:

Vref = 10*R2/100K and Vref = 2*(100K+R2)/100K – 10*R2/100K

This allows us to solve for R2 since:

10*R2/100K = 2*(100K+R2)/100K – 10*R2/100K

Which reduces to: R2 = 200K/18 = 11.1Kohms. If you want to be really exact the value of R2 should take into account the input resistance of the A/D. Although the error incurred by not including the input resistance can be compensated by properly calibrating the system.

Now we can solve for Vref: 10*11.11K/100K = 1.111v.

To check we can substitute an input voltage back into the equation of Circuit 2:

Let Vin = 10v: Vout = (10-1.111)*11.1K/(100K+11.1K) + 1.111
= 8.889 * .1 + 1.111 = 1.999

Let Vin = -10v: Vout = (-10-1.111)*11.1K/(100K+11.1K) + 1.111
= -11.111 * .1 + 1.111 = 0.0001

Without roundoff errors the results are exactly 2.0 and 0.0 respectively.

OP Amp Discussion for A/D Converter Scaling

This analysis is for Circuit 3 below and is based on the following characteristics of an "ideal" operational amplifier:

1) Infinite input resistance
2) 0 volts between the two inputs – in a properly configured circuit
3) 0 ohms output resistance

The advantage of this inverting configuration is that you can measure negative voltages with a system powered by a single positive power supply. A non-inverting configuration does not.

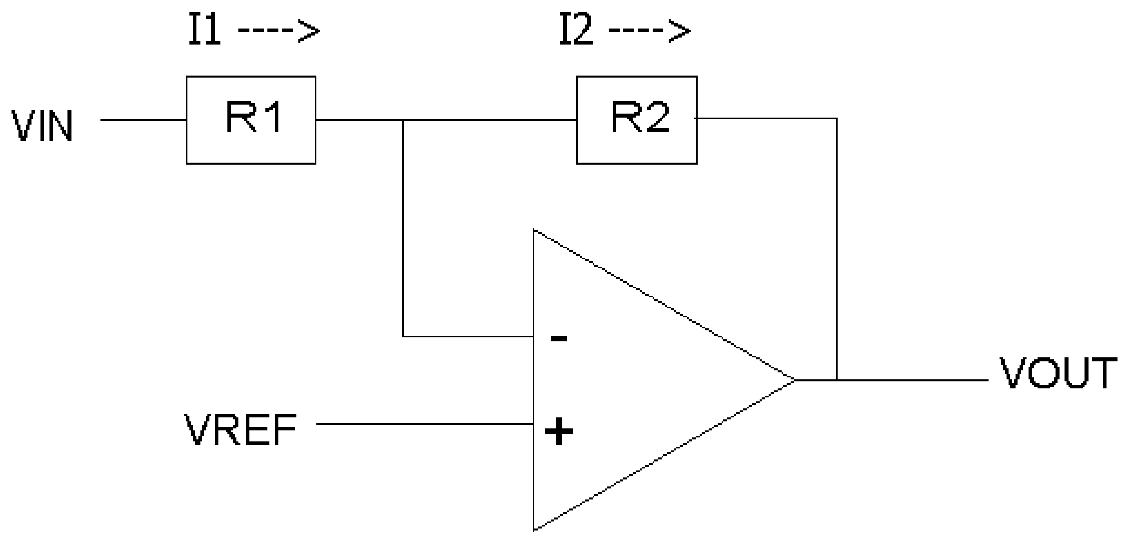
Because op-amp input resistance is infinite there is no current flow into the inverting input; therefore, I1 must equal I2. Also, the voltage being forced on the positive input will be present at the inverting input. These two characteristics result in formula (1).

(1) (VIN – VREF)/R1 = (VREF-VOUT)/R2

Rearranging the formula allows you to solve for VOUT in terms of VIN and VREF

(2) (VIN – VREF)(R2/R1) = VREF-VOUT
(2a) VOUT = VREF – (R2/R1)(VIN - VREF)
(2b) = VREF(1 + R2/R1) – VIN(R2/R1)

Circuit 3



IMPORTANT: Since VIN is applied to the negative input VOUTmin occurs at VINmax.

This circuit may be used to implement a function similar to Circuit 2 on the previous page but with higher input resistance. The easiest place to start is to determine the ratio of the input and output voltages. This will determine the ratio of R1 and R2. If you need an input voltage range of -10v to +10v and an output voltage range of 0v to +2.048, the ratio is 20/2.048. The calculations will be easier if the input voltage range is expanded to: -10.24v to +10.24v. This yields a ratio of 20.48/2.048 = 10.0 as well as giving the circuit some headroom.

The voltage values used to calibrate any of the above systems can be chosen approximately as:

Vmincal = Vmin + Vspan/20
Vmaxcal = Vmax – Vspan/20

Where:

Vmincal = the minimum applied calibration voltage
Vmin = minimum allowed input voltage
Vmaxcal = the mamimum applied calibration voltage
Vmax = maximum allowed input voltage
Vspan = Vmax- Vmin.

This enables calibration at the 5% and 95% points. It is not a good idea to calibrate at the endpoints since your applied voltage may be slightly outside the measurable range.

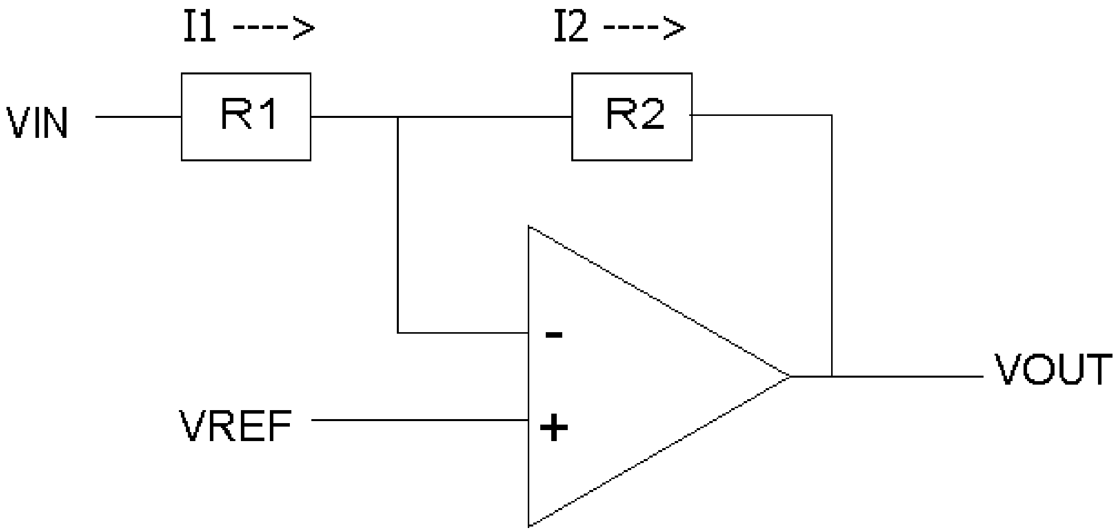
<u>OP Amp Discussion for D/A Converter Scaling</u>

The circuits described below use a bi-polar power supply if the output voltage is bi-polar although the equations work for bi-polar and uni-polar systems.

This analysis is for the figure below and is based on the characteristics of an "ideal" operational amplifier as previously listed. The formulas are repeated here for convenience:

(1) (VIN – VREF)/R1 = (VREF-VOUT)/R2
(2) (VIN – VREF)(R2/R1) = VREF-VOUT
(2a) VOUT = VREF – (R2/R1)(VIN - VREF)
(2b) = VREF(1 + R2/R1) – VIN(R2/R1)

Circuit 4



Typically, VREF is a fixed value while VIN varies. For the purposes of this example the input voltage is unipolar (0V to +4V). The required output voltage is –10V to +10V.

Now, since VOUT requires a span of 20 volts and VIN has a span of 4 volts then R2/R1 = 5.

The formula now becomes:

VOUT = 6*VREF – 5*VIN

Because VOUT is at maximum positive voltage when VIN is at 0V (inverting op-amp configuration) then:

VREF = VOUT(max) / 6 = 10.00V/6 = 1.666V

and VOUT(min) = 6*VREF – 5*VIN = 10.00V – 5*4.00V = -10.00V

These voltage values were chosen to simplify the calculations. Actual values will vary depending on the application.

You can just as easily reverse the functions of the VIN and VREF signals. This causes the output voltage to be in phase with the input signal.

Let me repeat equation (2b) from above but interchange VIN and VREF:

(2c) VOUT = VIN(1 + R2/R1) – VREF(R2/R1)

Lets use the same premise as above: input voltage from 0V to +4V and VOUT is -10V to +10V.

The required gain is still 20V/4V = 5. However, now R2/R1 needs to be 4 since there is a “1+” element for VIN. The equation now becomes:

VOUT = VIN*5 – VREF*4

We still have VOUTmax = +10V and VOUTmin = -10V. Since the output is now in phase with the input VOUTmax occurs at VINmax:

+10V = 4V*5 – VREF*4 = 20V – VREF*4

Which reduces to: VREF = (20-10)/4 = 10/4 = 2.5

The final transfer equation is now: VOUT = VIN*5 – 10V

Working with a smaller, single supply system that uses analog-to-digital or digital-to-analog signal processing can be a significant challenge for a designer. By using the examples provided in this note, the developer has some simple and low cost solutions that have a wide variety of application. These designs are also portable from one design to another and have a wide range of utility. By doing a little work to condition the signal an almost infinite range of values can be measured with modest hardware that will not break the budget and that is good news to any engineer.