SENSORS

1. Introduction

A sensor is a device that converts a physical phenomenon into an electrical signal. As such, sensors represent part of the interface between the physical world and the world of electrical devices, such as computers. Sensors help translate physical world attributes into values that the computer or a robot can use.

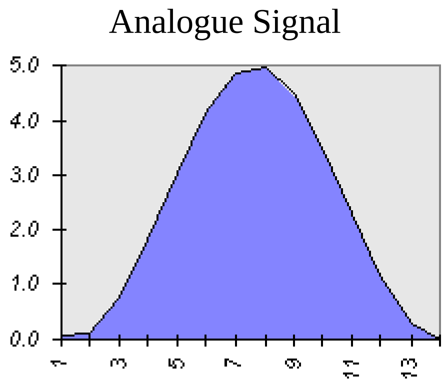
The translation produces some sort of output value that the micro-controller can use. All microprocessors need electrical input voltages in order to receive instructions and information. So, along with the availability of inexpensive microprocessors, has grown an opportunity for the use of sensors in a wide variety of products.

2. Sensor Output Values

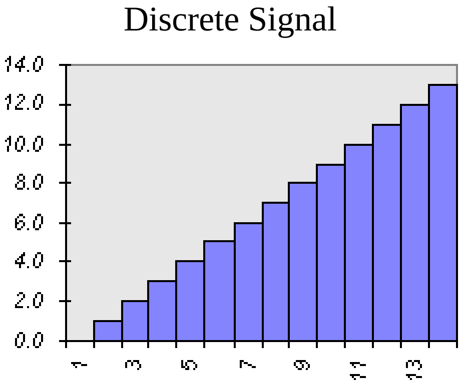
In general, most sensors fall into one of two categories:

1. Analogue sensors
2. Digital sensors

An analogue sensor, such as a CdS cell (Cadmium Sulphide cells, which measure light intensity) might be wired into a circuit in a way that it will have an output range from 0 volts to 5 volts. The value can assume any possible value between 0 and 5 volts. An 'analogue signal' is one that can assume any value in a range. An interesting way to think about this is that an analogue signal works like a tuner on an older radio. You can turn it up or down in a continuous motion. You can fine tune it by turning the knob ever so slightly.



Digital sensors generate what is called a 'discrete signal'. This means that there is a range of values that the sensor can output, but the value must increase in steps. There is a known relationship between any value and the values preceding and following it. 'Discrete signals' typically have a stair step appearance when they are graphed on chart. If you consider a television set's tuner, it allows you to change channels in step.



For example, consider a push button switch. This is one of the simplest forms of sensors. It has two discrete values. It is on or it is off. Other ‘discrete’ sensors may provide you with a binary value. A digital compass, for example, may provide you with your current heading by sending a nine-bit value with a range from 0 to 359. In this case, the discrete signal has 360 possibilities.

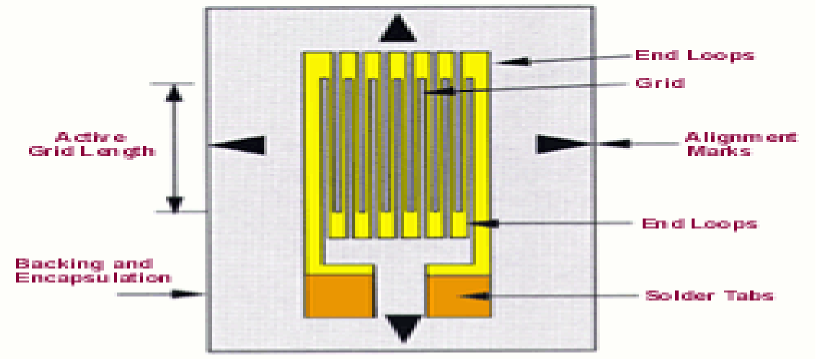
The most common discrete sensors used in robotics provide you with a binary output that has two discrete states. The distinction between analogue and digital is important when you are deciding which type of sensor you wish to use. Part of this decision depends on the type of resources available on your micro-controller.

3. Examples of Analogue Sensors

Remember, to successfully use an analogue sensor, you need some way to convert the data into a digital form. All of the circuits shown in this section are intended to be connected to an analogue/digital (‘A/D’) converter port. Many micro-controllers have A/D ports built in. Others require that you add an additional support chip.

Strain gauge

The strain gauge has been in use for many years and is the fundamental sensing element for many types of sensors, including pressure sensors, load cells, torque sensors, position sensors, etc.

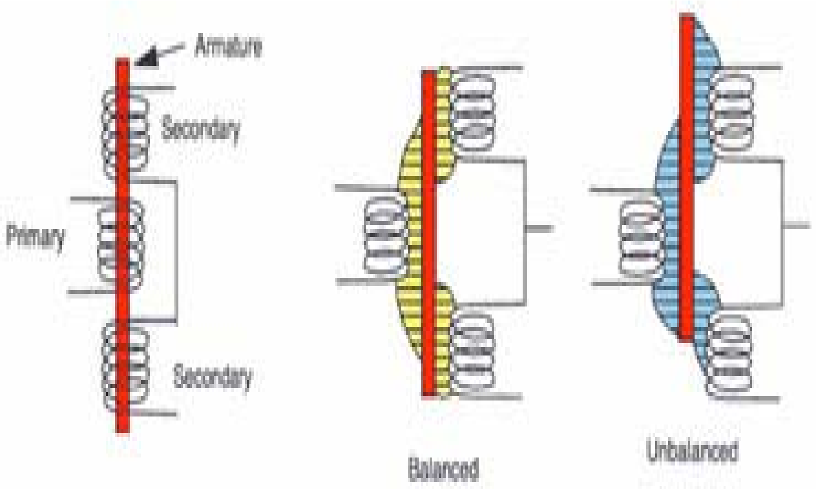


The majority of strain gauges are foil types, available in a wide choice of shapes and sizes to suit a variety of applications. They consist of a pattern of resistive foil which is mounted on a backing material. They operate on the principle that as the foil is subjected to stress, the resistance of the foil changes in a defined way.

Linear Variable Differential Transformer (LVDT)

The Linear Variable Differential Transformer (LVDT) is a displacement measuring instrument. It is a variable-reluctance device, where a primary centre coil establishes a magnetic flux that is coupled through a mobile armature to a symmetrically-wound secondary coil on either side of the primary.

Two components comprise the LVDT: the mobile armature and the outer transformer windings. The secondary coils are series-opposed; wound in series but in opposite directions.

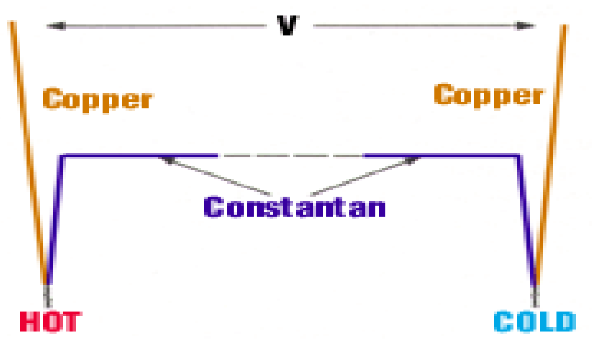


When the moving armature is centred between the two series-opposed secondaries, equal magnetic flux couples into both secondaries and the voltage induced in one half of the secondary winding is balanced and 180 degrees out-of-phase with, the voltage induced in the other half of the secondary winding.

The balanced condition provides total cancellation of secondary voltages and therefore, zero voltage output. When the moveable armature is displaced from the balanced condition, more magnetic flux will couple into one half of the secondary than into the other producing an imbalance voltage output at the primary coil excitation frequency. The output voltage of the LVDT is therefore a direct function of the displacement of the mobile magnetic armature.
The LVDT is, by definition, a transformer and requires an oscillating primary coil input.

Thermocouple

The thermocouple is frequently used as the sensing element in a thermal sensor or switch. The principle is that two dissimilar metals always have a contact potential between them, and this contact potential changes as the temperature changes.

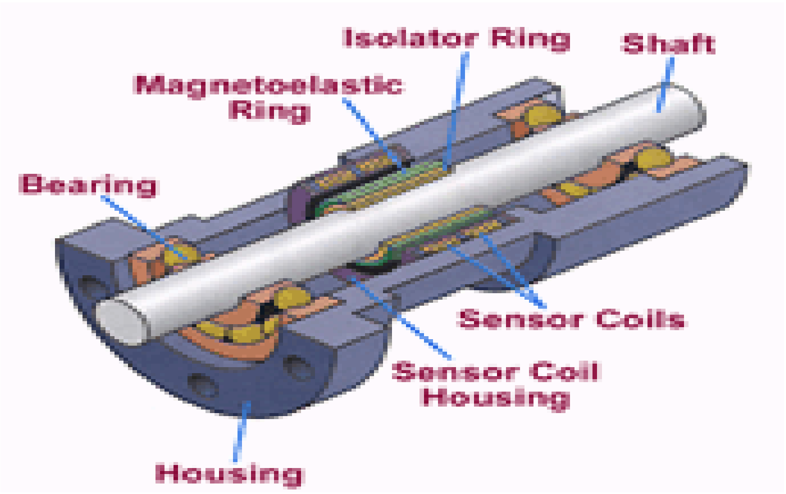


The contact potential is not measurable for a single connection (or junction), but when two junctions are in a circuit with the junctions at different temperature then a voltage of a few millivolts can be detected. This voltage will be zero if the junctions are at the same temperature, and will increase as the temperature of one junction relative to the other is changed until a peak is reached.

Torque sensor

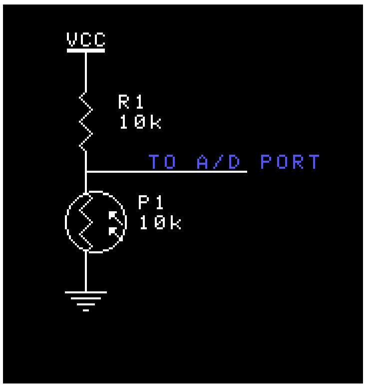
The importance and usefulness of torque measurement in fastening and other applications has been recognised for many years, but the challenge in the past has been to monitor and measure torque both accurately and economically in the manufacturing environment.

Although strain gauge torque transducers provide high accuracy, their high cost and bulkiness are features which have limited their use primarily to research and development laboratories and in quality assurance testing in order to verify standards. In addition, such transducers require high maintenance levels, making them unsuitable for mass integration into manufacturing systems.



CdS Cells

Cadmium sulphide is an interesting compound. Its resistance changes readily when exposed to light energy. Typically; the more light, the lower the resistance. This is useful for measuring the intensity of light.



The CdS cell, shown in the diagram to the left, has a resistance of 10k in average operating light. I have chosen R1 to have the value of 10k based on this. You should test the CdS cell that you are planning to use to determine its average value. By setting the values close to each other, the average value will be halfway through the range of possible values.

For example, in average light, the CdS cell has a resistance of 10k. Using a resistor divider equation, I know that the voltage going to the A/D port will be:

$$V = Vcc * P1 / (P1 + R1) = 5.0 * (10k / (10k + 10k)) = 2.5 \text{ volts}$$

Therefore, the A/D port should read around 128 in average light (see section 6).

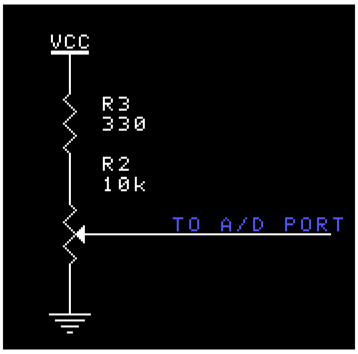
CdS Cell Wiring Diagram

Note that as the light increases, the resistance decreases. Assume that it is bright enough for P1 to be only 2k. $Vcc * (2k / (2k + 10k)) = 0.83$ volts. Using the .0195 voltage value (from section 6), the A/D conversion resulting value would be approximately 42. Hence, as the light gets brighter, the value from the A/D drops.

In summary, choosing the value for R1 based on the average reading for the CdS cell will centre the ‘average’ reading at half of Vcc. Doing so allows you to have maximum range on your sensor.

Potentiometers

An extremely simple and useful sensor is the potentiometer (‘POT’). They are especially useful for making angular measurements e.g. for determining the angles of a robot arm, for example.



Potentiometer Sensor Wiring Diagram

As with the CdS cell, a Potentiometer is a resistive sensor. Almost all resistive sensors are wired in a similar fashion. As you can see by comparing the diagram on the right with the CdS diagram, the key is to make the resistive sensor part of a voltage divider.

The circuit works just like the CdS example. A few things to point out:

- It is important that the POT is connected to both Vcc and GND. Otherwise, the divider network is broken and will not function properly.
- You also want to ensure that your POT is large enough to prevent too great a current flow. A POT with a resistance of >1k should be fine. A POT with >100k of resistance is also a good choice, since the amount of the current consumed by the circuit is extremely low.

Notice in the above circuit the current limiting resistor R3. This resistor is there to handle the case when the sweep on the POT is turned all the way to the 'top' position. Without it, a large amount of current could flow if the output was accidentally connected to the wrong port, or if the A/D port on your micro-controller was bi-directional.

Using the values in the above diagram, you can calculate what voltages ranges the POT will allow. With the sweep all the way to the 'top', the value for R2 at the sweep is 10k. The voltage drop across R2 = $Vcc * (R2 / (R2 + R3)) = 5.0 * (10k / (10k + 330)) = 4.84$ *volts*. Thus, the highest digital value will be $4.84 / 0.0195 = 248$. Actually, it will be 247 since the A/D conversions are zero based. The lowest value should be zero since, with the sweep all the way to the bottom, the A/D port will be connected to GND. Therefore, the limiting resistor has reduced the useful range of the POT.

To increase the range, you can increase the value of R2. For example, using a 100k POT means $5.0 * (100k / (100k + 330)) = 4.98$ *volts*. Thus, $4.97 / .0195 = 255$, which will be 254 when adjusted for the zero-based conversion.

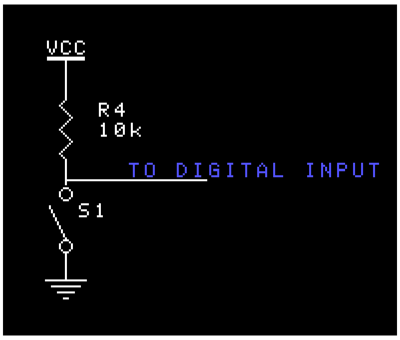
4. Examples of Digital Sensors

There are many different types of digital input sensors. Many of them are wired in the same form, which uses a pull-up resistor to force the line high, and to limit the amount of current that can flow.

Switches

One of the most basic of all sensors is a simple switch. Switches are used in bumper sensors, to detect limits of motion, for user input, and a whole host of other things.

Switches come in two types: ‘normally open’ (NO) and ‘normally close’ (NC). Many microswitch designs actually have one common terminal, and both a NO terminal and a NC terminal.

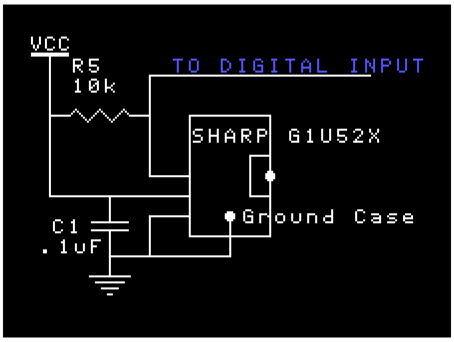


The wiring diagram for a switch is very easy. With a 10k pull-up, the amount of current is small, but many switches can add up to some noticeable power.

Important points are to use a pull-up resistor that doubles as a current limiting resistor. In the event that your program accidentally switches the input port to an output port, having the current limiting resistor will prevent damaging the micro-controller.

Infra-Red Detectors

Infra-red detection is a common in robotics. It allows the robot to determine when it has come in close proximity to an object without coming into physical contact.



Wiring a Sharp IR Detector

The basic wiring diagram for the Sharp module is shown on the right. The connections are to power, ground and the output signal. The output from the Sharp detector is a digital signal.

Notice that R5 acts as a pull-up resistor, similar to other digital inputs. Capacitor C1 acts as a bypass capacitor. Another unusual connection is between ground and the case. Most of the Sharp modules are intended to be mounted on a circuit board. It expects the case to be grounded. Ensure thee is an electrical connection between ground and the case by soldering a wire directly to the metal housing.

5. Sensor Performance Characteristics Definitions

Transfer Function:

The functional relationship between physical input signal and electrical output signal. Usually, this relationship is represented as a graph showing the relationship between the input and output signal, and the details of this relationship may constitute a complete description of the sensor characteristics. For expensive sensors that are individually calibrated, this may take the form of the certified calibration curve.

Sensitivity:

The sensitivity is defined in terms of the relationship between input physical signal and output electrical signal. The sensitivity is generally the ratio between a small change in electrical signal to a small change in physical signal. As such, it may be expressed as the derivative of the transfer function with regard to physical signal. Typical units: Volts/Kelvin. A thermometer would have ‘high sensitivity’ if a small temperature change resulted in a large voltage change.

Span or Dynamic Range:

The range of input physical signals that may be converted to electrical signals by the sensor. Signals outside of this range are expected to cause unacceptably large inaccuracy. This span or dynamic range is usually specified by the sensor supplier as the range over which other performance characteristics described in the data sheets are expected to apply.

Accuracy:

Generally defined as the largest expected error between actual and ideal output signals. Sometimes this is quoted as a fraction of the full scale deflection (‘FSD’). For example, a thermometer might be guaranteed accurate to within 5% of FSD.

Hysteresis:

Some sensors do not return to the same output value when the input stimulus is cycled up or down. The width of the expected error in terms of the measured quantity is defined as the hysteresis. Typical units: Kelvin or % of FSD.

Nonlinearity (often called Linearity):

The maximum deviation from a linear transfer function over the specified dynamic range. There are several measures of this error. The most common compares the actual transfer function with the ‘best straight line’, which lies midway between the two parallel lines that encompass the entire transfer function over the specified dynamic range of the device. This choice of comparison method is popular because it makes most sensors look the best.

Noise:

All sensors produce some output noise in addition to the output signal. In some cases, the noise of the sensor is less than the noise of the next element in the electronics, or less than the fluctuations in the physical signal, in which case it is not important. Many other cases exist in which the noise of the sensor limits the performance of the system, based on the sensor. Noise is generally distributed across the frequency spectrum. Many common noise sources produce a white noise distribution, which is to say that the spectral noise density is the same at all frequencies.

Resolution:

The resolution of a sensor is defined as the minimum detectable signal fluctuation. Since fluctuations are temporal phenomena, there is some relationship between the timescale for the fluctuation and the minimum detectable amplitude. Therefore, the definition of resolution must include some information about the nature of the measurement being carried out. Many sensors are limited by noise with a white spectral distribution.

Bandwidth:

All sensors have finite response times to an instantaneous change in physical signal. In addition, many sensors have decay times, which would represent the time after a step change in physical signal for the sensor output to decay to its original value. The reciprocal of these times correspond to the upper and lower cut-off frequencies respectively. The bandwidth of a sensor is the frequency range between these two frequencies.

6. Analogue to Digital Conversions

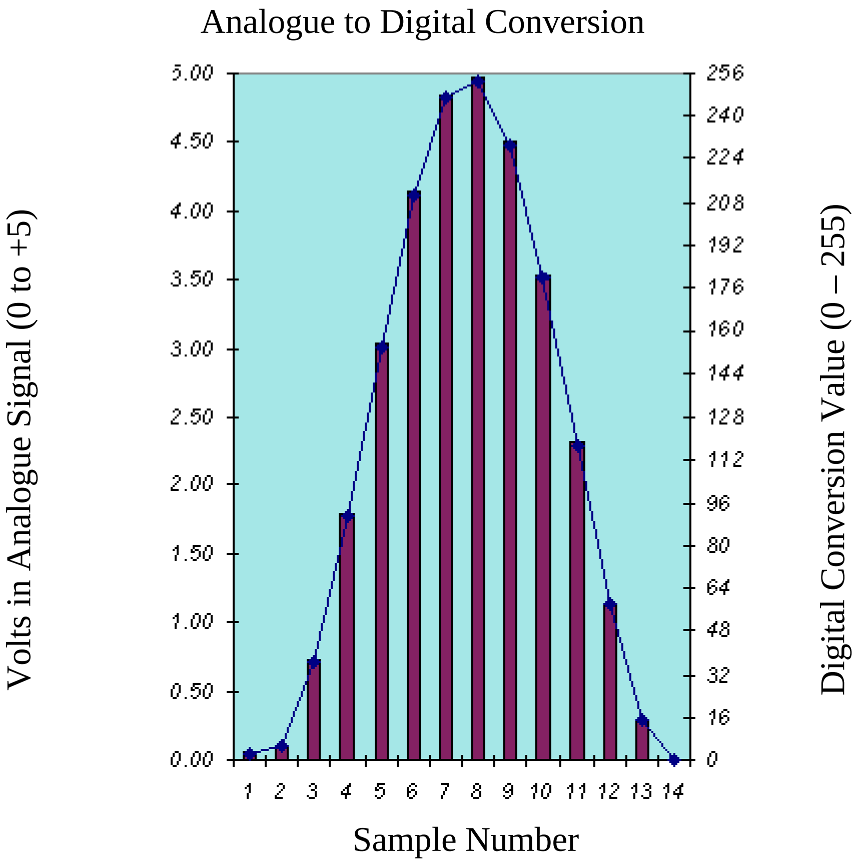
Micro-controllers almost always deal with discrete values. Many controllers deal with 8-bit values. An important part of using an analogue signal is being able to convert it to a discrete signal such as an 8-bit digital value. This allows the micro-controller to do things like compute values and perform comparisons. Fortunately, most modern controllers have a resource called an analogue to digital converter (A/D converter).

The function of the A/D converter is to convert an analogue signal into a digital value. It does this with a mapping function that assigns discrete values to the entire range of voltages. It is typical for the range of an A/D converter to be 0 to +5 volts.

The A/D converter will divide the range of values by the number of discrete combinations. For example, the table on the right shows five samples of analogue signals that have been converted into digital values.

>=Volts	< Volts	Conversion
0.0000	0.0195	0
0.0195	0.0391	1
0.0391	0.0586	2
0.0586	0.0781	3
0.0781	0.0977	4

The range of the analogue signal is 0 to +5 volts. It is an 8-bit A/D converter, which has 256 discrete values. Therefore, A/D converter divides 5 volts by 256 to yield approximately .0195 volts per unit. The table shows how voltages map to specific conversion values. Only the first five are included, but the table would continue up to conversion value 255.



The chart above shows the results of the A/D conversions for 14 samples. The sample numbers are shown along the X axis at the bottom. The left hand Y axis indicates the voltage of the analogue sample that was fed into the A/D converter. On the right hand side, the 8-bit value assigned to the conversion is shown.

As you can see from the line scale, this was an analogue function just like the original analogue signal graph shown above. The A/D converter has mapped a set of discrete values onto this graph.

There are many types of A/D converters on the market. An important feature is the resolution of the converter. An 8-bit converter is fairly common on micro-controllers. There are others. A ten-bit converter, for example, will divide by 1,204 samples. A sixteen-bit A/D converter can do 65,356 discrete values. The resolution required for your application depends on the accuracy your sensor requires. The higher the resolution, the greater the accuracy.

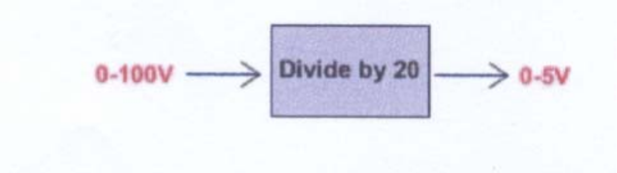
7. **Changing Sensor Output Voltage**

Sensors often create voltages in different ranges than those required by the controllers to which they are being interfaced, which requires the conversion of one voltage to another. This conversion often breaks down into a combination of one or more of three types; amplification, dividing, and shifting.

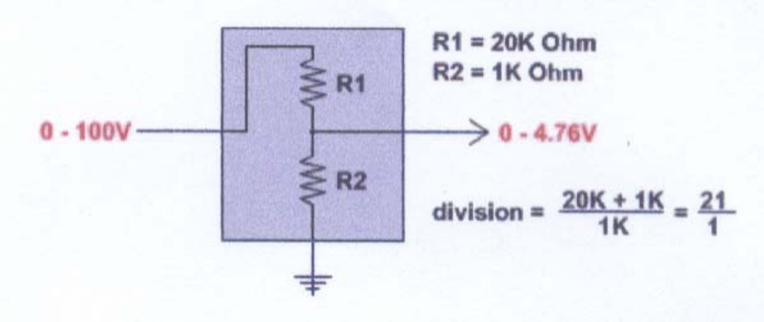
Dividing Voltages

Voltage dividing is probably the easiest transformation you can perform on sensor outputs to alter the value being connected to a micro-controller or other circuit.

The mathematical equivalent of what you are trying to achieve when dividing voltages is a simple division. For instance, say you have a sensor that outputs 0-100V and you want to convert this to 0-5V for interface to the A/D input. The aim would be to create a 20:1 ratio of voltage, which means dividing the original sensor output voltage by a factor of 20. Therefore we need a small circuit that will accomplish the following :-



The easiest way to accomplish this division is by using a few resistors to form a voltage divider. The resistors are wired up in series to create intermediate voltages based on the desired division. This could be done as shown below.



This voltage divider uses the input as the top of the resistor ladder and ground as the bottom. The actual division is defined by the proportion of resistance between the two resistors.

Notice that the above circuit does not work out to an exact division by 20. This is because the resistors used are commonly found resistor values. Precision resistors with other tolerances can be used, but are often not needed since the original output of sensors typically varies. Here, the resulting output voltage is slightly below the maximum of 5V but, with a reasonable A/D converter it would still offer plenty of dynamic range in the sensor readings.

Amplifying Voltages

Voltage amplification is required for a class of sensors that create small voltage output. Often, sensors of this type are converting some sort of physical energy such as acceleration, temperature, or other minimal physical force into a voltage. This conversion is often an inefficient one and the measured energy is minimal, which results in very small voltages generated by the sensor.

To make these small voltages meaningful, they must be amplified to a usable level.

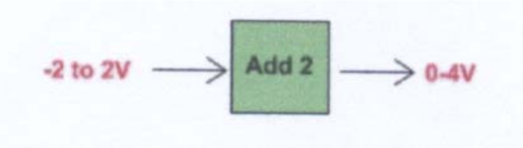
The equation for amplification is the exact opposite of dividing. You need to multiply the output voltage from a sensor to gain the full range of your A/D input to other interfaced circuits. Let's say you have an accelerometer, which measures acceleration in g (gravity) units. A sensor like this may have a response of 312, which means the sensor will generate 0.312V for each gravity unit of force it encounters. Now, say you would like to measure up to two gravity units (2g) with your detector with the full range of your 0-5V A/D converter. This means that you need to multiply the output voltage of your accelerometer by a factor of about 8 (5/0.624) to get the desired range and sensitivity in your measurements.

The gain for the amplifier may not be exactly linear, depending on the input and output voltages. This can often be hidden in the noise of the sensor and accuracy of the A/D conversion on the other end, but it should be considered. The higher the range of an amplifier, the larger the margin of error and noise.

Shifting Voltages

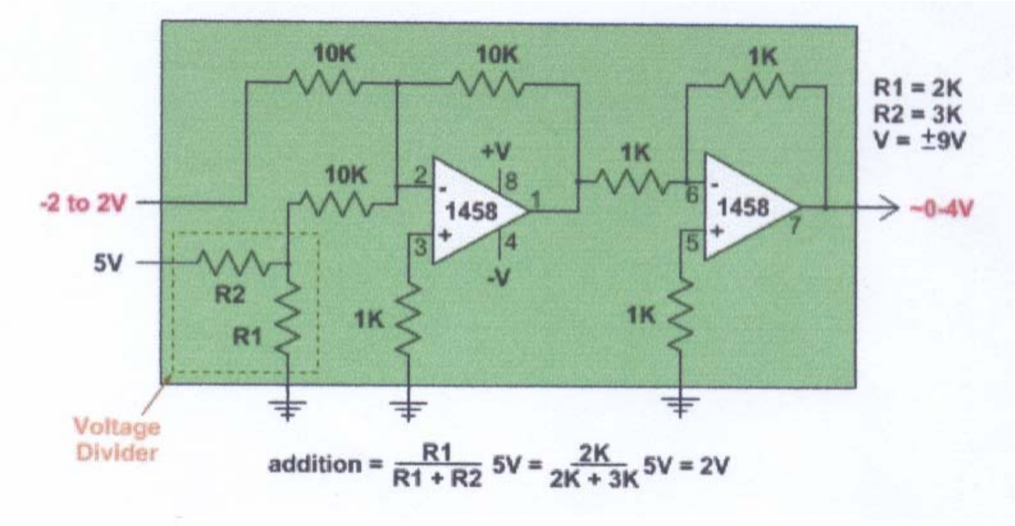
Shifting voltages can be a requirement for sensor data that is generated symmetrically about a common (often ground) voltage. A simple example of this would be a motor acting as a generator, where spinning in one direction creates a positive voltage and spinning in the other direction creates a negative voltage. Since most common converters in micro-controllers deal with a 0-Vcc range for conversions, sensors are symmetric about the ground voltage reference need to be shifted into the 0-Vcc range.

The equation for shifting is then the addition or subtraction of an offset from the original sensor's voltage. For example, if your sensor produces –2 to 2V, you would want to add 2V to the output for reading with a common 0-5V A/D converter. This addition would result in a final output of 0-4V which the A/D converter could then use. This conversion looks like that shown overleaf pictorially:



This circuit is a two-stage summing amplifier using an Op Amp chip. Notice there are some fixed values of resistors that essentially creates a voltage summing circuit. The input on one side is a resistor network that creates a fixed voltage to sum with the input voltage. The variable resistor values change this resistor network's set voltage. You could substitute a potentiometer for R1 and R2 to make the addition variable, by twisting the potentiometer.

The addition circuit also requires a plus/minus 9V power supply for the op amp addition; a tap from the 5V supply used for the logic is used, although this could be done with the positive 9V side as well, provided that the voltages are computed correctly.



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