Chapter 5

Sensor Design

Without sensors, a robot is just a machine. Robots need sensors to deduce what is happening in their world and to be able to react to changing situations.

This chapter introduces a variety of robotic sensors, explaining electrical use and practical application. While many ways to use the various sensors in the 6.270 are mentioned, please do not be limited by the ideas contained in this chapter! The sensor applications presented here are not meant to be exhaustive, but merely to suggest some of the possibilities.

Assembly instructions for the kit sensors are given in Section 1.9.

5.1 Sensors as Tranducers

The fundamental property of a electronic sensor is to measure some feature of the world, such as light, sound, or pressure, and convert that measurement into an electrically represented quantity.

Typical sensors respond to stimulus by changing their resistance (photocells), changing their current flow (phototransistors), or changing their voltage output (the Sharp IR sensor). One electrical output of a given sensor can be easily converted into other electrical representations.

5.1.1 Analog and Digital Sensors

A distinction is often made between a sensor that is *analog* and a sensor that is *digital.*

An analog sensor produces a *continuously varying* change in value over its range of measurement. For example, a particular photocell might have a resistance of 1kΩ in bright light and a resistance of 300kΩ in complete darkness.

Digital sensors, on the other hand, have only two states, "on" and "off." Perhaps the simplest example of a digital sensor is the touch switch. A typical touch switch has infinite resistance when it is not pressed, and zero resistance when it is.

Some sensors that produce a digital output are more complicated. These sensors produce *pulse trains* of transitions between the 0 volt state and the 5 volt state. With these types of sensors, the frequency characteristics of this pulse train convey the sensor's measurement.

An example of this type of sensor is the Sharp modulated infrared light detector. With this sensor, the actual element measuring light is an analog device, but signal-processing circuitry integral to the sensor produces a digital output.

5.2 Sensor Inputs on the 6.270 Board

All of the sensor inputs of the 6.270 board measure voltage levels. Some of the sensor inputs measure analog voltages. This means that they measure the voltage and convert it to a number corresponding to the voltage level.

Other sensor inputs are digital. These inputs discriminate only two states: the zero volt state and the five volt state.

5.2.1 Analog Inputs

The analog inputs of the board measure voltages from zero volts to five volts. They convert the voltage measured to a number from 0 to 255, where 0 corresponds to a reading of zero volts and 255 corresponds to a reading of five volts. The conversion scale is linear, so a voltage of 2.5 volts would generate a conversion value of 127 or 128.

The C library function `analog(`*port-#*`)` is used to return the value of a particular sensor port. For example, the C statement

```
val = analog(3);
```

sets the value of the variable `val` equal to the reading on analog port #3.

5.2.2 Digital Inputs

According to ditigal logic standards, if a voltage level on a digital input is less than 2.5 volts, it is considered to be a logic low, or binary zero. If the voltage level is greater than 2.5 volts, it is considered to be a logic high, or binary one. The digital inputs on the 6.270 have a pull-up resistor that makes the voltage input equal to 5 volts when nothing is connected.

However, many devices used as digital sensors are wired to be *active low*, meaning that they generate a 0 volt value when they are active (or true).

Thus a hardware-level measurement taken on a digital input port has the opposite truth value of the state of such a sensor. For example, when a touch sensor is depressed, it will register a 0 volt or logic zero value.

The C library function `digital(`*port-#*`)`, used to return a true-or-false value associated with a particular sensor port, performs a logical inversion of the signal measured on a digital port. Hence the depressed touch switch (measuring 0 on the hardware) causes the `digital()` function to return a 1 (logic true).

For example, the C statement

```
if (digital(2)) do_it();
```

calls the function `do_it()` if the value at port #2 was zero volts (indicating a depressed switch).

5.2.3 Connector Plug Standard

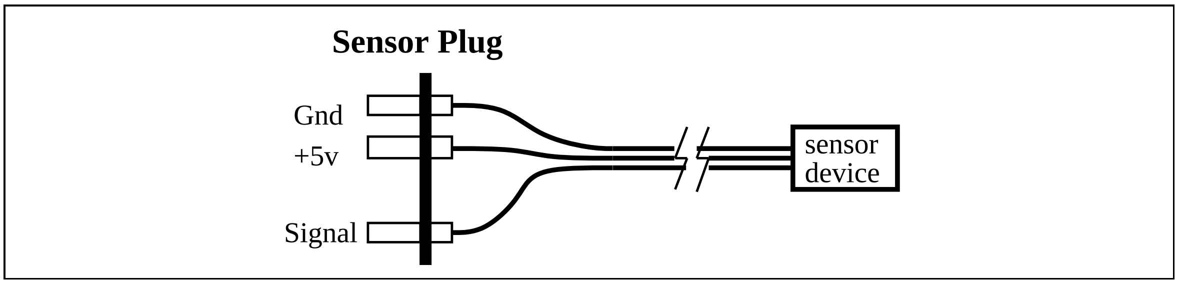

Figure 5.1: Wiring a Generic Sensor

A standard plug configuration has been developed to connect sensors to the 6.270 board, as shown in Figure 5.1.

Notice that one pin is removed from the plug, making it asymmetric and therefore *polarized*. This means that once the plug is wired correctly, it cannot be inserted into a sensor port backwards. This makes the plug much easier to use.

The sensor is connected to the plug with three wires.

Two of the wires are used to supply power from the 6.270 board to the sensor. These are the wires labelled "+5v" and "Gnd." The third wire, labelled "Signal" is the voltage output of the sensor.

It's the job of the sensor to use the power wires (if necessary) and return its "answer", as a voltage, on the `signal in` wire.

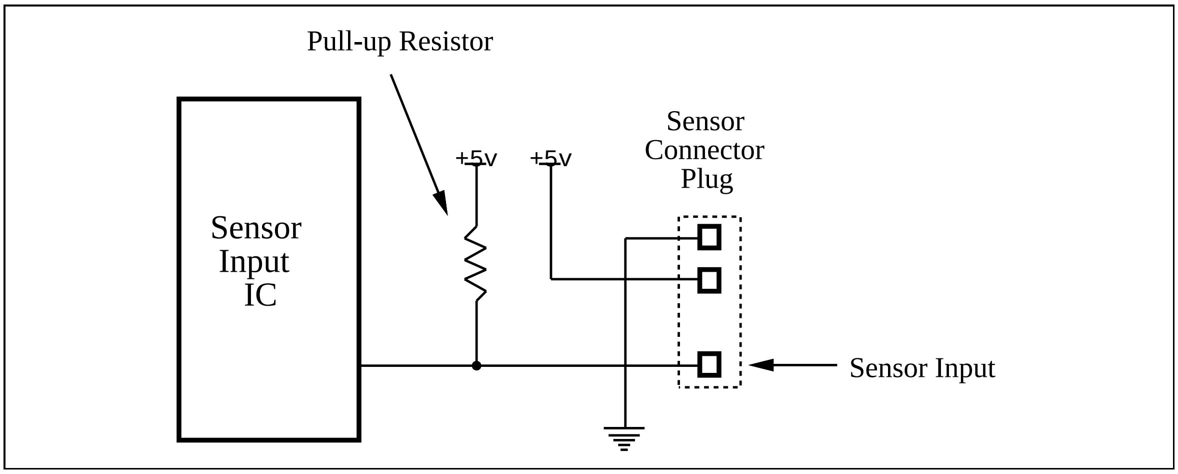

Figure 5.2: Sensor Input Wiring, One Sensor

5.2.4 Sensor Input Wiring

Figure 5.2 shows a diagram of circuitry associated with each sensor. This circuitry, residing on the 6.270 board, is replicated for each sensor input channel.

The key thing to notice about this diagram is the *pull-up resistor* wired from the sensor input signal to the 5 volt power supply.

There are several reasons why this resistor exists. One function it has is to provide a "default value" (value when no sensor is plugged in) to the sensor input. Many IC's do not perform well when their inputs are left unconnected. The pull-up resistor acts when nothing is plugged into the sensor port. It biases the voltage on the sensor input line, causing it to be 5 volts in this situation.

Because of the pull-up resistor, the default value of an analog input is 255. The default value of a digital input is binary 1 or logic true (although this value is inverted by the `digital()` library function, as explained earlier).

The pull-up resistor also acts in *voltage divider* circuits, explained immediately following, which are used in many analog sensors. It eliminates the need for a resistor on each of the sensors.

5.2.5 The Voltage Divider Circuit

Most of the sensors used in the 6.270 kit make use of the voltage divider circuit, shown in Figure 5.3. In the voltage divider, the voltage measured at the tie point of the two resistors, V_{out}, is a function of the input voltage, V_{in}, and the values of the two resistors, R_1 and R_2.

Using Ohm's Law, $V = I \times R$, the output voltage V_{out} can be solved for. i, the amount of current flowing through the circuit shown in the diagram, is $\frac{V_{in}}{R_1+R_2}$

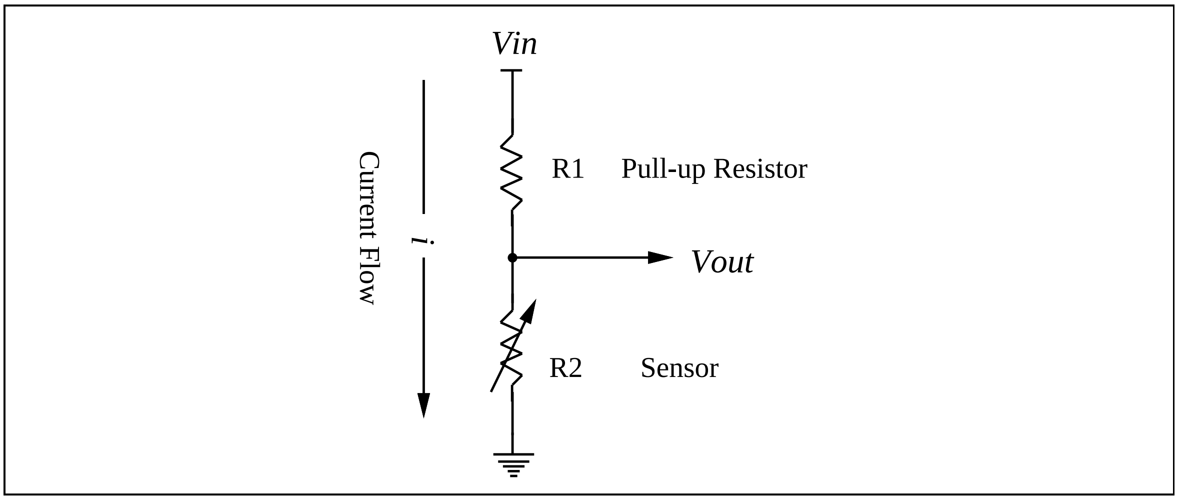

Figure 5.3: Voltage Divider Schematic

(calculated using the rule that series resistances add). Then V_{out}, the voltage drop across R_2, is $R_2 \times i$, which yields the result:

$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2} \tag{5.1}$$

In the 6.270 application, R_1 is a fixed value as part of the sensor input circuitry (as shown in Figure 5.2), and R_2 is the resistive sensor. V_{in} is the positive voltage supply, fixed at 5 volts.

Thus the V_{out} signal can be directly computed from R_2, the resistive sensor. From looking at the equation, it is easy to see that if R_2 is large with respect to R_1, the output voltage will be large, and if R_2 is small with respect to R_1, the output voltage will be small.

5.3 Tactile Sensors

Several types of sensors to detect tactile contact are exist in the 6.270 kit:

Touch Switch. A simple pushbutton or other momentary switch.

Bend Sensor. A unique device that measures amount of flex in a thin plastic strip.

Potentiometer. Rotary and linear potentiometers (variable resistors) can be used.

5.3.1 Touch Switch

The most primitive, but often very useful, sensor is a touch switch. It is simply a pushbutton or other momentary switch that is mounted on a robot so that when the robot runs into something, the switch is triggered. The robot can detect that it has made contact with some object.

Touch sensors used as collision detectors are imperfect in that it is hard to design a touch switch and bumper mechanism that can detect contact of any object from any angle. Creative mechanical design in implementing the bumper mechanism is important.

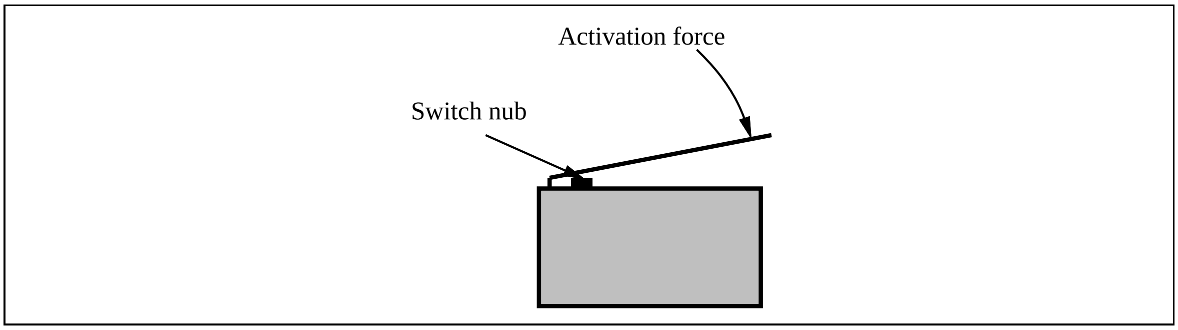

Figure 5.4: A Typical Microswitch

Microswitch is the brand name of a variety of switch that became very popular and is a generic term for this type of switch now manufactured by many companies. Microswitches are an especially good type of switch to use for making touch sensors.

A microswitch is housed in a rectangular body and has a very small button (the "switch nub") which is the external switching joint. Usually, microswitches are also equipped with lever arms to reduce the force needed to actuate the switch (see Figure 5.4).

Because of the lever arm, very little force is needed to actuate the switch. A very sensitive touch bumper can be made by connecting a mechanism as an extension of the microswitch's lever arm, as illustrated in Figure 5.5.

Limit Switch

Touch sensors can also be used to act as *limit switches* for devices that are confined to a known path of travel. For example, when using a mechanism riding on a gear rack, touch switches could detect when the mechanism reached the limit of travel on the rack.

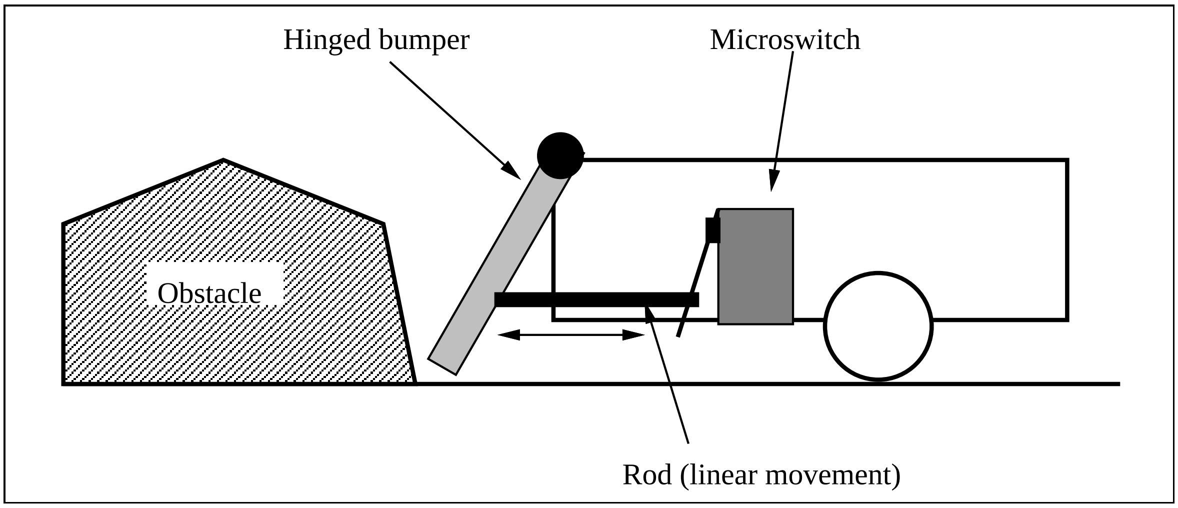

Figure 5.5: Robotic Platform Employing Bumper Coupled to Touch Sensor

Switch Circuitry

Figure 5.6 shows how a switch is wired to a sensor input port. When switch is open (as it is shown in the diagram), the sensor input is pulled to the 5 volt supply by the pull-up resistor. When the switch is closed, the input is tied to ground, generating a zero volt signal.

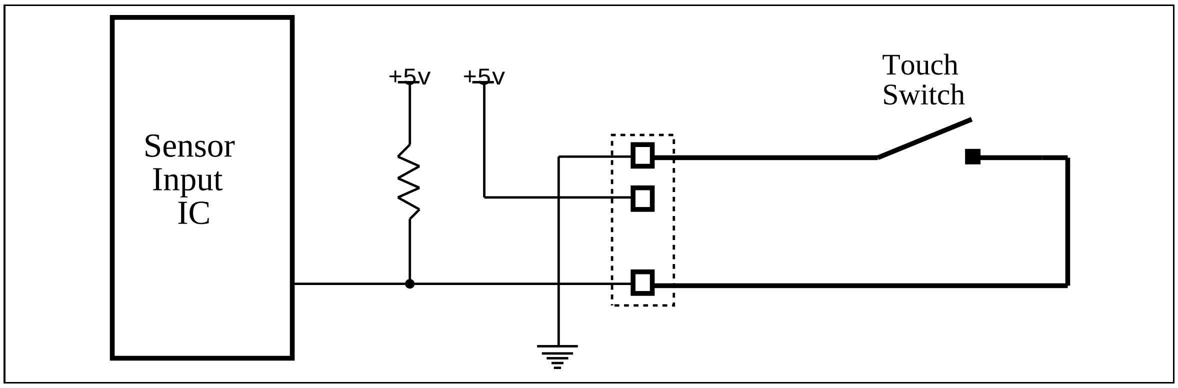

Figure 5.6: Touch Switch Circuit

Most pushbutton-style switches are "normally open," meaning that the switch contacts are in the open-circuit position when the switch is in the non-depressed state. Microswitches often have both normally open and normally closed contacts and a common contact. When wiring a touch sensor with a microswitch, it is customary to use the normally open mode because this is more common. Also, this configuration is the active-low mode expected by the standard library software used to input values from digital sensor ports.

5.3.2 Bend Sensor

The bend sensor included in the 6.270 kit is a unique device that was developed for use in the Nintendo (R) Power Glove, a product that allows hand and finger movement as input to the popular video game. The bend sensor is used in this device to measure the degree of flex in the fingers of the Power Glove.

The bend sensor device was developed by Abrams-Gentile Entertainment, Inc. (AGE), the manufacturers of the Power Glove. AGE is a sponsor of the 6.270 contest and has donated the bend sensors to the contest.

The bend sensor is a variable resistor. When the bend sensor strip is bent (so that the printed element is on the outside curve of the bend), the resistance of the element increases.

The bend sensor has two printed layers. The lower layer is a carbon-based material of constant resistance, similar to the material that is used to fabricate simple resistors. The upper layer is a silver-colored granulated conductive material.

When the strip is flat, the granules of the silver material lie close to each other and conduct electricity, reducing the amount of resistance created by the resistive material. When the strip is bent, the granules are forced apart, and the resistive material carries more of the current, causing an increase in resistance.

Applications

Bend sensors are often much more useful than touch sensors because they can indicate not only the presence of an obstacle, but its distance from the robot. It is quite possible to have a robot follow along a wall edge by using bend sensors to measure the robot's distance to the wall.

Electrical Data

The bend sensor is a simple resistor. It is interfaced to the 6.270 board by functioning as resistor R_2 in the voltage divider circuit shown in Figure 5.3.

The bend sensor assembly instructions propose the construction of a dual bend sensor, in which two bend sensors are laid back to back, so that the combined element can sense bend in either direction.

There are a few ways the configuration could be wired to the sensor input circuitry. One possibility is to wire the two bend sensors in parallel; if either one of them is bent in the active direction, the parallel resistance will decrease.

Another possibility (this one is recommended in the assembly notes) is to wire the two bend sensors into a voltage divider. The pullup resistor will effectively be in parallel with one of the bend sensors, skewing the response of the overall circuit. Still, this configuration will indicate which of the two bend sensors has been flexed, by having the voltage measurement increase or decrease from the relaxed state.

5.3.3 Potentiometer

A potentiometer (or "pot," for short) is a manually-adjustable, variable resistor of the type that is commonly used for volume and tone controls in stereo equipment. In robotics, a potentiometer can be used as a position sensor.

Rotary Potentiometer Use

A rotary potentiometer (the most common type) can be used to the measure the rotation of a shaft. It is easiest to use if the shaft being measured does not need to rotate continuously, but rather would rotate back and forth (as in a sensor "radar dish").

Use of gears is a simple way to lock the rotation of the shaft being measured to the potentiometer. By using a gear ratio other than 1:1, a shaft that needed to rotate more than the 270 degrees or so of the pot could be measured. It is also possible to modify the potentiometer to allow continous rotation, although there would be a portion of the rotation for which no measurement would be available.

Linear Potentiometer Use

A linear pot could be used to measure the position of a linear mechanism or other mechanisms for which a linear measurement could be taken.

Electrical Data

Potentiometers are variable resistors. They have three terminals with the center terminal being a center tap contact that slides across an element of constant resistance.

The assembly instructions suggest wiring the potentiometer in the voltage divider configuration, with the on-board pullup resistor in parallel with one of the potentiometer's two effective resistances (Figure 5.7). This will yield readings of greater precision (although they will not be linear) than if the pot were used as a two-terminal variable resistor.

5.4 Light Sensors

Light sensors may well be the most common form of robotic sensor (other than touch switches). A variety of light sensors are provided in the 6.270 kit:

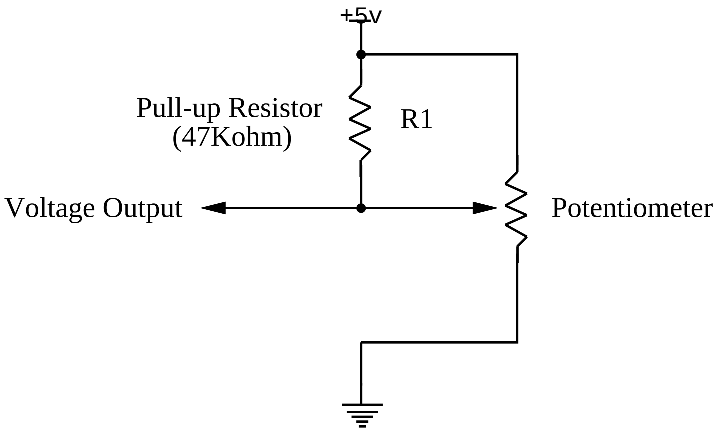

Figure 5.7: Potentiometer Circuit

Photocell. This device is a light-dependent resistor. It is most sensitive to red visible light.

Infrared Reflectance Sensor. This device combines a phototransistor (sensitive to infrared light) and an infrared emitter into a single package. The amount of light reflected from the emitter into the phototransistor yields a measurement of a surface's reflectance (when other factors, such as the distance from the sensor to the surface, are held constant).

This sensor can be used to detect features drawn on a surface or segments on a wheel used to encode rotations of a shaft.

Infrared Slotted Optical Switch. Similar to the aforementioned device, this devices uses an infrared emitter aimed directly at an infrared phototransistor. The phototransistor detects makes and breaks of the infrared beam of light.

This sensor can also be used to make a shaft encoder, using a wheel that has been drilled with holes inside the circumference edge.

Modulated Infrared Light Detector. This device senses the presence of infrared light that has been modulated (e.g., blinks on and off) at a particular frequency.

These devices are typically used to decode the signals of TV remote controls, but are used in the 6.270 application to detect the infrared beacon of the opponent robot.

5.4.1 Photocell

Photocells are made from a compound called cadmium sulfide (CdS) that changes in resistance when exposed to varying degrees of light. Cadmium sulfide photocells are most sensitive to visible red light, with some sensitivity to other wavelengths.

Photocells have a relatively slow response to changes in light. The characteristic blinking of overhead flourescent lamps, which turn on and off at the 60 Hertz line frequency, is not detected by photocells. This is in contrast to phototransistors, which have frequency responses easily reaching above 10,000 Hertz and more.

Applications

Photocells can be used to detect the incandescent lamp that acts as a contest start indicator. They also can be used to measure the reflectivity of the playing field surface if coupled with a light source such as a red LED or an incandescent lamp.

Photocells can be used to detect room ambient lighting. With the use of polarizing filters placed immediately in front of the photocell element, an array of such photocells can be used to detect the polarization angle of polarized light present in ambient lighting. Robot-level control programs can be used to seek out such sources of polarized light.

Electrical Data

The photocell acts as resistor R_2 in the voltage divider configuration discussed in Section 5.2.5.

Photocells yield a decrease in resistance with an increase in illumination. Because of the wiring of the voltage divider (the photocell is on the lower rung), an increase in light will correspond to a decrease in voltage measurement.

5.4.2 Infrared Reflectance Sensor

The infrared reflectance sensor is a small rectangular device that contains an phototransistor (sensitive to infrared light) and an infrared emitter. The amount of light reflected from the emitter into the phototransitor yields a measurement of a surface's reflectance (when other factors, such as the distance from the sensor to the surface, are held constant).

The phototransistor has peak sensitivity at the wavelength of the emitter (a near-visible infrared), but is also sensitive to visible light and infrared light emitted by visible light sources. For this reason, the device should be shielded from ambient lighting as much as possible in order to obtain reliable results.

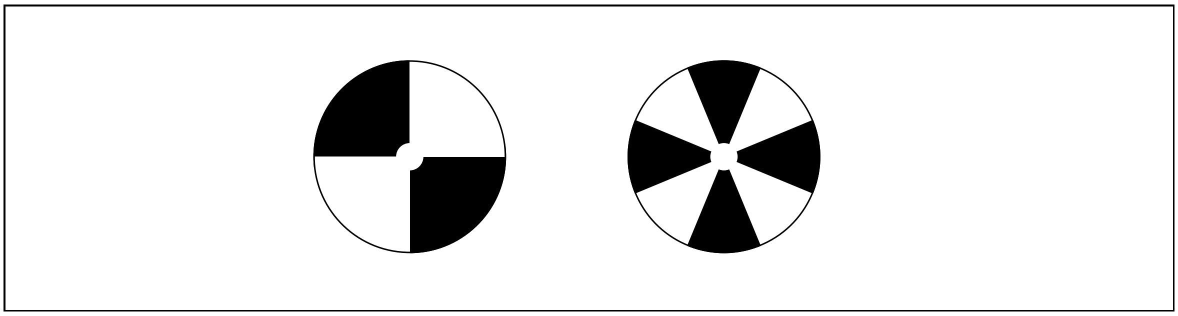

Figure 5.8: Two Optical Shaft Encoder Wheels

Applications

Reflectance Measurement The reflectance sensor is typically used to measure the reflective properties of a surface. If other factors that affect amount of reflected light are held constant, such as distance between the sensor and the surface and presence of ambient lighting, then the amount of light reflected by the surface will be measured.

It's important to remember that the reflectivity measurement is an indication of the surface's reflectivity at a particular wavelength of light (the near visible infrared). A surface's properties with respect to visible light may or may not be indicators of infrared light reflectance. In general, though, surfaces that absorb visible light (making them appear dark to the naked eye) will absorb infrared light as well.

Visible Light Measurement Since the phototransistor responds to visible light sources, the device can also be used to measure the light from the contest starting lamp.

Optical Shaft Encoder By measuring light and dark segments of a wheel mounted on a rotating shaft, the angular displacement and velocity of the shaft can be measured. Either LEGO encoder wheels designed for this purpose or handmade substitutes, as shown in Figure 5.8 can be used.

Standard 6.270 software library functions perform the action of counting transitions on the encoder wheel as measured by the reflectance sensor.

Electrical Data

Phototransistor The phototransistor acts as a transistor with the base voltage determined by the amount of light hitting the transistor. Hence it acts a variable current source. Greater amounts of light cause greater currents to flow through the collector-emitter leads.

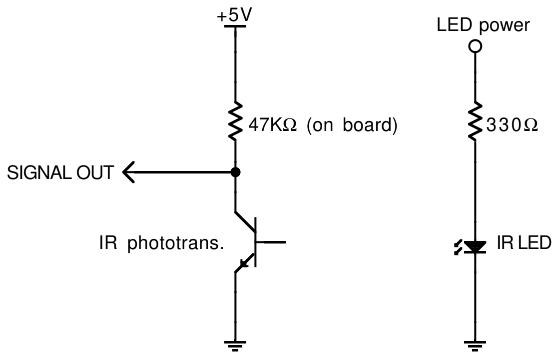

Figure 5.9: Phototransistor and Infrared Emitter Circuit

As shown in Figure 5.9, the phototransistor is wired in a similar configuration to the voltage divider. The variable current travelling through the resistor causes a voltage drop in the pullup resistor. This voltage is measured as the output of the device.

Infrared Emitter The emitter element uses a resistor to limit the current that can flow through the device to the proper value to about 10 milliamps.

5.4.3 Infrared Slotted Optical Switch

The infrared slotted optical switch is similar to the infrared reflectance sensor except that the emitter is pointed directly into the phototransistor.

Applications

The optical switch is commonly used to build shaft encoders. A wheel with holes or slots is necessary.

The optical properties of making and breaking a beam of light versus measuring reflectance are often superior.

Electrical Data

The optical switch operates in the same fashion as the infrared reflectance sensor, with the exception that a different value of pullup resistor must be added externally for the particular model of optical switch in use.

5.4.4 Modulated Infrared Light Detector

The modulated infrared light detector is a device that combines an infrared phototransistor with specialized signal processing circuitry to perform the function of detecting a particular frequency of light.

The 6.270 kit includes the Sharp GP1U52 sensor, which detects the presence of infrared light modulated at 40,000 Hz.

This sensor is used in the 6.270 application to detect infrared light that is emitted by the opponent robot.

Principles of operation and use are explained in Section B.7, which discusses also the infrared transmission circuit. An explanation of the software interface to the Sharp sensors is given in Section 7.8.2.

5.5 Other Sensors

5.5.1 Magnetism Sensor

A device called a Hall effect sensor is used to detect the presence of magnetic fields. The sensor provided in the 6.270 kit (SS41 series by Micro Switch) is a digital device that detects magnetic field.

The SS41 sensor is magnetically bipolar, meaning that it requires positive gauss (south pole) to latch to zero volts output, and negative gauss to release. The sensor latches at $+40$ gauss and releases at -40 gauss.

Application

The Hall effect sensor can be used to detect the magnetic strips present on the lower wall at the circumference of the 6.270 playing table. Some ingenuity may be required to make the device release after sensing the magnetic field. It might be possible to power the Hall sensor from an LED output. Turning the LED output power off should reset the device.

Hall effect sensors can be used to make a magnetic shaft encoders, by mounting a small piece of magnet on a wheel that rotates past the sensor element.

They can be used to build a proximity sensor or bounce-free switch, detecting when a magnet mounted on a moving member is near to the sensor element.

They can be used to make an inclination sensor by dangling a magnet above the sensor.

Electrical Data

The SS41 series Hall effect sensor included in the 6.270 kit is a digital device that operates off of a 5 volts power supply. It uses 4 mA of current for standard operation.

It can sink 10 mA of current into its output, creating a logic low. The sensor cannot drive a logic high and therefore requires a pullup resistor for proper operation.

5.5.2 Motor Current Sensor

Circuitry implemented on the motor output drivers of the 6.270 Microprocessor Board detects the amount of current being used by a motor. This corresponds to the load of the motor, and hence can be used as a stall sensor.

This functionality is explained in Section B.4.1.