Part II

How to Design and Build Working Electronic Circuits

By
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Important note:

This document is a rough draft of the proposed textbook. Many of the sections and figures need to be revised and/or are missing. Please check future releases for more complete versions of this text.

Outline

Part II – How to Design and Build Working Electronic Circuits

Part II – How to Design and Build Working Electronic Circuits

Understanding the fundamental principles described in part I is only half the challenge in designing and building working electronic circuits. This is because electronic components are often non-ideal and the designs of electronic circuits are strongly constrained by the characteristics of available components. For example, resistors can only be so large, op amps can only be so fast, and transistors can only handle so much power. The practical design challenge is to meet the functional requirements of a circuit given limitations of available component.

Part II describes the practical aspects of electronic circuit design, starting with sections on datasheets, electronic packaging technologies, and specifications of basic components such as resistors, capacitors, diodes, and transistors. Then, practical circuits for power supplies, op amps, sensors, and actuators are described in detail with a special emphasis on specifying and choosing the right components. The sections that follow discuss how to program microprocessors and how to use microprocessors to communicate with analog-to-digital converters and computers. Finally, the process for making a printed circuit board (PCB) is described, including instructions on PCB CAD software, soldering, and debugging.

11 Reading Datasheets

Every electronic component ranging from the simplest resistor to the most complex integrated circuit is described by a datasheet. Consequently, reading datasheets is one of the most important skills for an electronic circuit designer. Datasheets contain information on electrical properties, reliability statistics, intended use, and physical dimensions of the component. The amount of information contained in datasheets, can be very extensive and truly bewildering for the newcomers. The most important advice for reading datasheet is: **Don't panic! It is not necessary to understand every piece of information on a datasheet.** In most situations, circuit designers are browsing datasheets for one or two pieces of relevant information; the trick is to know what to look for.

Datasheets are typically organized in the followings sections, although not necessarily in this order:

Advertisement – Highlights the most notable features and specifications of the component. This is the section where manufacturers get to boast about performance specifications of the device. Beware of caveats to the specifications may be omitted.

Component Summary – Describes the function of the device and its intended use. For which application is this component designed for? Is this component optimized for precision, power, speed, or cost?

Absolute maximum ratings – Lists the maximum voltage, current, and temperature conditions that the component can tolerate. Permanent damage to the device may result if the device is operated beyond these limits.

Electrical characteristics – Lists the electrical characteristics for the device under recommended operating conditions by their *minimum*, *maximum*, and *typical* values.

Typical performance curves – Shows graphs of various operating characteristics.

Application information – Discusses certain component characteristics in detail and include example circuits where the component may be used.

Parts selection – Shows various packaging options for the component.

Mechanical data – Shows the mechanical dimensions of the component packages and provides information regarding how to solder the component on a PCB.

When reading a datasheet for the first time, the most relevant section to start with is the *Electrical Characteristics* section, which provides basic operating requirements and performance data to help to decide whether the component is appropriate for the circuit. Once initial requirements are met, the next step is to examine the *Application Information* and *Typical Performance Curves* to get detailed information on how the component should be used and its expected performance. After the part has been added to the design, the *Mechanical Data* section can provide information on physical considerations such as mounting or soldering the component to a PCB.

12 Electronic packaging

Electronic packaging is the physical container of an electronic component. The function of a package is to provide a robust mechanical structure for making electrical connects, as well as, to provide an enclosure to protect the electronic materials from dust and humidity. The three main types of electronics packaging are through-hole, surface-mount, and ball grid array.

12.1 Through-Hole

A through-hole (TH) component uses protruding pins at the bottom of the component to make solder connections to metal-plated holes on a PCB. Discrete components, such as resistors, capacitors, inductors, diodes, and transistors are typically molded in plastic or epoxy resin and connected with flexible metal pins as shown in Figure ###. For transistors, the common packages include TO-92 and TO-220, which are also shown in Figure ###. TH packages for small ICs, such as op amps and microprocessors, typically are dual-inline packages (DIPs), which contains two rolls of pins as shown in Figure ###. The separation between pins in each roll is 0.1”, while the distance between the rolls can be 0.3", 0.4", 0.5" or longer. Complex ICs that require high density interconnects, such as computer CPUs, use the pin-grid array (PGA) package as shown in Figure ###.

Figure ###: Through-hole resistors, capacitors, inductors, diodes, and transistors

Figure ###: DIP package for an op amp and a microprocessor, PGA package for a computer CPU

Each electrical interconnect on the package is assigned a pin number, which maps to its electrical function as indicated by the datasheet. By convention, the pins are numbered counter-clockwise around the component starting at pin 1, which is typically indicated by a physical indentation or a printed dot on the package.

12.2 Surface-Mount

Surface-mount (SMT) components contain flat metal leads which are soldered directly onto corresponding metal pads on top of the circuit board. Since drilled holes are not required, a SMT component can typically be packaged into a smaller volume than a TH component.

SMT resistors and capacitors are rectangular blocks with metal leads on both ends as shown in Figure ###. The size of these packages is specified by their length and width in units of 0.01". For example, a 1206 resistor is 0.12" long and 0.06" wide. The standard sizes are 1206, 0805, 0603, 0402, and 0201.

Discrete SMT transistors typically use the SOT-23 or SOT-223 package as shown in Figure ###. Power transistors use packages such as the TO-252, which is similar to the TO-220 through-hole package. Signal diodes typically also use SOT-23 or SOT-223, while LED's typically use packages compatible in size with 1206 and 0805 resistors.

SMT op amps can be found in a number of different packages including SOIC (small outline IC), SOP (small outline package), SSOP (shrink small outline package), TSOP (thin small outline package). Larger SMT ICs such as microprocessors use quad-flatpak (QFP).

12.3 Ball-Grid Arrays

Ball grid array (BGA) packages are used for high pin-count ICs, such as computer CPUs and DSPs, which have high interconnect density and where minimal PCB occupancy is desired. Instead of metal leads, the electrical interconnects on a BGA are routed through solder balls arranged in a matrix on the bottom of the package, as shown in *Figure 12.1*. BGA packages are soldered to PCBs via more extensive soldering procedures, which often require sending it to a specialized assembly shop. The assembly process for BGA packages can add approximately an extra week to each design-prototype cycle.

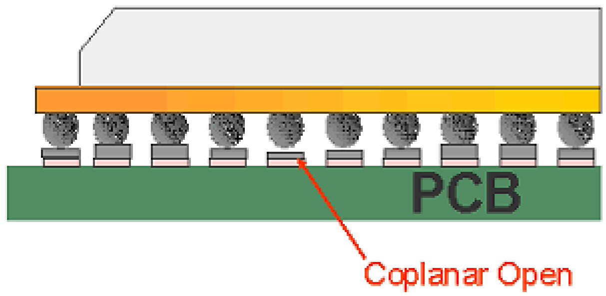

Figure 12.1: An illustration of BGA packaging technology, courtesy Data Circuit Systems

12.4 Comparing Packaging Technologies

For every electronic component, there are typically several packaging options available. While BGA packages are best suited for large-scale projects where absolutely minimum PCB occupancy is required, there is often debate on whether TH packages or SMT packages should be used for smaller projects. Many electronics hobbyists still prefer TH packages because TH components can be prototyped using a solderless breadboard before designing a prototyping PCB. However, in commercial electronics design, TH packages are essentially an obsolete technology used only for high power components and to support legacy designs. SMT components have many advantages over TH components including smaller size, occupancy on only one side of the PCB, easier to solder and de-solder (this point will be discussed in detail in the soldering section), and easier to assemble in a production manufacturing process. Not surprisingly, new components are often only available in SMT packages. With many PCB manufacturers offering low-cost, low-volume prototype runs, it is easier to skip the solderless breadboard, and directly design a prototype PCB. Therefore, SMT packages are the preferred choice when deciding among component packages for prototype design.

13 Specifications of Discrete Components

13.1 Resistors

13.2 Capacitors

13.2.1 Ceramic Capacitors

13.2.2 Electrolytic Capacitors

13.2.3 Tantalum Capacitors

13.3 Diodes

13.4 Transistors

14 Power Supply Circuits

14.1 Power Supply Basics

14.2 Bypass Capacitors

15 Understanding Op Amp Parameters

Electronic circuit designers intending to choose an op amp are often faced with a dizzying array of choices. Each op amp is specified by dozens of parameter which indicate deviations from the ideal op amp model. This section explains the meaning of each op amp parameter and gives reasonable expected values. The op amp parameters are ordered approximately in decreasing significance to the circuit designer, to lead the reader through the processing of selecting an op amp for his or her application.

15.1 Power Supply Range

Power supply range is the first parameter to look at when selecting an op amp. The datasheet specifies the recommended minimum and maximum supply voltage from V- to V+. As shown in *Figure 15.2*, point 10, the acceptable power supply voltage for the OPA374 ranges from 2.7V to 5.5V. The datasheet also specifies a power supply voltage or range of voltages at which all other parameters are measured.

15.2 Input and Output Voltage Range

The input and output range specifies the signal range in which the op amp's specifications are valid, and therefore in which it behaves like an ideal op amp. For traditional op amps, the input and output range is usually 1.5-2V below the positive supply rail and 1.5-2V above the negative supply rail. A class of op amps known as *rail-to-rail op amps* allows the input, output, or both to reach the supply rails. The detailed operation of these op amps is discussed in section 15.10.

Texas Instruments
www.ti.com

OPA373, OPA2373
OPA374
OPA2374, OPA4374

SBOS279D − SEPTEMBER 2003 − REVISED DECEMBER 2004

ELECTRICAL CHARACTERISTICS: V_S = +2.7V to +5.5V

Boldface limits apply over the specified temperature range, T_A = −40°C to +125°C.

At T_A = +25°C, R_L = 10kΩ connected to $V_S/2$, and V_{OUT} = $V_S/2$, unless otherwise noted.

	PARAMETER		CONDITIONS	OPA373, OPA2373, OPA374, OPA2374, OPA4374 MIN	TYP	MAX	UNIT
1	OFFSET VOLTAGE						
	Input Offset Voltage	V_{OS}	V_S = 5V		1	5	mV
	over Temperature					**6.5**	**mV**
	Drift	**dV_{OS}/dT**			**3**		**µV/°C**
	vs Power Supply	PSRR	V_S = 2.7V to 5.5V, V_{CM} < (V+) − 2V		25	100	µV/V
	over Temperature		**V_S = 2.7V to 5.5V, V_{CM} < (V+) − 2V**			**150**	**µV/V**
	Channel Separation, DC				0.4		µV/V
	f = 1kHz				128		dB
2	INPUT VOLTAGE RANGE		3				
	Common-Mode Voltage Range	V_{CM}		(V−) − 0.2		(V+) + 0.2	V
	Common-Mode Rejection Ratio	CMRR	(V−) − 0.2V < V_{CM} < (V+) − 2V	80	90		dB
	over Temperature		**(V−) − 0.2V < V_{CM} < (V+) − 2V**	**70**			**dB**
			V_S = 5.5V, (V−) − 0.2V < V_{CM} < (V+) + 0.2V	66			dB
	over Temperature		**V_S = 5.5V, (V−) − 0.2V < V_{CM} < (V+) + 0.2V**	**60**			**dB**
4	INPUT BIAS CURRENT						
	Input Bias Current	I_B			±0.5	±10	pA
	Input Offset Current	I_{OS}			±0.5	±10	pA
	INPUT IMPEDANCE						
	Differential				10^{13} ‖ 3		Ω ‖ pF
	Common-Mode				10^{13} ‖ 6		Ω ‖ pF
5	NOISE		V_{CM} < (V+) − 2V				
	Input Voltage Noise, f = 0.1Hz to 10Hz				10		μV_{PP}
	Input Voltage Noise Density, f = 10kHz	e_n			15		nV/√Hz
	Input Current Noise Density, f = 10kHz	i_n			4		fA/√Hz
	OPEN-LOOP GAIN						
	Open-Loop Voltage Gain	A_{OL}	V_S = 5V, R_L = 100kΩ, 0.025V < V_O < 4.975V	94	110		dB
	over Temperature		**V_S = 5V, R_L = 100kΩ, 0.025V < V_O < 4.975V**	**80**			**dB**
			V_S = 5V, R_L = 5kΩ, 0.125V < V_O < 4.875V	94	106		dB
	over Temperature		**V_S = 5V, R_L = 5kΩ, 0.125V < V_O < 4.875V**	**80**			**dB**
6	OUTPUT						
	Voltage Output Swing from Rail		R_L = 100kΩ		18	25	mV
	over Temperature		**R_L = 100kΩ**			**25**	**mV**
			R_L = 5kΩ		100	125	mV
	over Temperature		**R_L = 5kΩ**			**125**	**mV**
	Short-Circuit Current	I_{SC}			See Typical Characteristics		
	Capacitive Load Drive	C_{LOAD}			See Typical Characteristics		
	Open-Loop Output Impedance		f = 1MHz, I_O = 0		220		Ω
7	FREQUENCY RESPONSE		C_L = 100pF				
	Gain-Bandwidth Product	GBW			6.5		MHz
8	Slew Rate	SR	G = +1		5		V/µs
9	Settling Time, 0.1%	t_S	V_S = 5V, 2V Step, G = +1		1		µs
	0.01%		V_S = 5V, 2V Step, G = +1		1.5		µs
	Overload Recovery Time		V_{IN} • Gain > V_S		0.3		µs
	Total Harmonic Distortion + Noise	THD+N	V_S = 5V, V_O = $3V_{PP}$, G = +1, f = 1kHz		0.0013		%
	ENABLE/SHUTDOWN						
	t_{OFF}				3		µs
	t_{ON}				12		µs
	V_L (shutdown)			V−		(V−) + 0.8	V
	V_H (amplifier is active)			(V−) + 2		V+	V
	Input Bias Current of Enable Pin				0.2		µA
	I_{QSD} (per amplifier)				< 0.5	1	µA

3

Figure 15.1 Sample op amp datasheet for OPA374, part 1/2, courtesy Texas Instruments

OPA373, OPA2373
OPA374
OPA2374, OPA4374

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TEXAS INSTRUMENTS
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ELECTRICAL CHARACTERISTICS: V_S = +2.7V to +5.5V (continued)
Boldface limits apply over the specified temperature range, **T_A = −40°C to +125°C.**
At T_A = +25°C, R_L = 10kΩ connected to $V_S/2$, and $V_{OUT} = V_S/2$, unless otherwise noted.

PARAMETER		CONDITIONS	OPA373, OPA2373, OPA374, OPA2374, OPA4374 MIN	TYP	MAX	UNIT
POWER SUPPLY						
10 Specified Voltage Range	V_S		2.7		5.5	V
Operating Voltage Range				2.3 to 5.5		V
11 Quiescent Current (per amplifier)	I_Q	$I_O = 0$		585	750	μA
over Temperature					**800**	**μA**
TEMPERATURE RANGE						
Specified Range			−40		+125	°C
Operating Range			−55		+150	°C
Storage Range			−65		+150	°C
Thermal Resistance	θ_{JA}					°C/W
SOT23-5, SOT23-6, SOT23-8				+200		°C/W
MSOP-10, SO-8				+150		°C/W
SO-14, TSSOP-14				+100		°C/W

Figure 15.2: Sample op amp datasheet for OPA374, part 2/2, courtesy Texas Instruments

15.3 Input Offset Voltage

The Input offset voltage is the voltage difference at the input of the op amp, which is required to create a zero output voltage. In an ideal op amp, the input offset voltage is zero. However, for practical op amps, process variations create unavoidable mismatches between devices. Input offsets can be dependent on temperature as well as power supply. The offset temperature dependence is typically specified in units of $\mu V/^oC$, and is usually obtained by measuring the offset voltage at maximum and minimum temperature, and then dividing by the total temperature difference. The power supply dependence of offset voltage is quoted in $\mu V/^oC$ with respect to the power supply voltage and is related to the power supply rejection ratio.

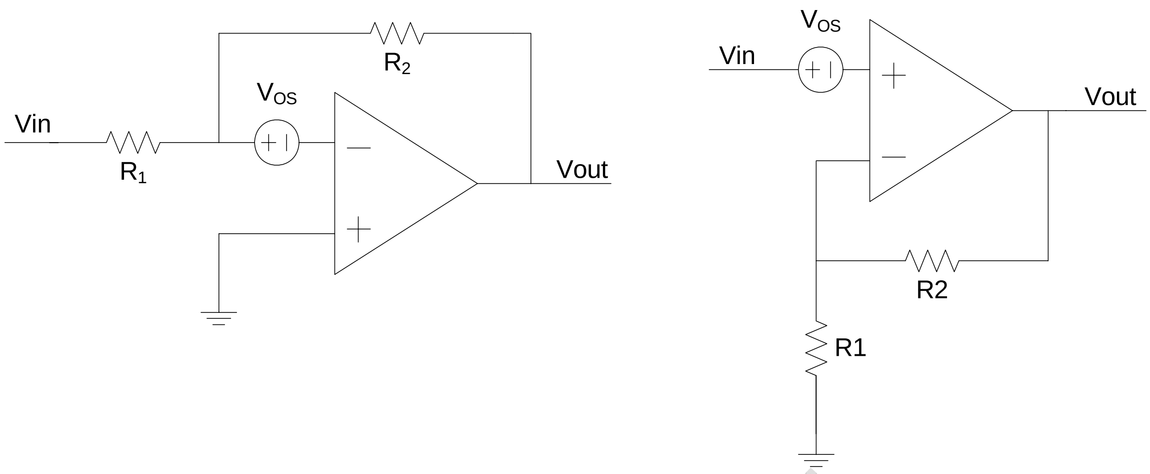

Figure 15.3: Input offset voltage modeled as part of an inverting and non-inverting amplifier.

15.4 Input Bias Current

In the ideal op amp model, the input impedance of the plus and minus terminals is considered to be infinite. However, for practical op amps, the input impedance is finite and a small input bias current is required. The input bias current can be either positive or negative and is usually specified as a typical and maximum value on the datasheet, as shown by point 4 on *Figure 15.1*.

The input bias current can range from as low as 100 fA (10^{-13} A) to more than 1 μA (10^{-6} A). Input bias current is important in high impedance applications, such as capacitive sensing, where this current is a significant source of error.

15.5 Gain-Bandwidth Product

The gain-bandwidth product (GBW), also known as the unity-gain bandwidth, is a measure of the speed of an op amp. As discussed in the feedback section, op amps are designed with a single-pole open-loop response as shown in *Figurer 10.7*. Accordingly, the open-loop gain is inversely proportional to the operating frequency and the product of the open-loop gain and the operating frequency is is constant. The GBW is the frequency at which the open-loop gain is unity. The GBW for the OPA374 is 6.5 MHz, as specified by point 7 of *Figure 15.1*.

The GBW of commercial op amps ranges from a few kHz for low power op amps to hundreds of MHz for high speed video op amps. The GBW should be specified by the desired maximum signal frequency and the desired open-loop gain at that frequency. A good rule of thumb is to choose the GBW to be at least two orders of magnitude greater than the maximum signal frequency. This op amp circuit will then be able to provide an open-loop gain of at least 100 at the maximum frequency. For general purpose op amps, a unity-gain bandwidth of 3-5 MHz is reasonable. It is important to note that a high GBW is not always advantageous. Higher bandwidth op amps generally have higher noise, higher cost, and more stability concerns.

15.6 Slew Rate

Slew rate is the maximum rate of change (*dV/dt*) of the op amp's output voltage. When a high *dV/dt* is required from an op amp, the output is limited by the internal circuitry of the op amp which includes a fixed current source charging an internal capacitor. The output response to a step input results in a linear ramp shown in *Figure 15.4* and the slope of this ramp is defined as the slew rate. The maximum slew rate for the OPA374 is 5 V/μs, as shown in *Figure 15.1*, point 8.

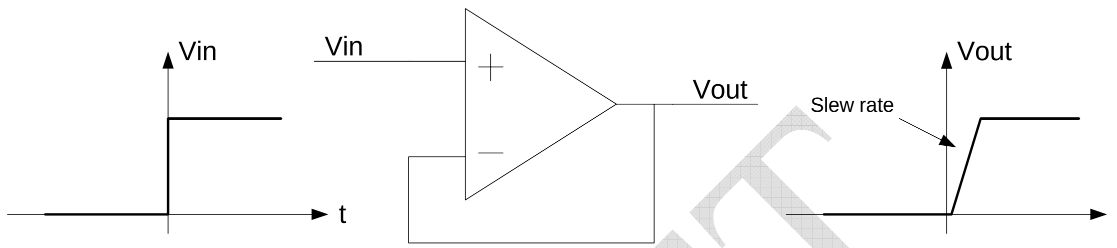

Figure 15.4: Slew rate of an op-amp circuit.

The required slew rate of an op amp circuit can be determined by finding the maximum possible *dV/dt* at the output of the op amp. For example, if an op amp circuit is expected to amplify a sine wave having 1 V peak-to-peak at 10kHz, by a factor of 5, the maximum slew rate can be found as follows:

$$V_{in} = 1\text{V} \times \sin\left(2\pi \times 10\text{kHz} \times t\right)$$

$$V_{in} = 5\text{V} \times \sin\left(2\pi \times 10\text{kHz} \times t\right)$$

Therefore, the maximum slew rate is

$$\frac{dV}{dt} = 5\text{V} \times 2\pi \times 10\text{kHz} = 0.314\text{V/}\mu\text{s}$$

An op amp should be selected with a slew rate of at least twice the maximum expected slew rate of the signal. The slew rate parameter in op amps is generally a trade-off with its quiescent current draw since an op amp with a higher internal bias current can more quickly produce changes at its output.

15.7 Equivalent Input Noise

Noise generated by the op amp is an important consideration for amplifier circuits having high gain. By convention, noise is measured at the output, but then divided by the gain of the circuit, and modeled as a noise voltage source and noise current source at the input to a noiseless circuit as shown in Figure ###. The spectrum of the noise source is typically a superposition of white noise, which is constant across all frequencies; and 1/*f* noise, which scales as 1/*f* and dominates below a corner frequency, as shown in Figure ###. In op amp datasheets, white noise is specified by a spectral density value measured at a particular frequency as shown by point 12 in *Figure 15.1*. 1/*f* noise is specified in the integrated form in units of μV for the spectrum below the corner frequency. Noise spectral density plots are often included in the datasheet, which allows circuit designers to obtain the expected equivalent input noise voltage of the op amp the following integration,

$$V_{noise} = \sqrt{\int_{\omega_1}^{\omega_1} V^2 dV} \ ,$$

where ω_1 and ω_2 are the lower and upper limits of the bandwidth of the sub-circuit of the op amp.

As shown in *Figure 15.5* and *Figure 15.6*, the LT1793 clearly has less noise and a lower 1/*f* corner frequency than the OPA374. For a wonderful discussion on noise in electronic circuits see chapter 10 of “Op Amps for Everyone”, Ron Mancini Ed. [###Ref].

###Insert figure here###
Figure ###: Noise equivalent circuit

###Insert figure here###
Figure ###: Superposition of white and 1/f noise spectra

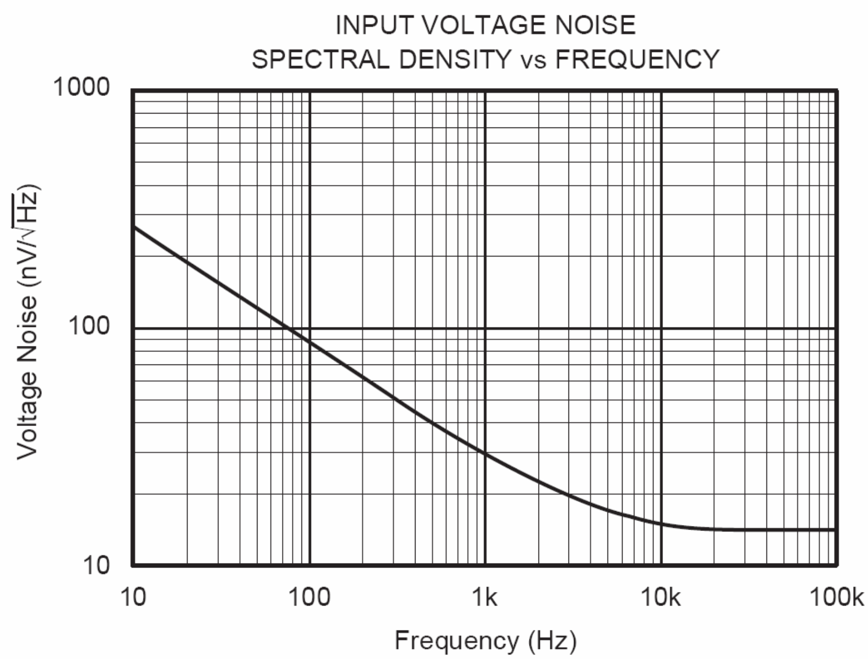

Figure 15.5: Voltage noise plots for the OPA374 (Courtesy of Texas Instruments)

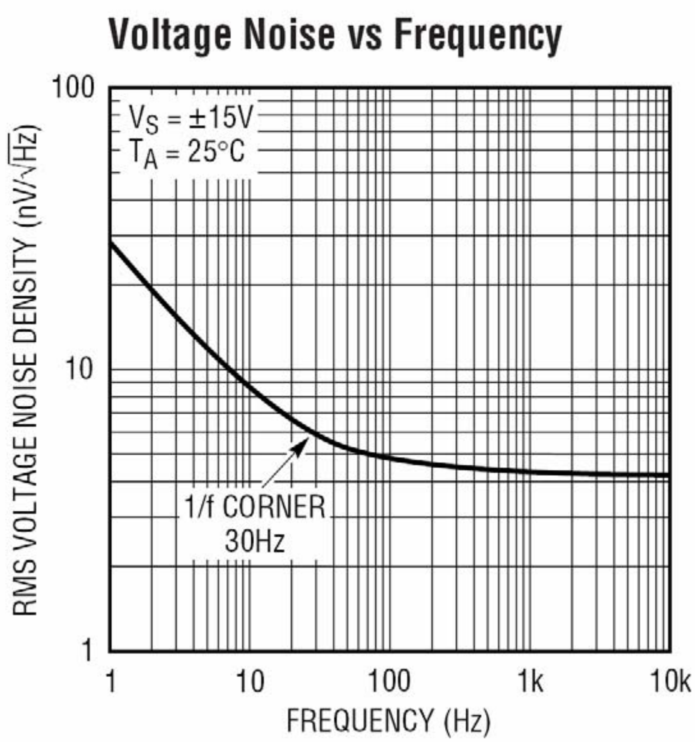

Figure 15.6: Voltage noise plots for the LT1972 (Courtesy of Linear Technology)

15.8 Common-Mode Rejection Ratio

In the ideal op amp model, the output is only affected by a differential voltage at the input. For practical op amps, the output also weakly depends on the common-mode voltage at the input terminals. The magnitude of this effect is specified by the common-mode rejection ratio (CMRR), which is the ratio between the op amp's differential open-loop gain and common-mode gain,

$$\text{CMRR}=\frac{A_{DIFF}}{A_{CM}}.$$

The mechanism responsible for the common-mode gain is actually a common-mode dependent offset voltage. The output signal arising from the changing offset voltage is

$$\Delta V_{OUT}=\Delta V_{OS}A_{DIFF}=\Delta V_{CM}A_{CM}.$$

Therefore,

$$\text{CMRR}=\frac{\Delta V_{CM}}{\Delta V_{OS}}.$$

Figure 15.7 shows the CMRR for the OPA374 as a function of frequency. Since the differential gain of the op amp decreases with increasing frequency, the CMRR also degrades with increasing frequency. In the *electrical characteristics* section of the datasheet, CMRR is specified by its DC value. The CMRR is typically specified in dB and typical values at DC range between 80-120dB. As shown in *Figure 15.7*, the CMRR for the OPA340 is 92dB at DC and drops down to 40dB at 100kHz.

Problems caused by the common-mode voltage can generally be avoided by using op amps in the inverting configuration where the common-mode voltage is zero or some constant voltage. In this case, the common-mode errors becomes a part of the input offset voltage.

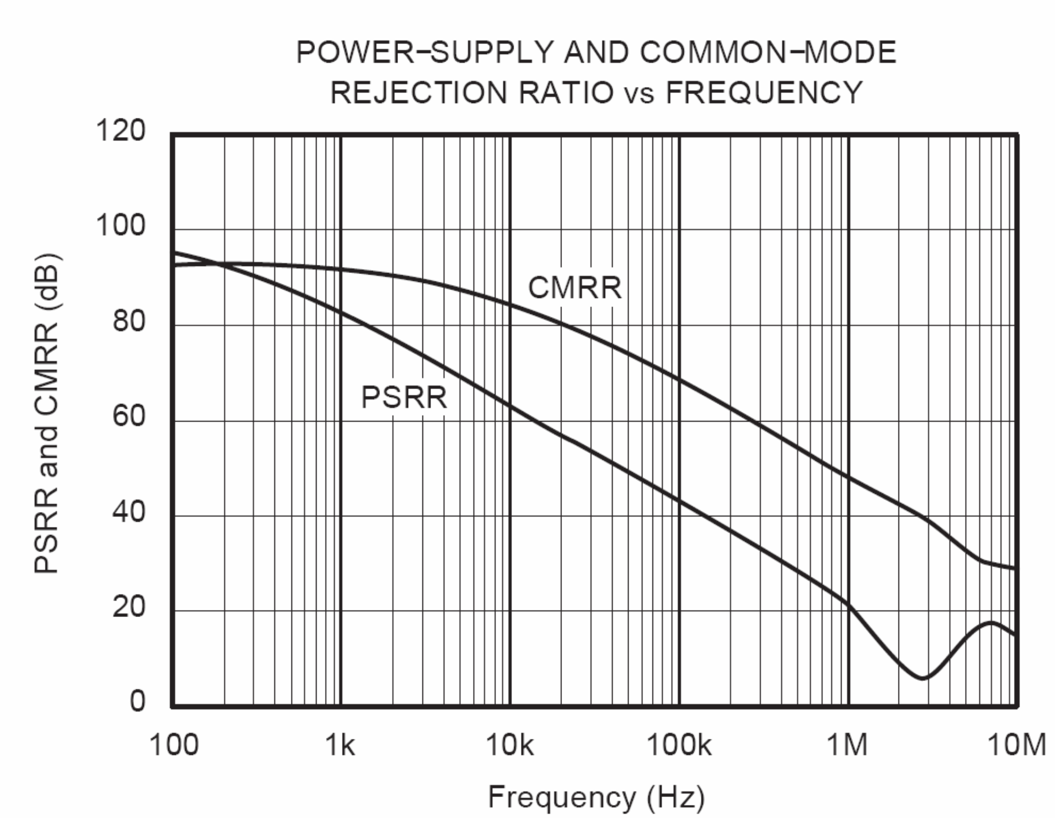

Figure 15.7: Common-mode rejection ratio and power supply rejection ratio for the OPA374 (Courtesy of Texas Instruments)

15.9 Power Supply Rejection Ratio

Similar to the CMRR, the Power Supply Rejection Ratio (PSRR) is a measure of the op amp's dependence on the power supply voltage. The PSRR analysis exactly follows that of the CMRR. Problems caused by PSRR can be eliminated by removing interference sources on the power supply by installing a dedicated voltage regulator for op amp involves in sensitive signal processing.

15.10 Rail-to-Rail

Rail-to-rail refers to the range of the op amp's input or output voltage with respect to its power supply voltage. While traditional op amps range from 1.5-2 V above the negative rail to 1.5-2 V below the positive rail, rail-to-rail op amps can often both positive and negative rails. An op amp can be rail-to-rail at its input, output, or both.

When an op amp has rail-to-rail output, the output can be very close to the rail voltages, but will never exactly equal to the rail voltages. Depending on the load resistance, the output can come within a few mV, or tens of mV, of the rails. As specified by the OPA340 datasheet in *Figure 15.1*, point 6, the output can reach 1 mV of the rail for a 200 kΩ load.

When an op amp is specified as rail-to-rail input, it means that the both plus and minus terminals can reach the rails, and in some cases, go few hundred mV beyond the rails. This is specified in the OPA374 datasheet in *Figure 15.1*, point 2.

Rail-to-rail input op amps have substantially inferior input offset characteristics compared to traditional op amps. In order for the input to reach both rails, the op amp uses two parallel input stages; one is designed to be active for signals near the negative rail, and the other is active for voltages near the positive rail. In the transition range between the two, both input stages are active. Unfortunately, the two input stages, in general, have different offset voltages, which mean that the input offset will depend on the common-mode input signal. *Figure 15.8* shows an example curve of the input offset voltage as a function of the common-mode voltage. In circuits that apply varying common-mode voltages to the op amp, such as a non-inverting amplifier, this offset error would result in a significant amount of signal distortion.

Details on the input stages of the OPA374 are provided in the application notes section of its datasheet. The transition region between the two input stages for the OPA374 nominally ranges from (V^+ - 1.9 V) to (V^+ - 1.4 V). Due to process variations, the position of the transition region can vary by +/-300 mV with respect to the positive supply. Errors caused by the transition region are specified by the CMRR in the *Electrical Characteristics* region of the datasheet. As shown in *Figure 15.1*, point 3, the CMRR is 10 to 14 dB better when the input signal avoids the transition region, i.e. from (V^- - 0.2 V) to (V^+ – 2 V).

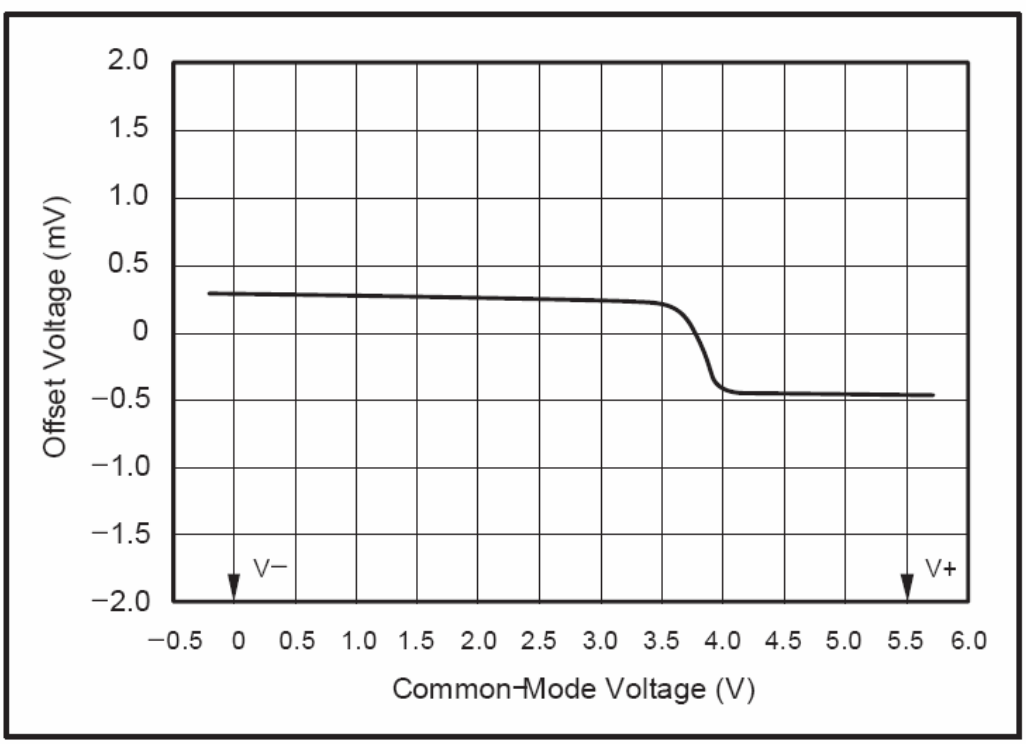

Figure 15.8: Typical behavior of offset voltage as a function of common-mode voltage for the OPA374 amplifier. (Courtesy of Texas Instruments)

The best strategy for avoiding transition region errors is to use the op amp in the inverting configuration to maintain a constant common-mode voltage. If non-inverting amplifiers are absolutely necessary, another strategy is to maintain the signal swing close to the negative supply to provide enough headroom between the power supply and the signal such that the transition region is never reached.

15.11 Single Supply

When a datasheet specifies an op amp as a *single supply op amp*, it refers to a very specific parameter: the valid input range of this op amp can extend to the negative rail. Therefore, a *single supply* op amp is simply a limited form of a rail-to-rail input op amp.

15.12 Settling Time and Stability

###to be added…

15.13 Quiescent Current Draw

Quiescent current draw is the static current draw of the op amp with no load. In the OPA374 datasheet, this parameter is specified as 585 μA per amplifier (*Figure 15.1*, point 11)

15.14 Op Amp Packages

Each op amp part is typically available in a number of packages as shown in *Figure 15.9*, taken from the OPA340 datasheet. In addition to single package amplifiers, several amplifier IC's are also packaged together and sold as dual or quad amplifiers. Standard through-hole op amps use 0.3" wide DIP packages, while single and dual amplifiers generally use 8-pin DIPs, while quad amplifiers generally use 14-pin or 16-pin DIPs. Some surface-mount packages include the SOIC, MSOP, SSOP, TSSOP, VSSOP, and the SOT-23-5. Some standard pin routings for these packages taken from the OPA340 datasheet are shown in *Figure 15.10*.

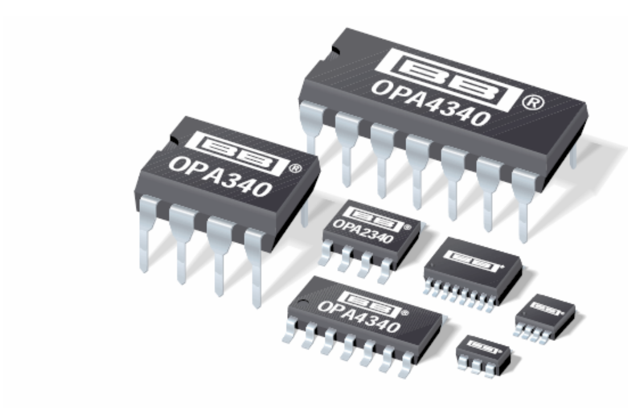

Figure 15.9: Various packaging options for the OPA340 (courtesy of Texas Instruments)

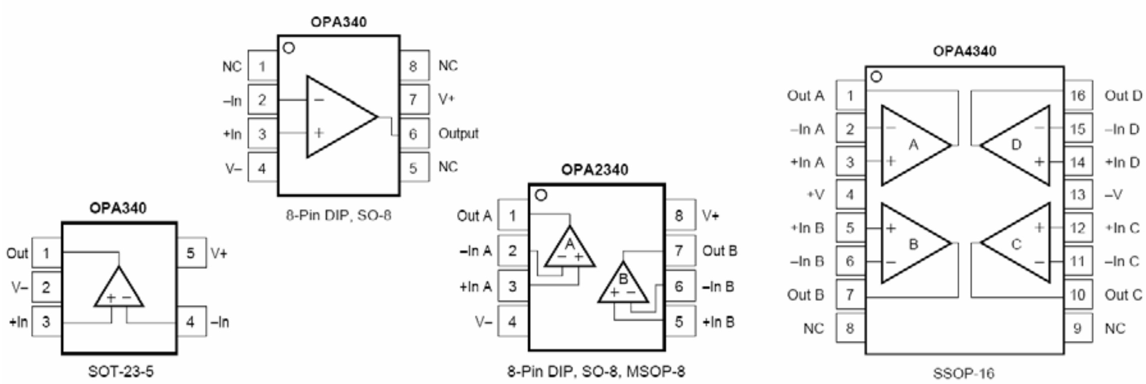

Figure 15.10: Standard pin routings for various packages of OPA340 (courtesy of Texas Instruments)

15.15 Sample Op Amps

The following are some common choices for op amps available at the time of writing:

- TL081: Inexpensive, general purpose op amp, with relatively low input bias current.
- AD711: A newer and better version of the TL081 with improved specifications on almost every parameter
- LT1007: Very low offset, low noise, precision op amp for +/-12V bipolar supplies
- LT1792: Even lower noise than the LT1007, and has a slightly higher offset.
- OPA340: Rail-to-rail op amp, with relatively low noise, which operates on 2.7-5.5V supply, and is also relatively fast.
- OPA374: An inexpensive version of the OPA340, which compromises on offset and CMRR.
- LTC1150: Chopper-stabilized op amp for absolutely minimum offset.
- OPA129: Absolute minimum input bias current for high impedance applications such as front-end amplifiers for capacitive sensing and photodiode.

16 Single Supply Op Amp Circuits

17 Interfacing with Sensors

Sensors link the physical world and electronic circuits by producing an electrical output in response to a physical quantity. This section describes some common types of sensors and the detection circuits that are necessary to interface the sensors with further signal processing or analog-to-digital conversion electronics. The goal of any sensor detection circuitry is to convert the sensor signal to a low-impedance output voltage signal that is buffered and has a voltage range maximized to a value acceptable by the next stage of circuitry.

17.1 Switches

Switches can be used as mechanical sensors or user input devices. When used as a mechanical sensor, switches can indicate when a mechanism has reached a stopping point, when a certain amount of pressure has been applied to an area, or when an autonomous robot has collided with an obstacle. The signal from a switch is usually connected to a digital logic gate or directly to the digital input of a microprocessor.

A switch mechanism consists of a fixed electrical contact, known as a pole, and a movable electrical contact, known as a throw. Therefore, a single-pole, single-throw switch can short (connect) or open one circuit connection; a single-pole, double-throw switch can simultaneously short or open two circuit connections; and a double-pole, single-throw switch can connect one of two possible circuits. Switches can be either latching or momentary. Latching switches hold their position once switches, while momentary switches contain a spring to restore their default position. Typical switch symbols are shown in *Figure 17.1*.

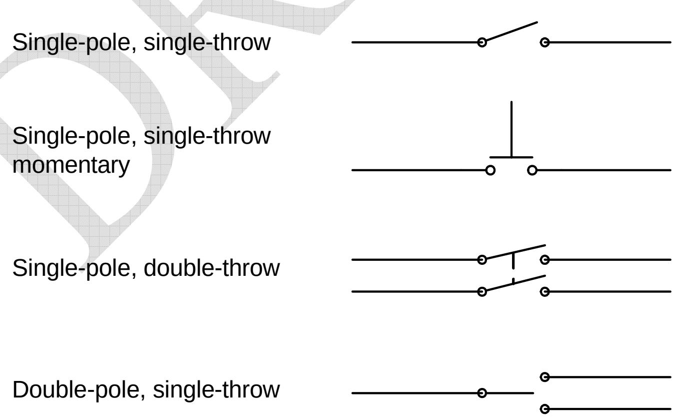

Figure 17.1: Typical switch symbols

When used as a sensor or a user input device, the desired output signal from a switch is usually either ground or a non-zero voltage. This can be achieved using the circuit shown in *Figure 17.2*. Since switches are usually designed for minimum resistance, a resistor is needed to limit the current when the switch is turned on. The exact value of resistance is not important; a resistor anywhere from 4.7-47 kΩ is usually sufficient. The selected resistance value may depend on the switch de-bouncing scheme discussed next.

A major issue when using a switch in a circuit is *de-bouncing*. When a switch is turned on or off, the electrical signal does not reach its final state instantaneously. Instead, small-scale electromechanical dynamics at the switch contact cause a brief period of oscillatory signal as shown in Figure ###. Therefore, the switch signals need to be de-bounced in order to eliminate false input signals to the detection circuit.

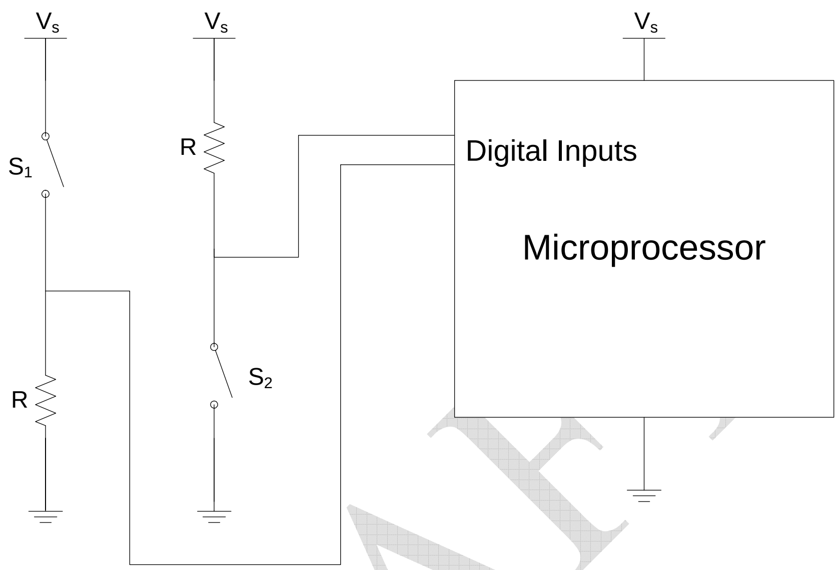

Figure 17.2: Switches used as digital inputs to a microprocessor. S_1 defaults to low while S_2 defaults to high.

A simple, fool-proof method to de-bounce a switch is to use a low-pass filter to eliminate the fast swinging signals as shown in *Figure 17.3*. Usually, a 1 ms time constant should be sufficient, which can be achieved using $C = 0.1$ μf and $R_2 = 10$ kΩ.

###Insert figure here###
Figure ###: Switch bouncing signal

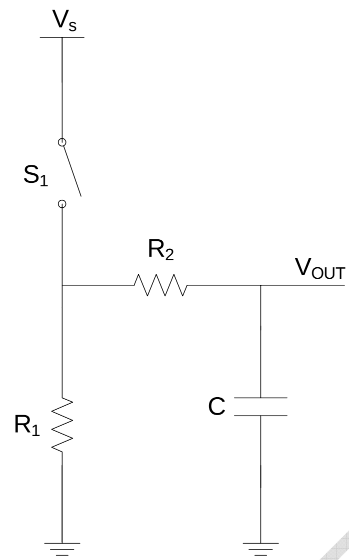

Figure 17.3: Switch De-bouncing Circuit Using a Low-pass Filter

17.2 Potentiometer-Based Sensors

A potentiometer is a resistor with a third contact that slides along the resistance element. As shown in *Figure 17.4*, when a voltage is applied across terminals 1 and 2, the potentiometer becomes a variable resistive divider, where the voltage at terminal 3 is some percentage of the voltage between terminals 1 and 2. Typically, the slider mechanism on potentiometers is rotary and come in 1-turn, 5-turn, 10-turn, and 25-turn varieties. Some examples of potentiometers are shown in Figure ###.

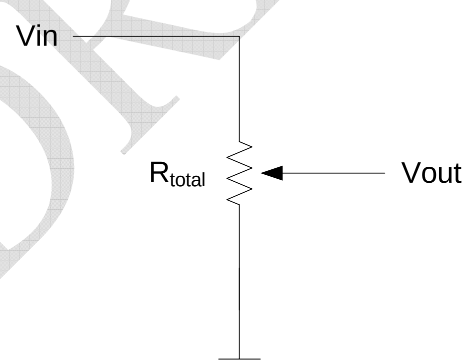

Figure 17.4: Potentiometer circuit symbol

(insert pictures here)
Figure ###: Potentiometers

A potentiometer can be used both as a sensor or a user input device. As a sensor, a potentiometer can be mounted on a shaft to measure angle and position, as shown in Figure ###. As a user input device, a potentiometer can be used for continuous adjustment of a parameter such as the volume on a stereo. One drawback of potentiometers is that the sliding mechanical contact eventually wears out. Therefore, potentiometers are not suitable for sensor applications where frequent angular motion is necessary.

(illustrations of mechanisms where potentiometers are used to measure angle and position)
Figure ###: Mechanisms where potentiometers are used to measure angle and position.

Circuits for interfacing with potentiometers are shown in *Figure 17.5*. The reference voltage should be a stable and low-noise voltage source. Typical values of R_{total} range from 5kΩ to 100kΩ. Smaller value potentiometers consumes more power while larger value potentiometers have larger impedance and are therefore more susceptible to noise. In addition, an RC low-pass filter can be added to reduce noise of the potentiometer as shown. The value of R_1 should be at least 10 times greater than R_{total} and the cut-off frequency of the low-pass filter should be less than the anticipated bandwidth of the potentiometer signal.

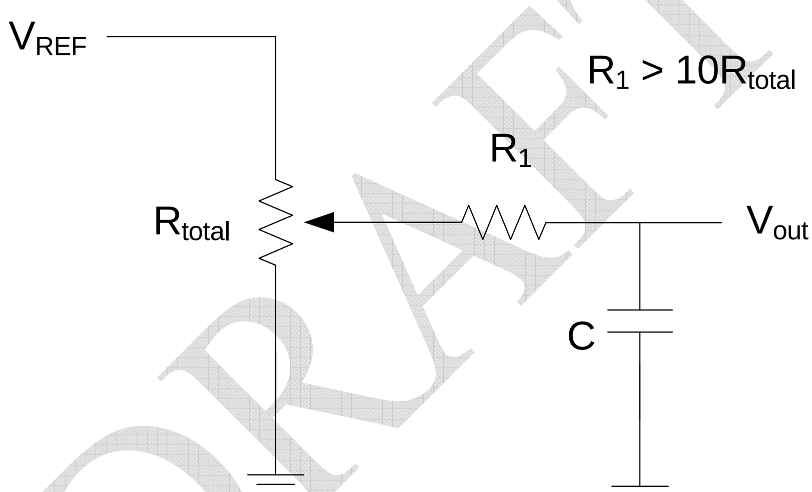

Figure 17.5: Circuit for interfacing with a potentiometer

<u>17.3 Optical Sensors</u>

Optical Sensors are terrific devices for non-contact measurement. They are simple to use, inexpensive, and have little or no mechanical wear. Typical sensing modalities include presence detection by blocking and unblocking an optical path; proximity sensing by measuring the amplitude of reflected light from an object; distance sensing by measuring the falloff of light-level from a source; angular rotation sensing by measuring light transmission through a patterned rotary wheel. “Forrest Mims Engineer’s Notebook” [###ref] presents some very inventive ways to use light detectors. There are three main types of light sensors: photo-resistors, photodiodes, and phototransistors.

17.3.1 Photo-resistors

Photo-resistors are conductors having a resistance that varies depending on the intensity of incident light. Typically, photo-resistors are made from a cadmium-sulfide

(CdS), as shown in *Figure 17.6*. These components are commercially known as photocells, which has resistances higher than 100 kΩ when the incident light intensity is high and lower than 10 kΩ when the light intensity is low. The response rate of CdS photo-resistors is excruciatingly slow—no more than a few Hz at best. Consequently, CdS photoresistors are best suited for detecting static light intensity.

(insert pictures here)
Figure ###: Photograph of CdS photo-resistors

The electrical properties of a CdS photo-resistor are similar to those of a variable resistor. Therefore, incident light intensity can be converted to a voltage using a resistive divider as shown in Figure ###. The complementary resistor R_2 should be chosen to match the resistance of the CdS photo-resistor at the mean light-level. For example, if R_1 is measured to be 50 kΩ at the mean light-level, then R_2 should also be 50 kΩ to obtain the greatest possible differential when R_1 changes from less than 50 kΩ to greater than 50 kΩ.

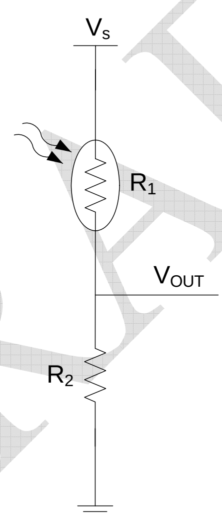

Figure 17.6: Interface circuit for a CdS photo-resistor

17.3.2 Photodiodes

Photodiodes are the most ubiquitous light detectors. Photodiodes can be very fast for communications over optical fibers, very sensitive for imaging distant galaxies, or very inexpensive for use in consumer electronics. Photodiodes are not only sensitive in the visible part of the spectrum, but also in the near infrared (fiber optic communications, distance measurement), the far infrared (remote temperature measurement by blackbody radiation), UV (flame sensors).

Photodiodes are PN-junctions that convert photons to electrical current. The physical mechanism of photodiodes is shown in *Figure 17.7*. Photons striking the depletion-region of the PN-junction generate electron-hole pairs which result in a cathode-to-anode current. Electrically, photodiodes can be modeled as a one-way current source, which in *Figure 17.8* is shown as a current source and an ideal diode.

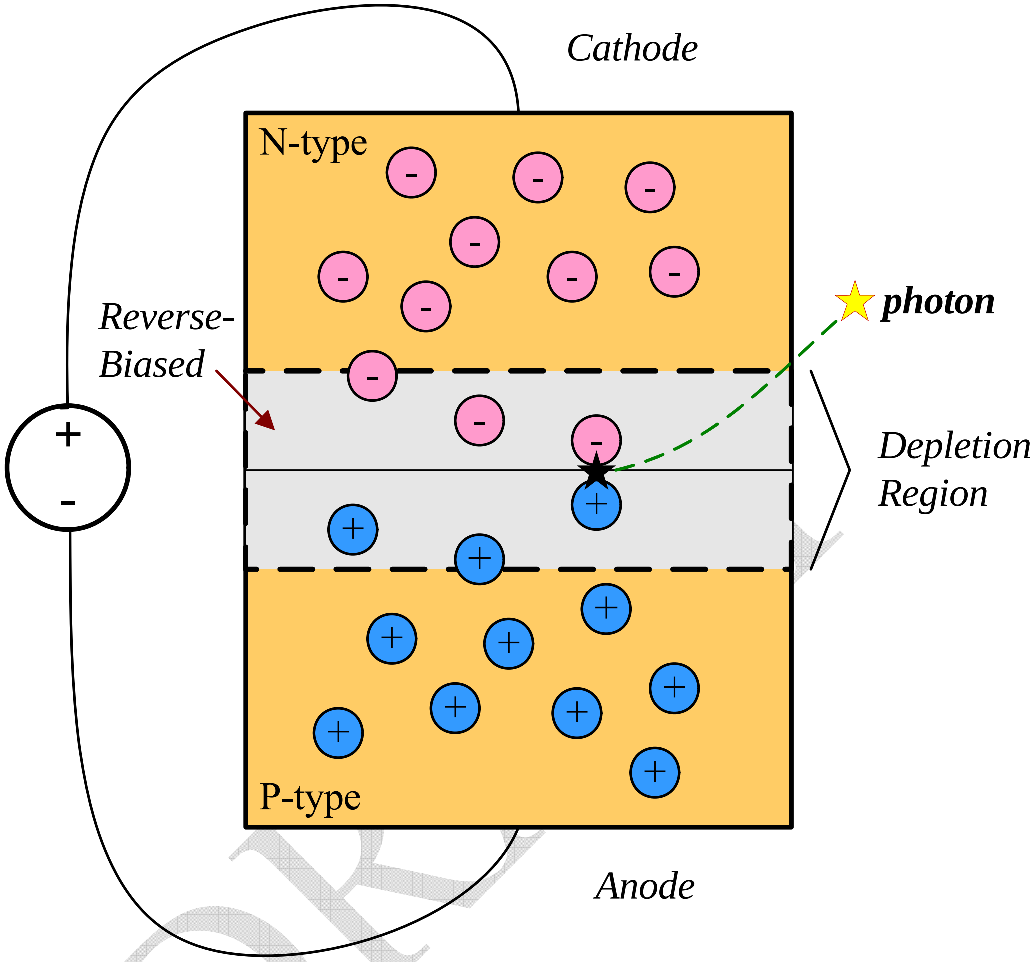

Figure 17.7: Physical mechanism of a photodiode sensor

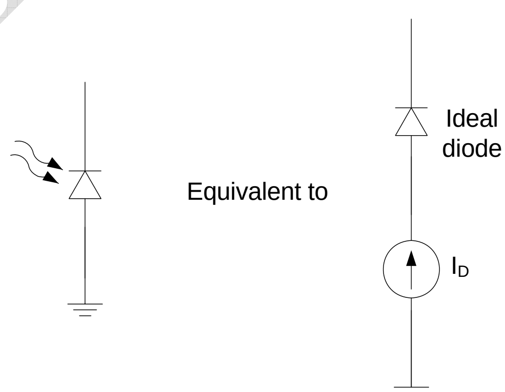

Figure 17.8: Equivalent circuit for a photodiode

The sensitivity of the photodiode, or the conversion efficiency from photons to electrical current, can be enhanced by applying a reverse-bias voltage to the photodiode. The reverse-bias voltage increases the width of the depletion region and thereby increasing the probability that a photon will interact with an electron-hole pair. The limit of the applied reverse-bias voltage is the reverse breakdown voltage of the diode, which is readily available in the datasheet. The reverse-bias voltage also carries a tradeoff: increasing the reverse reverse-bias voltage increases the parasitic current through the diode. This parasitic current is known as the *dark current* and it is not dependent on light intensity. The dark current can be a source of error in photodiode circuits, since variations in the reverse-bias voltage can result in an error signal. The conversion efficiency can also be increased by selecting photodiodes with a larger PN-junction area. However, these photodiodes will also have a higher the parasitic capacitance and therefore have slower frequency response.

Photodiode detection circuits are designed to convert the photodiode current into useful voltage values for further processing or analog-to-digital conversion. The current-to-voltage conversion can be made using an op amp transimpedance amplifier shown in the first circuit in *Figure 17.9*, which converts the photodiode current to voltage while applying a reverse bias voltage of Vs-. The transfer function of the transimpedance circuit is that ratio between the output (a voltage) and the input (a current) as follows,

$$\frac{V_{out}}{I_{in}} = -R\,.$$

The input bias current of the op amp can be a major source of error in this circuit. Since any amount of current generated by the photodiode that is absorbed by the minus input of the op amp will not be converted to a voltage at the output, it is important to choose an op amp which has a low input bias current. FET input op amps with input bias current levels from 10pA to 100pA should be sufficient for the task.

The second circuit in *Figure 17.9* is the same transimpedance amplifier built on a single-supply circuit instead of a dual-supply circuit. The reverse bias voltage across the photodiode is set by V_{REF} instead of the negative rail. This scheme has significant advantages since V_{REF} can be generated with a precision reference, which can be much more stable thant the negative supply rail.

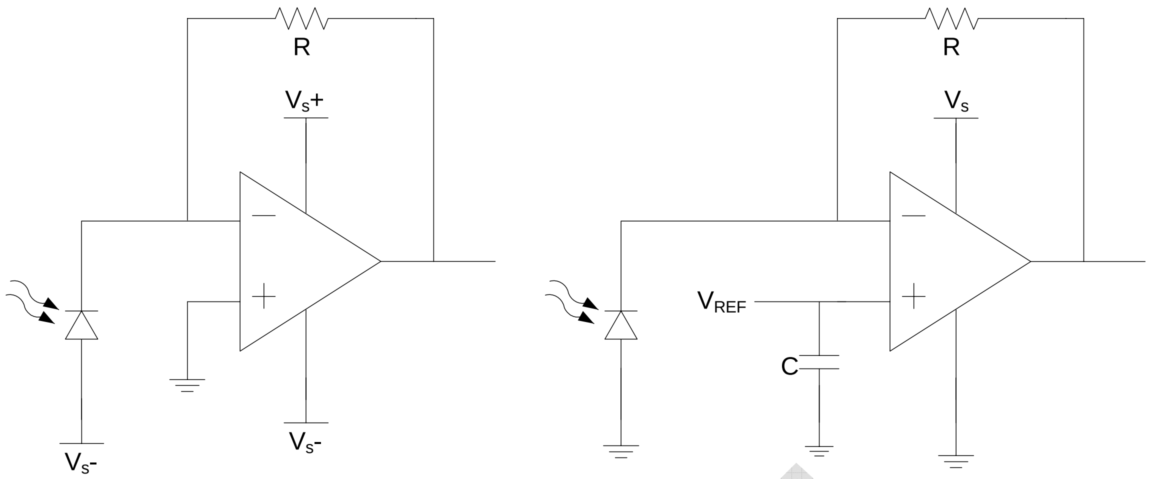

Figure 17.9: dual-supply (left) and single-supply (right) photodiode amplifiers

OPT101 is a monolithic photodiode detector from Texas Instruments, where the photodiode and transimpedance amplifier is integrated into the single 8-pin DIP or SOIC package shown in *Figure 17.10*. The transimpedance amplifier circuit is similar to that of circuit 2 in *Figure 17.9*. However, the photodiode is effectively not biased since V_{REF} is only 7.5 mV. In this case, the manufacture has optimized the sensor for low dark current rather than maximum photodiode current. The output voltage level and bandwidth of the amplifier can be set by adjusting the value of the feedback resistor. The optimization procedures are discussed in the OPT101 datasheet.

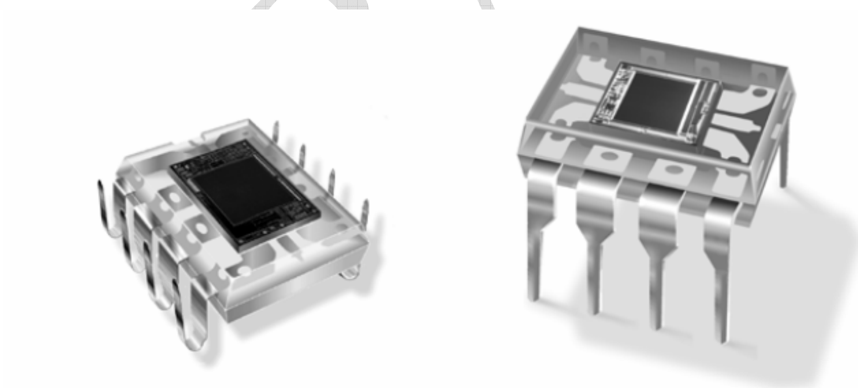

Figure 17.10: OPT101 photodiode sensor. (courtesy of Texas Instruments)

17.3.3 Avoiding Ambient Light

One of the pesky problems when using optical sensors for measuring quantities such as distance or proximity is the presence of ambient light, which presents an interfering signal. There are three main ways of dealing with this problem. The first method is to enclose both the illuminator and the detector in a sealed chamber, which is typical for optical encoders. The second is to use infrared emitters and infrared photodiodes; however, both sunlight and tungsten filament light bulbs are strong infrared sources. The third is to use an AC source signal at a carrier frequency, and then electronically isolate the signal at the carrier frequency at the detector side.

When using an AC source signal, it is first important to choose a frequency that is within the bandwidth of the emitter and the receiver. *Figure 17.11* shows a photodiode amplifier and detection circuit for measuring the amplitude of an AC optical signal, which assumes that a working circuit is driving the source at ω_o. The front-end amplifier is exactly the photodiode amplifier as previously shown in circuit 2 in *Figure 17.9*. The output signal from the front-end is first high-pass filtered through C_1 and R_2, removing signals from frequencies lower than $1/(2\pi R_1 C_1)$, and resulting in a primarily sinusoidal signal at the carrier frequency. The second op amp circuit is designed to rectify the sinusoidal signal and low-pass filter the resulting waveform into a DC signal.

This circuit can be understood by first neglecting the effects of diode D_2 and capacitor C_2, which makes this circuit like another transimpedance amplifier. Since the input current is sinusoidal, the output voltage has a gain of $-R_3$ and centered about V_{REF}. Adding the diode D_2 to the circuit, the output will now only follow the input signal when the output signal is below V_{REF}; otherwise, the output is equal to V_{REF}. Finally, C_2 averages the bottom-half sine signal created by the diode and the result is a DC voltage between ground and V_{REF} that is proportional to the amplitude of the AC signal. This can be buffered and then converted to a digital signal. The DC signal can be further amplified or digitized using an analog-to-digital converter. A convenient feature of this design is that V_{REF} can also be used as the reference voltage for the analog-to-digital converter. Since the signal chain is referenced to V_{REF}, variations in V_{REF} are automatically cancelled.

The resistor and capacitor values for this circuit should be chosen in the following order:

1. Choose V_{REF} as the maximum reference voltage for the ADC.
2. Choose R_1 according to the expected current from the photodiode, with an expected peak-to-peak output of $2(V_{REF} - 0.7)$.
3. Choose C_2 and R_3 based on the desired bandwidth of the entire receiver circuit. For example, if the circuit is designed to detect light amplitude level changes below 10 Hz then $C_2R_3 = 2\pi(10\text{ Hz})$.
4. R_2 should be equal to R_3.
5. Choose $C_1$to make a high-pass filter with a cut-off frequency below the carrier frequency.

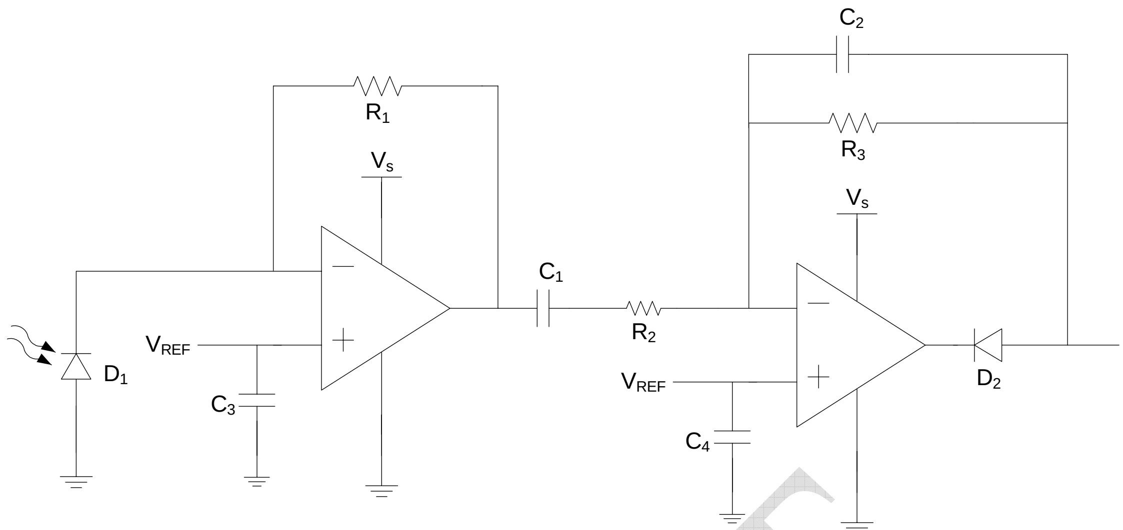

Figure 17.11: Single-supply photodiode amplifier designed to measure the amplitude of an AC optical signal

###Insert example waveforms on this diagram
Figure ###: Example waveforms of the AC photodiode amplifier.

17.3.4 Phototransistors

Phototransistors are BJTs where the base current has been replaced by a light-induced current generated at the base-collector junction. Compared to photodiodes, phototransistors can produce significantly higher currents at the same light intensity, but have significantly slower response times.

The detector circuit for a phototransistor consists simply of a bias resistor as shown in *Figure 17.12*. The appropriate resistor size is usually provided by the datasheet. However, if this information is not available, the appropriate resistance can also be determined using the guess-and-check method to select a resistor such that the mean light intensity produces an output voltage in the middle of the acceptable voltage range.

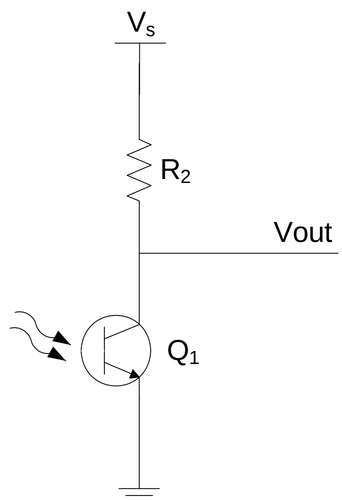

Figure 17.12: Phototransistor Detector Circuit

17.3.5 Opto-Interrupters

Opto-interrupters are simple, non-contact sensors for detecting when a mechanism has reached a limit point. Opto-interrupters consist of an optical emitter, which is usually an infrared LED, and an optical detector, which is usually an infrared phototransistor. The output is a binary high (1) or low (0) based on whether light from the emitter is received by the detector. Some common opto-interrupters are shown in *Figure 17.13*. There are two emitter and detector configurations: transmissive and reflective. The transmissive type has a direct line of sight from emitter to detector that can be interrupted by an opaque material. The reflective type has the emitter and detector facing in the same direction. Light from the emitter is reflected off a reflective surface, and back into the detector. The amplitude of the reflected light falls with the distance of the object from the opto-interrupter.

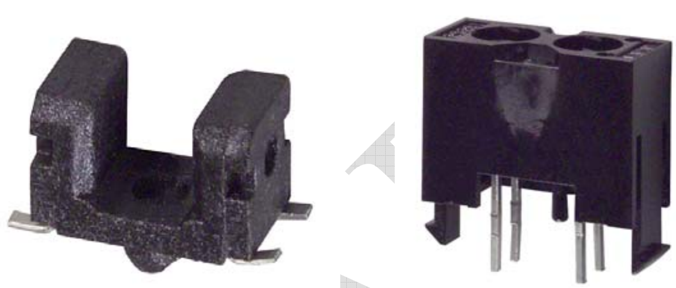

Figure 17.13: Typical opto-interrupters. Left: transmissive type, Sharp GP1S092HCPI. Right: reflective type, Sharp GP2S28. (Courtesy of Sharp Electronics)

The required circuitry for an opto-interrupter is shown in *Figure 17.14*. Resistor R_1 is required to set the bias current for the emitter LED D_1, while resistor R_2 is required to set the sensitivity of the phototransistor. The recommended values for R_1 and R_2 can be found on the datasheet. The output can be routed directly to a digital input on a microprocessor.

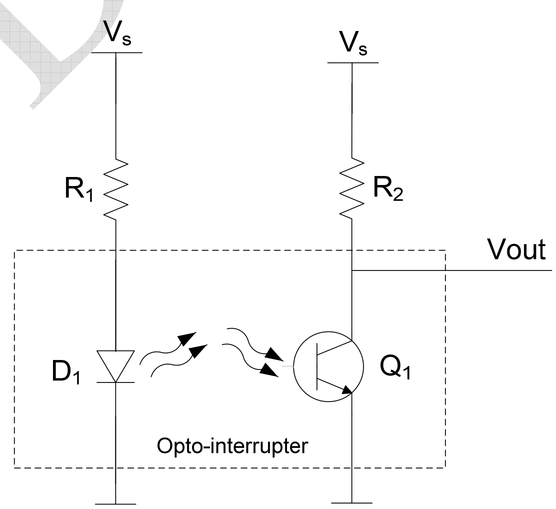

Figure 17.14: Opto-interrupter circuit

17.3.6 Optical Encoders

Optical encoders measure angular motion by sensing light transmission through a patterned rotating wheel. The wheel is patterned in alternating opaque and transparent angular slices, such that the output signal is an alternating square wave pattern. The rotation angle is measured in discrete steps ranging from 16 to more than 1024 steps per revolution. Each encoder unit has one emitter and two detectors. The two detectors are offset by one quarter of the spatial period on the rotating wheel, and are used to determine the direction of rotation. Optical encoders are significantly more expensive than encoders based on mechanical switches. However, since optical encoders do not require direct electrical and mechanical contact with the rotating element, much higher rotation speeds and longer lifetimes can be achieved.

Like opto-interrupters, optical encoders use an LED as the emitter and phototransistors as the detectors. The detection circuitry is also the same, requiring a resistor for each emitter and detector. Frequently, the required resistors are included with the optical encoder unit, which is specified with power, ground, and two data output pins. The internal circuitry for a Grayhill series 63K optical encoder (excerpt from the datasheet), is shown in *Figure 17.15*. The output passes through a digital inverter to produce a sharp transition even at slow angular speeds.

An optical encoder calculates a rotation angle by counting the low-high transitions of the output square wave using a microprocessor. *Figure 17.16* shows an example output for the Grayhill series 63 optical encoder. The direction of rotation can be determined from the phase difference of the two output channels by a simple algorithm: If the output of channel B is low at the low-to-high transition of channel A, then channel A is ahead of channel B and the encoder is rotating in the first direction; If the output of channel B is high at the low-to-high transition of channel A, then channel B is ahead of channel A and the encoder is rotating in the opposite direction.

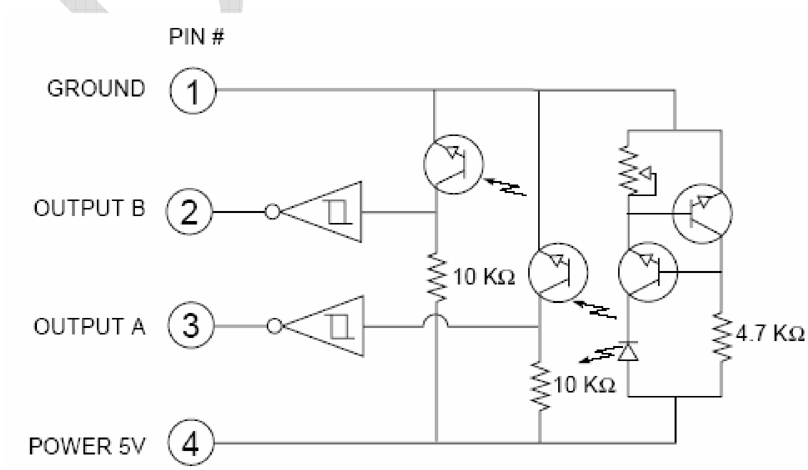

Figure 17.15: Internal circuitry for Grayhill series 63K optical encoder. (Courtesy of Grayhill Inc.)

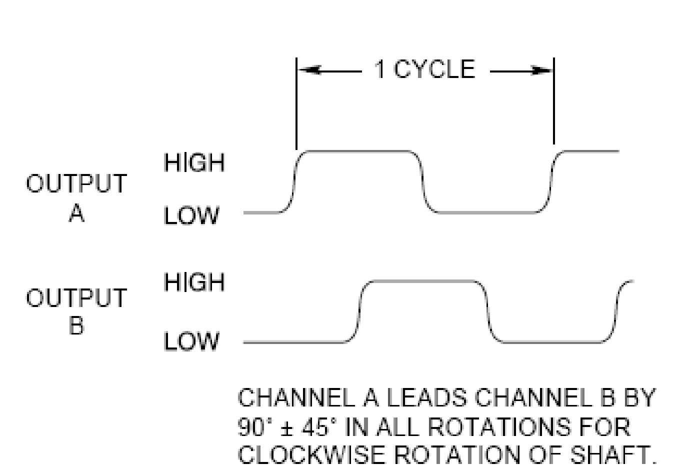

Figure 17.16: Example output waveform for Grayhill series 63K optical encoder. (Courtesy of Grayhill Inc.)

17.4 Magnetic Sensors

Magnetic field sensors can be used in many of the same ways as optical sensors for non-contact measurement of proximity, position, and angle. Compared to optical sensors, magnetic field sensors have the advantage of being able to measure through materials such as opaque liquids and plastics. Disadvantages of magnetic field sensors are a smaller sensing distance and potential interference from ferromagnetic metals. The main type of magnetic sensor is the Hall-effect sensor, which is discussed below. More advanced magnetic sensors, such as the linear variable differential transformer (LVDT), are beyond the scope of this text.

The *Hall Effect* is an electromagnetic phenomenon where a flow of electrical current is affected by the presence of magnetic field. As shown in *Figure 17.17*, when an electrical current is flowing (y direction) perpendicular to a magnetic field (in the z direction), the moving electrical charges also experiences an electric field in the direction perpendicular (x) to both the electric current and the applied magnetic field. This electric field causes the charges to accumulate at one end of the conductor and as a result, build up a voltage across the conductor.

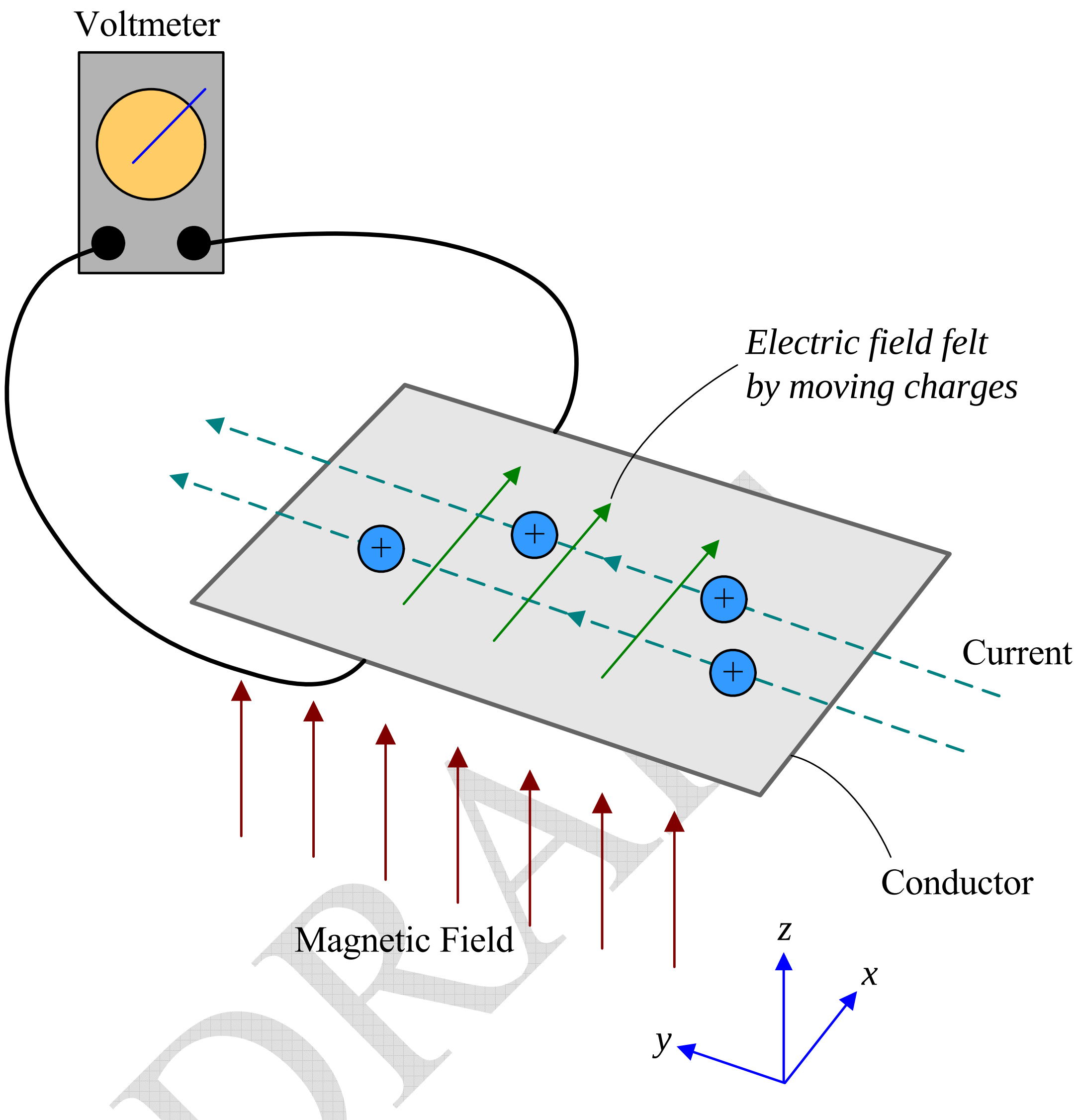

Figure 17.17: The Hall effect

Commercial Hall-effect sensors generally encapsulate the conductor element along with an output buffer in a plastic 3-pin package as shown in *Figure 17.18*. The source of magnetic field has to be provided separately and may be a permanent magnet or an electromagnet. The majority of Hall-effect sensors are designed for a digital out, meaning that the Hall signal is polarized by a comparator or Schmidt-trigger to produce a high or low output. The output stage of these digital devices is usually an NPN transistor with an open-collector output, as shown in *Figure 17.19*. An external pull-up resistor, R_1 is required before these devices can be connected with the digital input of a microprocessor or similar devices. A resistor value between 4.7 kΩ and 47 kΩ should suffice. Some Hall-effect sensors, such as those produced by Honeywell and Melexis, have an analog output, where the output voltage is proportional to amplitude of the magnetic field. The output from these devices can be connected to analog signal processing circuitry.

Figure 17.18: A typical Hall-effect sensor package, the Optek 365-TO-92. (Courtesy of Optek Technologies)

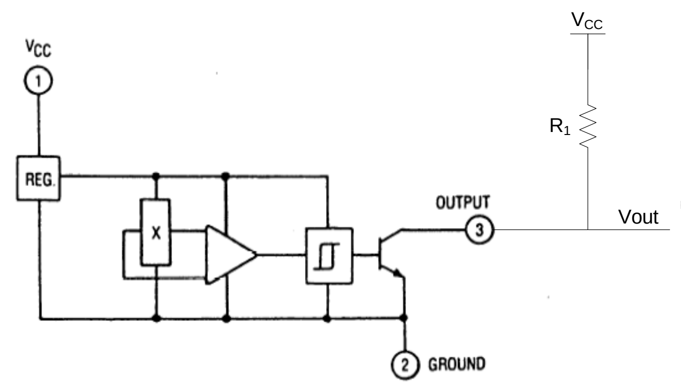

Figure 17.19: The output stage for the Optek 365-TO-92, with an external pull-up resistor. (Courtesy of Optek Technologies)

17.5 Strain gages

17.6 Accelerometers and Gyroscopes

18 Interfacing with Actuators

Electromechanical actuators convert electrical energy to mechanical output. The most prevalent forms of electromechanical actuators are based on electromagnets, which produce force and torque from magnetic fields generated by an electrical current. Since electromagnetic actuators typically require orders of magnitude more power compared to sensor and signal conditioning circuits, specialized circuits are required to efficiently deliver power.

This section introduces the power electronics circuits used for controlling some common types of electromagnetic actuators. The first part discusses the general architecture of power driver circuits. The following parts describe common types of electromechanical actuators, including solenoids, brushed DC motors, stepper motors, and servo motors. The electrical specifications and driver circuits are presented for each type of actuator. The final part describes common power electronics components and discusses how to choose them to meet the driver requirements for each type of actuator.

18.1 The Architecture of Power Driver Circuits

A power driver is an amplifier used for driving high power loads. While amplifiers for sensors and signal conditioning circuits are typically linear amplifiers based on op amps, this architecture is generally impractical for power drivers. Since linear amplifiers operate on a constant bias current, the current drawn by te amplifier for a given load resistance is independent of the output voltage. As a result, when power is not dissipated by the load, it is dissipated by the amplifier itself. For power circuits that require a large current, this design is unacceptable because its inefficiency and associated heat dissipation problems.

Power driver circuits work around the inefficiencies of linear amplifiers by using switches that turn on and off connections between the power supply and the actuator load. When the switches are on, the full voltage of the power supply is applied to the load. When the switches are off, almost no power is drained from the power supply. Variable output voltage is obtained by modulating switches with a square wave signal and adjusting the relative durations of the on and off periods. This technique is known as pulse-width modulation (PWM), and is discussed in detail in section 18.3.2.

The general architecture of a power driver circuit is shown in *Figure 18.1*. Power delivery to the load is controlled by a set of switches, which are typically power MOSFETs designed to handle large currents. The input power to the MOSFETs is controlled by specialized MOSFET driver circuits or ICs designed to buffer the input digital signal and produce the proper voltage levels for switching the MOSFET. The control signals, PWM or otherwise, are typically generated by a microprocessor, which can takes commands from an analog or digital signals.

The MOSFET output stage is powered directly from the battery or power supply to obtain maximum power output. Disruptions to the power supply line caused by current swings in the actuator load are suppressed using transient voltage suppressor (TSV) diodes, which are explained in section 18.6.2. The analog and digital circuits upstream from the MOSFET drivers are powered from a voltage regulator in order to provide a stable power supply voltage.

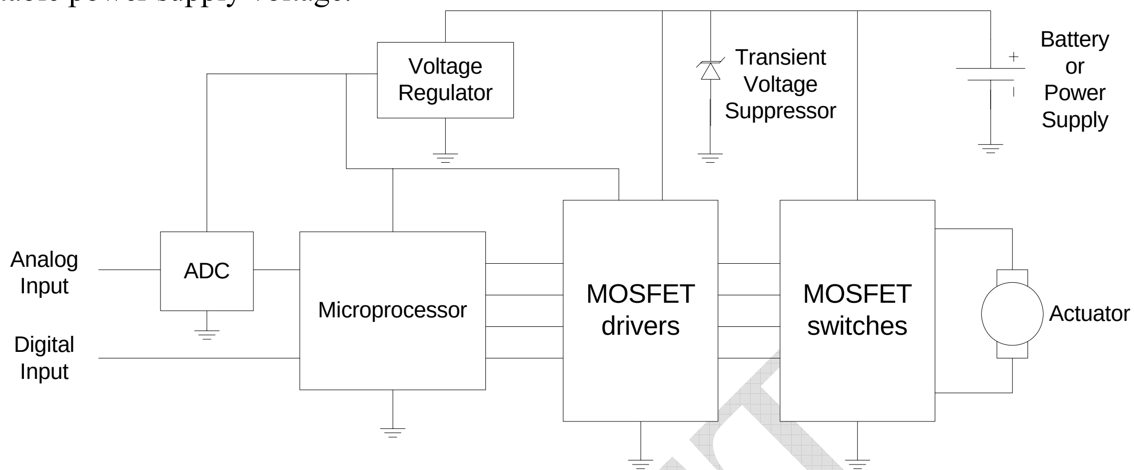

Figure 18.1: The general architecture for a power driver circuit

18.2 Solenoids

Solenoids are coils of wire which are wound in the shape of a cylinder. Each section off wire generates a magnetic field, and these fields superimpose to a magnetic field which is strong and uniform magnetic field inside the solenoid, and is equivalent to that of a bar magnet on the outside of the cylinder. The strength of the magnetic field is proportional to the electric current in the coil, and therefore a solenoid is referred to as an electromagnet.

A solenoid-based actuator typically consists of a coil with an iron core, an iron casing, and a spring return, as shown in Figure ###. When energized with a current, the iron core moves to maximize its internal magnetic field and therefore is pulled inside the casing. An alternative explanation is that the magnetic field of the coil induces opposing magnetic fields between the core and casing, which exert a force on the core. When the current in the coil is turned off, the spring return mechanism pushes the iron core back to its original position, where it protrudes from the casing.

(###insert figure here)
Figure ###: Schematic diagram of a solenoid actuator

Solenoid-based actuators are best suited for two-state mechanisms, such as automatic door locks in cars, electronically-controlled fluid valves, and dispensing mechanisms in vending machines. General purpose solenoids contain a push-rod that can typically deliver a force of up to 50 N, with a total stroke of 3 cm.

A special class of solenoid-based actuators, known as relays, uses the solenoid mechanism to operate an electrical switch. As shown in Figure ###, relays are used to switch large amounts of current, in a regime where the resistances in FET switches are unacceptably high.

(###insert figure here)
Figure ###: Electromechanical Relays

Solenoids can be represented in a circuit model as an inductor and a resistor in series. The driver circuit for a solenoid is a voltage source and an electronic switch. The required switching voltage is specified in the datasheet and typically ranges from 5-24 V. The voltage source which switches the solenoid can be controlled either by a solid state device such as a MOSFET, or by another mechanical a relay.

The fundamental concern when switching a solenoid on or off is inductive kickback. Since the energy in an inductor is stored in the momentum of its electron current, dangerously high voltages can be built up across the inductor when current flow is abruptly interrupted. This action can be described mathematically by the equation

$$V_L = L\frac{dI}{dt}.$$

When *di/dt* is large during fast switching, *V* will also become very large, sometimes reaching more than 1 kV. Therefore, in the circuit shown in Figure ###, if the FET switch is opened after it has been closed for a long time, the solenoid inductor respond by developing a large negative voltage. This voltage is called inductive kickback and can damage components connected in parallel with the solenoid or the cause the solenoid itself to suffer from electrical breakdown. Inductive kickback can be remedied by adding a diode anti-parallel with the inductor to clamp the reverse voltage, as shown in *Figure 12.1*. This diode is sometimes known as a *free-wheeling diode*.

(###insert figure here)
Figure ###: Illustration of inductive kickback with switch.

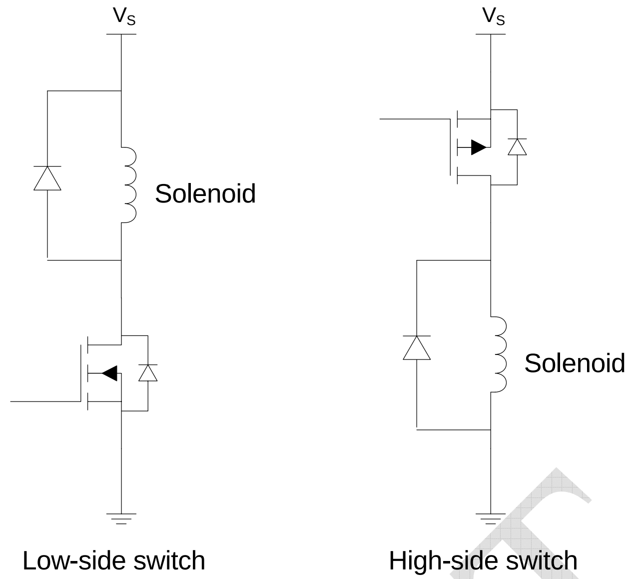

Figure 18.2: Low-side and high-side switch circuits for driving solenoids

18.3 Brushed DC motors

As introduced in Chapter 7, brushed DC motors consist of a rotating part known as the rotor (also know as armature) and a stationary part known as the stator (also know as the field). Electromagnets in the rotor and stator produce magnetic fields that interact with each other to create a continuous rotation. The speed and torque output of the motor depend on the current in the motor.

18.3.1 Motor Driver Circuits

Brushed DC motors are typically driven by solid-state switches that turn a voltage supply on and off. If the motor is only required to turn in one direction, then the drive circuit can be exactly the same as the solenoid driver, which can be either a low-side switch or high-side MOSFET switch as shown in Figure ###. The low-side switch uses an N-type MOSFET, which requires a high input to turn on, while the high-side switch uses a P-type MOSFET that requires a ground input to turn on. Of course, free-wheeling diodes should be added anti-parallel to the motor in order to prevent inductive kickback.

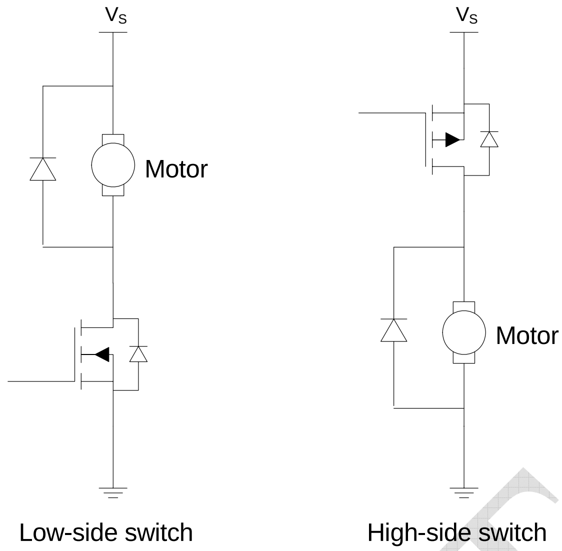

Figure 18.3: Low-side and high-side switch circuits for driving brushed DC motors

If the motor is required to turn in both directions, then a more complicated switching circuit, known as an H-bridge, is needed to switch the polarity of the applied voltage. A conceptual H-bridge circuit, which uses four switches, is shown in *Figure 18.4*. If forward rotation is desired, switches 1 and 3 are turned on while switches 2 and 4 are turned off, and a positive voltage is applied to the motor. Conversely, if reverse motor rotation is desired, switches 2 and 4 are turned on while switches 1 and 3 are turned off and a negative voltage is applied to the motor. The inductive kickback problem is taken care of by four free-wheeling diodes that clamp both ends of the motor to within 1 V of power supply and ground.

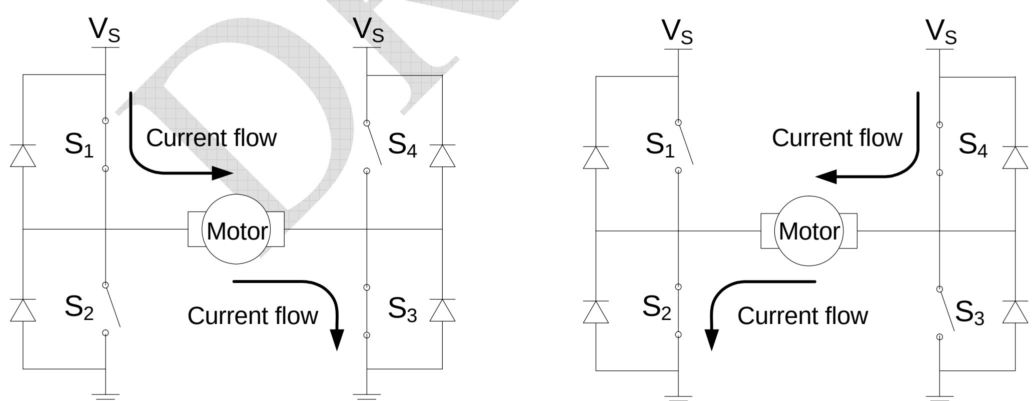

Figure 18.4: Conceptual diagram of an H-bridge circuit

Practical H-bridge circuits are typically built using MOSFETs as shown in *Figure 18.5*. In the MOSFET H-bridge, transistors 1 and 4 are P-type devices that require a low voltage to turn on, while transistor 2 and 3 are N-type devices that require a high voltage to turn on. External free-wheeling diodes are not required for a MOSFET circuit since an intrinsic diode between drain and source is built into each transistor.

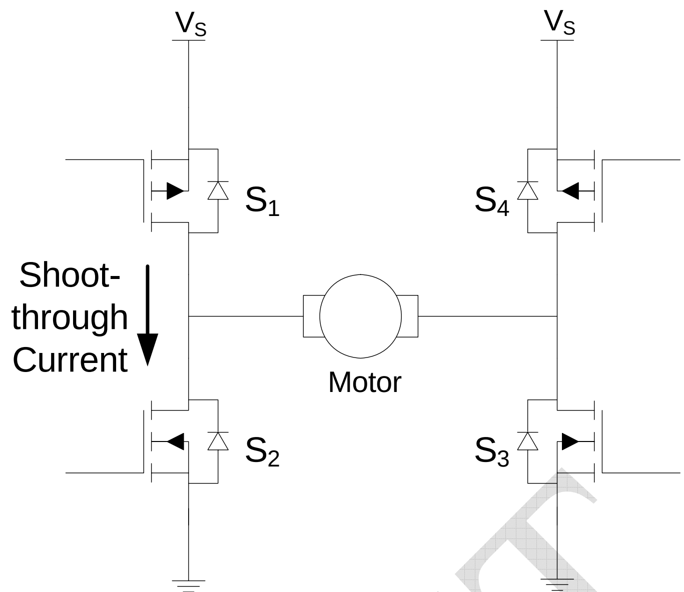

Figure 18.5: MOSFET H-bridge circuit

A fundamental problem for H-bridges is *shoot-through* current. Since all switches require a finite time to turn on and off, if switches 1 and 3 turn on at the same time as switches 2 and 4 turn off, there is a brief moment when switch 1 and 2 are both turned on. This condition creates a low resistance short-circuit from the power supply to ground causing massive amounts of current to flow through switches 1 and 2 while bypassing the motor as shown in *Figure 18.5*. Shoot-through current significantly decreases the efficiency of the driver circuit. Worse, the over-current can exceed the maximum current limit of the MOSFET and permanently damage the transistors. This problem can be remedied by estimating the time required to turn on and off the MOSFETs and then adding an appropriate delay time between turning off one set switches and turning on another set of switches.

18.3.2 Pulse-width Modulation

The output voltage applied through the motor driver is varied using a technique known as pulse-width modulation (PWM). The principle of PWM involves applying a full scale square wave at a frequency that is much greater than the bandwidth of the load. The load low-pass filters the drive signal and the resulting output voltage is the average DC value of the square wave. The output voltage can be varied by modulating the ratio of the high pulse with respect to the total period to obtain a DC voltage ranging from zero to 100% of the total supply voltage, as shown in Figure ###. For example if a 6V output is desired from a 12V supply, the PWM should be set at 50%.

Insert Figure Here
Figure ###: PWM waveform

PWM signals are typically generated by a microprocessor with a timer unit that precisely controls the timing of the pulses. The input signal can be a preset value from the microprocessor program or an analog voltage converted to an equivalent digital value. Alternatively, specialized PWM generators that produce a specified PWM signal based on an analog voltage are also available.

The PWM frequency typically can range from 100 Hz to 1MHz, and the choice is largely dependent on the application. The advantage of a higher PWM frequency is that the output will have less torque ripple and the rotation speed of the motor will therefore be smoother. The disadvantage of higher PWM frequency is that faster, more expensive switches are required to keep up with the input signal. Furthermore, since there are resistive losses associated with each switching event, a higher switching frequency is also less efficient. The advantage of a lower PWM frequency is a less stringent requirement on switch speed and lower losses in the switch. However, when the frequency falls below 20 kHz, the acoustic noise generated from the motor windings interacting with other mechanical parts of the motor may become audible. Since torque ripple is not a concern for most applications, the PWM frequency should be chosen to be the lowest possible value, considering the acceptable amount of acoustic noise from the motor.

The precision of PWM signals is determined by the resolution of the timer circuits in the microprocessor. Most microprocessor timers can measure time with at least 1 μs resolution. Therefore, for a 20 kHz PWM frequency, the PWM resolution is one part in 50.

18.3.3 Electrical Specifications for Driving Brushed DC Motors

Brushed DC motors can typically be represented electrically as an inductor, a resistor, and a voltage source connected in series as shown in Figure ###. The motor inductance and resistance are determined from the length and geometry of the motor windings. The voltage source is the voltage induced by the rotation of the rotor. This voltage, known as the back EMF, is proportional to the angular velocity of the motor. When the motor shaft is stalled, for example, from heavy loading, the angular velocity of the motor is zero and the back EMF is also zero.

Insert Figure Here
Figure ###: Motor equivalent circuit

The motor draws its maximum possible continuous current when the motor shaft is stalled and the back EMF is zero. In motor datasheets, this current is specified as the *stall current* or *starting current*, which can also be determined by dividing the applied voltage by the resistance of the coil. It is important to remember that motors are not designed to operate under a stall condition for an extended period of time since the motor's internal cooling mechanisms are dependent on the rotation of the rotor. After continued stalling, heat generated by the windings will eventually cause the motor components to melt. Therefore, the mechanical design must prevent the motor from being stalled.

The general rule-of-thumb for designing robust and durable motor drivers is that the maximum continuous current of the driver circuit should be at least double the expected maximum continuous current of the motor.

18.4 Stepper Motors

18.4.1 The Basics

Stepper motors are a different type of electromagnetic motor that is used in low torque, high precision positioning application such as printers, floppy drives, and X-Y positioning stages. The shaft of a stepper motor moves in discrete angular increments based on a digital control signal. Depending on the exact configuration, the stepping increments can be as small as a few degrees. A stepper motor attached to a lead-screw mechanism can provide very accurate position control. A successful example of this technique can be found in inkjet printers, where the printing head can be positioned with a resolution of 5 μm.

Similar to brushed DC motors, stepper motors consists of a rotor and a stator. In the simplest version, the rotor is a permanent magnet shaft and the stator consists of four coils, known as phases, to create a magnetic field through the center of the rotor. The coils are energized one at a time to pull the rotor in a clockwise or counter-clockwise rotation, as shown in Figure ###.

A number of improvements can be made on the basic stepper motor configuration to increase its torque output and angular resolution.

Insert Figure Here
Figure ###: The basic stepper motor concept

18.4.2 Bipolar Drive

The basic design implementation of a motor drive is known as unipolar drive, where the electromagnets in the stator are energized one at a time and always in the same polarity to attract the opposing magnetic pole in the rotor. The holding torque of the motor can be increased using a bipolar drive method, where two stator magnets are energized simultanteously and with opposite polarity to attract both sides of the rotor, as shown in Figure ###. The bipolar stepper motor drive increases the holding torque of the motor by approximately 40%, but the drive circuit is more complex since H-bridges are needed to switch the polarity of the current in the stator coils. However, not all stepper motors can be used in a bipolar drive; some stator coils are connected such that only unipolar drive operation is possible.

Insert Figure Here
Figure ###: Bipolar driving a stepper motor

18.4.3 Half-stepping

The angular resolution of stepper motors can be doubled using a technique known as half-stepping. The stepper motor is driven as shown in Figure ###; when one set of stator coils is switched on and another set is switched off, the shaft rotates by 90^o. If both sets of coils are turned on simultaneously, the magnetic field from both coils add together and the resulting angular increment is 45^o, as shown in Figure ###.

Insert Figure Here
Figure ###: Half-stepping a stepper motor

18.4.4 Variable Reluctance Motor

The resolution of a stepper motor can be significantly increased using a design known as a variable reluctance motor shown in Figure ###. The permanent magnet rotor is replaced with a pleated iron shaft. In the example shown in Figure ###, there are four pleats in the rotor and six coils in the stator that are organized in three sets of two. The rotor pleats and stator magnets are offset such that one half of the pleats are aligned with the stator magnet, and the other half are not aligned with the stator magnet. As the rotor spins, magnetic circuits between corresponding magnets in the stator are connected through the pleats of the rotor. By energizing the correct sequence of magnetic circuits, the rotor is rotated within the stator. In a practical variable reluctance motor, increasing the number of rotor pleats and stator coils increases the angular precision (decreases the step size) of the motor. Furthermore, the techniques of bipolar drive and half-stepping can also be applied.

Insert Figure Here
Figure ###: Variable reluctance motor design

18.4.5 Electrical and Mechanical Specifications

The important mechanical specifications for choosing a stepper motor include step size and torque. The step size determines the resolution of the motor. Common step sizes range from 3.6-7.5^o, corresponding to 48-100 steps per revolution. Some specialized stepper motors can reach 0.9^o/step, or 400 steps per revolution. The torque is typically specified by the *holding torque*, which is the amount of torque required to rotate the shaft when the windings are energized. The holding torque depends on the power supply voltage and typically ranges from 0.5-10 N-m. During active rotation, the maximum torque output of a stepper motor decreases with increasing speed of rotation, as shown in *Figure 18.6*. For a robust and long-lasting design, the maximum torque required from the stepper motor should not exceed 50% of the specified torque.

The important electrical specifications for a stepper motor are the power supply voltage and the expected current draw. These two specifications are used to select the power supply and the components of the driver circuit. Like solenoids and brushed DC motors, stepper motor driver circuits use MOSFET switches to turn on and off the voltages to the coil. Therefore, when selecting the MOSFET, the power supply voltage determines the maximum drain-to-source voltage and the expected current draw determines the maximum current that the MOSFET should be able to handle.

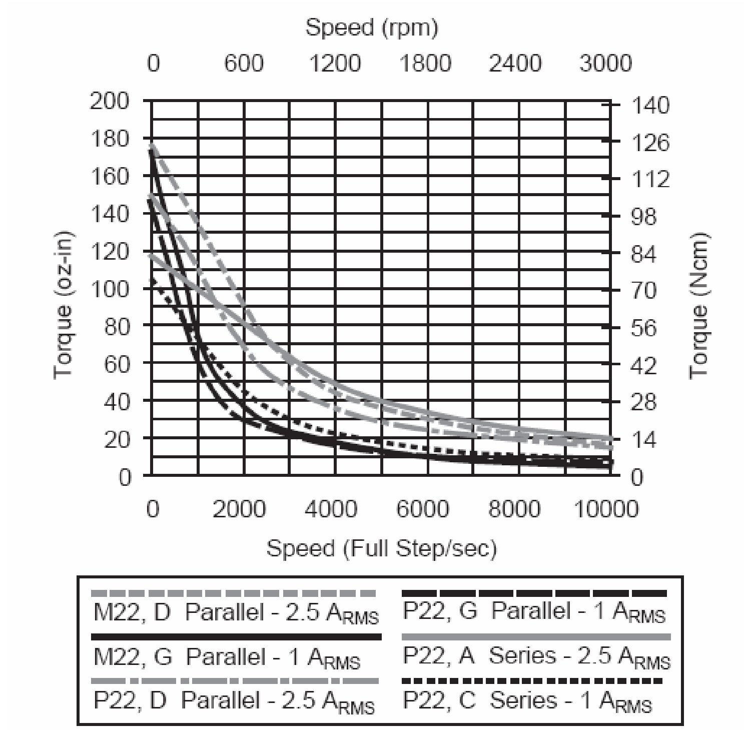

Figure 18.6: Stepper motor torque versus speed curve for PowerMax II motors with 24V power supply (Courtesy of Portescap Danaher Motion US, LLC)

18.4.6 Stepper Motor Driver Circuit

The drive circuits for stepper motors are simple to design given their usually low current requirements. A unipolar drive circuit is shown in Figure ###. Each motor phase is energized using the simple MOSFET switch circuit used for solenoid and DC motors. Of course, a free-wheeling diode is required in parallel with each motor winding in order to prevent inductive kickback. A bipolar motor drive circuit is shown in Figure ###. Each pair of motor coils is driven with an H-bridge as shown for the brushed DC motor.

(###insert figure here)
Figure ###: A four-phase unipolar drive circuit

(###insert figure here)
Figure ###: A four-phase bipolar drive circuit

The drive signal for stepper motors is typically generated from a microprocessor. The rate of the drive signal output should be controlled since the stepper motor's torque output is drastically limited at higher speeds, as shown in Figure ###. In most cases, it is not practical to run stepper motors faster than 1000 steps per second.

For a much more details discussion on stepper motors and drive circuit see *Stepper Motors Fundamentals*, Microchip Application Note #907, by Reston Condit and Doug W. Jones. This document is available in PDF format from the Microchip website.

18.5 Servo Motors

18.6 Choosing Power Electronics Components

The important components for power electronics include MOSFETs, diodes, MOSFET drivers, and prepackaged power driver ICs.

18.6.1 MOSFETs

Transistor-based switches are the workhorses of power electronics circuits. While both BJT and MOSFET power transistors can be used, the vast majority of power circuits prefer MOSFETs over BJTs because of their lower on resistance, higher power handling capability, and faster switching time. Furthermore, MOSFETs typically have an inherent diode between the body and drain that can be used as a free-wheeling diode to prevent inductive kickback.

The process for selecting MOSFETs for a power driver circuit is typically based on three main criteria: voltage range, power handling, and switching speed. The MOSFET parameters used to evaluate these criteria are summarized in Table ###.

The voltage range of a MOSFET determines whether or not it is designed to operate at the power supply voltage of the circuit. This is specified by the drain-to-source breakdown voltage, the gate-to-source breakdown voltage, and the gate threshold voltage. The drain-to-source breakdown voltage is the maximum voltage that can be applied between the drain and source when the MOSFET is off. The gate-source breakdown voltage is the maximum voltage that can be applied between the gate and source. Both parameters should be at least twice the expected applied voltages.

The gate threshold voltage is the gate voltage required to produce a nominal drain current. This parameter can be deceiving since the nominal current is typically significantly lower than the desired drain current when the MOSFET is turned on. A better specification can be found by the drain-to-source on resistance parameter since each listed resistance value is accompanied by a gate-to-source voltage. To establish the desired on resistance, the gate-to-source voltage should be within the voltage range of the circuit driving the MOSFET, with 1-2 V of safety margin.

The power handling capability of the MOSFET is specified by the drain-to-source on resistance, the maximum continuous drain current, the maximum pulsed drain current, and the maximum power dissipation. These parameters should be chosen according to the current requirements of the actuator. For a robust and durable design, both the maximum continuous and pulsed drain current should be at least twice the expected continuous and pulsed current draw of the actuator. The expected maximum power dissipation can typically be estimated as $I_D^2 R_{DS(on)}$ for the expected maximum value of I_D. However, for MOSFETs intended to be driven by a PWM signal, the losses associated with the switching process can be significant if the time required for switching approaches the PWM period. The details of this discussion are beyond the scope of this text, although it is advisable to choose the time required for switching to be at least two orders of magnitude smaller than the PWM period.

Parameter	Symbol	Description
Polarity		Identifies if the device is N or P-type, which determines if a positive or negative voltage is required to turn on the device
Drain-to-source breakdown voltage	$V_{(BR)DSS}$	Maximum voltage that can be applied from drain to source when the MOSFET is switched off
Gate threshold voltage	$V_{GS(th)}$	The gate voltage required to produce a nominal drain current at some specified drain-to-source voltage. The nominal current is usually absurdly low. The required gate voltage is better determined by the drain-to-source on resistance, since each $R_{DS(on)}$ is listed with a corresponding gate-to-source voltage.
Gate-to-source breakdown voltage	$V_{(BR)GS}$	The maximum gate-to-source voltage
Drain-to-source on resistance	$R_{DS(on)}$	Drain-to-source resistance when the MOSFET is turned on. This parameter is usually specified at several gate-to-source voltages.
Maximum drain current, continuous	I_D	Maximum current through the device when turned on. Since R_{DS} is temperature dependent, this parameter is usually specified at several temperatures.
Maximum drain current, pulsed	I_{DM}	Maximum pulsed current through the device. This parameter is usually many times greater than I_D.
Maximum power dissipation	P_D	Maximum power dissipation of the transistor package.
Total gate capacitance	C_{GSS}	The total gate capacitance is used to determine the switching dynamics of the MOSFET, which can be approximately modeled as an RC circuit involving the output resistance of the signal source and the input capacitance of the MOSFET.
Total gate charge	Q_G	The total gate charge required to switch the MOSFET

Table 18.1: Important MOSFET specifications used for designing power driver circuits

The switching speed of MOSFETs is typically specified on a MOSFET datasheet by the total gate charge and by the total gate capacitance. The total gate charge is the total charge transfer required to switch the MOSFET. The switching time can then be estimated as

$$\Delta t = \frac{Q_G}{I_{in}},$$

where I_{in} is the maximum current output of the MOSFET driver circuit. The switching time can also be estimated by considering the output resistance of the MOSFET driver circuit and the gate of a MOSFET as a RC circuit.

18.6.2 Diodes

Diodes are used in power electronic circuits to prevent under-voltage and over-voltage conditions from endangering the circuit. Under-voltage conditions are typically caused by inductive kickback, which happens when current through inductive components, such as solenoids and motors, is abruptly switched off. The high *di/dt* results in a large negative voltage across the inductor which can cause havoc in other parts of the circuit. The large negative voltage can be prevented by adding a diode anti-parallel to the direction of current flow, known as a free-wheeling diode. When the voltage begins to swing negative, the diode insures that the negative voltage applied across the circuit is no more than approximately 1 V.

The important specifications for choosing a free-wheeling diode are the peak forward current and the reverse breakdown voltage. The expected pulsed forward current that the diode will need to sustain is the current in the inductor at the instant when the switch is opened. The specified peak forward current of the diode should be at least twice the designed maximum current through the inductor. The reverse voltage experienced by the diode is the maximum voltage applied across the inductor. The specified reverse breakdown voltage of the diode should also be at least twice the expected voltage across the diode.

Inductive loads can also cause over-voltage conditions on the power supply, especially when the power supply has a high source voltage. Over-voltage conditions can be prevented by adding a transient-voltage suppressor (TVS) diode across the power supply. TVS diodes are essentially Zener diodes designed to quickly break down once the Zener voltage has been reached. In power electronics design, it is generally good practice to include TVS diodes in parallel with every power rail. TVS diodes are their should be chosen such that their reverse standoff voltage, V_{WM}, is lower than the power supply voltage. V_{WM} is typically as 10% lower than the actual Zener voltage.

18.6.3 MOSFET Drivers

The gate of power MOSFETs can be a difficult load to drive directly from digital circuits, such as microprocessors, because of their high capacitance. Since it is desirable to turn MOSFETs on and off as quickly as possible, charging the gate capacitance may require a large amount of instantaneous current, which can be difficult to produce using a low- power digital circuit. For this reason, it is generally necessary to use a MOSFET driver to drive the gate of power MOSFET from a low power digital signal.

While MOSFET drivers can be designed using discrete BJTs, a great deal of headache and PCB space can be saved by using a prepackaged IC designed for this purpose. One example of such an IC is the SN75372 from Texas Instruments. The SN75372 is a dual MOSFET driver that can accept input from logic levels as low as 2V and drive MOSFETs with up to 24V output. The input stage is powered using a 5V power supply while the output stage is powered from the same power source as the MOSFETs. The output of the SN75372 can instantaneously deliver up to 500mA of current to the gate of a MOSFET, which typically has a turn-on time less than 100ns for a reasonably sized power MOSFET.

18.6.4 Prepackaged Power Drivers

-Intelligent power switches from IRF → protected MOSFET
-DRV101 from TI → Protected low-side solenoid power switch
-LMD18200 from National Semiconductors → prepackaged H-bridge motor driver

What does prepackaged power drivers do for you:
-output current limiting, i.e. short-circuit protection
-MOSFET driver is included, just provide digital input
-thermal protection – shutdown when threshold temperature is exceeded
-Some PWM function included, such as delays to prevent shoot-through