

Robotic Sunflower Lesson 4: Dual Axis Light Tracking

DC Motors

In this lesson we will learn the basics of DC motor control. DC motors are so called because they run on *direct current*. They are rated in terms of their voltage, speed, torque and power. DC motors run very fast typically, so to be used in robots they are often fitted with gearboxes that slow down their output and increase their torque. The motors used in this lesson are 5 volt motors with gearboxes and a flatted shaft output. We will be using Parallax Boards of Education fitted with Basic Stamp microcontrollers for this lesson, so get one of the ENGR 170 kits to use, as well as a 5 V DC motor.

Activity 0. Basic DC motor operation

DC motors are incredibly easy to use. All you have to do is connect the motor to power and ground as indicated in Figure 4.1 and watch the motor go. Confirm this by connecting the green motor wire to Vdd and the white wire to Vss. Simply switch power and ground to drive the motor the opposite direction.



Figure 4.1: a) Basic power connection for a DC motor ; b) Connections for current measurement

Electric power is measured as $P = V \times i$, where P is the power measured in Watts, V is the voltage measured in Volts, and i is the current measured in Amperes (Amps). Obviously the more powerful the motor, the more voltage it requires and/or the more current it draws. How much current does your DC motor draw? It depends on how heavily you load it. Measure the current through the motor by adding an ammeter (Figure 4.1b). What is the current when the motor is running freely? This is called the no-load current.

$$i_{no\ load} = \underline{\hspace{2cm}}$$

How much electric power is needed in order to deliver this much current at 5 V? Note that not all this power is actually available at the gearbox's output shaft. Because neither the motor nor the gearbox is 100% efficient, the available mechanical power will always be less than $P = V \times i$.

$$P_{no\ load} = \underline{\hspace{2cm}}.$$

The opposite extreme of the no-load current is the stall current. This is the current the motor draws when it is loaded so much that it can't turn. Hold the gearbox output shaft strongly

enough to cause the motor to stall and measure the current. Note: do not do this for very long, as it is bad for the motor. $i_{stall} = \underline{\hspace{2cm}}$

How fast does the output shaft rotate under no-load conditions? The easiest way to answer this is to measure the time it takes to rotate 10 revolutions, then compute the revolutions per second.

Time to rotate 10 revolutions: . Cycles per second:

Power the motor with a 1.5 V battery instead of the $V_{dd} = 5\text{ V}$. What do you notice?

Activity 1. (1 pt. Instructor's initials) Basic DC motor control

You may recall from ENGR 170 that the Basic Stamp's I/O pins can provide as much as 20 mA of current at 5 volts. Compare this to the no-load motor current you measured in Activity 0. Obviously, you can't connect the motor directly to the microcontroller and expect anything to happen. Instead the microcontroller must control the current indirectly, for example, using a transistor as a switch (Figure 4.2).

1. Build the circuit shown in Figure 4.2. Use a simple wire touching and untouching V_{dd} to act as the switch. The motor should turn on and off as you touch and untouch the wire.

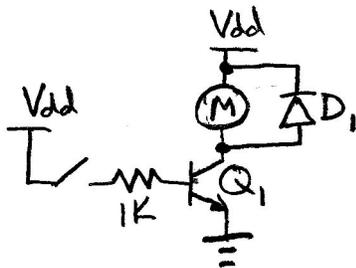


Figure 4.2. Simple transistor switch for a DC motor. $Q_1 = 2N3904$, $D_1 = 1N5817$

Things to notice

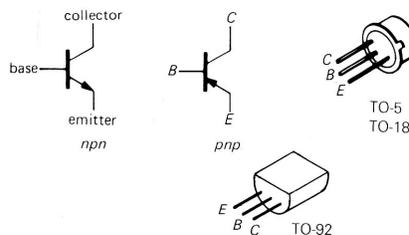
- a. The 2N3904 is an *npn* transistor that can conduct 200 mA continuously. If you don't remember how transistors in general work, and *npn* transistors in particular, please read the transistor review given below in the box.
- b. One problem with DC motors is that they are strong inductors. Among other things, an inductor resists any change in current. When you turn off power to a motor it tries to keep the current flowing. For reasons too difficult to explain (but take ENGR 210 for a full explanation), the result can be a huge voltage (possibly 20 times the original voltage) across the motor *in the opposite direction from the original voltage*. This means there also is a huge voltage across the transistor, potentially enough to destroy it. To protect against this we use diode D_1 as a *clamp diode*. The clamp diode limits the reverse voltage (sometimes called *counter electromotive force*, or CEMF) across the motor to no

more than 0.7 V. A clamp diode may have to conduct quite a bit of current. The 1N5817 can handle 1 A continuously and 25 A briefly. Notice how heavy its leads are.

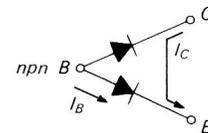
Transistor Review

The following is a simplified tutorial on transistors, referenced (with some modifications) from The Art of Electronics, by Horowitz and Hill (which is an excellent book to have).

- a. A transistor is a 3-terminal device that comes in one of two flavors: *npn* and *pnp*. *npn* stands for negative-positive-negative and refers to the way the semiconductor is made. We can't afford to go into the details of that here. The 2N3904 is an *npn* transistor; everything that follows will relate to *npn*. The symbols for both *npn* and *pnp* transistors are shown in the figure, as are 2 typical transistor "packages."



- b. The 3 terminals are called the emitter (E), the collector (C), and the base (B). These names come from the days of vacuum tubes: The emitter emits electrons and the collector collects them. So the emitter must always be more negative than the collector.
- c. There are 4 rules governing how an *npn* transistor operates:
- i. The collector must be more positive than the emitter.
 - ii. The base-emitter and base-collector circuits appear to an ohmmeter as diodes as shown in the figure. When a transistor is in operation, the base-emitter acts like a conducting diode, with a constant voltage drop of 0.6 – 0.8 V from the base to the emitter. *This having been said*, it would be a mistake to think of a transistor as two diodes connected back-to-back. The transistor action, described in rule iv. below, transcends the action of two diodes.
 - iii. Any given transistor has maximum values of I_C , I_B , and V_{CE} which cannot be exceeded without costing the exceder the price of a new transistor.
 - iv. If rules i. through iii. are obeyed, then I_C is roughly proportional to I_B and can be written $I_C = h_{FE}I_B$, where h_{FE} , called the current gain (also called beta), is typically around 100. It is this property that makes a transistor useful: A small current flowing into the base controls a much larger current flowing into the collector.



2. Connect the transistor's base to the Basic Stamp's Pin 8 (Figure 4.3). Write a program to switch the motor on and off at 1 second intervals and demonstrate operation.

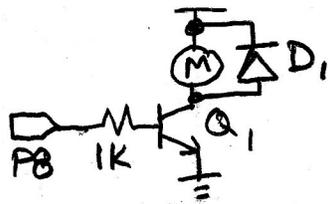


Figure 4.3. Simple transistor switch to control a motor using a microcontroller.

Activity 2. (5 pt. Instructor's initials _____) Speed Control with Pulse Width Modulation

You saw in *Activity 0* that you can vary the speed of a DC motor by varying its supply voltage. This is great, except that in the digital world there are only 2 voltages: 0 and 5 volts. How can we give the motor 2.5 V? The answer is shown in Figure 4.4a. If you give the motor a rapid series of pulses such that half the time it's getting 5 volts and half the time it's getting 0, then on average, it gets 2.5 volts. This approach to speed control is called *pulse width modulation* (PWM). If you give a rapid series of pulses such that 20% of the time it's 5 volts and 80% it's zero, the average is 1 V (Figure 4.4b). *Duty cycle* is the percentage of time the voltage is high.

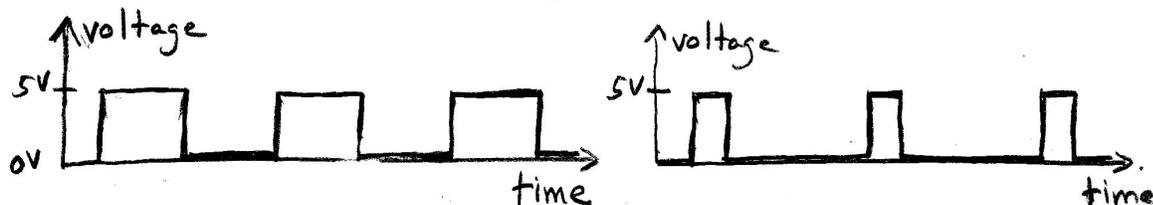


Figure 4.4. (a) Pulse width modulation, 50% duty cycle; (b) 20% duty cycle

1. Using the configuration shown in Figure 4.3, run the following program which illustrates pulse width modulation.

```

duty CON 50
main:
  HIGH 8
  PAUSE duty
  LOW 8
  PAUSE (100 - duty)
  GOTO main
    
```

Comments:

- a. The total period of each on-off cycle is 100 ms, 50% of which the motor is on, 50% it is off. This means there are 10 pulses per second. This is very low. There is debate about what PWM frequency is best for motor control, but usually the debate is about frequencies higher than 1 kHz. However 10 Hz works well enough to illustrate the point.
- b. The Basic Stamp has a command called **PWM** and it theoretically should work here, but I couldn't get it to.

2. Complete the following table relating motor speed to duty cycle:

Duty cycle	Rotational speed (cycles per second)
0	
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	

- 3. Design a variable motor speed controller using a potentiometer. When the pot is turned all the way one way, the motor should be off. When the pot is turned all the way the other way, it should be fully on. In between, the motor speed should vary with the potentiometer. How could you use this as the throttle for an electric motorcycle? Demonstrate operation and attach a copy of your program. Include a schematic.

Activity 3. (5 pt. Instructor's initials _____)

Reversing the motor

A robot needs to be able to back up as well as to advance. If we want to propel it using DC motors, we need a way to reverse it. The most reliable approach to this is to use a device called an *H-bridge*. An H-bridge works using 4 switches as shown in Figure 4.4

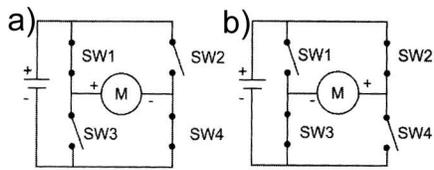
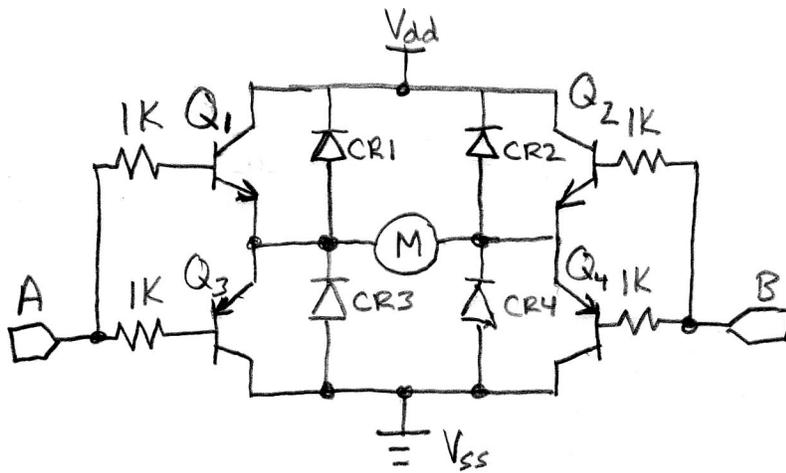


Figure 4.4. H-bridge basic operation. a) motor rotates clockwise. b) motor rotates counterclockwise

1. We will use transistors as the switches. Build the H-bridge circuit shown in Figure 4.5. Note carefully that Q_3 and Q_4 are different from Q_1 and Q_2 . Q_3 and Q_4 are *pnp* transistors, so they will go into the circuit differently from Q_1 and Q_2 . Refer to the figures in the *Transistor Review* box.



Q_1, Q_2	2N3904
Q_3, Q_4	2N3906
$D_1 - D_4$	1N5817

Figure 4.5. H-bridge using complementary npn and pnp transistors

Complete the following table:

	Result
A = 0 V, B = 0 V	
A = 5 V, B = 0 V	
A = 0 V, B = 5 V	
A = 5 V, B = 5 V	

How the H-bridge in Figure 4.5 works:

- a. The 2N3906 is a *pnp* transistor whereas the 2N3904 is an *nnp* transistor. These two transistors have many of the same switching characteristics, which permits them to be used together as *complementary transistors*. The difference between them is that when you apply a high voltage to the base, the *nnp* turns on, while the *pnp* turns off.

Conversely, when you apply a low voltage to the base, the *npn* turns off while the *pnp* turns on. This means that when Q_1 is on, Q_3 is off, and vice-versa. Likewise with Q_2 versus Q_4 . This permits the H-bridge to behave like the circuit in Figure 4.4.

- b. Notice the motor speed. Why does it seem slow? It must be that it is getting less voltage. Here's why: Suppose Q_1 and Q_4 are conducting. The voltage drop across Q_1 's base-emitter junction is about 0.7 V. Likewise with the voltage drop across the collector-base junction in Q_4 . This robs us of 1.4 V right there. In addition, there is about 0.5 mA current into the base of each transistor, meaning about a 0.5 V drop across the 1K resistors. Together this adds another 1 V lost to the motor. So the motor is actually getting only about 2.5 V. Measure the motor voltage to confirm this. $V_{motor} = \underline{\hspace{2cm}}$
- c. You can regain about 1 of those lost volts by replacing the 1K resistors with straight wires. Ordinarily this may be a bad idea as the resistors serve to limit the base current to no more than 5 mA in a 5 V system, which you might want to do if the current source is an output pin of a Basic Stamp. However, in our case the motor is small enough that the collector current won't exceed 1 A, so the base current should never exceed about 10 mA, assuming h_{FE} is about 100. This puts it well within the range of the Basic Stamp's capabilities. So go ahead and replace the resistors with wire. Does the motor speed up a little?
- d. It turns out with an H-bridge that Vdd can be different from the A and B high voltages. For example if you are driving a 12V DC motor, you can use $V_{dd} = 12\text{ V}$, while still controlling it with 5 V signals. Be careful: If you use large motors, use large transistors that can handle the voltage and current.

2. Write a computer program to drive the DC motor in one direction for 3 seconds, then drive it the opposite direction 3 seconds, repeating the cycle forever. Demonstrate operation.
3. It should come as no surprise that there are integrated H-bridge circuits. One example is the L293D, which can control 2 motors at 1 A each, and includes internal clamp diodes. Build the circuit shown in Figure 4.6. Write a program that drives both motors full speed one way, then full speed the opposite way, for periods of 3 seconds each.

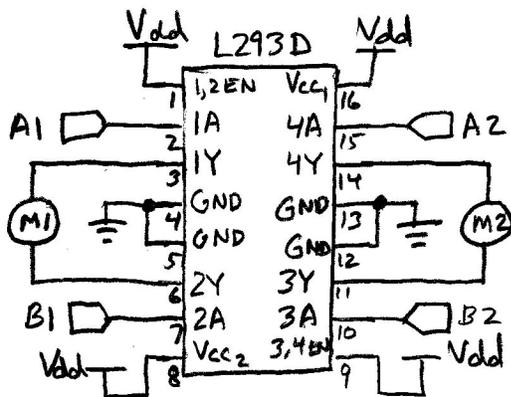


Figure 4.6. 2-motor H-bridge circuit using an L293D.

4. DC motors produce torque only when current flows in their coils. This can present a problem. Suppose you want a DC motor to hold a position without rotating. If you simply turn off power, the motor won't rotate, but it won't be able to hold position either. Imagine for example, an elevator motor. If you turn off power to the motor to stop the elevator at the 14th floor, the motor won't be able to hold the elevator and it will start to descend. This is obviously unattractive to the elevator's occupants. What we need is to run the motor, but not have it rotate. Use what you know about PWM and H-bridge control of forward and reverse motor operation to develop a way to hold a motor steady in one position. Demonstrate operation to the instructor.

Activity 4. (5 pt. Instructor's initials _____) Robot with DC motors

Build a robot using 2 DC motors. The instructor will provide some materials and an example of an easy robot to build, but you may do it however you want. The robot should demonstrate the ability to 1) go forward, 2) back up, 3) turn right and 4) turn left.

If you have time, feel free to add sensors or the ability to ramp up or ramp down in speed.

Final comments

DC motors are generally less expensive than servo motors or stepper motors, although a gearbox can increase the cost significantly. As you go up in power, DC motors start to become the only choice available to the roboticist. This lab is merely an introduction to the topic, and you are urged to inquire further. One important topic we have not covered for example is torque, how it is defined and measured and how torque varies with motor speed.

References

Building Robot Drive Trains, D. Clark and M. Owings, ISBN 0-07-140850-9, McGraw-Hill, 2003.

The Art of Electronics, 2nd Ed., P. Horowitz and W. Hill. ISBN 0-521-37095-7, Cambridge University Press. 1989.