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ECEN 2270
Lab 3
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**Abstract**

In this lab, we continue to build on the robot's motor functionality. In Part A, we built a DC Motor Driver. This addition permits for forward and reverse rotation of the wheels. In Part B, we created a simple Speed Control circuit. These new parts allow for reliable control of the robot's speed and direction. This is essential in order for the robot to move from place to place in a precise and useful way.

## Part A

# DC Motor Driver Circuit

Building on the Speed Sensor from Lab 2, two DC Motor Driver circuits were built. Resistors $R_{B1}$ and $R_{B2}$ were calculated and then tested. This part of the circuit has the following expected parameters:

- $V_{BE_{1,4}} \approx 0.8[V]$
- $\beta \approx 200$
- $I_{DC} \leq 1[A]$
- $R_M = 2[\Omega]$
- $V_{CC} = 10[V]$
- $R_{B1} = R_{B2} = R_B$

This lab also builds on previous findings:

- $k = 0.927$
- $f_{enc_{max}} = 1.214[kHz]$
- $J = 2.61 * 10^{-3}$
- $t_{on} = \frac{3}{4f_{enc_{max}}}$

## 1 Constructing DC Motor Circuit

Using the proto board supplied, the BJTs were placed onto the board and connections were soldered such that the connections matched the provided schematic for the motor driver circuit.

# 2 Finding $R_B$

## 2.1 $R_B$ by hand

The specifications for $R_B$ are simple; $|I_{DC}| < 1[A]$ if $V_{DC\ Supply} = 10[V]$. Also, $R_{B1} = R_{B2} = R_B$. The outputs from the driver, $DC_1$ and $DC_2$, should have a total of $|1[A]|$ through the terminals if the wheels are locked. When the wheels are locked, the DC Motor from previous labs acts like a plain old $2[\Omega]$ resistor.

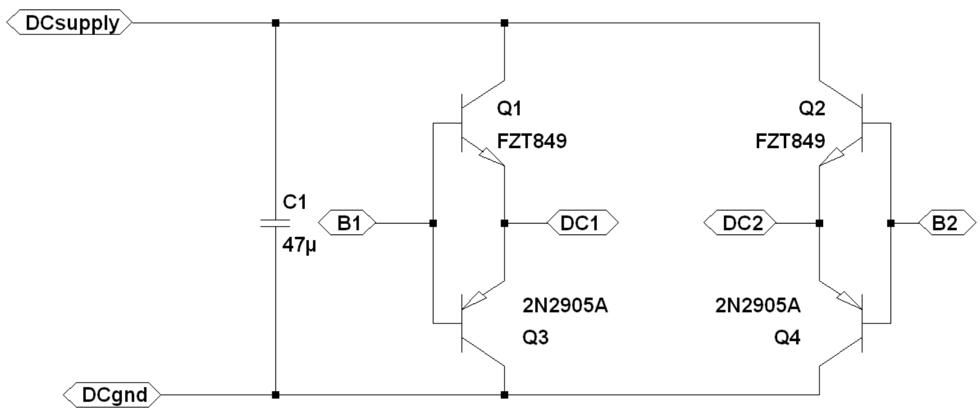


Figure 1: Complete Motor Driver Circuit

From Figure 1, it can be observed that only half of the BJT transistors are in action for a given direction (the other two BJTs are in cutoff mode). Therefore, a simplification can be made, which is shown in Figure 2. Since the mode of the two transistors is in active mode, yet another simplification can be made using dependent sources, shown in Figure 3. At this point, solving for $R_B$ is much more straightforward:

$$V_{DC_1} - V_{DC_2} \leq 2[V] \tag{1}$$

$$i_B = \frac{1[A]}{(\beta + 1)} \approx 4.98[mA] \tag{2}$$

$$\beta i_B + \frac{V_{CC} - V_{BE} - V_{DC_1}}{R_B} = \frac{V_{DC_1} - V_{DC_2}}{R_M} \tag{3}$$

$$\frac{V_{DC_1} - V_{DC_2}}{R_M} \leq 1[A] \tag{4}$$

$$\text{Assuming } V_{DC_1} = 6[V], V_{DC_2} = 4[V] \tag{5}$$

$$R_B = \frac{V_{CC} - V_{BE} - V_{DC_1}}{i_B} = \frac{(10 - 0.8 - 6)[V]}{4.98[mA]} = 642[\Omega] \tag{6}$$

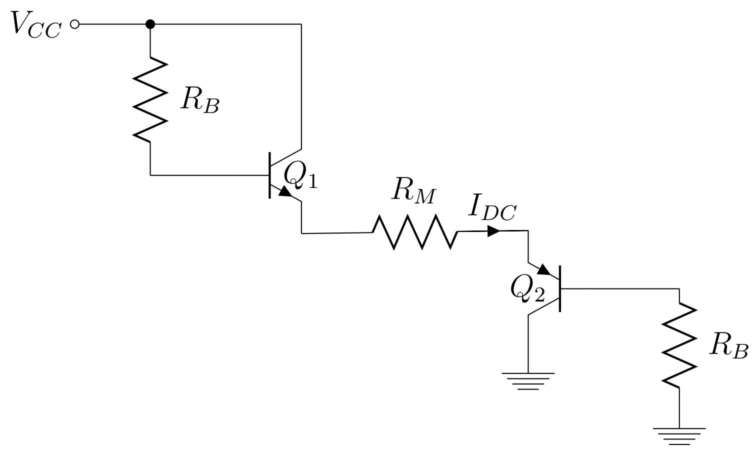


Figure 2: Simplified Model of Circuit

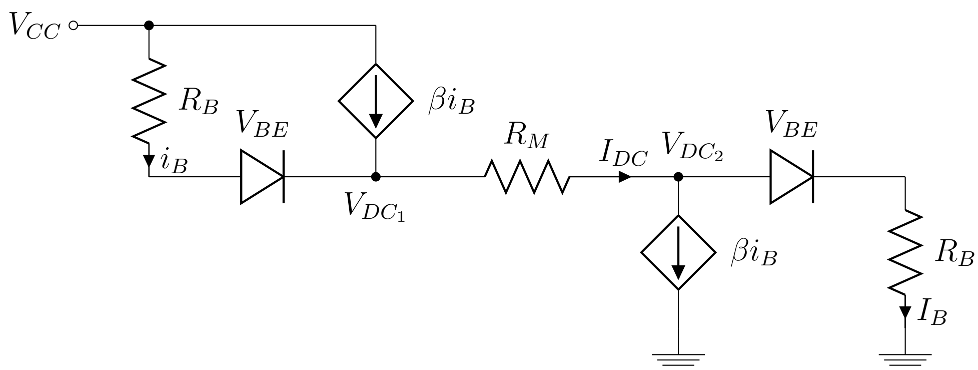


Figure 3: Further Simplified Model of Circuit

## 2.2 $R_B$ by simulations

Using LTSpice, the circuit found in Figure 1 was built and then tested to see if it in fact would provide the required 1 Amp across the loading terminals. The test circuit is shown below in Figure 4. Note that $X_1$ is the circuit in Figure 1. Using the calculated $R_B$, the current through $R_M$ was found to be $853[mA]$. The voltage $V_{DC_1}$ was found to be $6.7[V]$ and $V_{DC_2}$ was found to be $5V$. Their difference was $1.7[V]$. While not ideal, this setup fulfills the required functionality. From this model, the power dissipated by the transistors can be calculated using Equation (7).

$$P[W] = (V_C - V_E)I_{DC} \approx 2.81[W] \tag{7}$$

From this expression, up to about 3 Watts of power will course through the BJTs, which is why heat sinks are used to prevent the transistors from breaking down after extensive operation.

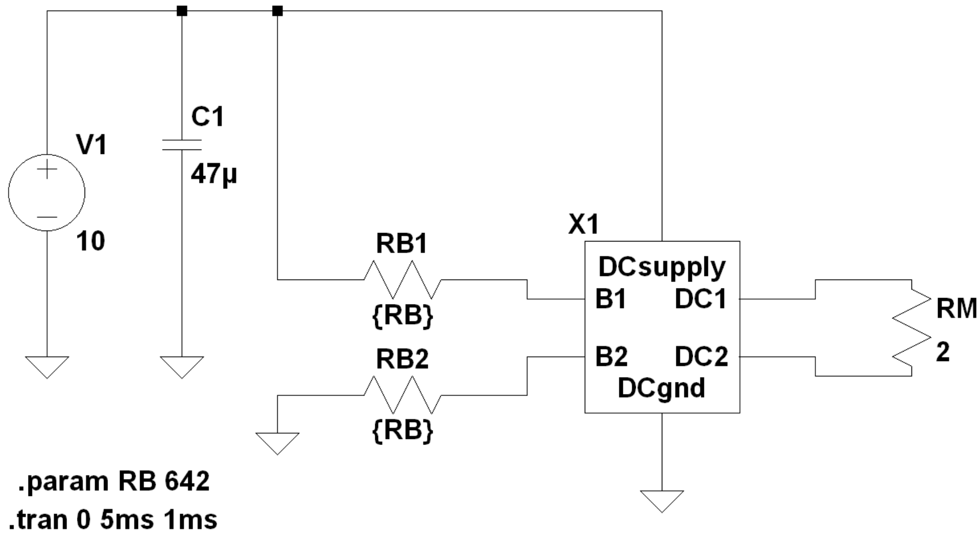


Figure 4: Motor Driver Circuit Test

### 2.3 $R_B$ by experiment

Using the actual board, the same values were measured by holding the wheel in place and taking measurements. The resistor used was a pair of $642[\Omega]$ resistors.

- Locked; Clockwise configuration: $I_{DC} = 880[mA]$
- Locked; Counter-Clockwise configuration: $I_{DC} = 870[mA]$
- Either Direction Free-Rolling; $I_{DC} = 150[mA]$; Speed is $962[Hz] = 7.87[rot/s]$

Some adjustments to $R_B$ were made throughout the expirement, but the most accurate and reliable found was the original $642[\Omega]$ resistors calculated in previous sections.

## Part B

# Closed-Loop Motor Driver Circit

In this part of the lab, we constructed and tested the complete speed control circuit for a single wheel. The overall schematic for the speed control unit is shown below as Figure 5. This circuit is a feedback circuit, and can be diagramed as such in Figure 6.

Of the parts in Figure 6, we have already built the Speed Sensor and the Driver/Motor units. The remaining part is the integral compensator, which serves the important role of improving steady-state error characteristics. This is done by adding a pole at the origin of the complex plane.

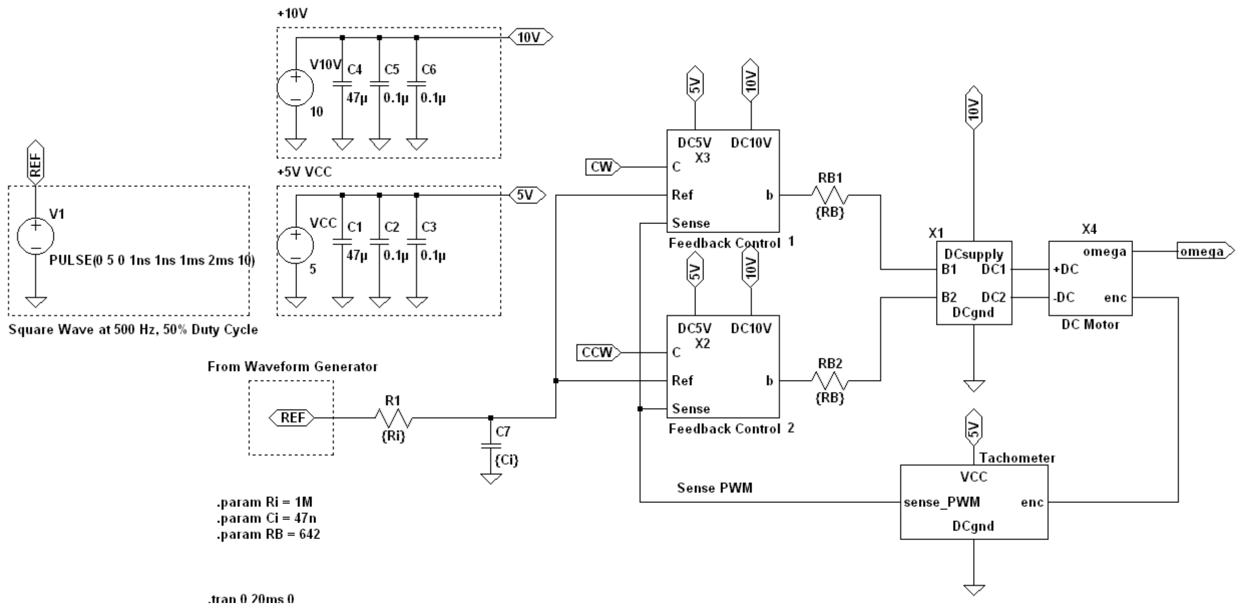


Figure 5: The Total Speed Control Schematic

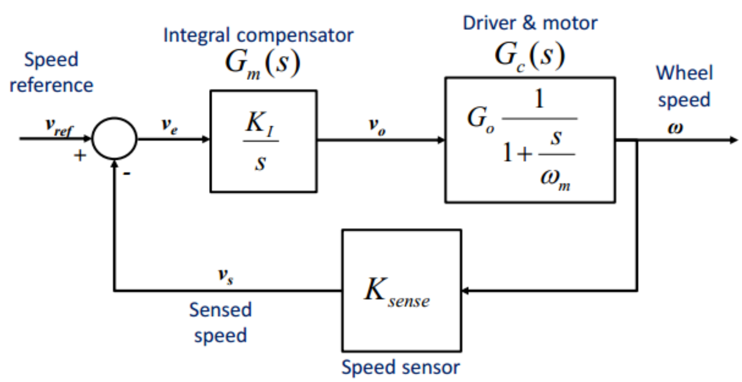


Figure 6: System Schematic of Circuit

# 3 Integral Compensator

We built the Integral compensator, shown below in Figure 7.

We used the original low-pass filter components $R_3$ and $C_3$ as an initial set of starting values. However, the integral compensator is not an isolated part of the circuit; its output in turn will affect its own input. Using a function generator for $V_{ref}$ with a square wave amplitude $0-5[V]$, with a frequency of $1[kHz]$, we varied the duty cycle and found that the wheel's speed was proportional to the percent time on for $V_{ref}$. Ideally, the wheel speed would reach the highest speed possible. However, because $t_{on} = \frac{3}{4f_{enc}}$, the highest PWM duty cycle is limited, meaning the final speed is some fraction of the maximum encoder frequency $f_{enc}$, which was measured previously as approximately 1.2[kHz].

The transfer function for the integral compensator $G_m(s)$ is derived below:

$$v_n = v_p$$
$$i_n = i_p \approx 0$$
$$\frac{v_s - v_n}{R_I} - \frac{v_n - v_o}{\frac{1}{sC_I}} = 0$$
$$\frac{v_{ref} - v_p}{R_I} - \frac{v_p}{\frac{1}{sC_I}} = 0$$
$$v_o(s) = \frac{v_{ref} - v_s}{sR_IC_I}$$
$$K_I = \frac{1}{R_IC_I}$$
$$G_m(s) = \frac{K_I(v_{ref} - v_s)}{s}$$

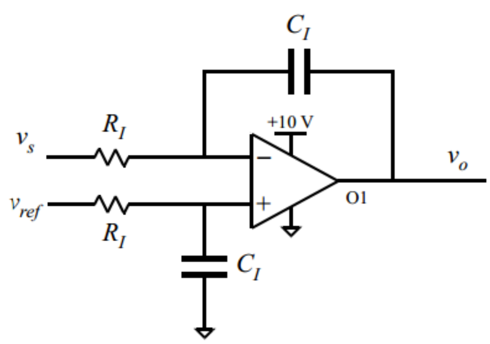


Figure 7: Integral Compensator

# 4 Transient Response

The integral compensator, however, would not necessarily work with the values used for $R_3$ and $C_3$ used in the Low-Pass Filter of Lab 2. This is because the feedback system gives rise to a Second- Order system. Our next task was to find a better value for $R_I$ and $C_I$. As seen in Figure 8, we had to first seek out values for $C_I$ and $R_I$ that would not violate parameters from previous labs, but also be critically damped, that is, have a $\zeta = 1$. In order to calculate this, we have to find $G(s)$ and then set up the expression to solve for $\zeta$ seen in Equation (8).

$$\frac{v_o(s)}{v_{ref}(s)} = G(s) = \frac{H_0}{1 + 2\zeta\frac{s}{\omega_0} + (\frac{s}{\omega_0})^2} \tag{8}$$

Also, given in the lectures, we have important values $K_{sense}$ and $\omega_0$.

$$K_{sense} = \frac{V_{s_{max}} * 12 * 64}{2\pi f_{enc_{max}}}$$
$$\omega_0 = \sqrt{\frac{kK_I K_{sense}}{JR_I}}$$

$$\zeta = \frac{1}{2}k\sqrt{\frac{k}{K_I K_{sense} J R_I}}$$

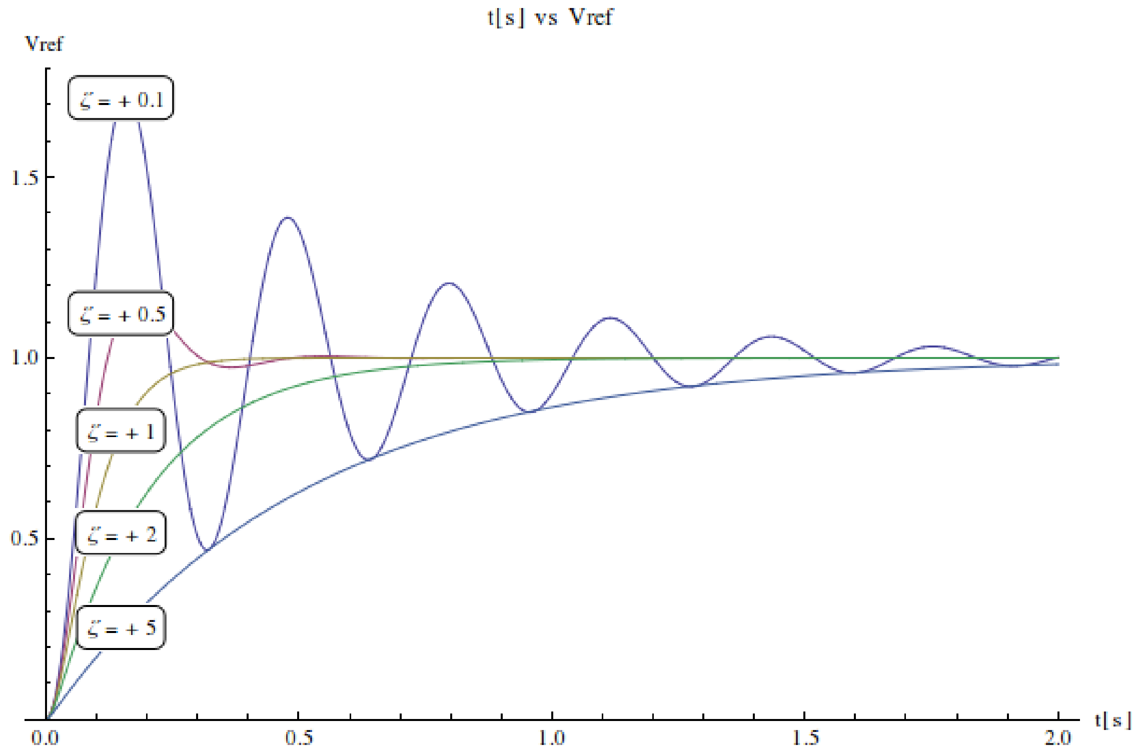


Figure 8: Transients and $\zeta$

### 4.1 $w$ vs $V_{ref}$ for CW and CCW Operation

### 4.2 $K_{sense}$

### 4.3 Derivation of Closed-Loop Transfer Function $G(s)$

### 4.4 Poles of $G(s)$

### 4.5 Step Response Evaluation

### 4.6 Response time of the Speed Controller

## 5 Stop and Go Control

Using a PMOS transistor, with the Source tied to $5[V]$, the Drain to the point after the $R_I$ on the negative terminal on the op amp