UNIVERSITY OF COLORADO - BOULDER

ECEN 2270

ELECTRONICS LAB | SPRING 2024

ECEN 2270 Electronics Lab: Lab 3

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I. Introduction

In Experiment A, we delved into the world of Bipolar Junction Transistors (BJTs) to develop a PCB motor driver, a critical component for controlling the motors on our robot. This phase was not only about understanding the theoretical aspects of BJTs but also about mastering practical skills such as soldering. We dedicated time to learn and apply effective soldering techniques, ensuring a solid and reliable assembly of our motor driver onto the PCB. The experiment didn't stop at assembly; it extended into rigorous testing of the motor driver. This testing phase was crucial for verifying that our assembled motor driver could indeed control the robot's motors as intended.

Transitioning to Experiment B, our focus shifts to the intricate design, simulation, and practical implementation of feedback controllers. Here, we're tasked with creating a precise system for controlling motor speed and direction—a fundamental skill for developing anything from robotics to sophisticated automated systems. The experiment guides us through establishing a virtual ground, rigorously testing Compensator circuits in both open and closed loops, and finally, incorporating direction control mechanisms. These exercises are not just academic; they're directly applicable to real-world scenarios where exacting control over movement is paramount.

II. Experiment A

A. Exploration Topics

1) **What are the different types of MOSFETs?**
   - P-Channel Depletion MOSFET
   - P-Channel Enhancement MOSFET
   - N-Channel Depletion MOSFET
   - N-Channel Enhancement MOSFET

2) **What are their schematic symbols and their main properties?**
   MOSFETs have the ability to amplify or switch electronic signals, relying on their three main properties: a metal gate electrode, an insulating layer of oxide, and a semiconductor substrate, which collectively regulate the flow of current in electronic circuits.

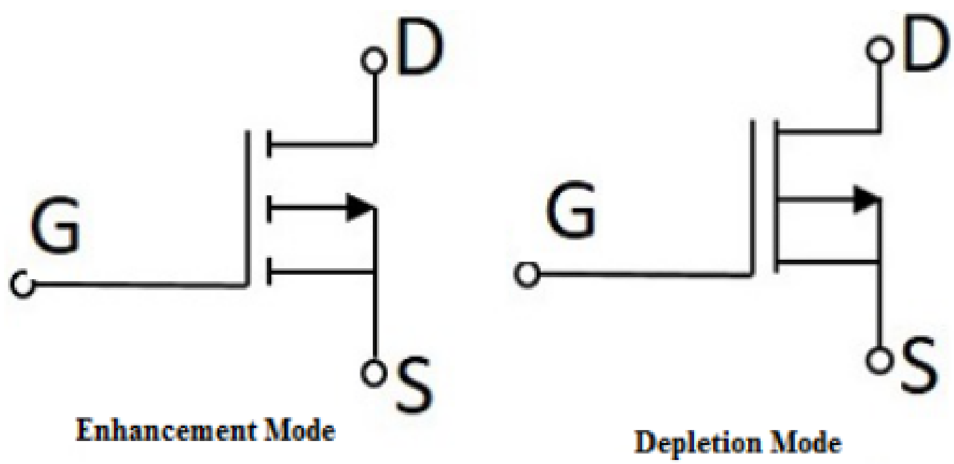


Fig. 1 P-channel

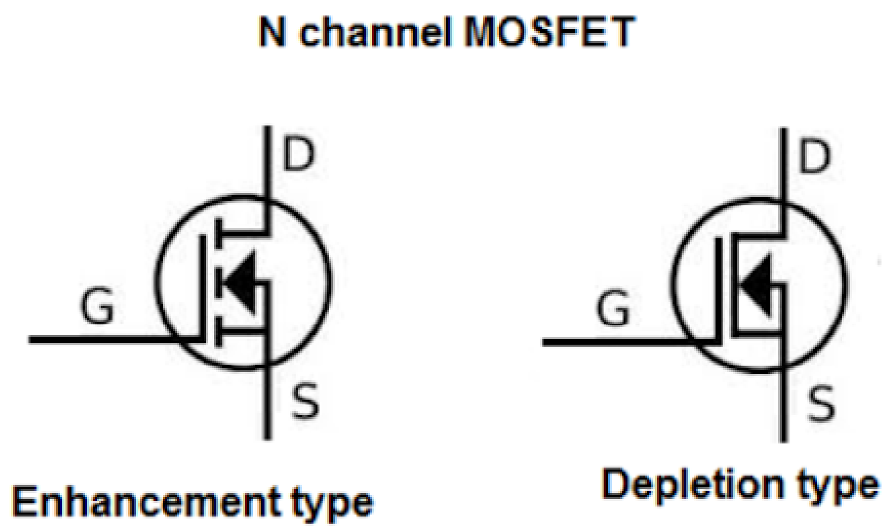


Fig. 2 N-channel

3) **What are they made from and what is their physical structure?**
MOSFETs are typically constructed from silicon and feature a physical structure comprising a silicon substrate, a thin layer of silicon dioxide as the insulating oxide, and a metal gate electrode, forming a crucial part of modern semiconductor technology.

4) **What is their operating principle?**
The main working principle of a MOSFET is to control the voltage and the current which is flowing between the source terminal and the drain terminals.

5) **What is a simple equivalent circuit for MOSFETs?**

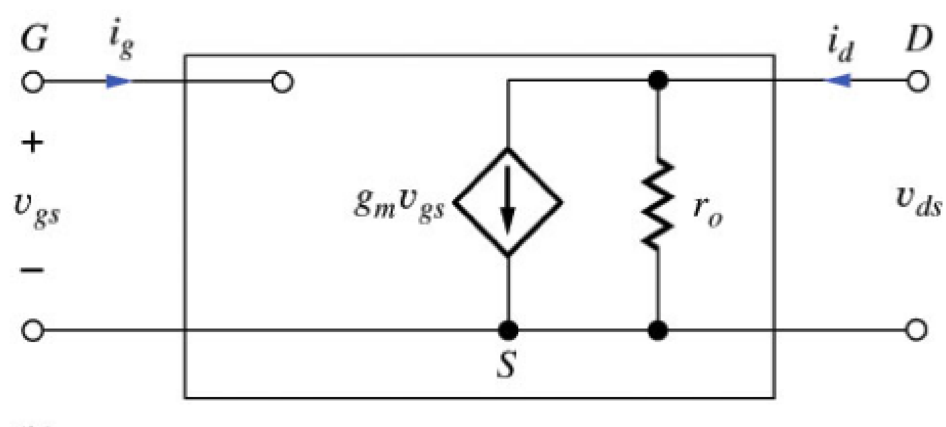


Fig. 3 MOSFET equivalent circuit

6) **How do MOSFETs differ from BJTs?**
MOSFETs are particularly useful in amplifiers due to their input impedance being nearly infinite which allows the amplifier to capture almost all the incoming signal. The main advantage is that it requires almost no input current to control the load current and that's why we choose MOSFET over BJT.

B. 3.A.2

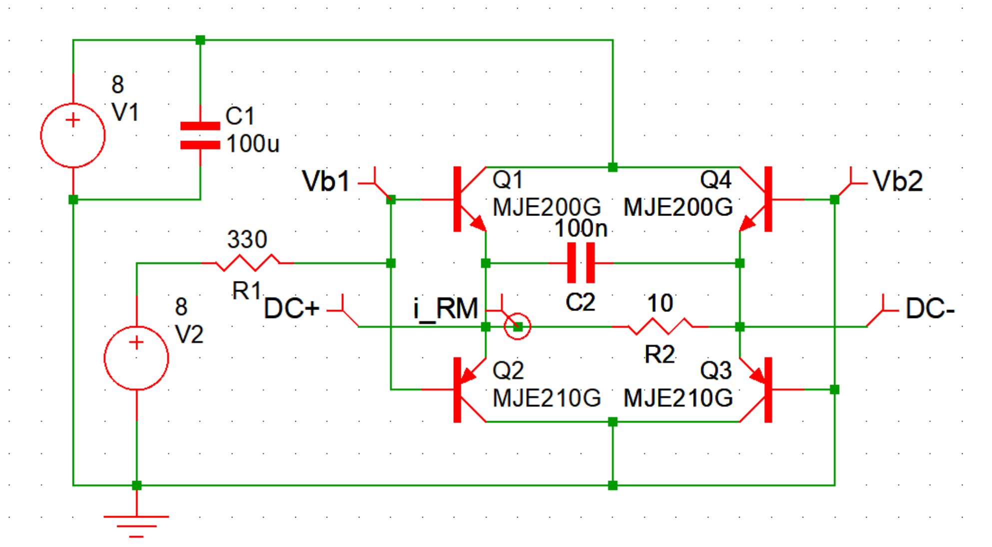


Fig. 4 H Bridge Measurement Setup

R_M [Ω]	V_{B1} [V]	V_{B2} [V]	DC^+ [V]	DC^- [V]	I_{RM} [A]	P_{Q1} [W]	P_{Q2} [W]	P_{Q3} [W]	P_{Q4} [W]
1.5	3.53	0	2.77	764.4m	1.34	6.933	125.9p	22.71p	1.022
10	6.37	0	5.65	720.4m	493m	1.15	126.6p	78.67p	355.1m

Table 1 Component Properties for Forward Bias

R_M [Ω]	V_{B1} [V]	V_{B2} [V]	DC^+ [V]	DC^- [V]	I_{RM} [A]	P_{Q1} [W]	P_{Q2} [W]	P_{Q3} [W]	P_{Q4} [W]
1.5	0	3.53	764.4m	2.77	-1.34	125.9p	6.933	1.022	22.71p
10	0	6.37	720.4m	5.65	-493m	126.6p	1.15	355.1m	78.67p

Table 2 Component Properties for Reverse Bias

C. 3.A.3

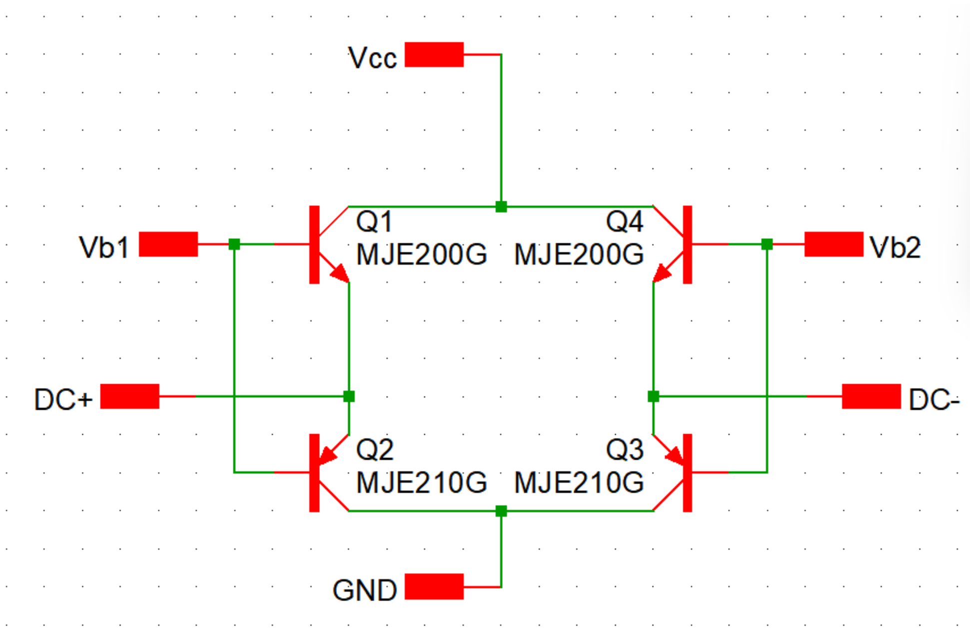


Fig. 5 Motor Driver Schematic

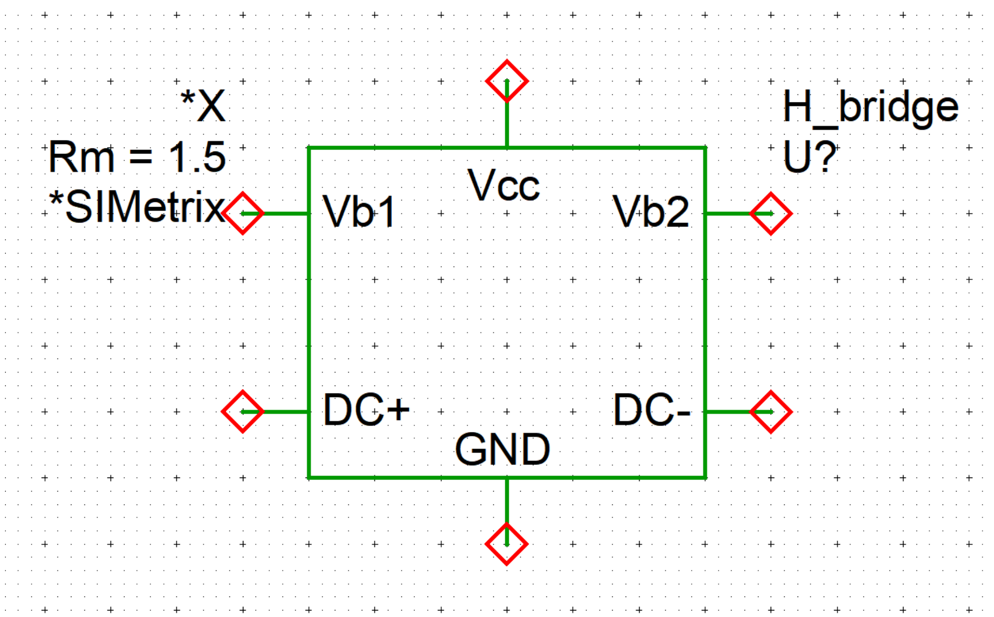


Fig. 6 DC Motor Driver Symbol

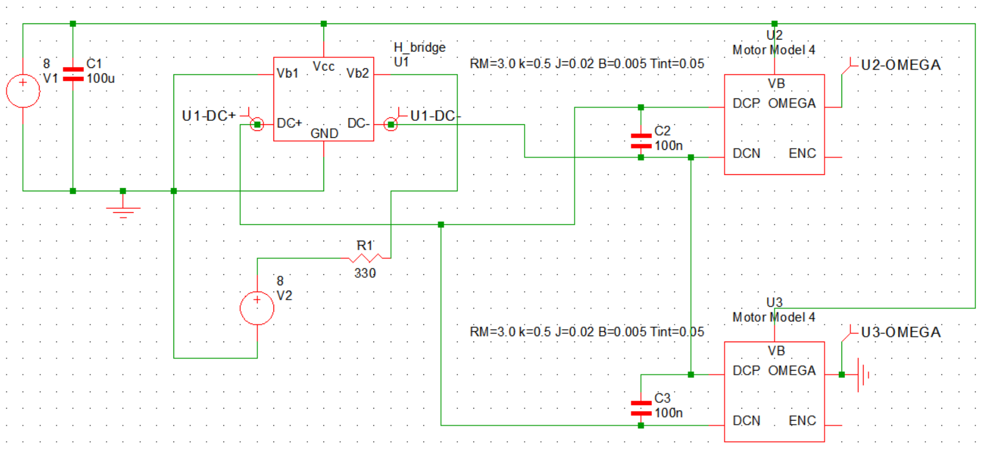


Fig. 7 Total Motor Driver Circuit for Measurements

Condition	ω_1 [rad/s]	ω_2 [rad/s]	i_{DC} [A]
U2 and U3 Free	9.4	-9.4	391m
U2 Stalled	0	-4.8	1.1
U3 Stalled	4.8	0	1.1
Both Stalled	0	0	1.34

Table 3 Motor Values when Forward Biased

Condition	ω_1 [rad/s]	ω_2 [rad/s]	i_{DC} [A]
U2 and U3 Free	-9.4	9.4	-391m
U2 Stalled	0	4.8	-1.1
U3 Stalled	-4.8	0	-1.1
Both Stalled	0	0	-1.34

Table 4 Motor Values when Reverse Biased

1) **You will notice that X2 runs forward and X3 runs backward. Why is it wired that way? Hint: Look at the orientation of the motors in the robot chassis.**
X2 runs forward, and X3 runs backward because the actual motor in our robot build is flipped 180 degrees. Therefore, this model accurately represents our build. The motors are flipped along the center axis, which causes the directions of the motor movement to also be flipped, making the forward direction become the reverse direction.

2) **Measure the total motor current and omega1 and omega2 for the cases (i) when both motors are freely running, (ii) when one motor is stalled and one is free running, and (iii) when both motors are stalled.**
To measure the total motor current we want to measure the current at DC+ or DC-. From prelab we remember calculating the current through RM, however, now we actually have both motors hooked up. DC+ and DC- should be equal because they are only separated by a resistor in series.

D. 3.A.4

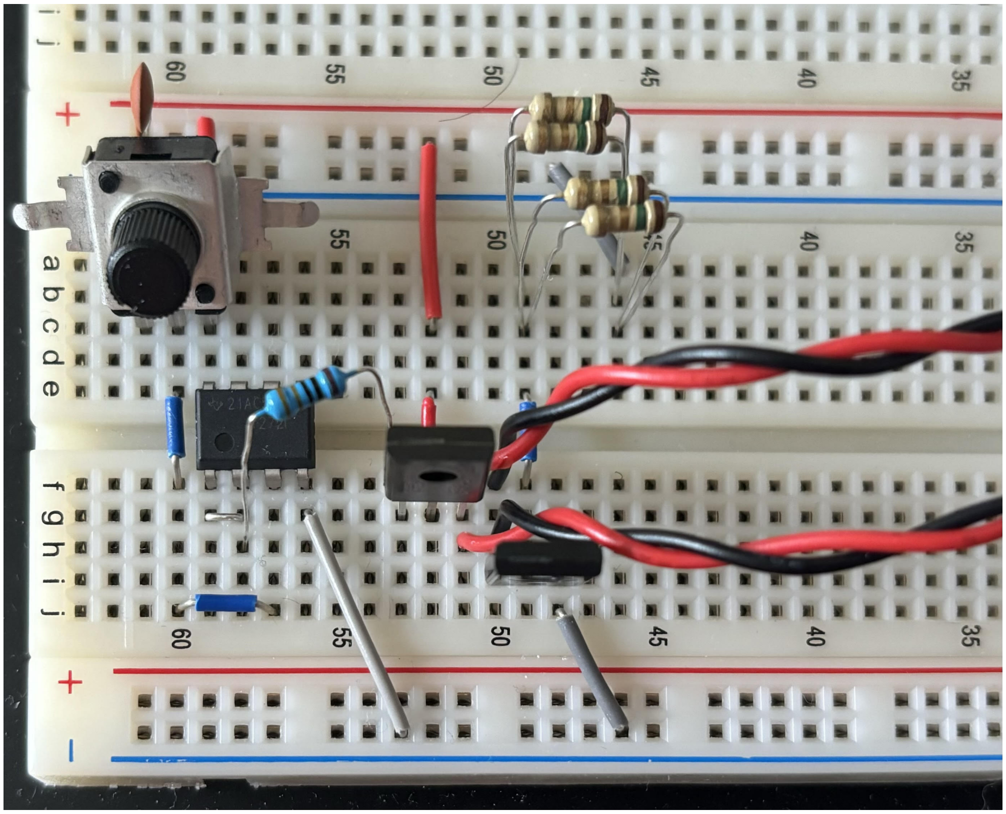


Fig. 8 Motor Driver Test Circuit

Condition	Motor Voltage [V]	Voltage across R1 [V]	Motor Current [A]
Both Spinning	5.16	0.19	0.75
Motor 1 Stalled	2.00	0.47	1.90
Motor 2 Stalled	3.29	0.50	2.01
Both Stalled	1.076	0.58	2.33

Table 5 Motor Values for both Motors in parallel, Note: R_1 = 0.25.

To measure the current at different motor conditions, we measured the voltage across the motor using a DMM and the voltage across R_1 in reference to the ground. Once these measurements were taken, we calculated the current through the motor using Ohm's law (i.e. V_1/R_1). The current through the resistor is the same as the current through the motor since they are in series.

E. 3.A.5

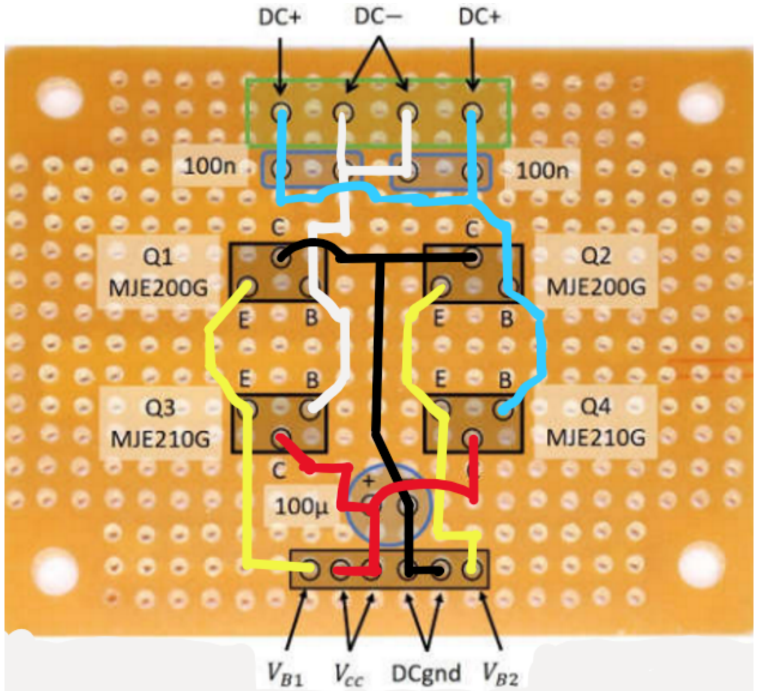


Fig. 9 Motor Driver Wiring Diagram

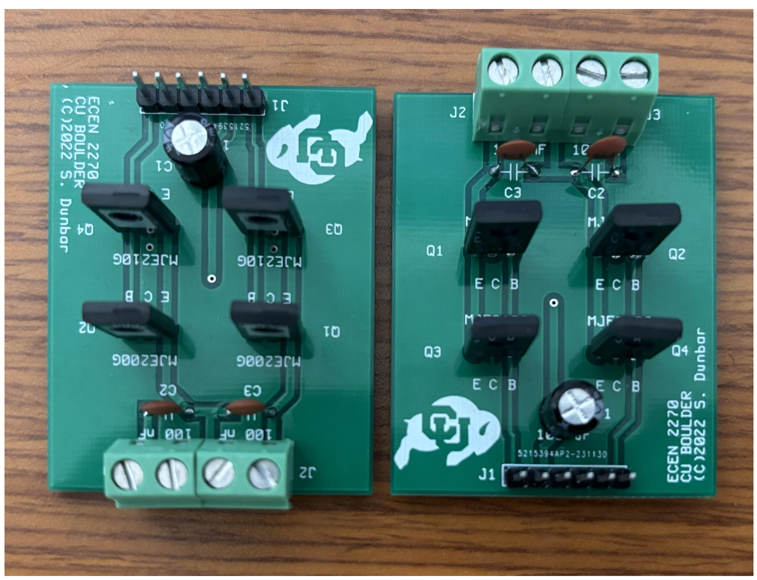


Fig. 10 Motor Driver PCB Circuit

F. 3.A.6

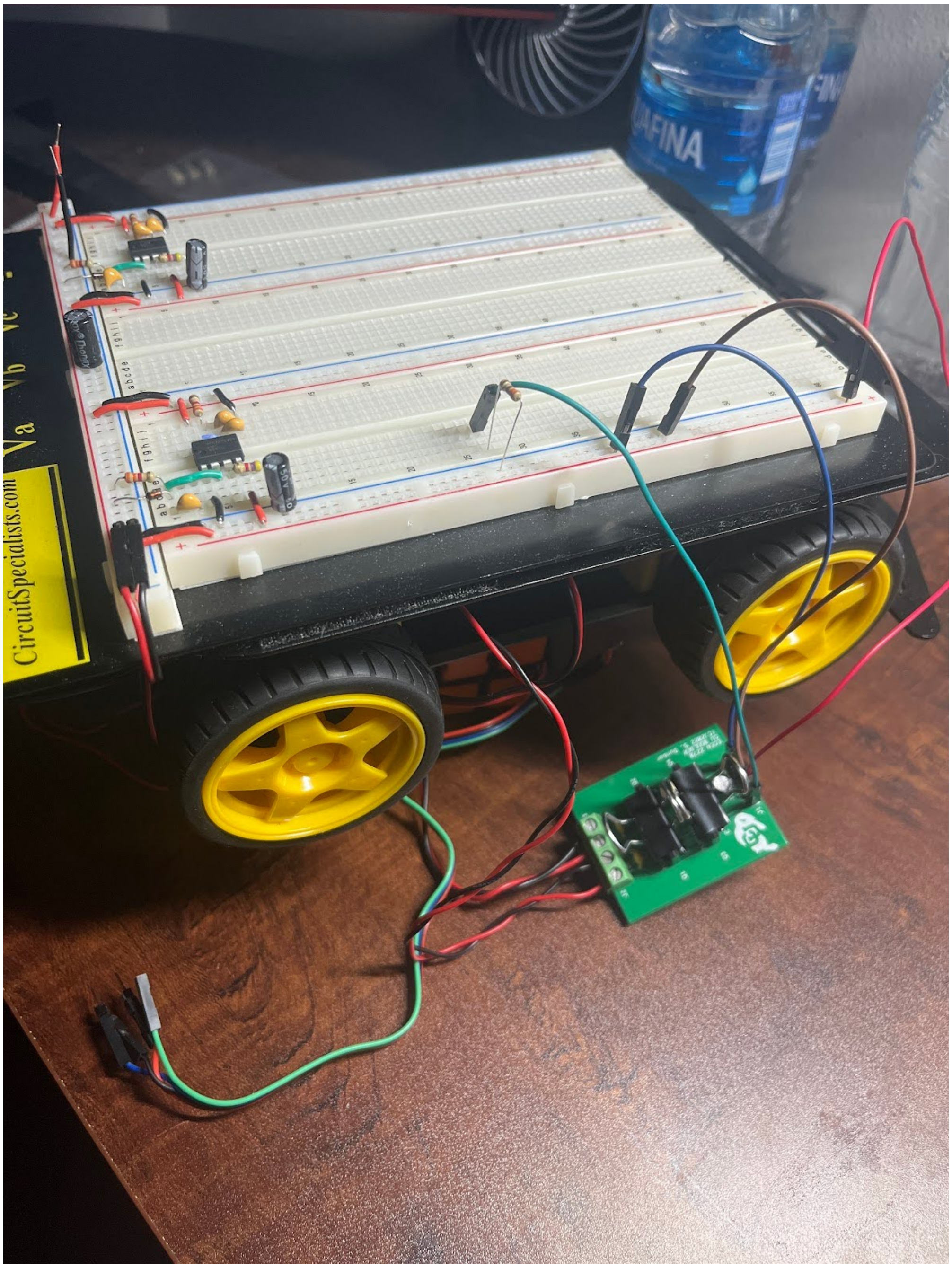


Fig. 11 Testing Setup for Motor Driver

Both PCB's have been tested (for all team members) as shown in **Figure 11** and they behave as expected! They can spin in both opposite and the same direction depending on the positive and negative connections of each motor.

G. 3.A.7

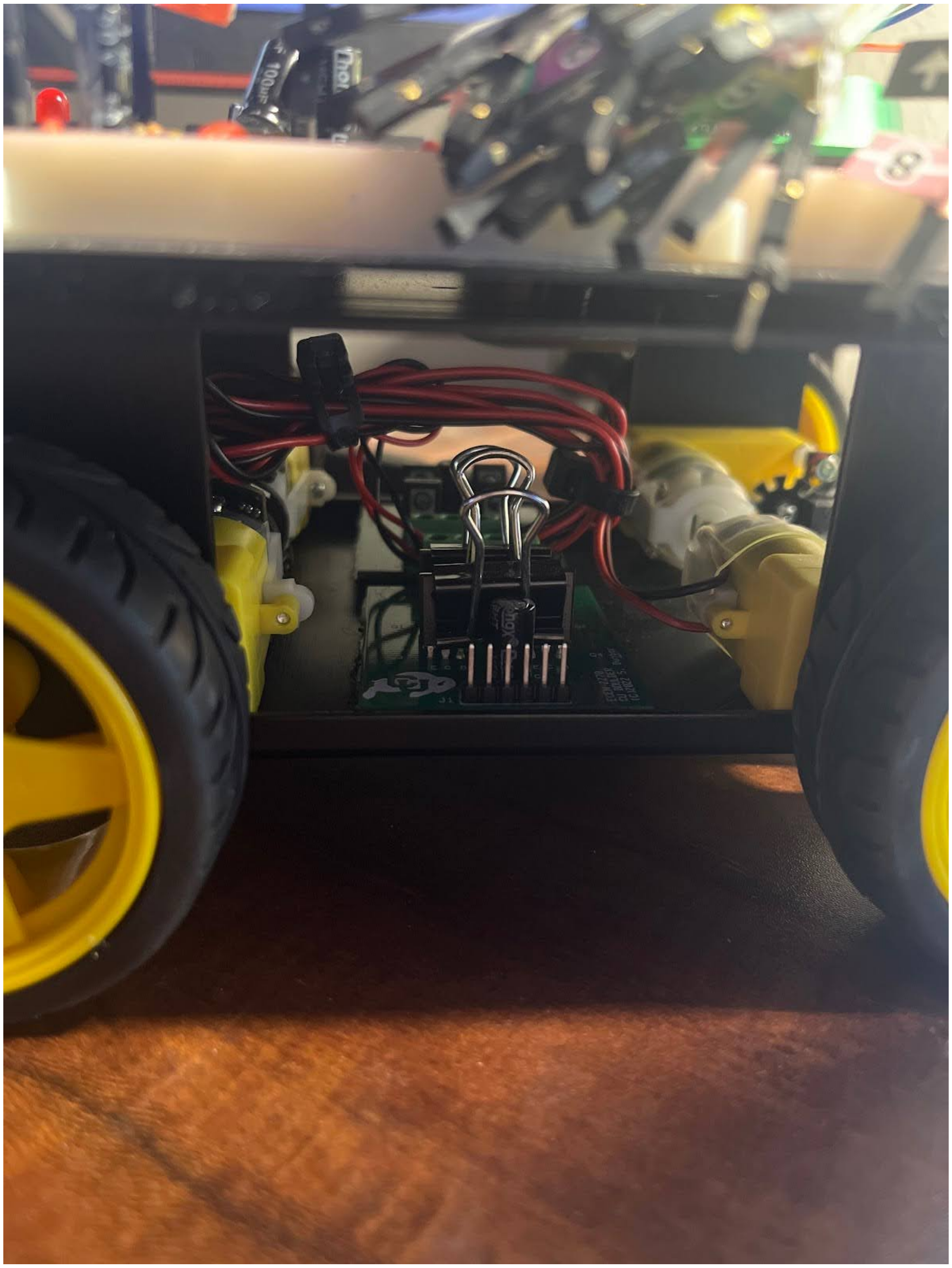


Fig. 12 Mounted Motor Driver and motor wiring

As shown in **Figure 12**, Motor Driver PCB's have been mounted to underside of robot chaises for all team members!

III. Experiment B

A. Exploration Topics

1) **What are some common examples of feedback control systems?**
One common example is home heating and cooling systems, which adjust to heat or cool based on temperature sensing. Another common example is cruise control in a car, which monitors the current speed and either accelerates or decelerates to maintain a constant speed

2) **How do the functions of positive and negative feedback systems differ?**
Positive and negative feedback systems differ in the function and application. The main function difference is that in a positive feedback the loop the feedback signal is added with the input signal, this is beneficial for rapid responses, however, it is much less accurate than negative feedback. In a negative feedback loop, the feedback signal is subtracted from the input signal, this enhances stability and accuracy of the control system. Examples of positive and negative feedback shown below.

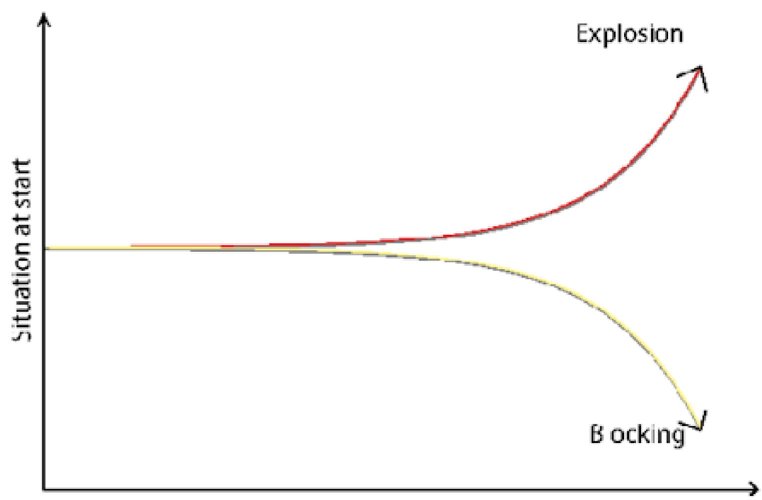


Fig. 13 Positive Feedback

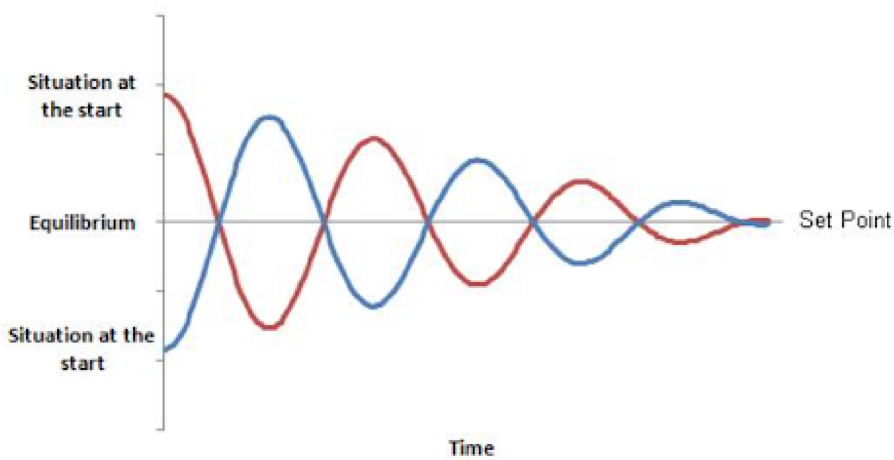


Fig. 14 Negative Feedback

3) **What is proportional, integral, and derivative control?**
   - **Proportional Control:** Modifies the output proportionally to the error.
   - **Integral Control:** Integrates the error over time to adjust and reduce the steady state error.
   - **Derivative Control:** Calculates rate of change in order to predict future trends.

4) **What is a good block diagram that shows the main principles of feedback control?**
The block diagram below shows a feedback control loop, which is a system that manages a process to achieve a desired output. It starts with a target or setpoint, followed by a controller that compares the target with the actual, measured output and calculates the necessary adjustment. An actuator, known as the final control element, then applies these adjustments to the process. The real-time output of the process is measured by sensors, and this information is fed back to the controller. This continuous cycle ensures that the actual output closely matches the desired outcome, allowing for dynamic and automatic regulation of the system.

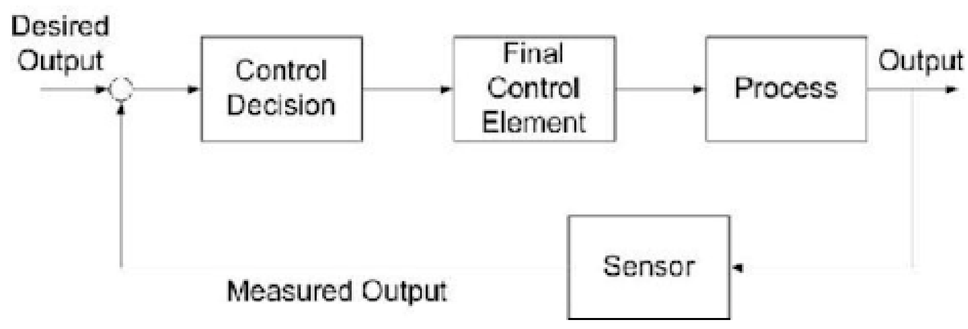


Fig. 15 Feedback Block Diagram

5) **What are advantages of feedback control systems?**
The advantages of feedback control lie in the fact that the feedback control obtains data at the process output. Because of this, the control takes into account unforeseen disturbances such as frictional and pressure losses. Feedback control architecture ensures the desired performance by altering the inputs immediately once deviations are observed regardless of what caused the disturbance. An additional advantage of feedback control is that by analyzing the output of a system, unstable processes may be stabilized.

6) **What are disadvantages of feedback control systems?**
Time lag in a system causes the main disadvantage of feedback control. With feedback control, a process deviation occurring near the beginning of the process will not be recognized until the process output. The feedback control will then have to adjust the process inputs in order to correct this deviation. This results in the possibility of substantial deviation throughout the entire process.

B. 3.B.2

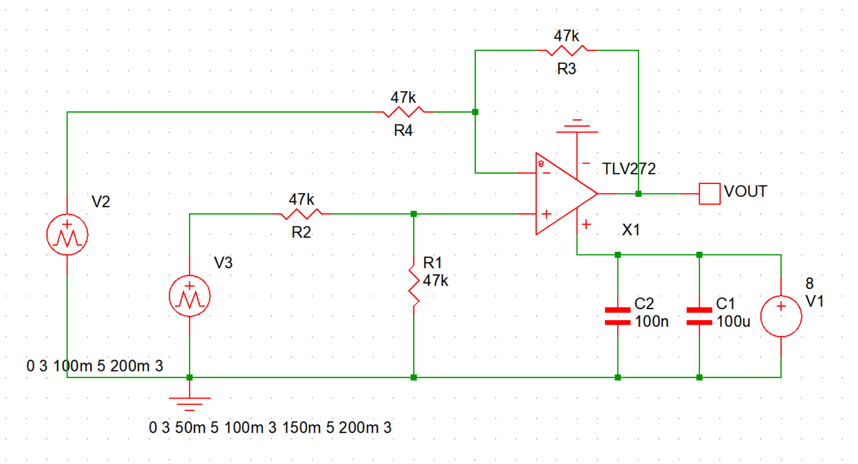


Fig. 16 Circuit Schematic

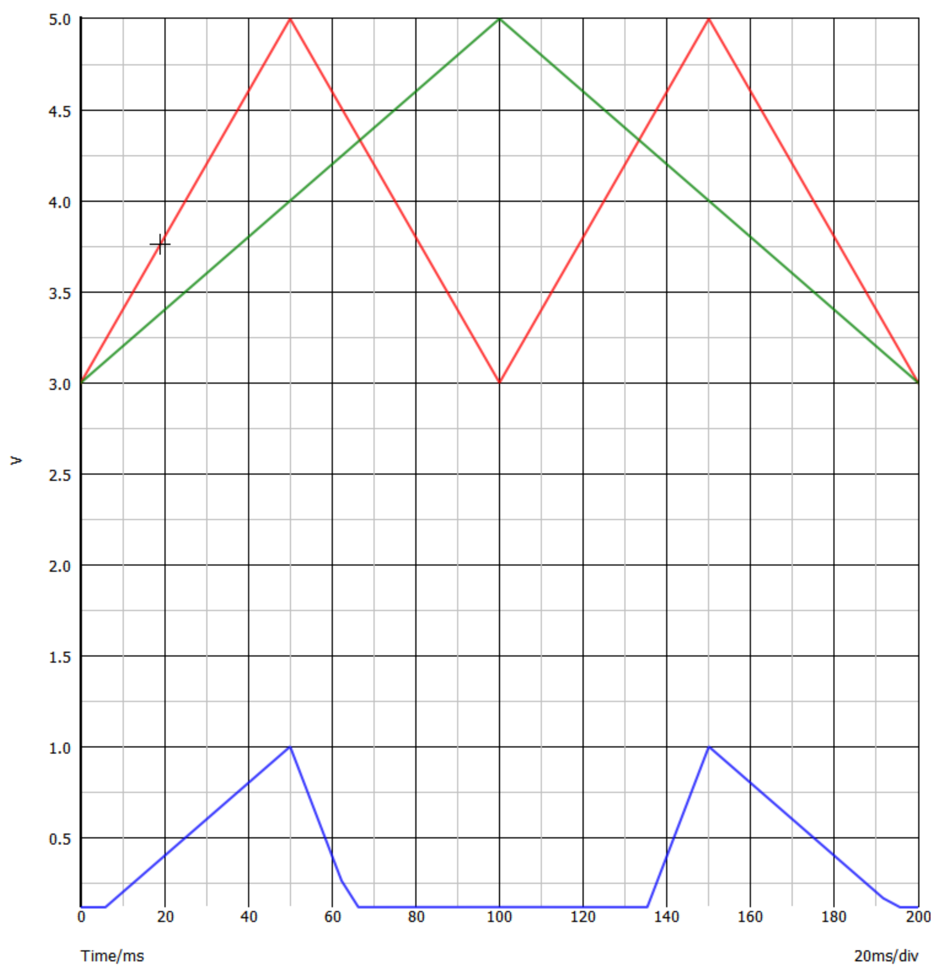


Fig. 17 Output Voltage

This Op-Amp configuration is called a Differential Op-Amp. It is governed by the equation:

$$V_{out} = \frac{Z_2}{Z_1}(V_2 - V_1) + V_0$$

Where in our case $V_0 = 0$ V and $Z_2 = Z_1 = 47\text{k}\Omega$. V_2 is labeled $V3$ in **Figure 16** and is denoted by the red line in **Figure 17** and V_1 is labeled $V1$ in **Figure 16** and is denoted by the green line in **Figure 17**.

This circuit subtracts the green line form the red line as seen in **Figure 17**, giving us the result seen in the blue line (V_{out}). There is a gain of one for this Op-Amp system, which can be modified by changing the impedance of either Z_2 or Z_1.

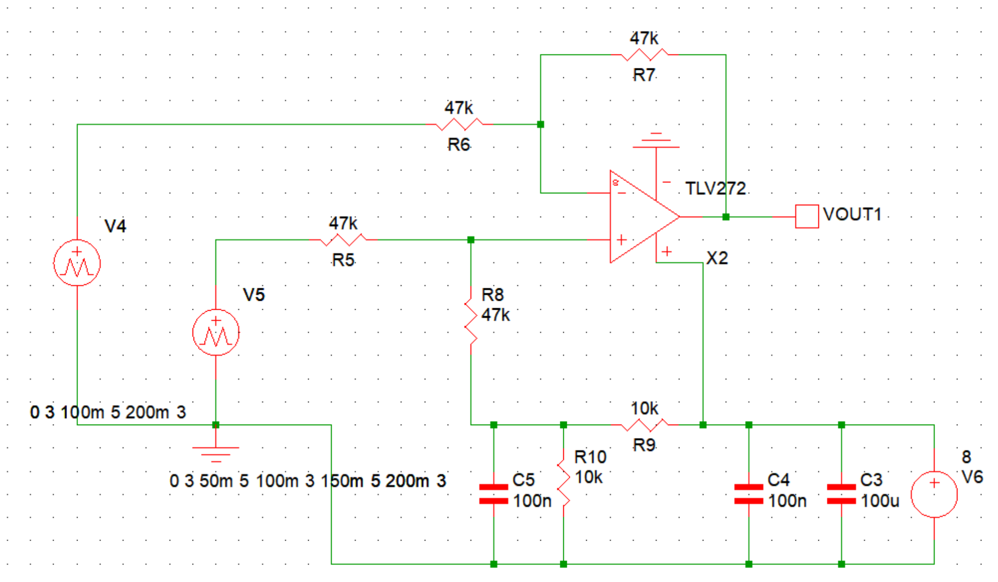


Fig. 18 Circuit Schematic

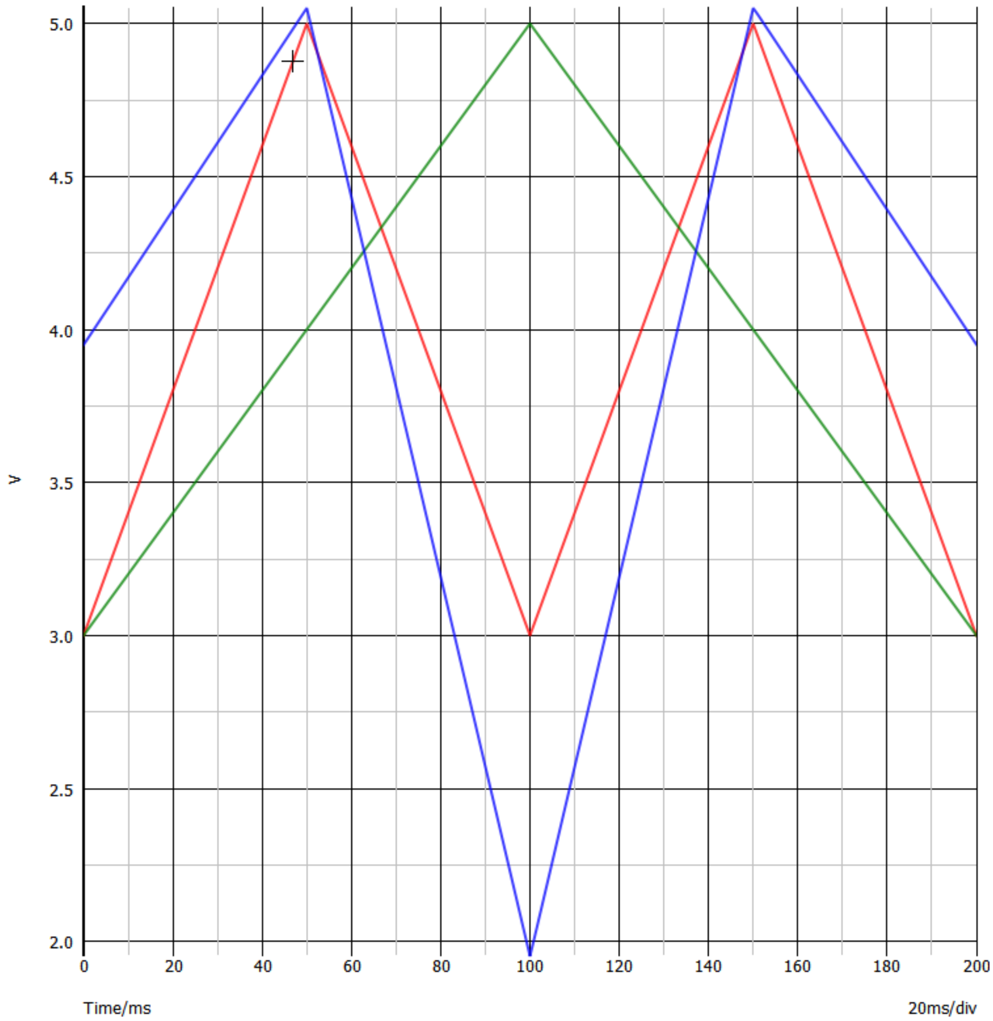


Fig. 19 Output Voltage

This circuit uses a Virtual Ground, which is useful for offsetting a desired output of a system by an arbitrary value. In this system, the Op-Amp still behaves exactly as described previously, however, the presence of the Virtual Ground changes the value of V_0 to 4 V. Thus, once the value of V_2 - V_1 (labeled $V5$ and $V4$ respectively in **Figure 18** and colored green and red respectively in **Figure 19**) is calculated, the value of V_0 = 4 V is added to the resulting difference.

This makes sense as at various points in **Figure 19** we can see the the difference between the green and red lines plus 4 V is reflected in the blue line (still represented by V_{out}).

These two circuits make use of the above equation, specifically its value of V_0 and how we can selectively pick this value in order to make sure that our result is always within the bounds we desire for it to be in. This circuit is used as a part of the Closed-Loop Circuit documented below by allowing us to subtract the current speed voltage from the desired reference voltage and determine how to change the output of further systems in order to minimize the difference between these two systems.

The Virtual Ground is needed, despite the Op-Amp already being powered) as it allows us to keep a steady and reliable Virtual Ground for reference as needed within our circuit, and to boost up the output of this stage of the I-Compensator (documented below) into the expected output range.

C. 3.B.3

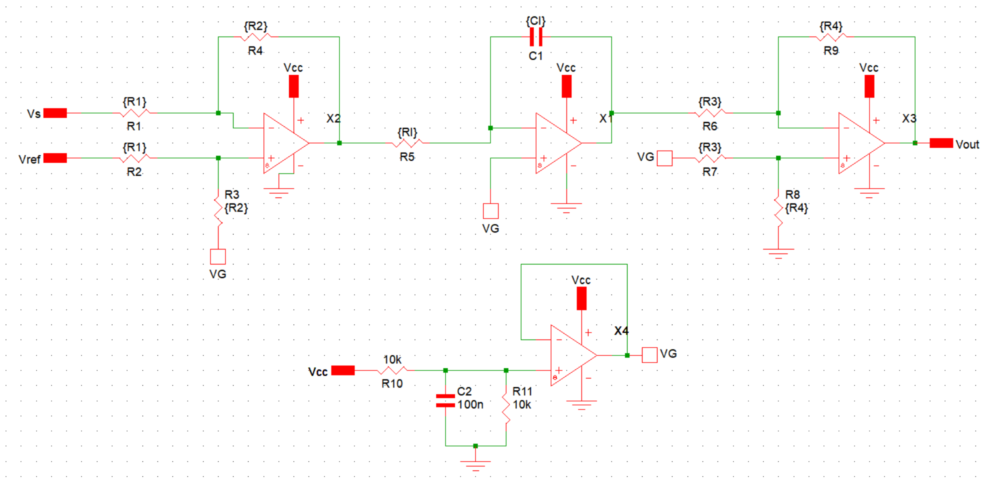


Fig. 20 I-Compensator Internals

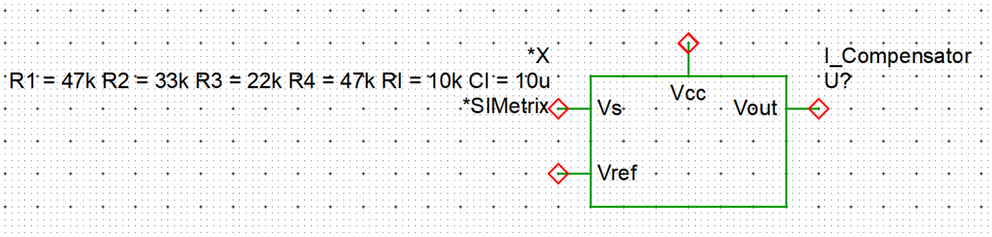


Fig. 21 I-Compensator Symbol

In order to achieve a time constant (τ) of 100 ms we can use a R_i = 10kΩ and C_i = 10μF.

D. 3.B.4

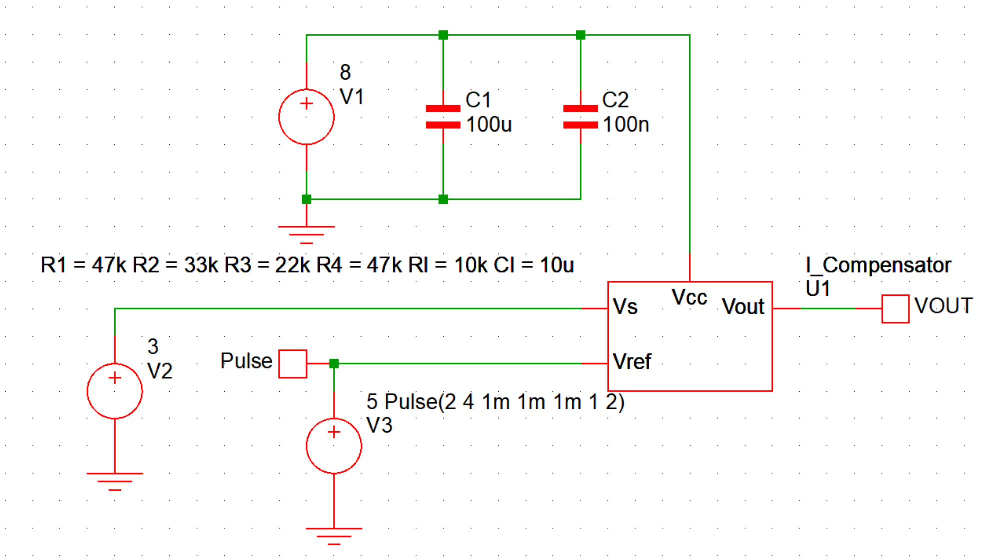


Fig. 22 Open-Loop Feedback Test Circuit

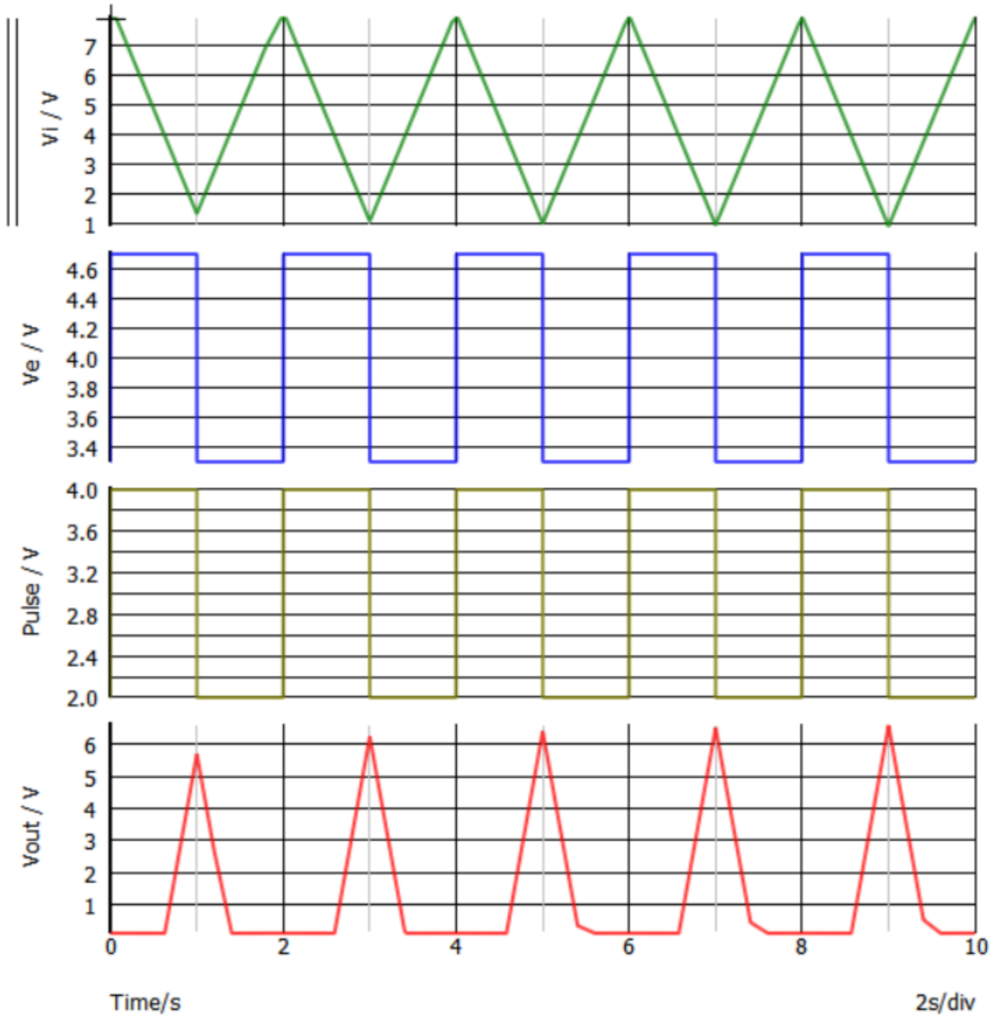


Fig. 23 Open-Loop Voltages

The outputs of the first and second Op-Amps as seen in **Figure 20** are known as V_e and V_i respectively. The purposes of each one allows the full system to work and fulfills a specific process seen in the following figure:

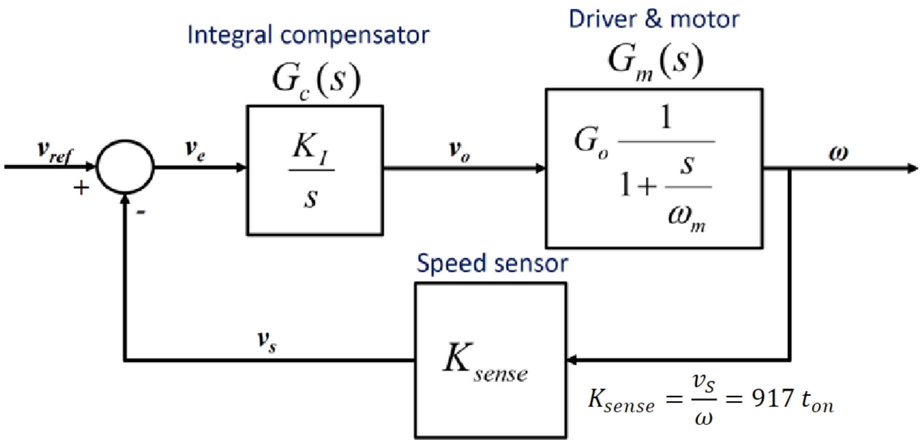


Fig. 24 Open-Loop System Block Diagram

V_e achieves the purpose of the Sum/Difference Node by taking the difference of the reference and current speed voltages and boosting it up (via the Virtual Ground) into desirable ranges. This resulting difference is called the error voltage.

Similarly, the value V_i, called the integrator/integrated voltage, is responsible for carrying out the process desired in the "Integral Compensator" block in **Figure 24**. This Op-Amp takes returns the "area under the curve" or integral of the output waveform of the error voltage (V_e) and outputs that voltage. In most normal systems, when using an integral system in control law/theory, it is important to make sure your integration result does not "cascade" or excessively build-up. This may end up overloading the system and lead to problems. In our physical system, this is limited by the rails of the Op-Amp (limiting the Op-Amp to a 8 V maximum output).

Lastly, the output V_{out} (sometimes denoted V_o) is the output of the full system. This voltage is what is passed along to the H-bridge or Direction Control system (both documented later) to drive the motor(s). This value, being responsible for the motors driving voltage, also directly effects the encoder pulsing of the motor, in turn effecting the current speed voltage and bringing us back to the start of the block diagram and making this a Closed-Loop system.

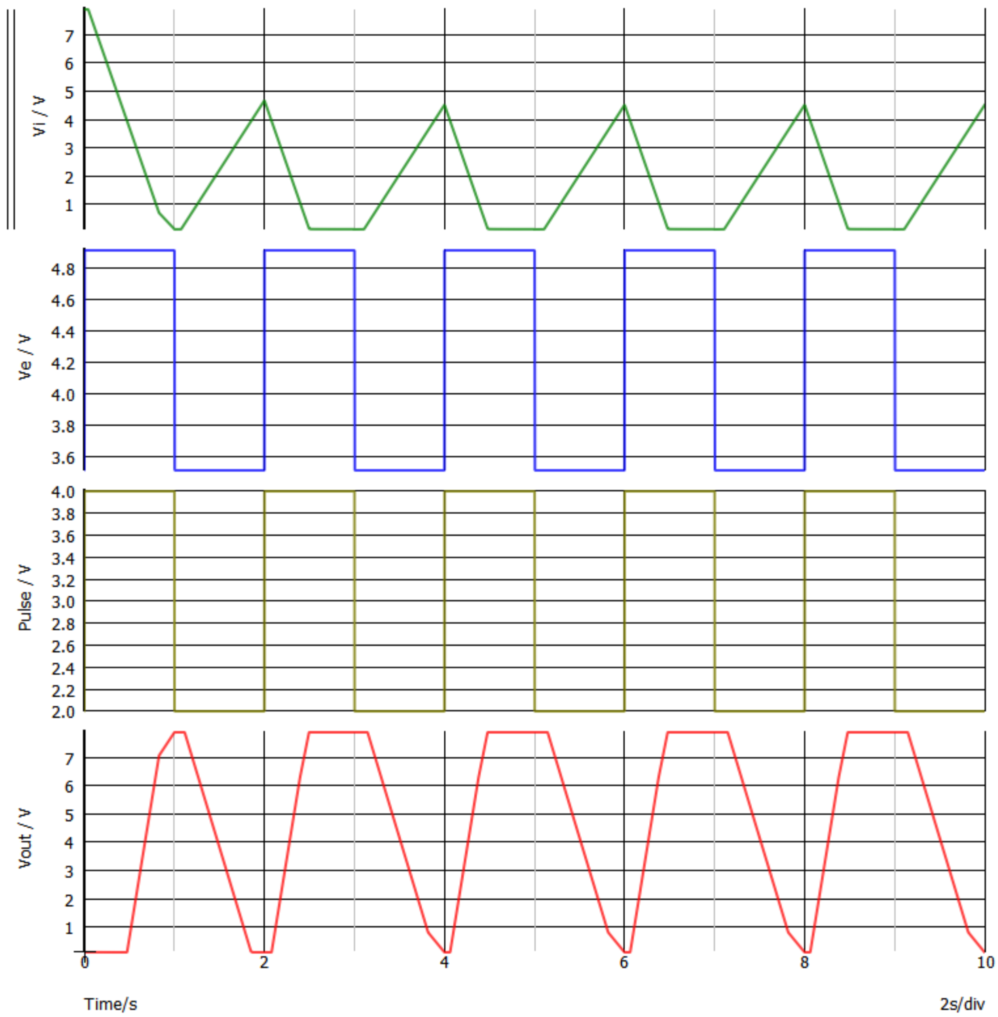


Fig. 25 Open-Loop Voltages (V_s = 2.7 V)

As seen when comparing **Figure 23** and **Figure 25**, Decreasing V_s in turn increases V_e, the error between the V_s and V_{ref}, because V_{ref} stays the same while decreasing V_s. With the error increasing its offset, V_i decreases which causes heavy clipping at the bottom because it is an inverting Op-Amp. This causes the output, V_{out}, to also offset positively causing clipping on the top.

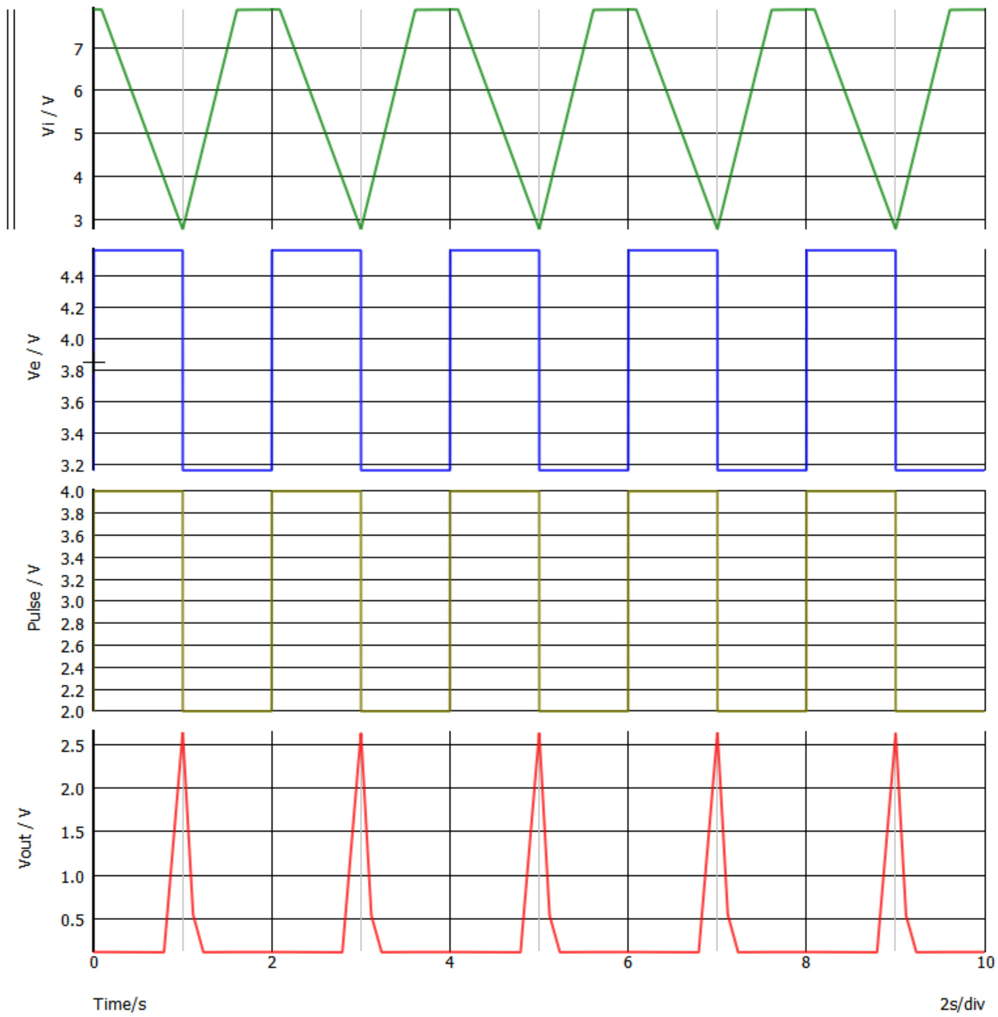


Fig. 26 Open-Loop Voltages (V_s = 3.2 V)

As seen when comparing **Figure 23** and **Figure 26**, Increasing V_s in turn decreases V_e, the error between the V_s and V_{ref}, because V_{ref} stays the same while increasing V_s. With the error increasing its offset, V_i increases which causes clipping at the top rail because it is an inverting Op-Amp. This causes the output, V_{out}, to also offset negatively causing clipping on the bottom.

E. 3.B.5

Calculations for Finding the Right C_i and R_i for $\zeta = 1$ and using our motor parameters:

$R_B(\Omega)$	β	J	k	R_M
330	100	0.00442	0.274	2.51

Table 6 Motor Parameters

$$
\begin{aligned}
R &= R_M + \frac{R_B}{\beta} \\
&= 2.51 + \frac{330}{100} \\
&= 5.81 \\
\omega_m &= \frac{k^2}{Jk} \\
&= \frac{(0.274)^2}{(.00442)(2.51 + 3.3)} \\
&= 2.923 \\
G_o &= \frac{1}{k} \\
&= \frac{1}{0.742} \\
&= 3.65 \\
k_{sense} &= (max(V_s))(t_{on})(\frac{960}{2\pi}) \\
&= (6)(249 * 10^{-6})(153) \\
&= 0.229 \\
\zeta &= \frac{\omega_m}{2 \cdot \sqrt{G_0 \cdot \omega_m \cdot k_1 \cdot k_{sense}}} \\
k_1 &= \frac{(\frac{\omega_m}{2\zeta})^2}{G_o \cdot \omega_m k_{sense}} \\
&= \frac{(\frac{2.923}{2})^2}{(3.65)(2.923)(0.229)} \\
&= 0.874 \\
Let\ C_1 &= 100 \cdot 10^{-6} \\
k_1 &= \frac{1}{C_1 \cdot R_1} \\
R_1 &= \frac{1}{k_1 \cdot C_1} \\
&= \frac{1}{(0.874)(100 * 10^{-6}} \\
&= 11441\Omega
\end{aligned}
$$

We are going to use a 10kΩ resistor from our kit along with a 100uF capacitor.

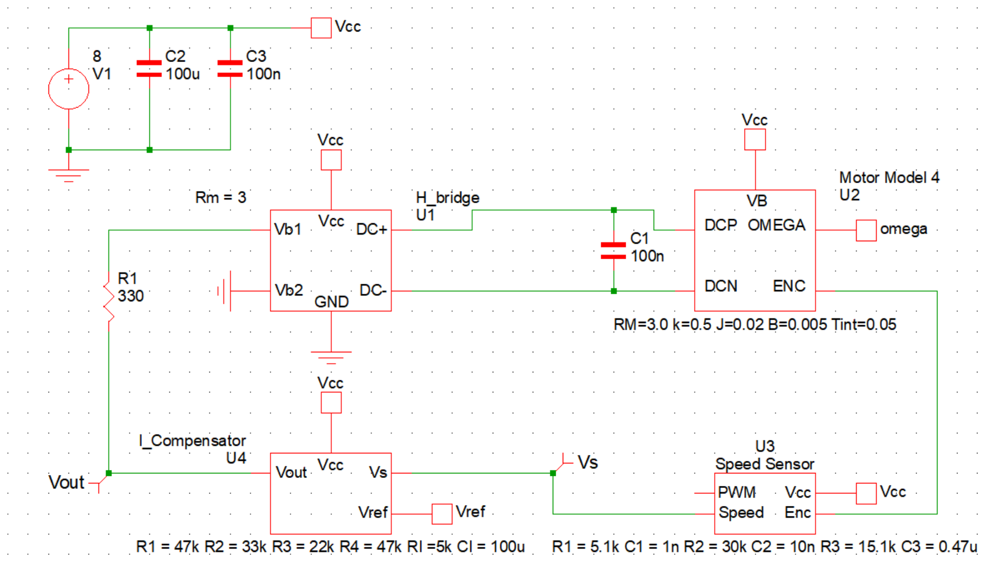
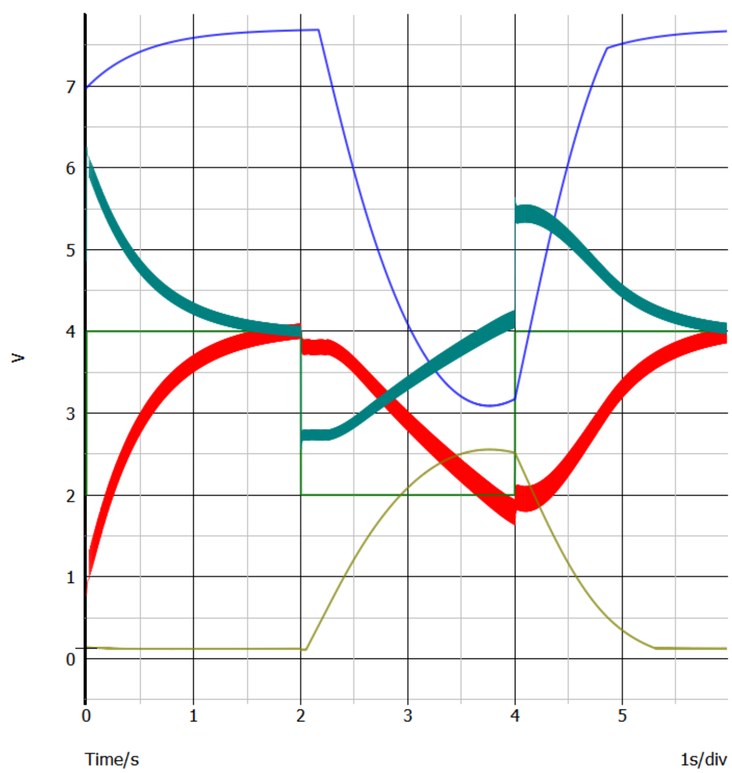


Fig. 27 Closed Loop Circuit Schematic



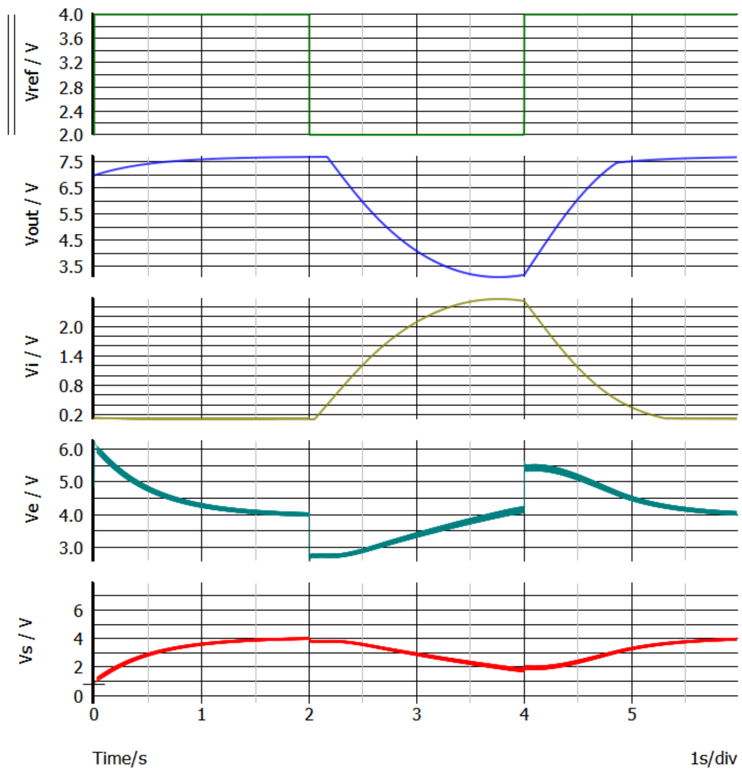


Fig. 28 Closed Loop Circuit Voltages (unstacked and stacked)

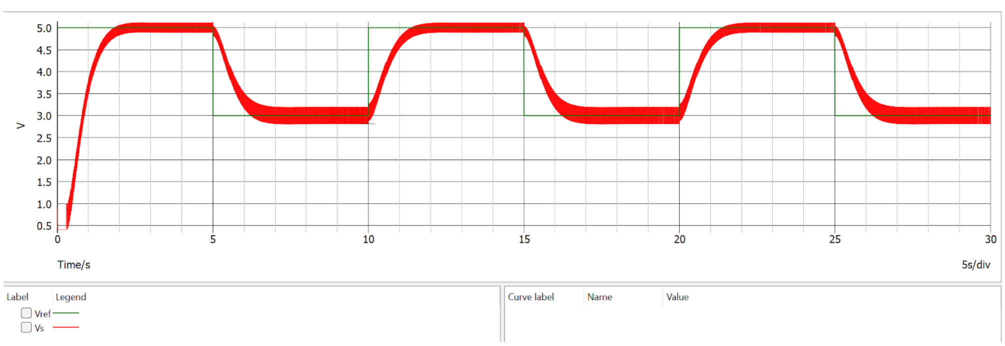


Fig. 29 V_{ref} with period of 5 sec to compare V_s and V_{ref}

These results are exactly what we would expect. As seen in **Figure 28** the changing reference voltage (V_{ref}, marked in green) causes the error voltage (V_e, marked in turquoise) to rise to the value of the difference between the reference voltage and the speed voltage (V_s, marked in red). The integrator voltage (V_i, marked in gold) takes the integration (across all time) and propagates it forwards in order to apply at the output (V_{out}, marked in blue) and drive the motor faster or slower so the current speed voltage is the same as the reference voltage thus making the V_e = 0 V and driving V_i to 0 as well).

The values of R_i and C_i were picked specifically so that the damping coefficient (ζ, a value dependent on the physical system parameters) is roughly equal to 1. This makes the system critically damped. This choice was made so that we have reasonable risetime with little to no overshoot compared to faster rise times with more significant overshoot (an underdamped system) and/or a long risetime but no overshoot (an overdamped system).

F. 3.B.6

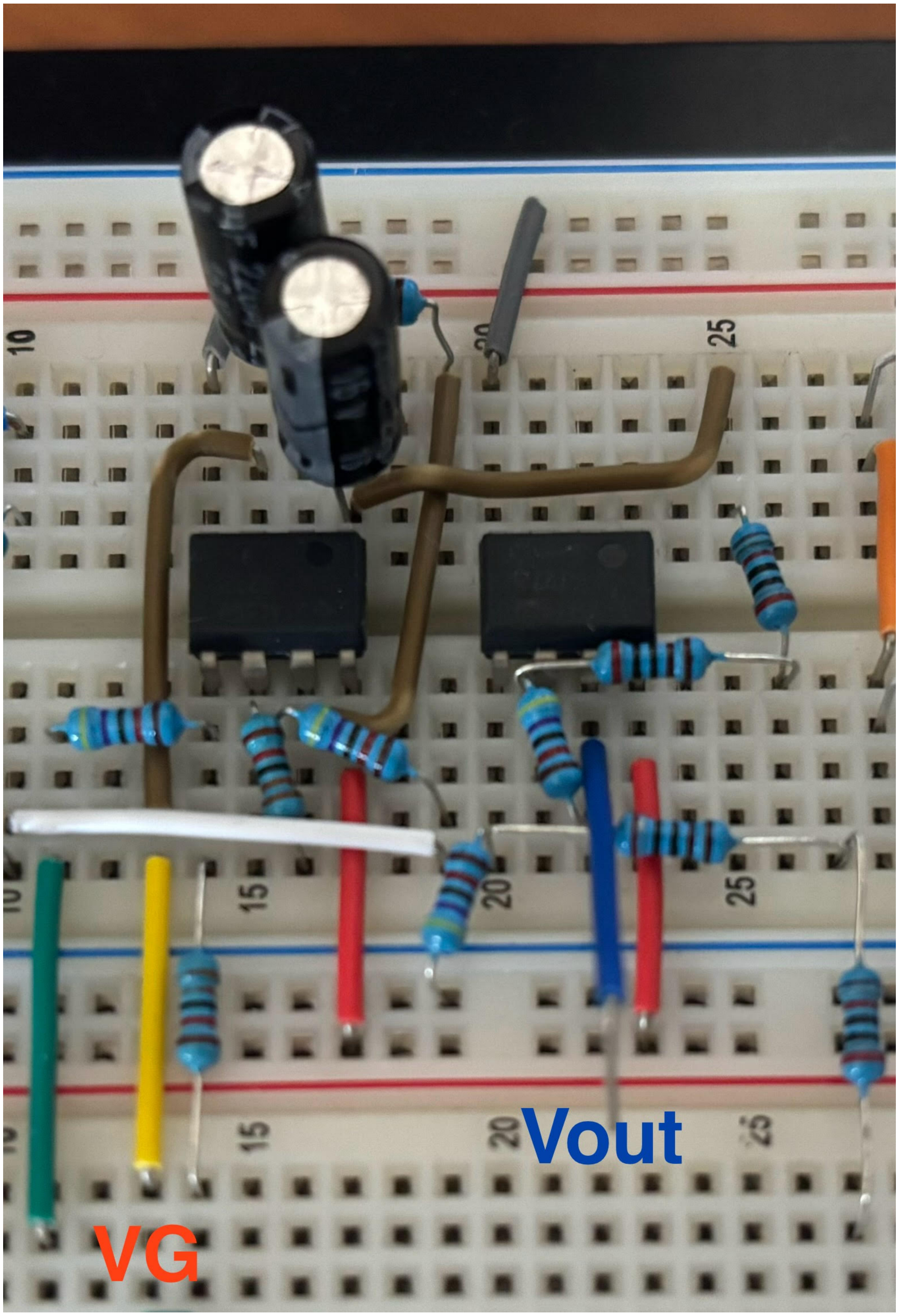


Fig. 30 Physical Compensator Circuit

G. 3.B.7

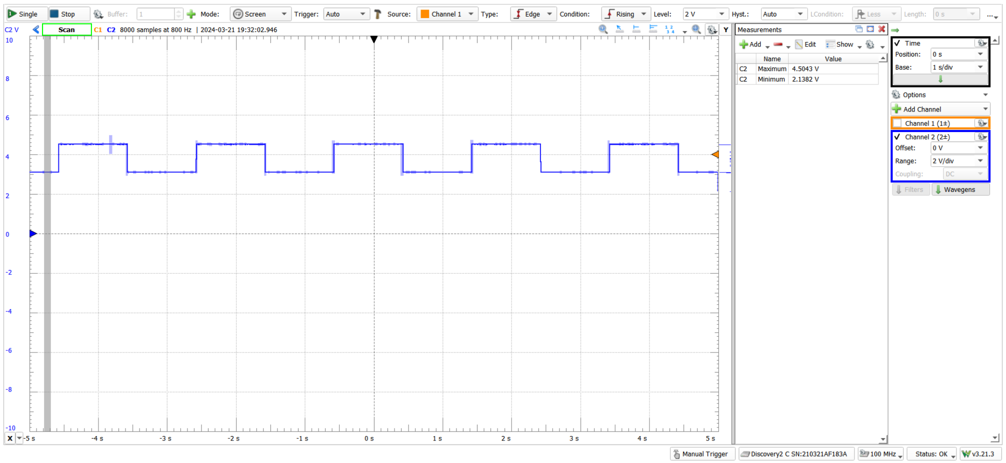


Fig. 31 Compensator Circuit V_e

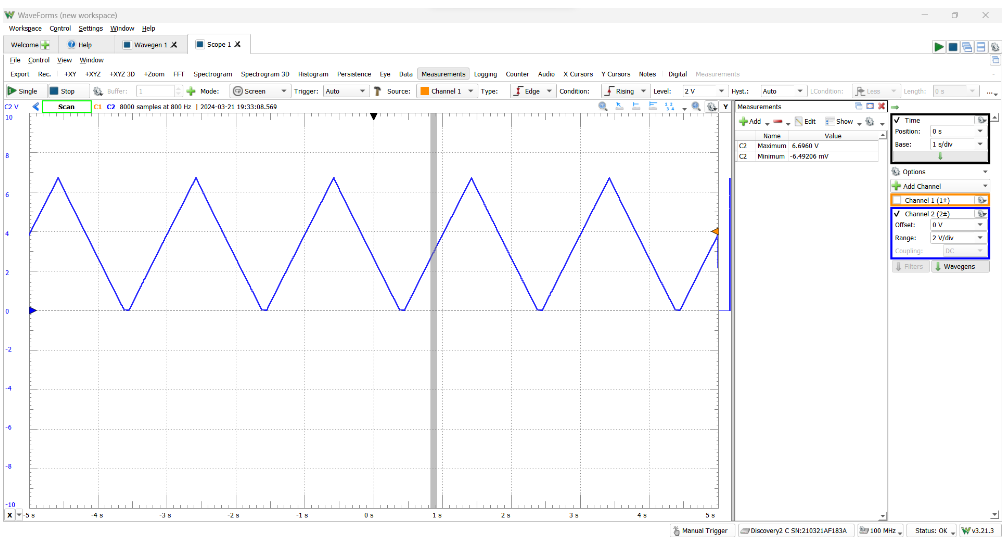


Fig. 32 Compensator Circuit V_i

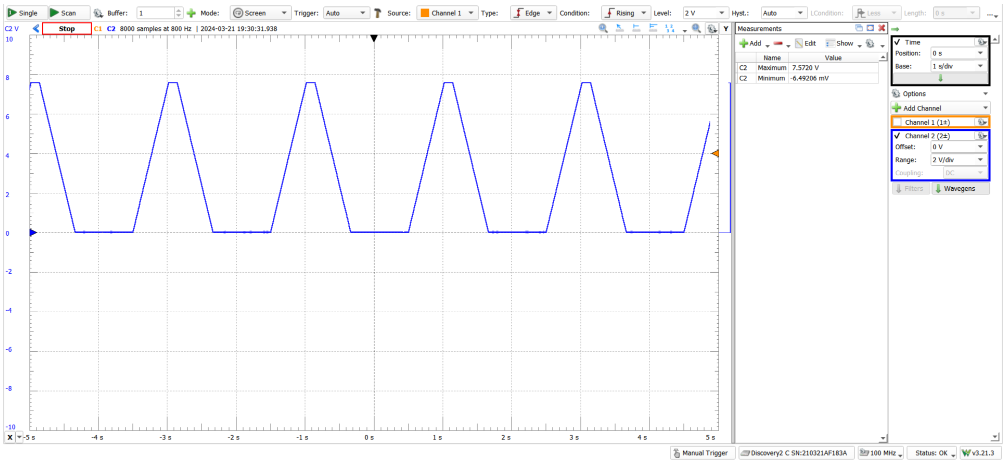


Fig. 33 Compensator Circuit V_{out}

Changed V_s to 2.7 V:

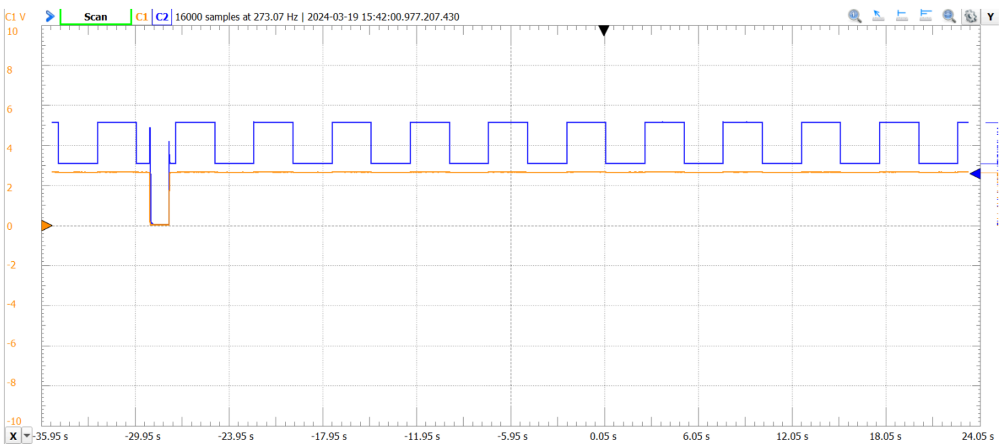


Fig. 34 V_e

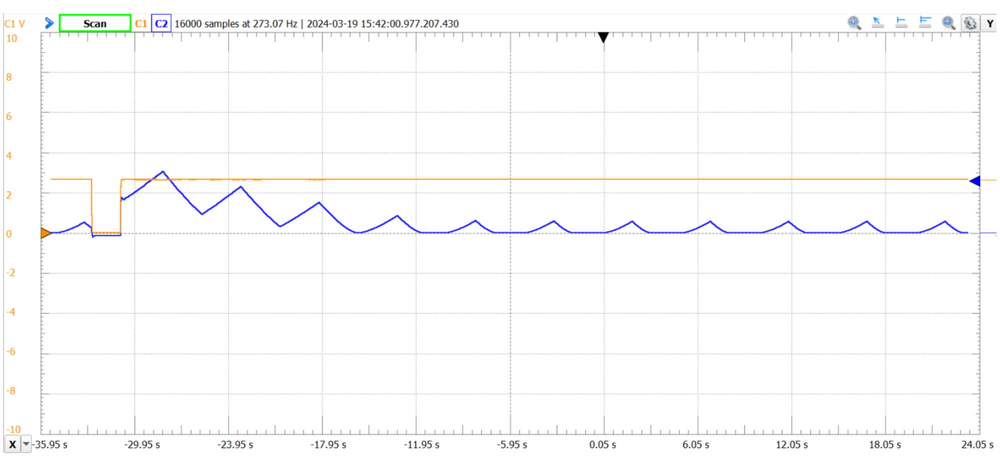


Fig. 35 V_i

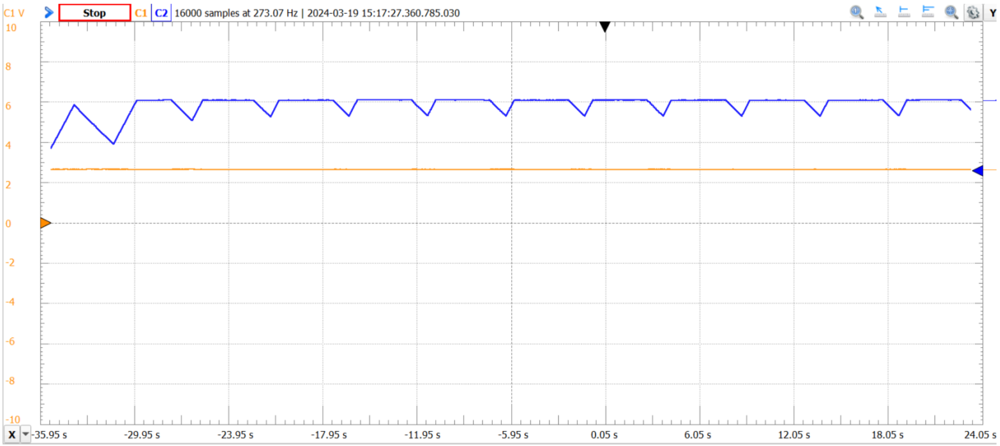


Fig. 36 V_{out}

Changed V_s to 3.2 V:

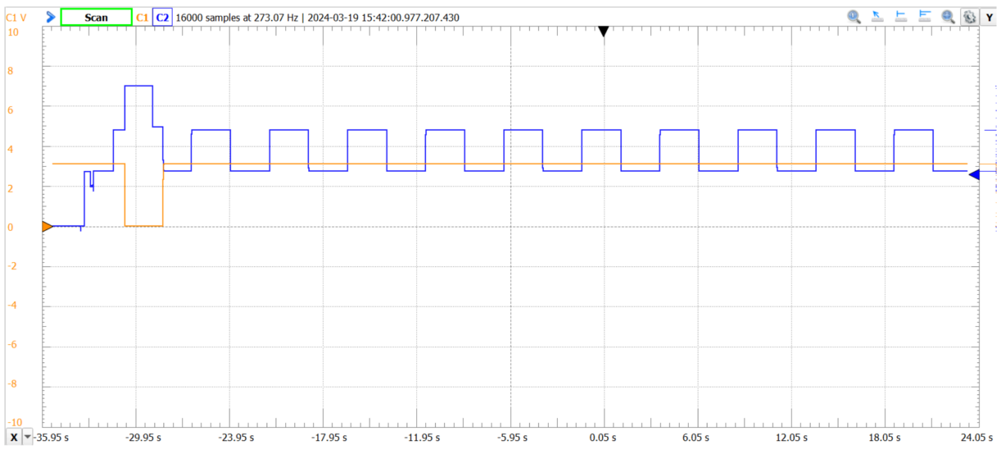


Fig. 37 V_e

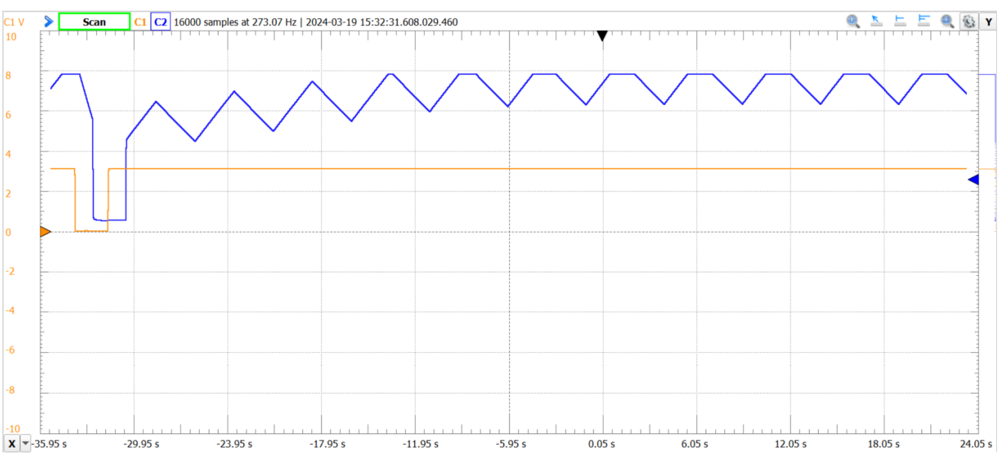


Fig. 38 V_i

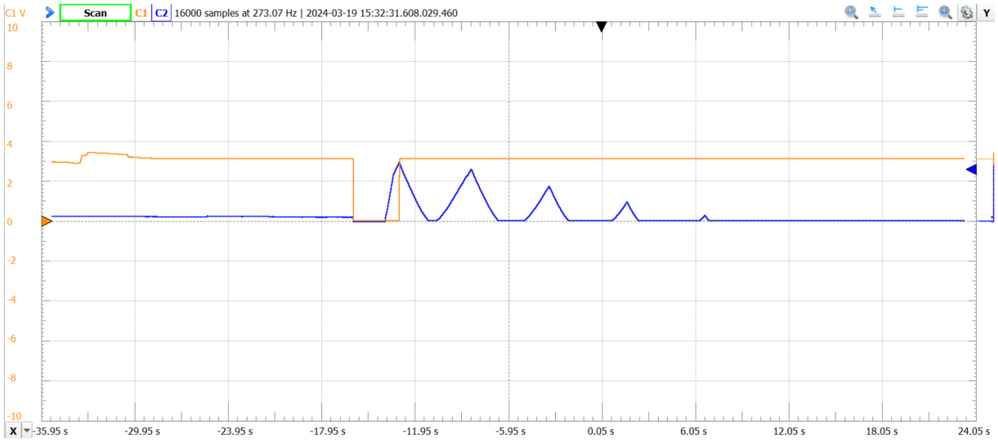


Fig. 39 V_{out}

Note: V_i and V_{out} are saturating at 8 V and 0 V because we are supplying Vcc with 8 V.

As seen by the simulation, changing V_s to a lower voltage made V_e shift up, V_i shift down, and V_{out} shift up, and increasing V_s to a higher voltage made V_e shift down, V_i shift up, and V_{out} shift down.

H. 3.B.8

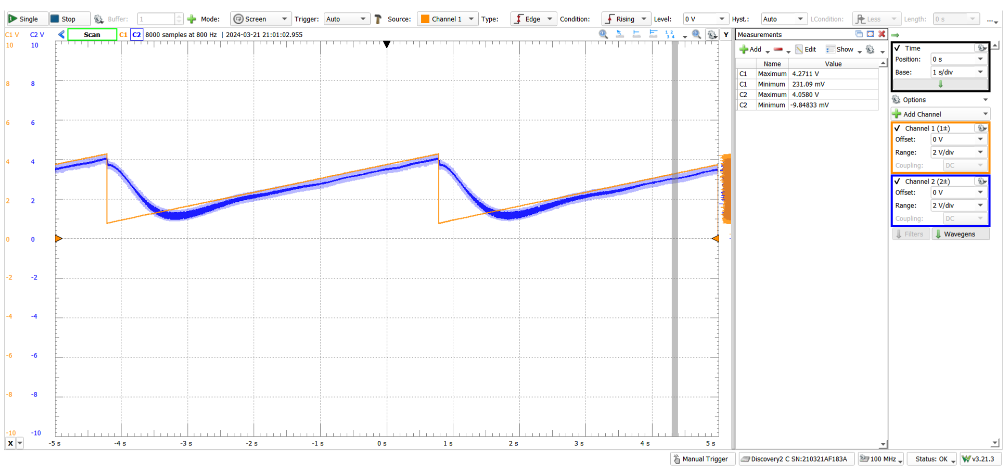


Fig. 40 Compensator Circuit V_{ref} vs. V_s

The full speed range appears to be obtainable, V_s tracks V_{ref} very well.

R_i = 5.1kΩ and C_i = 110μF were used for these results. These values are slightly different than the simulated values but cause no significant changes and is deemed acceptable.

V_{ref}	V_s
4.39	4.4
3.91	3.924
3.424	3.442
2.934	2.958
2.448	2.476
1.962	1.99
1.474	1.504
0.988	1.028

Table 7 Linearity test for V_{ref} and V_s

I. 3.B.9

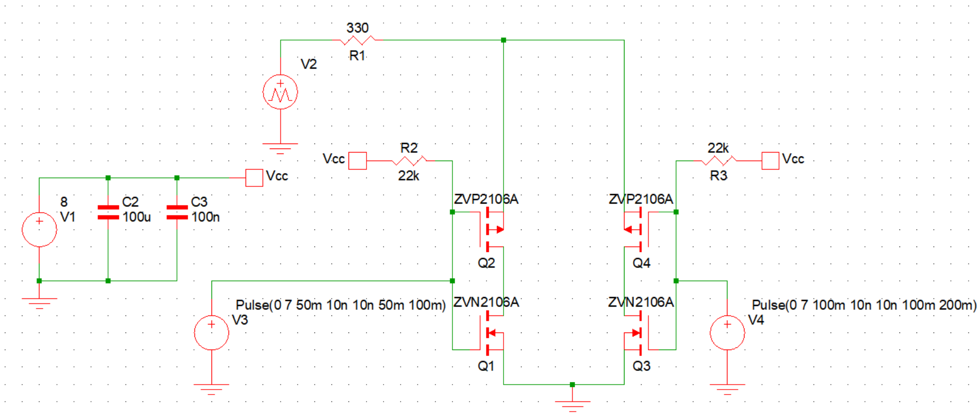


Fig. 41 Direction Control Circuit

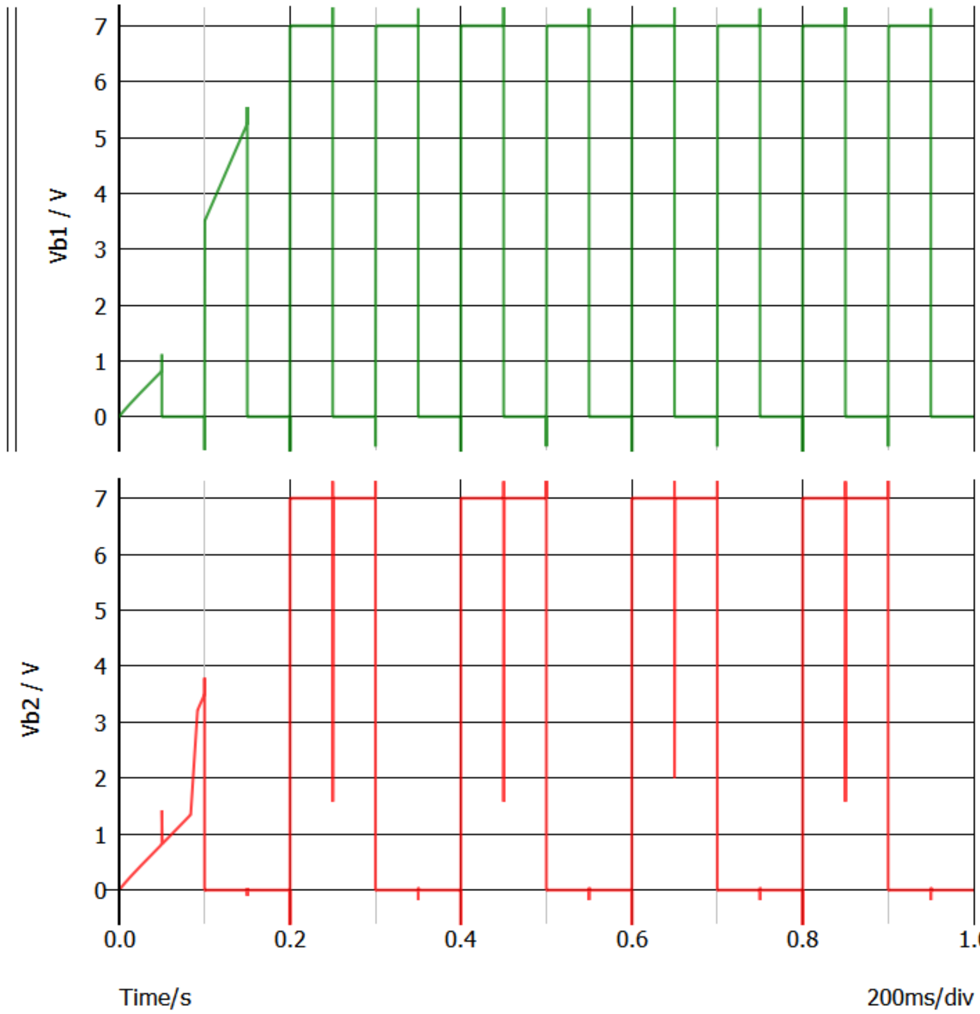


Fig. 42   Direction Control Circuit Voltages

VG_{left} [V]	VG_{right} [V]	V_{B1} [V]	V_{B2} [V]	M1	M2	M3	M4
0	0	7	7	ON	ON	OFF	OFF
0	7	7	0	ON	OFF	OFF	ON
7	0	0	7	OFF	ON	ON	OFF
7	7	0	0	OFF	OFF	ON	ON

Table 8   Direction Control Circuit Logic

In order to test this circuit after building the physical system, we will probe V_{B1} and V_{B2}, then apply sufficient voltage to either V_{G1} or V_{G2} while applying ground to the other terminal and ensuring that it spins the wheels in opposite directions without effecting the motor dynamics.

J. 3.B.10

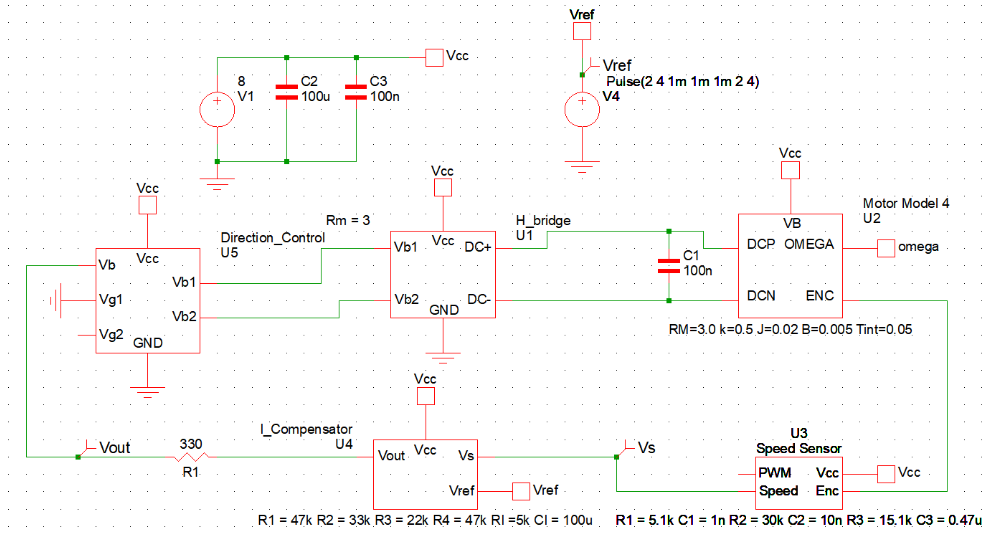


Fig. 43 Direction Control Circuit

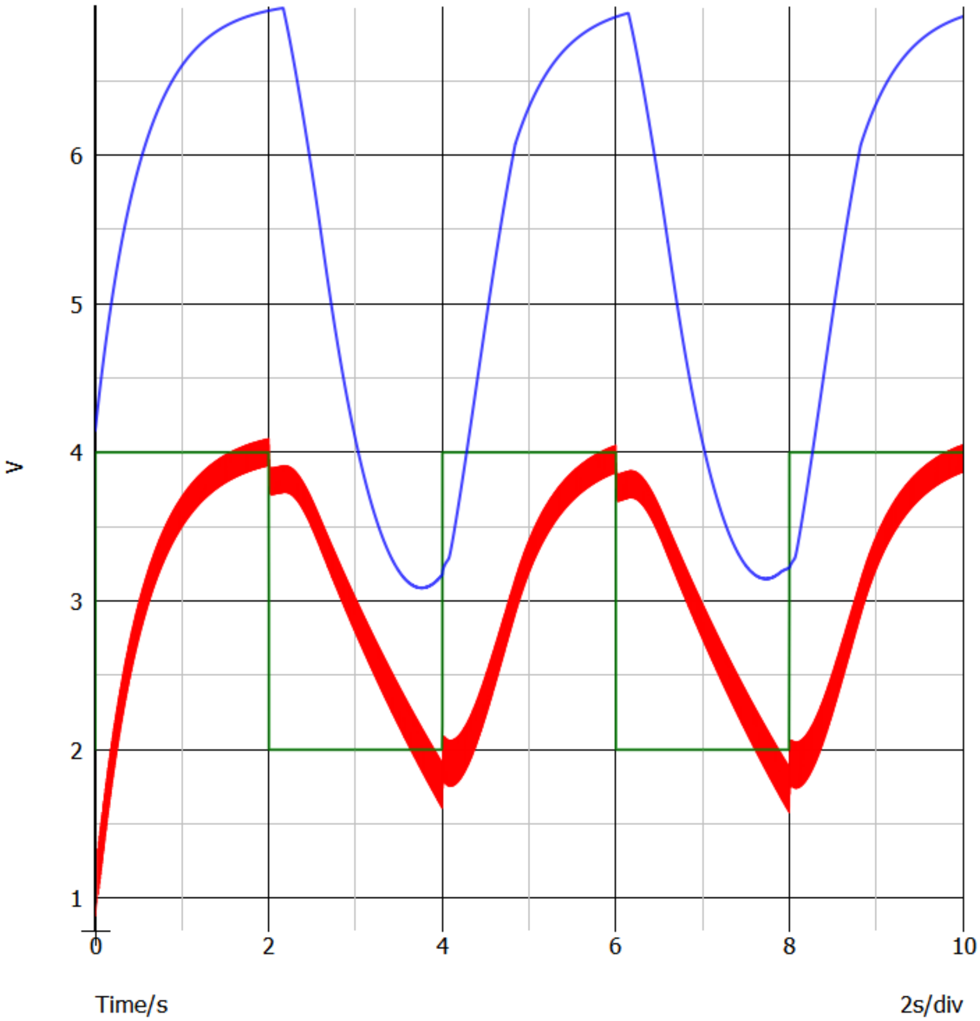


Fig. 44 Direction Control Circuit Voltages

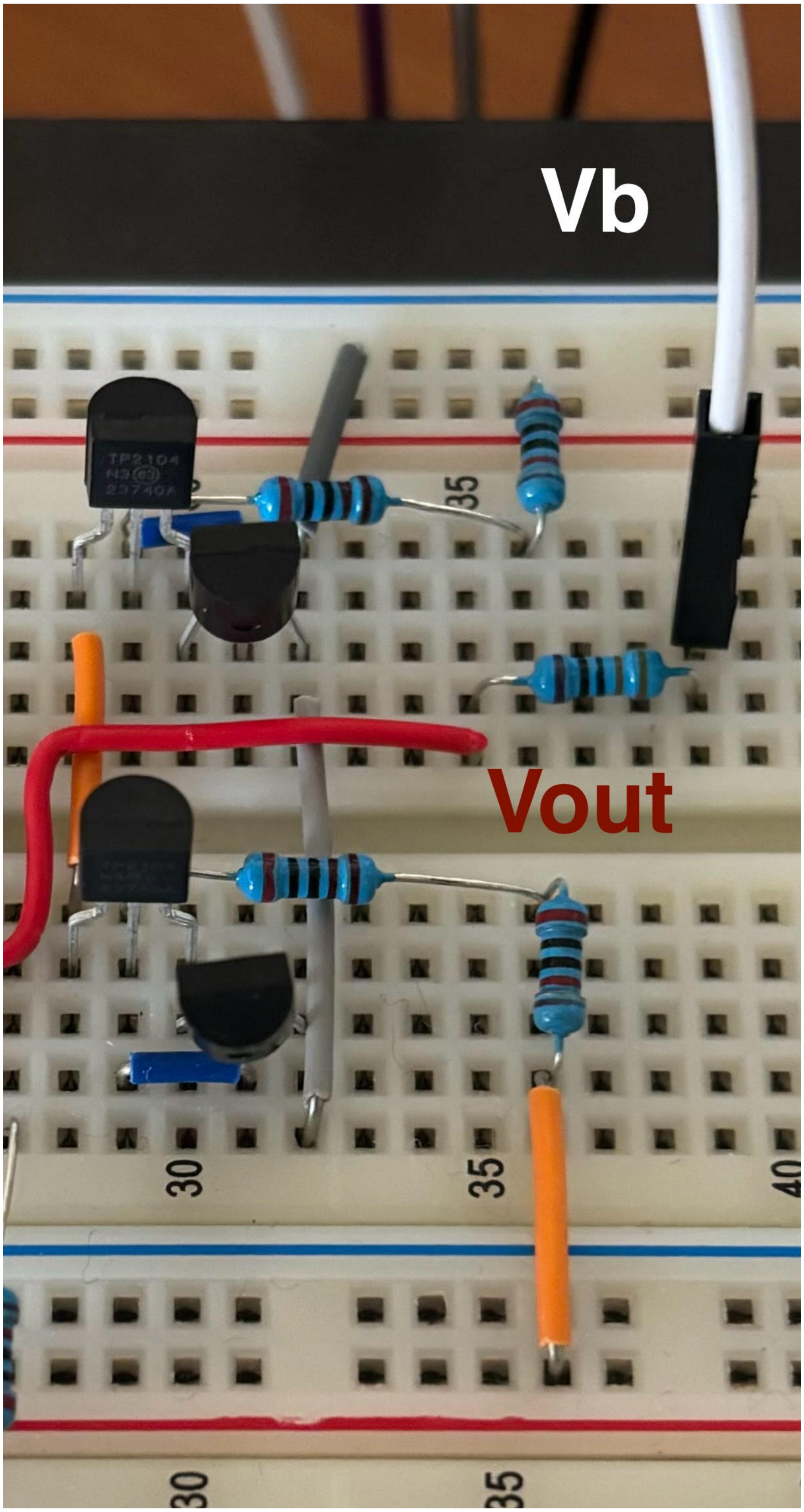


Fig. 45 Physical Direction Control Circuit

$V_{G_{left}}$ [V]	$V_{G_{right}}$ [V]	V_{B1} [V]	V_{B2} [V]	M1	M2	M3	M4
0	0	6.92	6.95	ON	ON	OFF	OFF
0	6.92	6.91	0	ON	OFF	OFF	ON
6.93	0	0	6.89	OFF	ON	ON	OFF
6.98	6.94	0	0	OFF	OFF	ON	ON

Table 9 Direction Control Circuit Logic Measured

K. 3.B.11

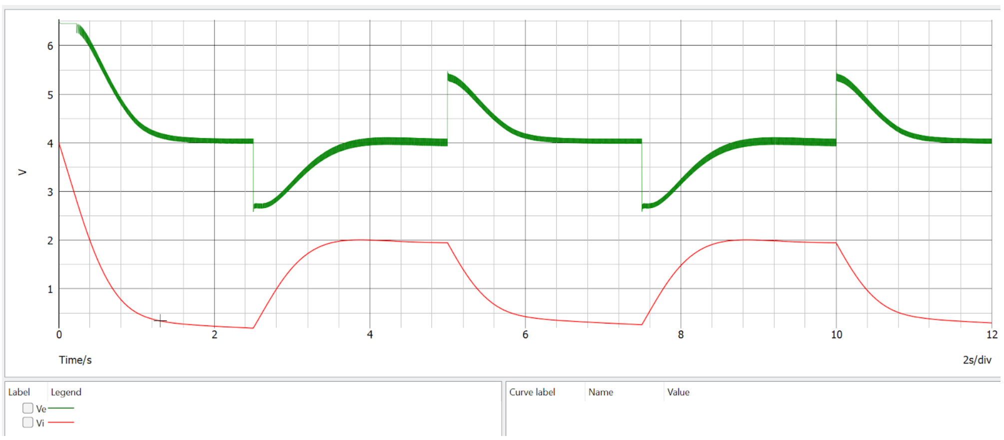


Fig. 46 Simulated V_e and V_i

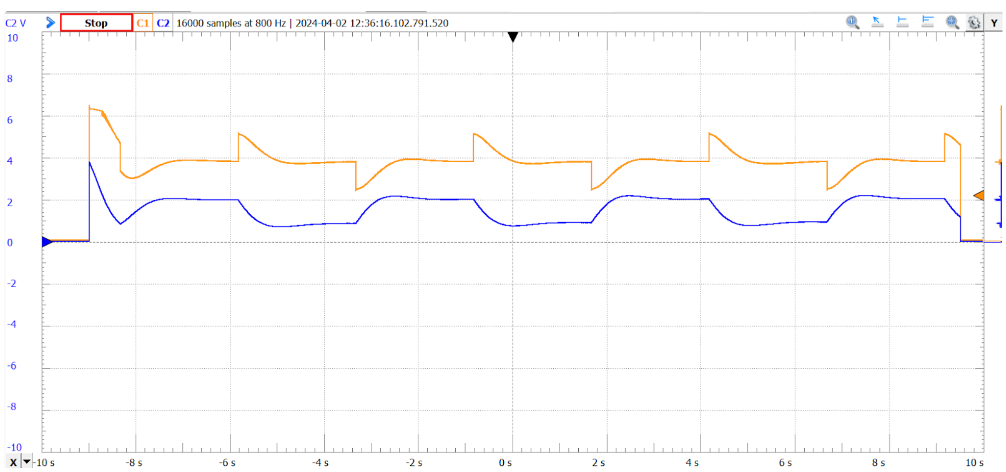


Fig. 47 Measured V_e and V_i

Using the circuit from **Figure 43**, the simulated values of V_e and V_i are as shown in **Figure 46**, which very closely matches our measured V_e and V_i shown in **Figure 47**. This indicated that our complete circuit is working properly.

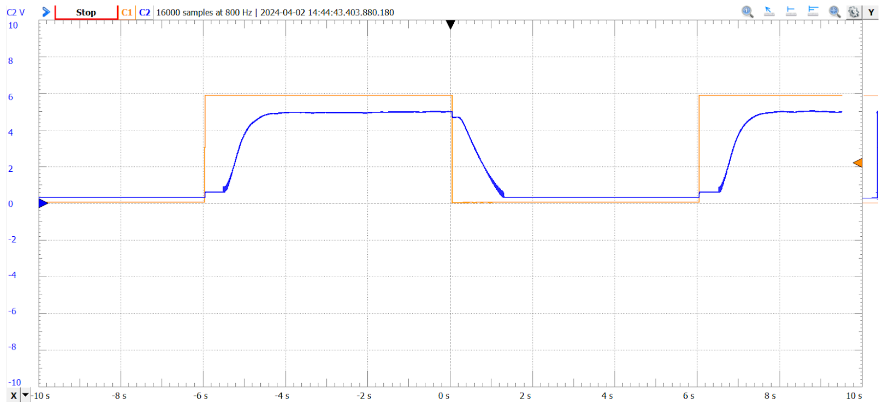


Fig. 48   Static Testing in the Forward Direction

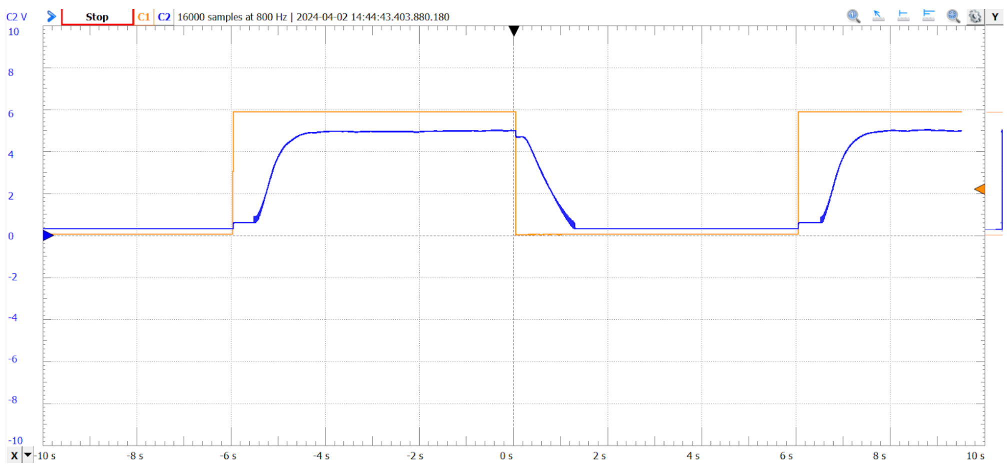


Fig. 49   Static Testing in the Backward Direction

After completing our static testing, we notice the max speed to be just above 5 V in both the forward and backward directions. This is acceptable because the Arduino going forward will not be supplying more than 5 V.

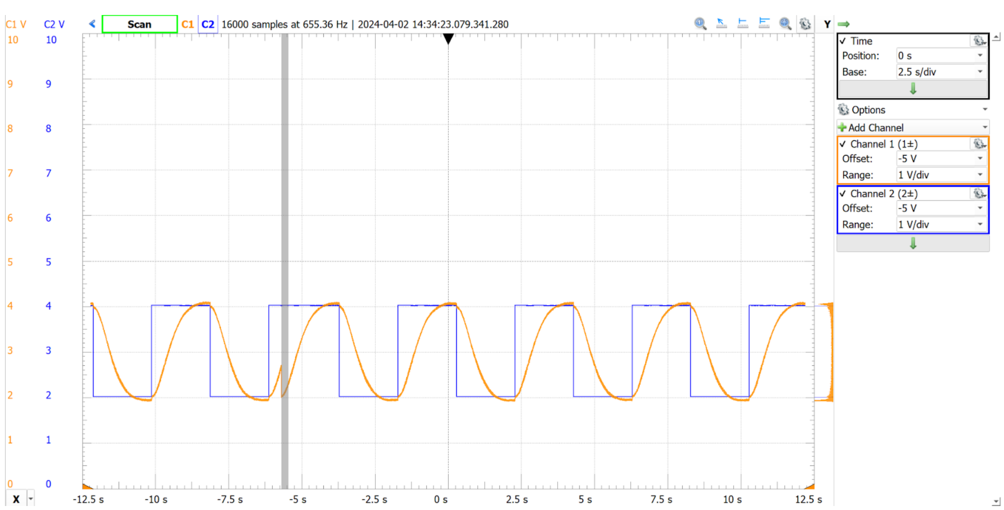


Fig. 50   Dynamic Testing with a smaller R_i, $\zeta < 1$

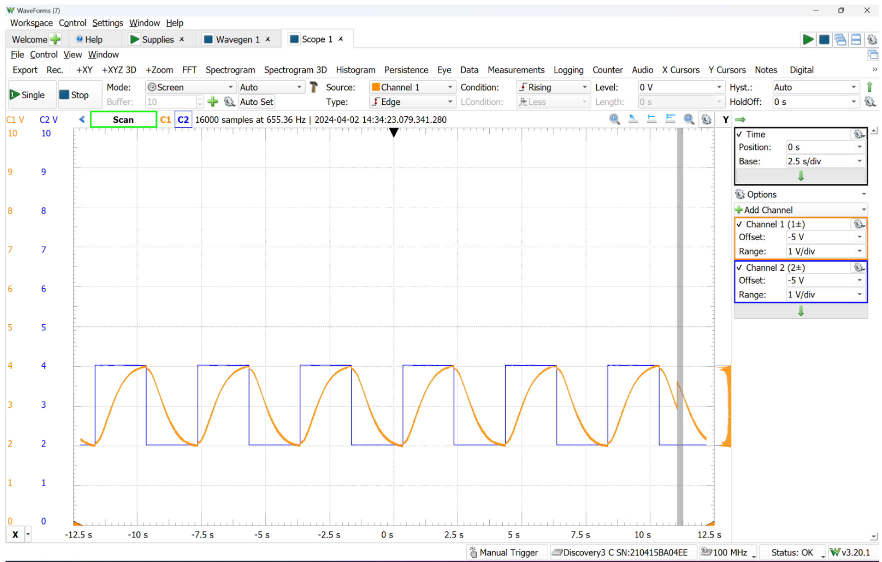


Fig. 51 Dynamic Testing with a larger R_i, $\zeta > 1$

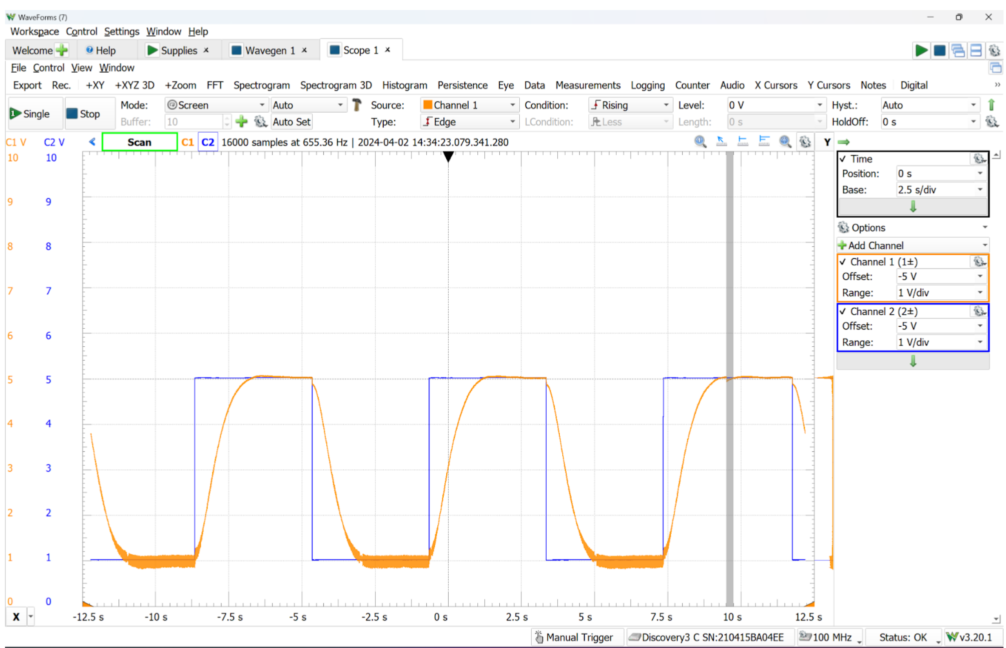


Fig. 52 Dynamic Testing with larger V_{ref} amplitude and period

Our initial dynamic testing shows in **Figure 50** shows the V_s response to our calculated R_i and C_i values, in this case, R_i = 18kΩ and C_i = 50μF. This response is underdamped, to fix this we increase R_i to 22kΩ as the result is **Figure 51**. This response appears to be slightly overdamped. **Figure 52** helps by increasing amplitude and period so that we can more clearly see the damping effect. This figure also is using R_i as 22kΩ and it shows us that the response is more accurately approximately critically damped. However it is important to note that if we want a faster rise time, one way to achieve that is by underdamping the circuit within a viable range.

IV. Conclusion

In Experiment A, we focused on constructing a PCB motor driver using Bipolar Junction Transistors (BJTs), enhancing our understanding of electronic components and honing our soldering skills. Experiment B led us through designing and building a Compensator circuit for precise motor direction and speed control, challenging us with complex debugging but ultimately enriching our practical electronics engineering expertise.

One of the most formidable challenges we encountered was debugging the Compensator circuit in Experiment B. The process was arduous, with a myriad of potential errors to sift through, making it an incredibly daunting task. However, this difficulty became a valuable learning experience, teaching us the importance of patience, systematic problem-solving, and thorough understanding of circuit operation. This challenge not only tested our technical knowledge but also our perseverance and determination to overcome obstacles.