University of Colorado - Boulder

ECEN 2270

Electronic Design Lab

Lab 3: DC Motor Analysis and Testing

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Engineering & Applied Science

UNIVERSITY OF COLORADO **BOULDER**

Lab 3.A

1. Introduction and Objectives

In this lab, we are going to test the H-bridge circuit on breadboard via LTspice and AD2, and build the H-bridge on perfboard, then test it again via AD2 and Multimeter. The main purpose of this lab is to understand how H-bridge circuits control the direction of motors going forward and backward. At the end of this lab, we will be able to construct the H-bridge circuit and mount it inside the robot.

1. Methods and Results

Test Equipment:

1. Analog Discovery 2 with BNC adapter and oscilloscope probes
2. Breadboard with the DC motor circuit
2. Li-ion batteries
3. LTspice with H-Bridge circuit

Lab 3.A.2 Getting to Know the H-Bridge Circuit

First, we need to familiarize ourselves with how the H-Bridge circuit will work. We assembled two different versions of the H-Bridge circuit in LTspice, in the forward and backwards directions using our computed resistance for R_B in PreLab 3.A, 330 Ω.

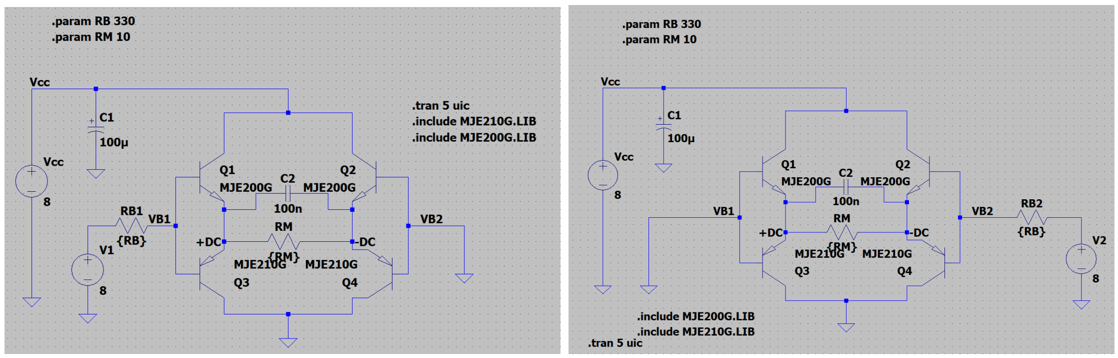


Figure 1: LTspice Schematic of Forward and Backward Direction H-Bridge Circuits (TM3); R_M is a parameterized value at either 1.5 Ω or 10 Ω for both motors stalled in parallel and both motors spinning freely, respectively.

Using the above schematic, the following table shows the measurements of different nodes and circuit components for the forward direction:

R_M	V_{B1}	V_{B2}	$DC+$	$DC-$	I_{RM}	P_{Q1}	P_{Q2}	P_{Q3}	P_{Q4}
1.5 Ω	3.5338 V	0 V	2.771 V	.7644 V	-1.337 A	6.9334 W	70.07 pW	16.048 pW	1.022 W
10 Ω	6.37 V	0 V	5.65 V	.7204 V	-.4929 A	1.15 W	69.49 pW	43.10 pW	.3551 W

And for the backward direction:

R_M	V_{B1}	V_{B2}	$DC+$	$DC-$	I_{RM}	P_{Q1}	P_{Q2}	P_{Q3}	P_{Q4}
1.5 Ω	0 V	3.5338 V	.7644 V	2.8726 V	1.3374 A	70.07 pW	6.9334 W	1.022W	15.9 pW
10 Ω	0 V	6.37 V	.7204 V	5.64 V	.4929 A	69.56 pW	1.15 W	3.551 W	43.15 pW

Lab 3.A.3 Simulate the Motor Driver Circuit

After evaluating the simulated H-Bridge circuit, we were tasked with making a sub-circuit for the H-Bridge to simplify our circuit when used with the DC Motor Model and the evaluated parameters determined for the motor model in Lab 2. The motor driver subcircuit was based off the schematic shown in **Fig. 2**:

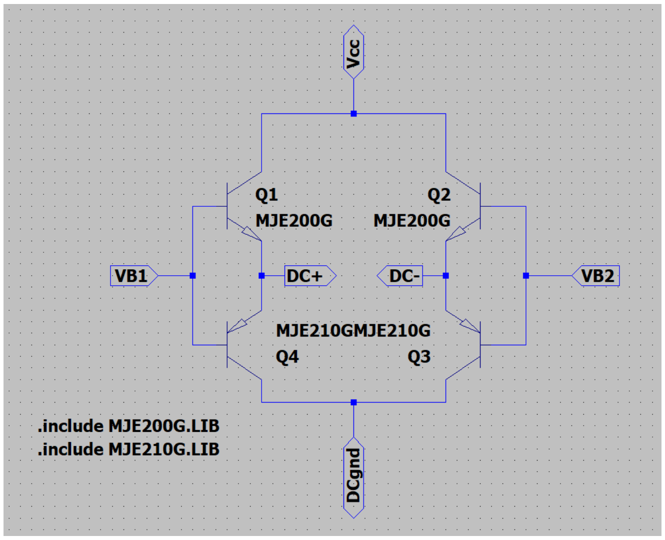


Figure 2: Schematic that the DC Motor Driver Sub-circuit is based off (TM3)

Once the motor driver sub-circuit was built, the simulated motor driver circuit for the forward direction follows the schematic shown in **Fig. 3**:

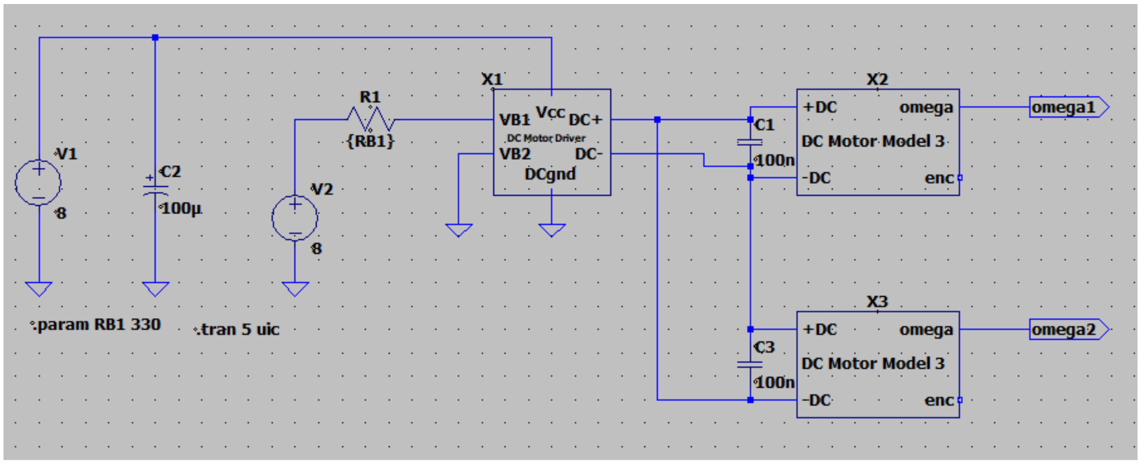


Figure 3: Schematic of DC Motor Driver Circuit in the Forward Direction (TM3)

Using the simulated motor driver circuit, the total motor current and omega 1 and 2 were measured in the cases (i) when both motors are freely running, (ii) when one motor is stalled (outputs omega 1 or 2 are grounded to simulate the stalled motor), (iii) when both motors are stalled (omega 1 and 2 are both grounded). The values for the total motor current and omega 1 and 2 for the forward direction are seen in the following table:

	Both motors spinning freely	One motor stalled	Both motors stalled
I_M	-.372 A	-1.07 A	-1.32 A
ω_1	7.005 V	0	0
ω_2	-7.005 V	-3.679 V	0

And for the backward direction:

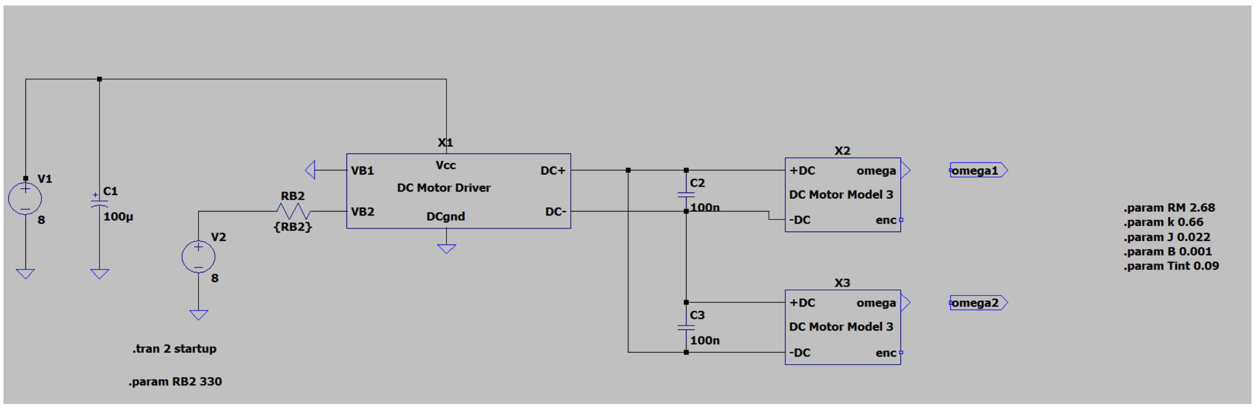


Figure 4: Schematic of DC Motor Driver Circuit in the Backward Direction (TM1)

	Both motors spinning freely	One motor stalled	Both motors stalled
I_M	0.224 A	1.15A	1.408A
ω_1	-7.989 V	-3.48 V	0 V
ω_2	7.989 V	0 V	0 V

When setting up the circuit we noticed that we intentionally wired it so X2 and X3 run in opposite directions and when both motors are spinning freely we see equal and opposite values for omega 1 and 2. The circuit schematic was set up this way to accommodate for the motors being on opposite sides of the robot, if both wheels input voltages had matching polarity then one wheel would be rotating in the opposite direction of the other wheel. So by reversing the polarity on one of the motors, it'll make both wheels move in the same direction despite opposite values of omega 1 and 2. Another thing to take note of is the slightly different magnitudes of motor current and omega values between the forward and reverse directions. This is because each team member found slightly different values for the motor parameters in Experiment 2.

Lab 3.A.4 Testing the Motor Driver Circuit on the Breadboard

After confirming our subcircuit of the motor driver circuit works correctly, we now want to test (half of) the circuit on a breadboard to insure that our determined parameters and simulated results match up with the experimental results. This step is done prior to soldering the motor driver circuit together, so that any mistakes can be preemptively corrected. This circuit is built alongside the variable power supply circuit assembled in Lab 2.A. The motor currents and voltages were experimentally determined when both motors on one side of the robot were freely running and when one wheel was stalled and when both wheels were stalled.

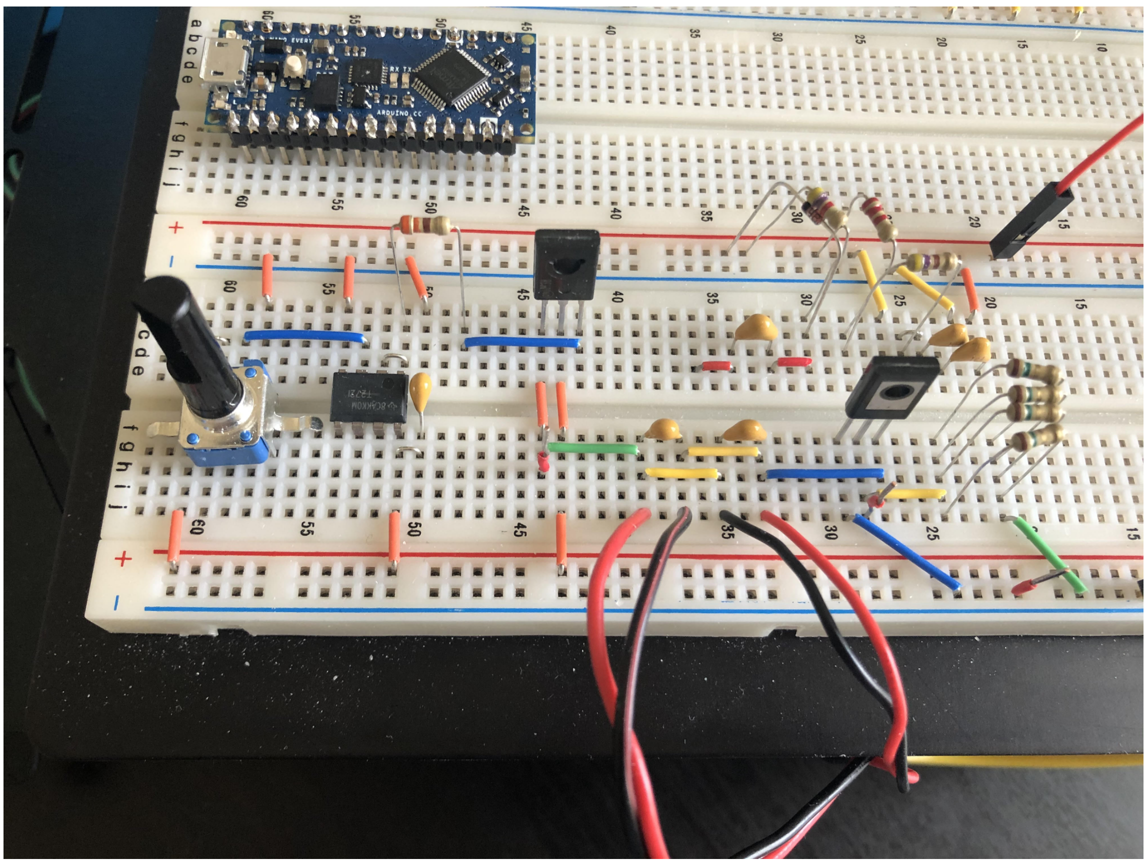


Figure 5: Assembled Motor Driver Circuit on Breadboard (TM 2)

Hardware	Both motors spinning freely	One motor stalled	Both motors stalled
I_M	0.3916 A	1.289 A	1.55 A
V_M	5.541 V	3.029	2.1411

The above table shows the measured values for the motor current and the motor voltages, with the opposite side's motor yielding opposite values, this was expected from our simulations and wasn't included in the above table to avoid redundancy.

Lab 3.A.5 Construct the Motor Driver Circuit

After testing half of the H-bridge circuit on the breadboard and verifying our results with the LTspice simulation from 3.A.3, we are ready now to assemble the full H-bridge on a soldered breadboard. The below figure shows the top and bottom of the H-Bridge

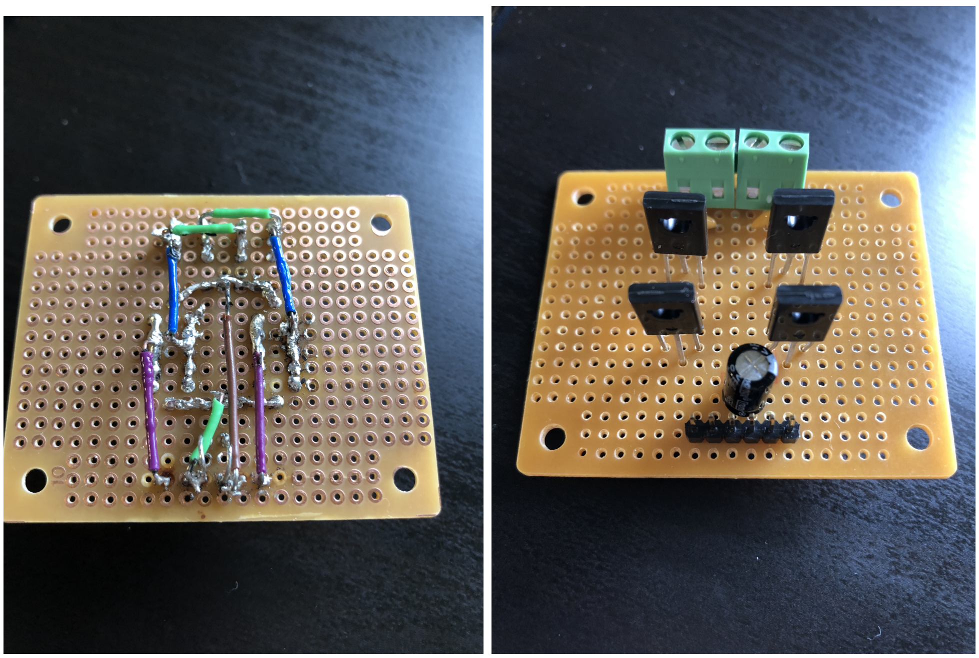


Figure 6: Motor Driver Circuit Soldered onto a Breadboard (TM2)

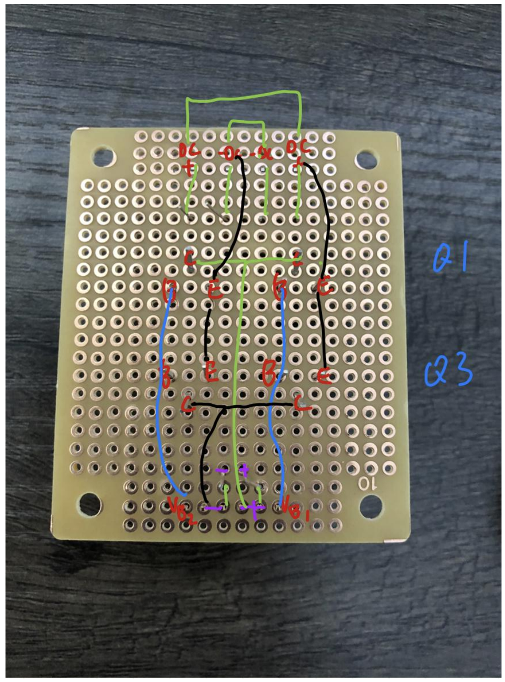


Figure 7: Underside of Motor Driver Circuit with Labeled Connections (TM2)

Lab 3.A.6 Test the Motor Driver Circuit

After assembling and soldering the H-bridge circuit on the breadboard, we want to test to make sure that our circuit works correctly. This will be done by testing the voltage across the rear wheel motor (the difference between DC+ and DC-) and current in the forward and reverse directions for the three cases: both wheels spinning freely, one motor stalled, and both motors stalled. The motor current will be measured in the same method as before, by connecting the DC ground pin across RI (.375 Ω) and measuring the voltage drop across that resistor and applying Ohm's Law to determine the current.

The table below shows the measured values in the forward direction:

Hardware	Both motors spinning freely	One motor stalled	Both motors stalled
I_M	-.636 A	-1.36 A	-1.55 A
V_M	-5.136 V	-3.23 V	-2.2 V

The below figure shows an example of the WaveForms voltage readings for motor voltage at the positive and negative DC ports of the motor in the forward direction:

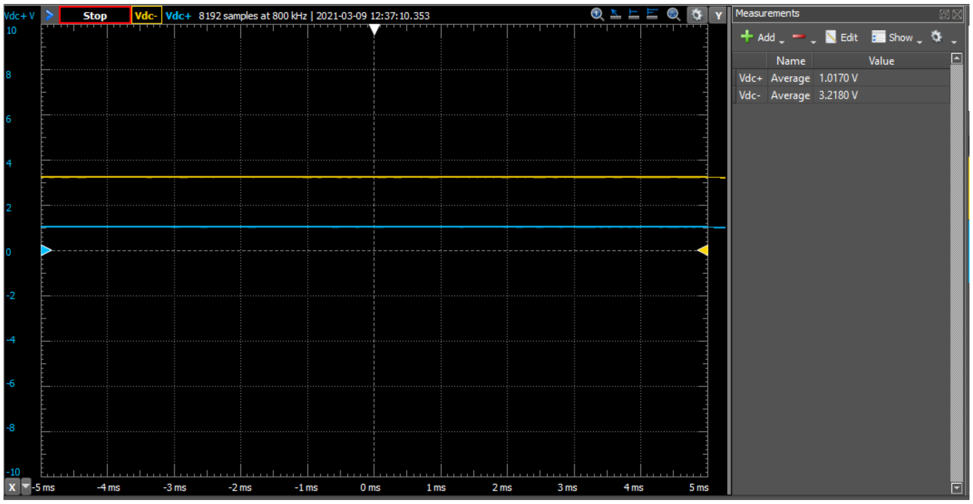


Figure 8: WaveForms Voltage Readings for Both Motors Stalled in the Forward Direction (TM3); V_{DC+} = 1.017 V and V_{DC-} = 3.218 V, by taking the difference of these two values V_M = -2.2 V

And for the reverse direction:

Hardware	Both motors spinning freely	One motor stalled	Both motors stalled
I_M	.581 A	1.344 A	1.56 A
V_M	5.214 V	3.176 V	2.18 V

Fig. 9 below shows an example of the WaveForms voltage readings for motor voltage at the positive and negative DC ports of the motor in the reverse direction:

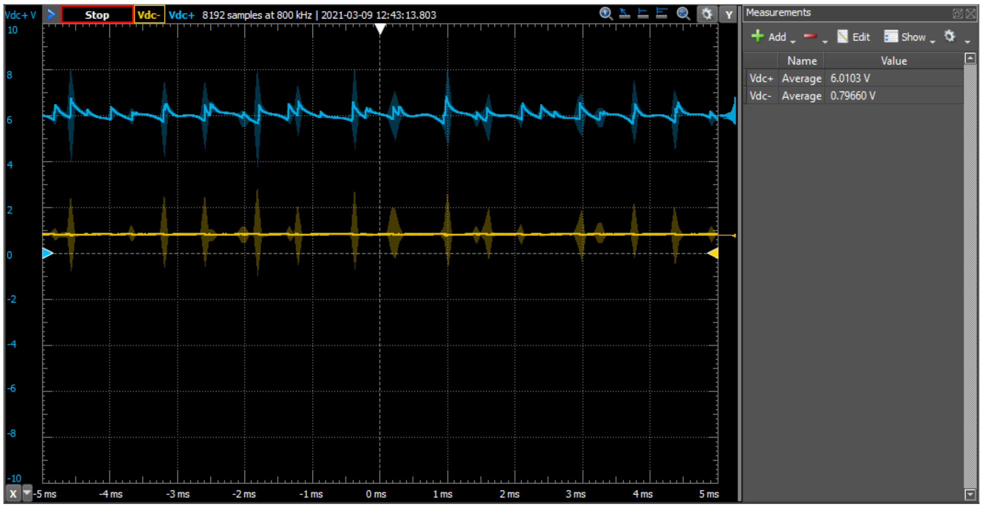


Figure 9: WaveForms Voltage Readings for Both Motors Freely Running in the Reverse Direction (TM3); V_{DC+} = 6.0103 V and V_{DC-} = .7966 V, by taking the difference of these two values V_M = 5.214 V

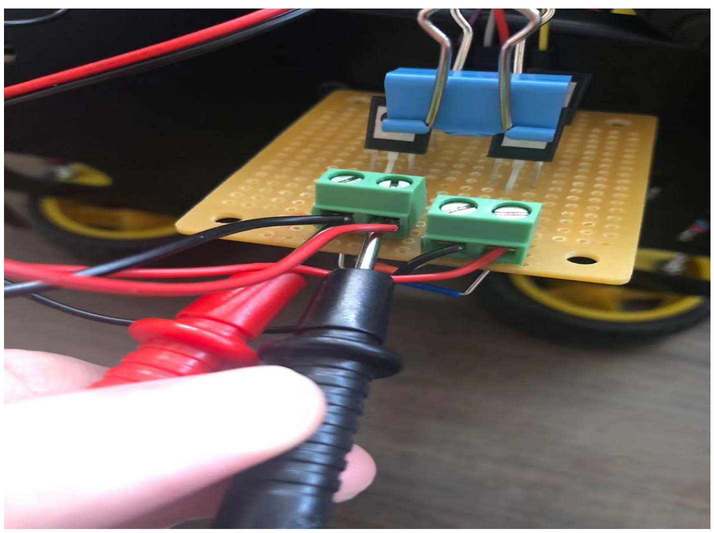


Figure 10: Test Setup to Determine V_{DC+} and V_{DC-}

Lab 3.A.7 Mount the Motor Driver Circuit Inside the Robot

Finally, after confirming the validity of the motor driver circuit and it's expected functionality the motor driver circuit is then mounted inside of the robot. The mounted motor driver circuit can be seen in **Fig. 11** .

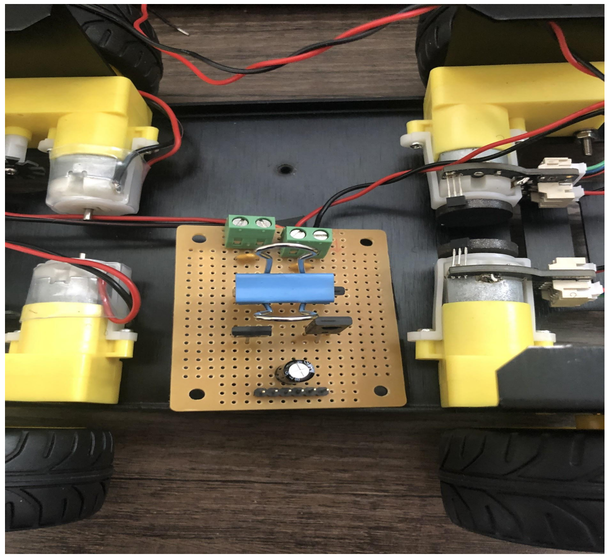


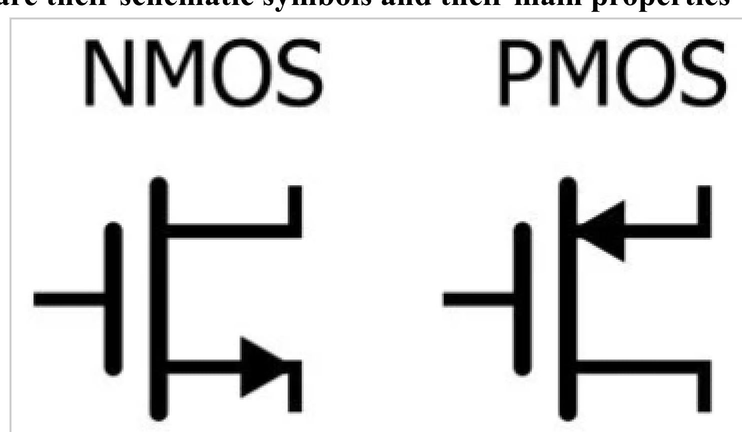
Figure 11: Mounted Motor Driver Circuit for Half of the Robot (TM1)

3. Discussion and Conclusion

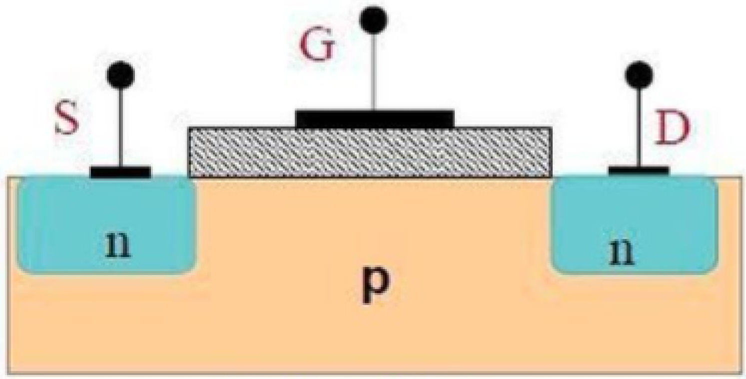
This lab centered around the testing and construction of the motor driver circuit for the robot, more commonly known as an H-Bridge. We began by familiarizing ourselves with how the motor driver should work in simulation and then testing it out on the robot's breadboard. The final step, after confirming we got the desired results, was to solder the H-bridge on a smaller breadboard. This lab was fairly simple in comparison to some of the other labs the team has performed as fewer calculations had to be performed and more assembly was prioritized. The hardest part of this lab was soldering the H-bridge together but after a bit of practice it became much easier. For this part of the lab there weren't any suggestions for improvement from the team.

4. Exploration Topic

1. **What are the different types of MOSFETs ?**
   There are two types of MOSFETs: Depletion Mode and Enhancement Mode.
   And there are two channels of MOSFET: N-Channel and P-Channel
2. **What are their schematic symbols and their main properties**



3. **What are they made from and what is their physical structure?**
   A MOSFET is made of a semiconductor material, most commonly silicon.



MOSFET Structure

4. **What is their operating principle?**
   MOSFETs have three different modes of operation: Cut-off Region, Linear Region and Saturation Region.
   Cut-off Region: it behaves like an open switch when there is no current flow
   Linear Region:They can be used as amplifiers.
   Saturation Region: it behaves like an closed switch when Vds>Vp
5. **What is a simple equivalent circuit for MOSFETs?**
   It behaves like a voltage controlled current source circuit
6. **How do MOSFETs differ from BJTs?**
   The MOSFET(voltage controlled) is a metal-oxide semiconductor whereas the BJT (current controlled) is a bipolar junction transistor.
   The MOSFET are more ideal for high-power applications whereas the BJT are more ideal for low-current applications.
   The MOSFET depends on the voltage at oxide-insulated gate electrode whereas the BJT depends on the current at its base terminal.

Lab 3.B

1. Introduction and Objectives

In this lab, we are going to design an Integral Compensator that contains a difference amplifier, an inverting integrator, and direction control that contains the H-bridge with MOSFET transistors, all together forming a closed loop. We first need to simulate the circuit using LTspice, then build it on the breadboard for both sides of the robot. We will also feed pulse voltage source into Vref of the integrator for dynamic tests of the robot circuit.

2. Methods and Results

Test Equipment:

1. **AD2**
2. **Wavegen generator**
3. **Speed Control Loop**
4. **TLV272 Op-Amps**
5. **Various Resistors and Capacitors**

Lab 3.B.2 Making the Case for Virtual Ground

First, we need to prove that the virtual ground is a valid analytical method to be used for future circuit analysis in this experiment. This is done by first constructing a dual-supply difference amplifier circuit with a regular ground set up. The schematic follows the provided circuit in the lab document and can be seen below in **Fig. 12:**

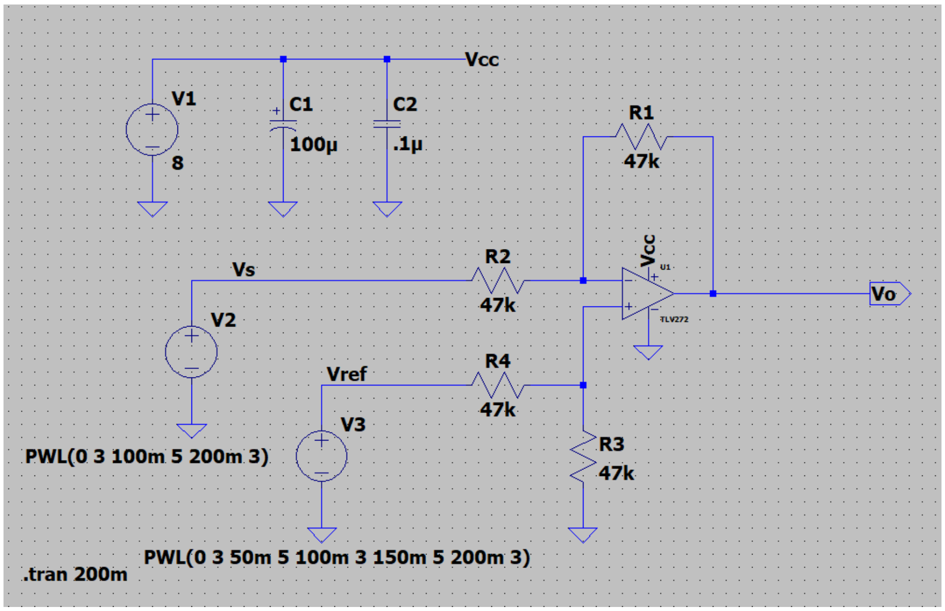


Figure 12: Dual-Supply Difference Amplifier Schematic in LTspice (TM3)

We analyzed what this circuit should be doing ideally (if it has a $\pm$ 8V power supply) and compared it against the LTspice simulation results. The ideal comparisons were based on the equations developed in class, which are provided below:

$$V_o = \frac{(Z_1+Z_2)Z_3V_2 - (Z_4+Z_3)Z_1V_1}{(Z_4+Z_3)Z_2}$$

Where Z_1= R1, Z_2= R2, Z_3= R3, Z_4= R4; And V_1= Vs, V_2= Vref. This equation is simplified with a symmetry argument: $Z_3 = Z_1$ and $Z_4 = Z_2$ and yields the simplified equation for V_o:

$$V_o = \frac{Z_1}{Z_2}(V_2 - V_1)$$

This equation is simplified even further since $Z_1 = Z_2$, so our output voltage is just the difference between Vs and Vref or $V_2 - V_1$. This equation can be shown on the LTspice simulation results and allows us to see the difference between what the circuit should be doing ideally and what the simulation with real ground yields. The results from the simulation are shown in **Fig. 13:**

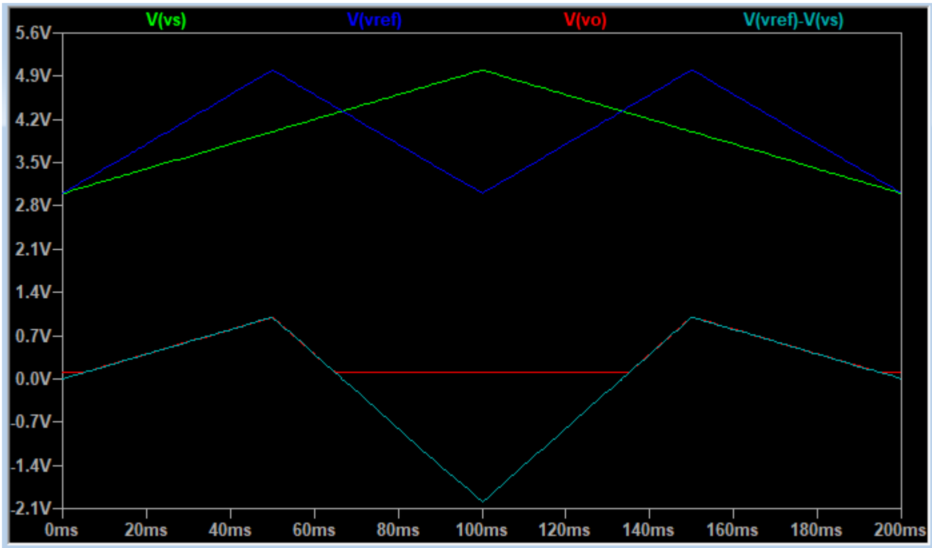


Figure 13: LTspice Simulation Results of Schematic in **Fig. 12** (TM3); Added trace Vref-Vs to show expected ideal results, Vo limited to minimum voltage of about 103 mV and ideal results go to a minimum voltage of about -2 V

We can see a discrepancy between what we expected and what the simulation results are, as we expected to see negative voltage values for Vo when Vref is less than Vs but Vo didn't even reach 0 V. This is what makes the case for the virtual ground, since the op-amps power supply alternates between 8 V and 0 V (ground) as opposed to $\pm$ 8V it can't reach the negative voltage values we will need to reverse the motor's directions. By using a virtual ground the reverse direction of the motor will be achievable.

By adding a few circuit components to the schematic and adding the virtual ground to the op-amps positive feedback input we will be able to compare to the real ground simulation and see if the negative voltages we expected occur. The modified **Fig. 12** schematic with the virtual ground can be seen in **Fig. 14:**

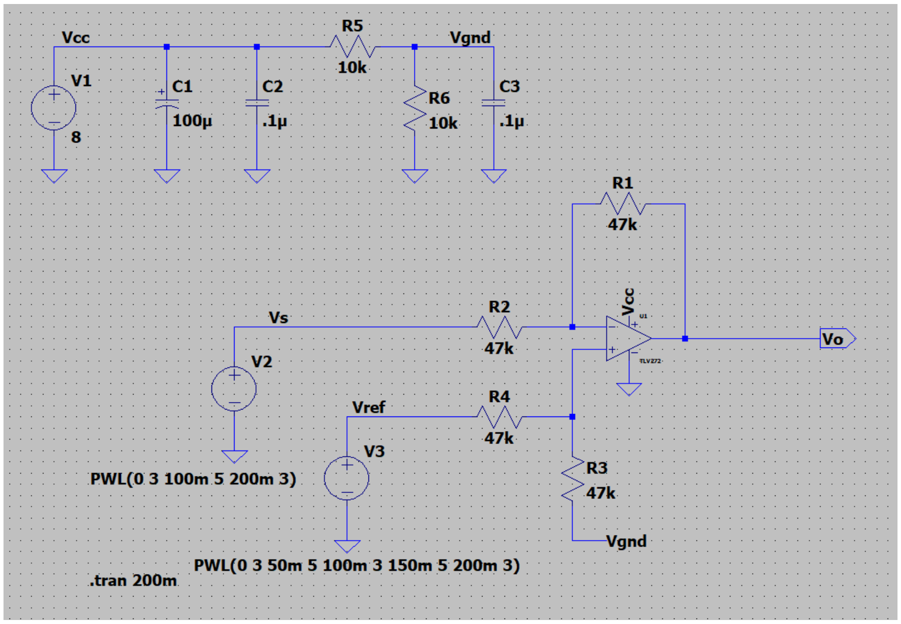


Figure 14: Dual-Supply Difference Amplifier with Virtual Ground

By adding the virtual ground and taking our measurements of Vo with respect to the virtual ground, we will now be able to achieve the expected results that we weren't able to get without the virtual ground. The results can be seen in **Fig. 15:**

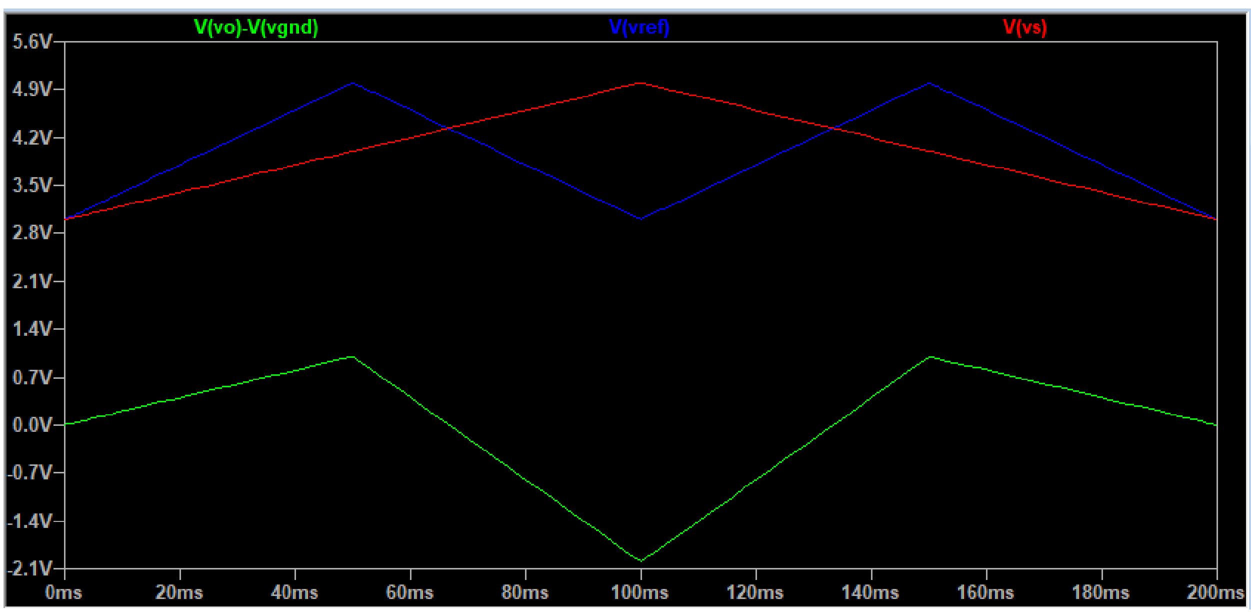


Figure 15: LTspice Simulation Results of Schematic in **Fig. 14** (TM3); Vo measurements taken with respect to the virtual ground

Now the negative voltages we expected to see initially are present, showing that the virtual ground is a necessary addition to the circuit.

Lab 3.B.3 I-Compensator Circuit in LTspice

The I-Compensator Circuit in LTspice can be seen in **Fig. 16:**

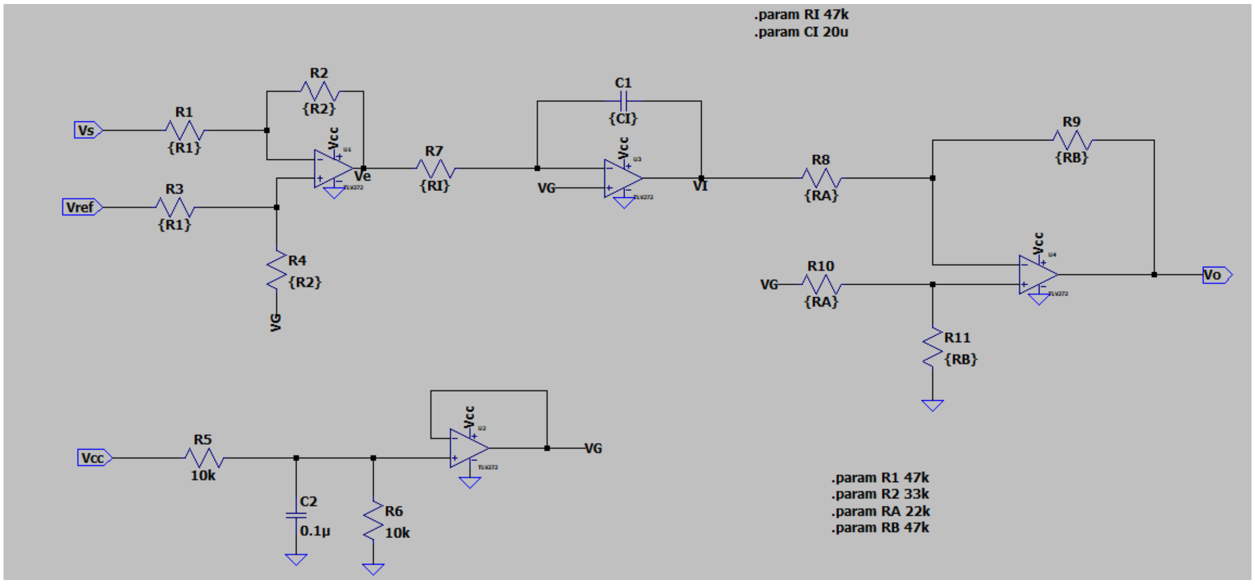


Figure 16: I-Compensator Circuit in LTspice (TM1)

There are two important parts in the I-Compensator Circuit: the difference amplifier and inverting integrator. For the difference amplifier, we could measure the difference between the Ve and VG to check whether they are equal to the difference between the Vref and Vs. And, for the integrator, we set Vref as a pulse voltage source and measure the voltage at Vi to see whether it is a upside down triangular waveform. Because the integrator will integrate the input signal and respond to the input signal over time. To determine RI and CI, a variety of equations developed in class were used in conjunction with determined motor parameters from previous labs. Below shows the equations used to determine the values:

$$G_0 = \frac{k}{k^2+BR} \text{ and } \omega_m = \frac{k^2+BR}{RJ}$$

$$K_{sense} = 1834 * 1.1 * R_2 C_2$$

$$K_I = \frac{1}{R_I C_I} = \frac{\omega_m}{4K_{sense} * G_0 * \zeta^2}$$

All the values that go into these differs for each teammate, so providing a table of values would be exhaustive and complicated for all of the team members. The values of R_I and C_I were chosen around a damping factor of 1 and a time constant of 1 ms.

Lab 3.B.4 Closed-loop with I-Compensator Circuit in LTspice

The closed-loop with I-Compensator Circuit can be seen in **Fig.16.**

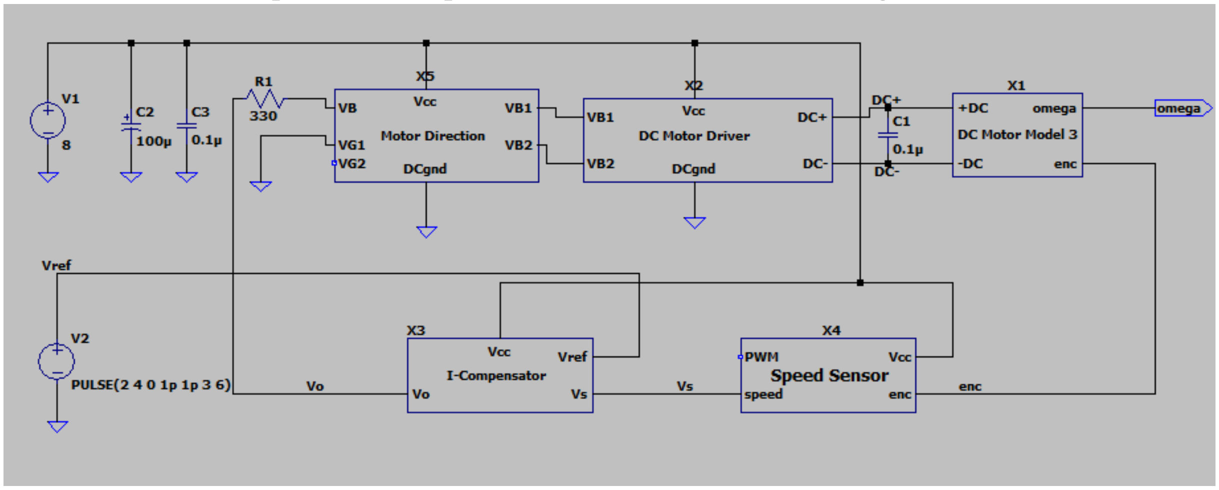


Figure 16: Closed-loop with I-Compensator Circuit (TM1), $R_I = 47\ k\Omega$ and $C_I = 20\ \mu F$

The simulated results can be seen below in **Fig. 17:**

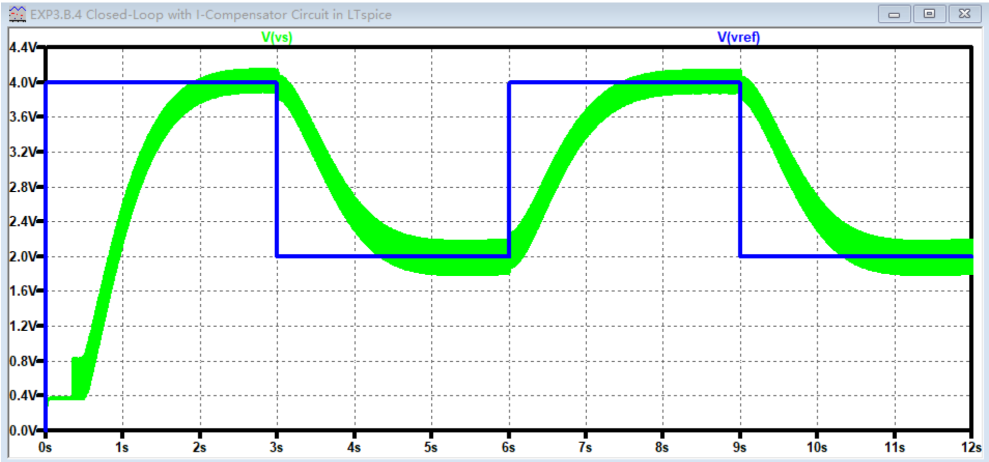


Figure 17: Simulation of Closed-loop with I-Compensator Circuit (TM1); comparing Vref and Vs

Component Values (Simulation)	TM1	TM2	TM3	Average
$R_I (k\Omega)$	47	30	25.7	34 $k\Omega$

$C_I(\mu F)$	20	22	20	20.6 μF

Component Value (Hardware)	TM1	TM2	TM3	Average
$R_I(k\Omega)$	47	47	47	$47 k\Omega$
$C_I(\mu F)$	5	5	5	5 μF

The above tables show the component values used for R_I and C_I in both simulation and hardware. The hardware values had to be adjusted from the original calculated values used in the simulation to accommodate the imperfections of the physical components.

Lab 3.B.5 Build Compensator Circuit

After simulating the circuit in LTspice, the circuit was constructed on the robot's breadboard and the test strategy developed in 3.B.3 was utilized to ensure the validity of the constructed circuit. Below the assembled circuit can be seen in **Fig. 18:**

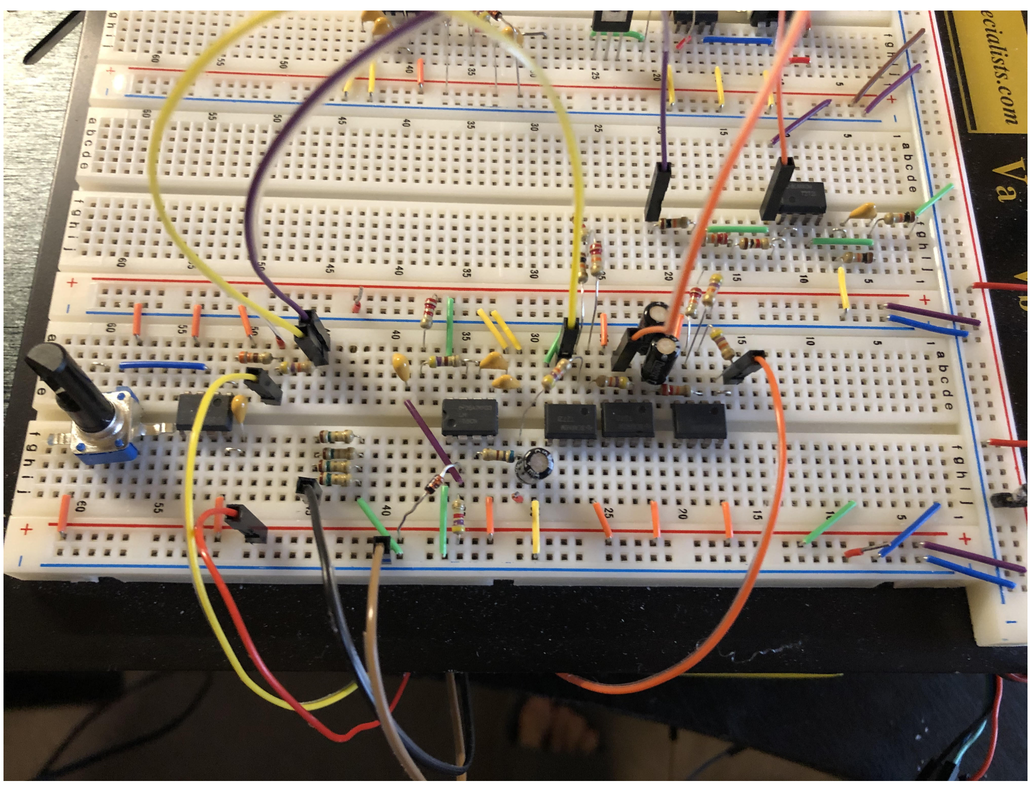


Figure 18: Circuit with I-Compensator (TM2)

Below shows examples of WaveForm readings taken at various points in the I-Compensator circuit, to confirm the validity of the design.

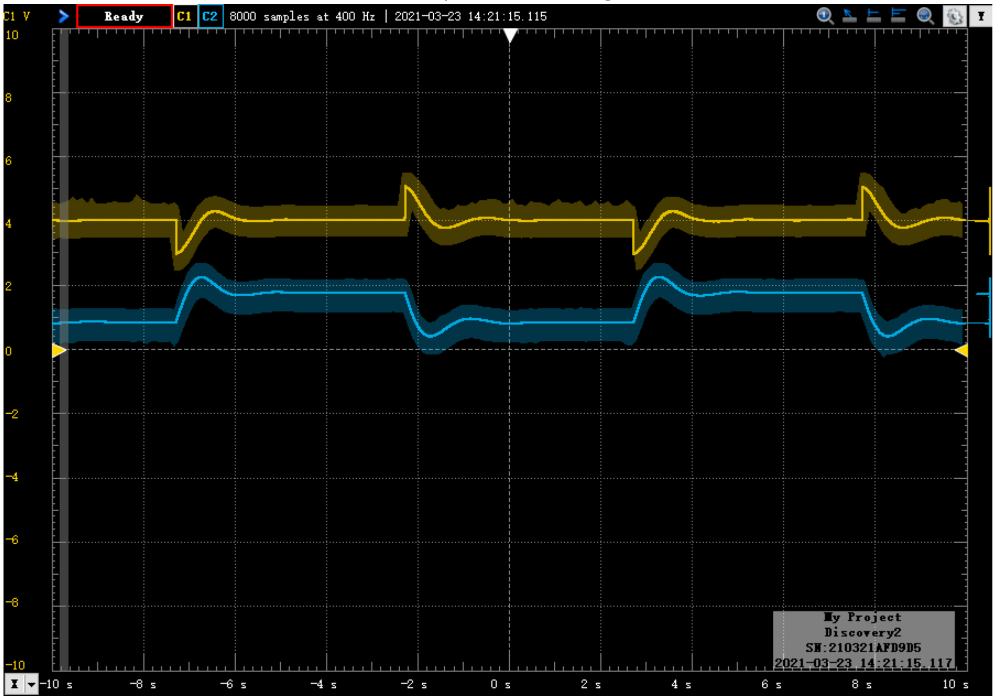


Figure 19: Ve (yellow) and Vi (blue) (TM1); Vref is a rectangular waveform between 2V and 4V. Since Vi is an upside-down triangle, the circuit is known to be working correctly

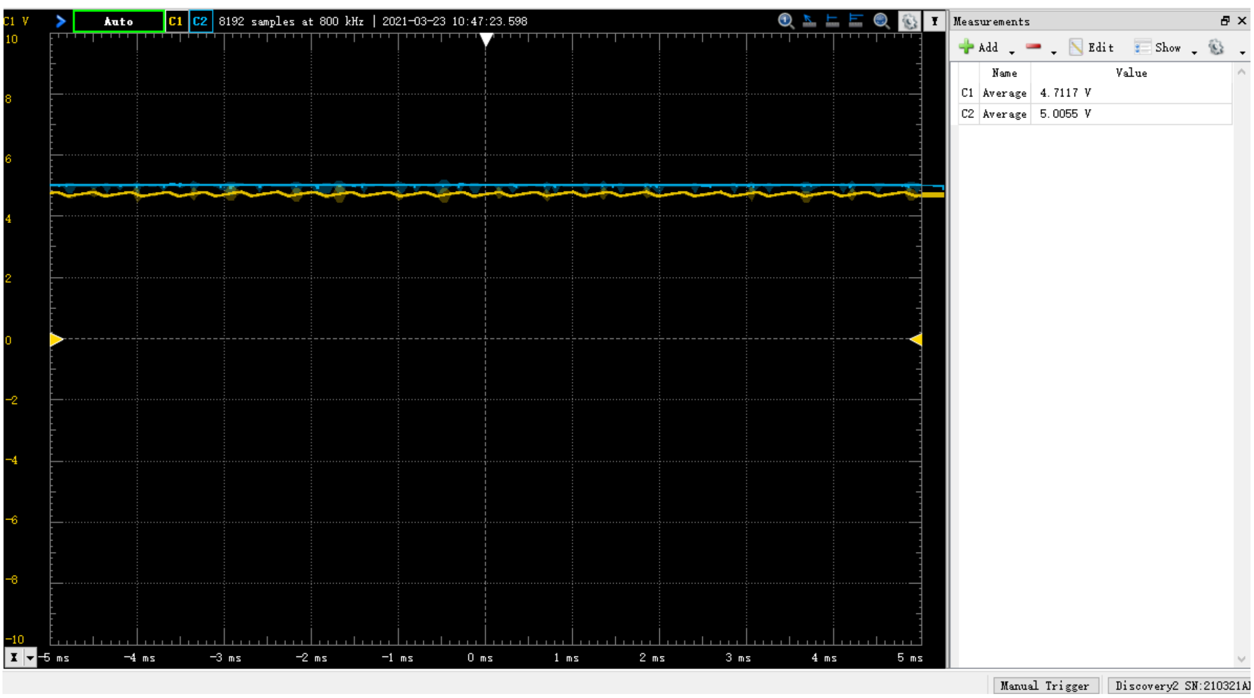


Figure 20: Vs (yellow) and Vref (blue) at 5V (TM1); Average measurement of Vs at 5V reference voltage = 4.7117 V

In **Fig. 20**, Vref is the output of the variable power supply circuit built in Experiment Two. The compensator circuit is working correctly because Vs closely follows Vref whenever it is adjusted. The two voltages match up fairly closely until Vref is greater than 5V, primarily due to the limitations of the LM555 timer used in the speed-sensor.

Lab 3.B.6 Test Closed-loop with Compensator Implementation

After constructing the closed loop circuit, we tested Vref vs Vs/Vspeed to see the full range of speed that the robot has. Below is a table of TM1's measurements, again we noticed the trend that Vspeed couldn't break 5V, due to the limitations of the LM555 timer, but below 5V from Vref we saw the speed follow closely to Vref.

Vs (V)	Vref (V)
4.75	8
4.7	5
3.29	3.06
2.4	1.95

Lab 3.B.7 Direction Control in LTspice

The next step of our robot was to construct a circuit of PMOS and NMOS transistors to get direction control for the motors. First, we built the circuit in LTspice, the below series of figure and tables shows the circuit in LTspice and the simulated results:

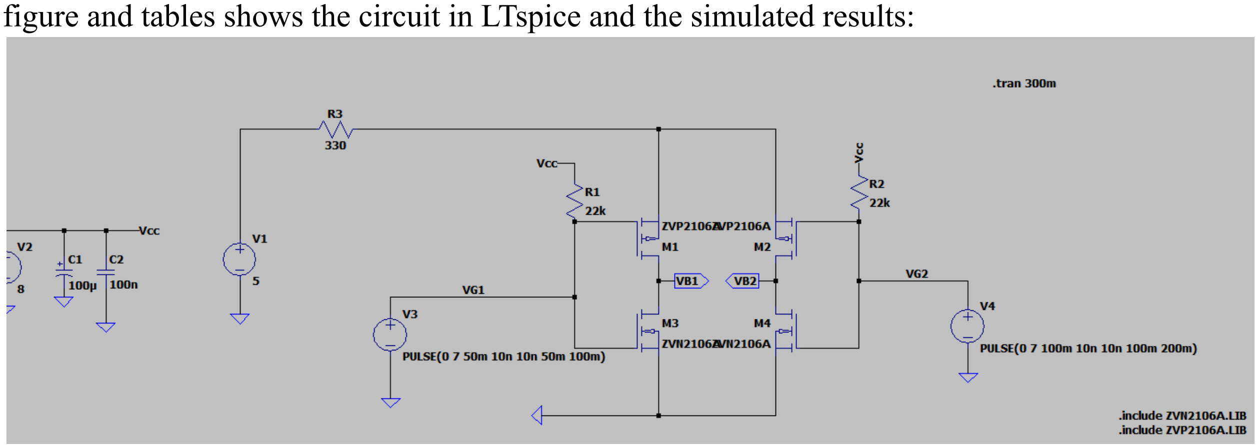


Figure 23: Direction Control Circuit (TM1); The gate voltage sources were set to pulses so the alternating voltage could be seen when VB1, VB2, VG1, and VG2 were measured

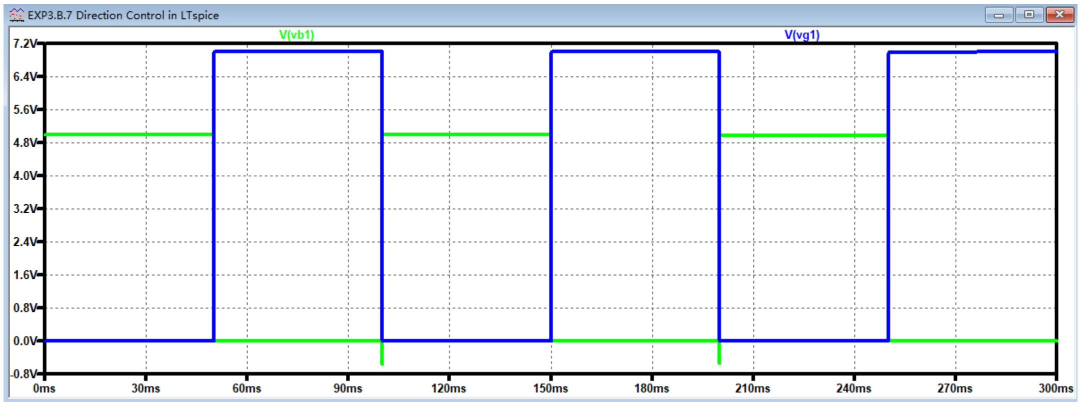


Figure 24: VG1 and VB1 when V1 = 5V

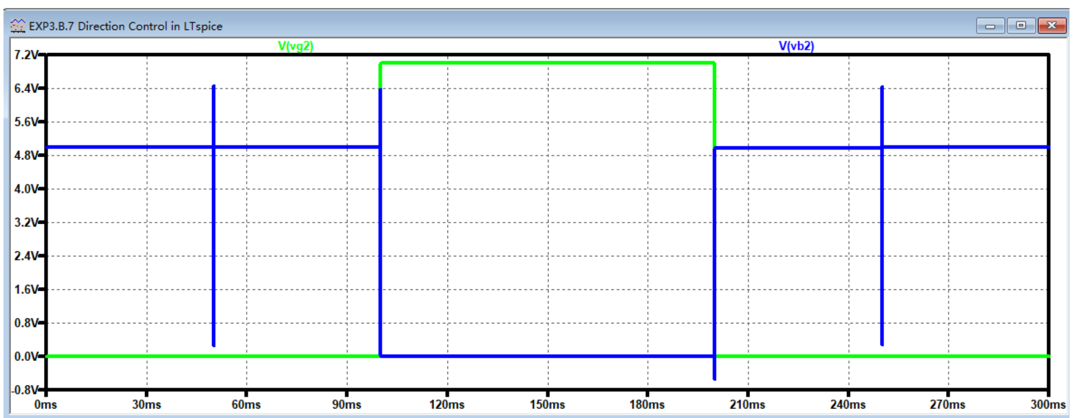


Figure 25: VG2 and VB2 when V1 = 5V

Time (ms)	0	50	100	150	200	250	300
VG1(V)	0	7	0	7	0	7	0
VB1(V)	5	0	5	0	5	0	5

Relationship between VG1 and VB1(TM1)

Time (ms)	0	100	200	300
VG2(V)	0	7	0	7
VB2(V)	5	0	5	0

Relationship between VG2 and VB2(TM1)

From the LTspice results, we can see what happens when the transistors' gates are grounded. If VG1 is grounded the motors go forward with components M3 & M1 on and M4 & M2 off. If VG2 is grounded the motors go forward with components M3 & M1 off and M4 & M2 on.

To test this circuit on our breadboard, we will either ground VG1 or VG2 and then measure VB1 and VB2 as well as check to make sure the motors go in the expected direction. Another check, for visual confirmation, would be to ground or connect to Vcc both VG1 and VG2 and we shouldn't see any of the wheels rotate in this situation.

Lab 3.B.8 Add Direction Control to Closed-loop Circuit Implementation

Finally, we add the direction control circuit to our breadboard after verifying the expected results with LTspice. Below is a table showing comparisons between VG1, VG2, VB1, and VB2 from TM1:

Hardware	VG1(V)	VG2(V)	VB1(V)	VB2(V)
	0	0	8	8
	0	8	6.78	0
	8	0	0	6.78
	8	8	0	0

We can see the expected results in the above table. When both gates are grounded we see VB1 and VB2 both equal 8 volts, but since they act in opposite directions there's no rotation occurring and the opposite values when neither are grounded. When one gate is grounded and the other connected to a voltage we see either forward or reverse rotation as expected.

Lab 3.B.9 Test Overall Speed Control Loop Implementation

Now that the whole circuit has been built we can test the overall functionality of the loop. The testing of the loop is done both statically and dynamically to confirm the functionality. Below is a series of figures measuring different points along the circuit in static or dynamic tests:

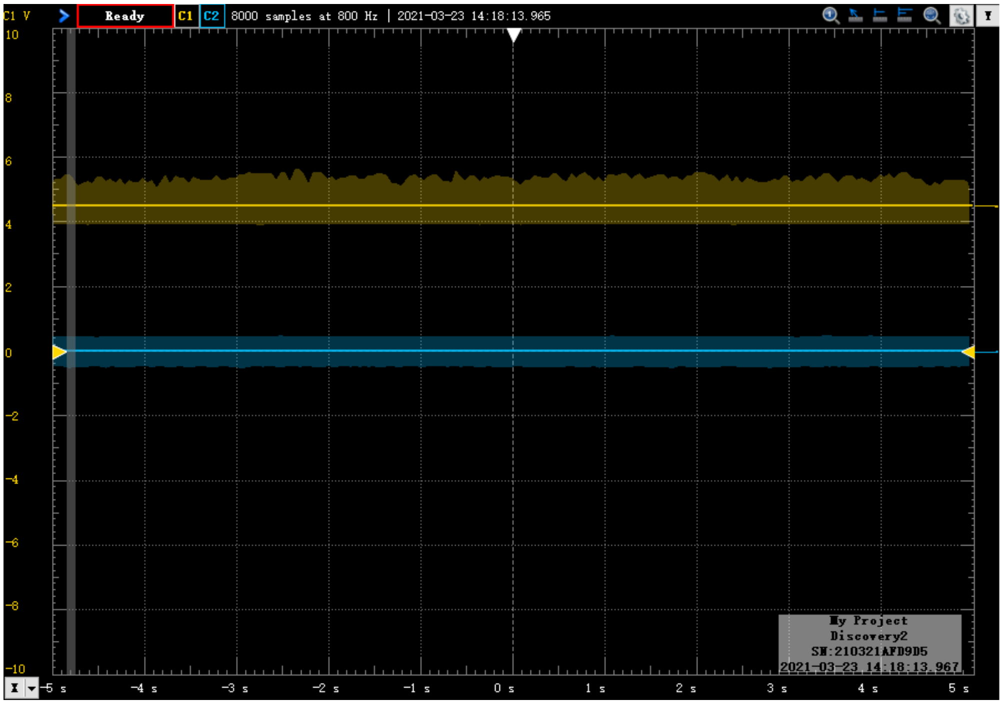


Figure 26: Ve (yellow, C1) and Vi (blue, C2) in static test (TM1)

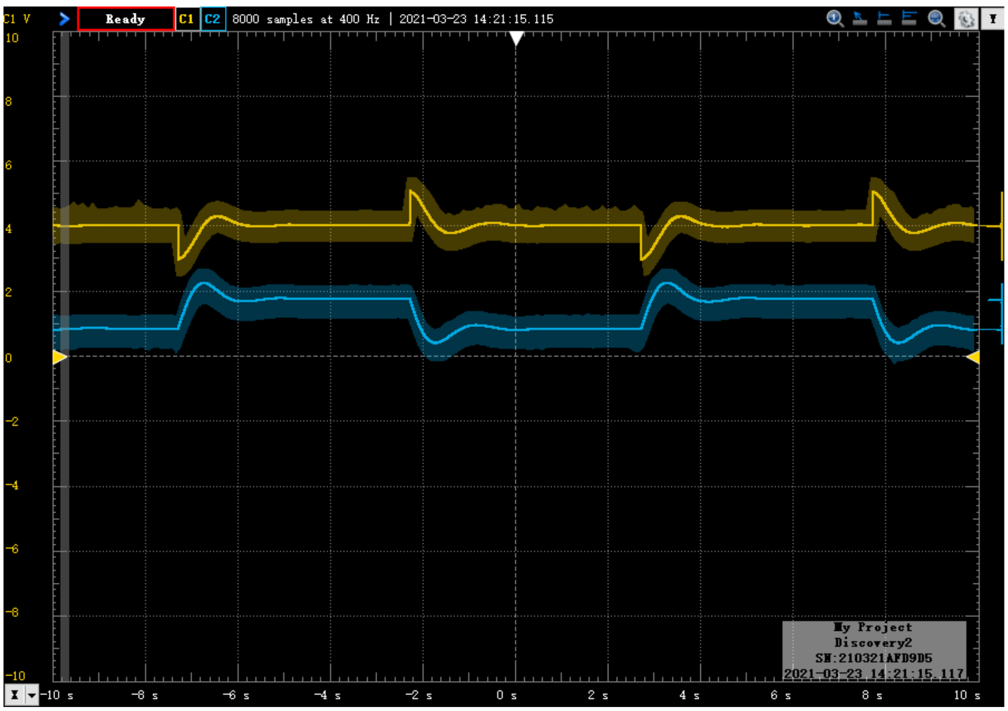


Figure 27: Ve (yellow, C1) and Vi (blue, C2) in dynamic test (TM1)

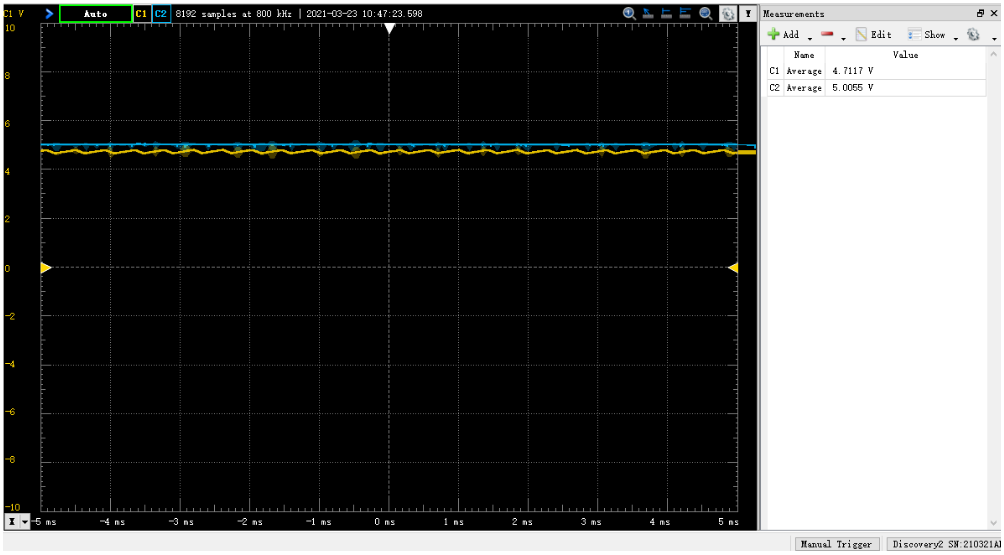


Figure 28: Vs and Vref in the static test(TM1)

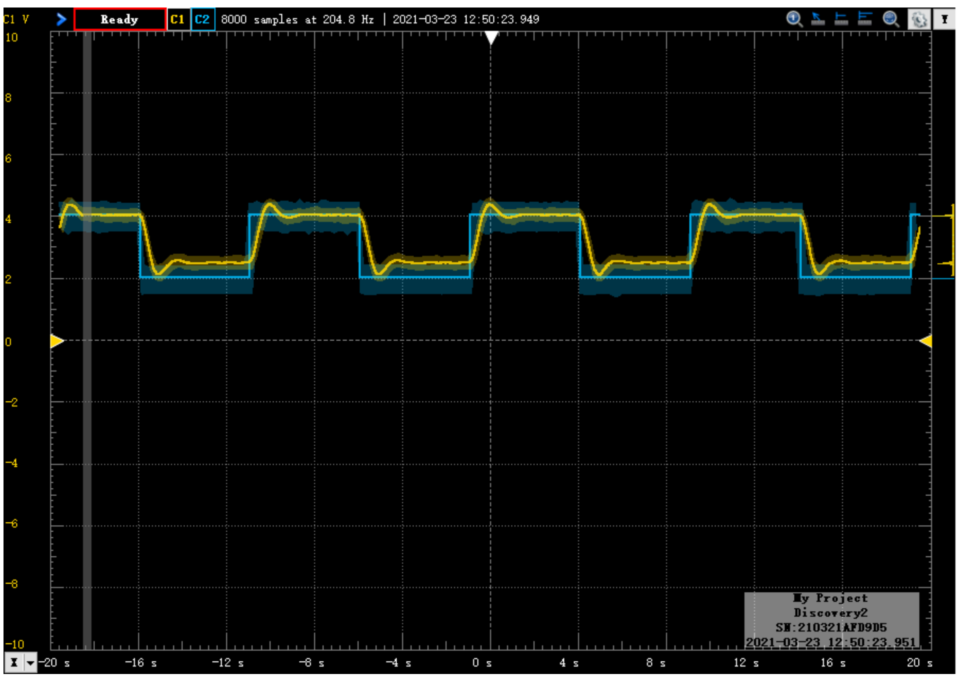


Figure 29: Dynamic Property of Speed Control Loop, Vref (blue,C2) and Vs (yellow, C1) (TM1)

The dynamic properties of the speed control loop can be seen in the above figure and it appears to be slightly underdamped. TM1 estimates the value of ζ to be about .7.

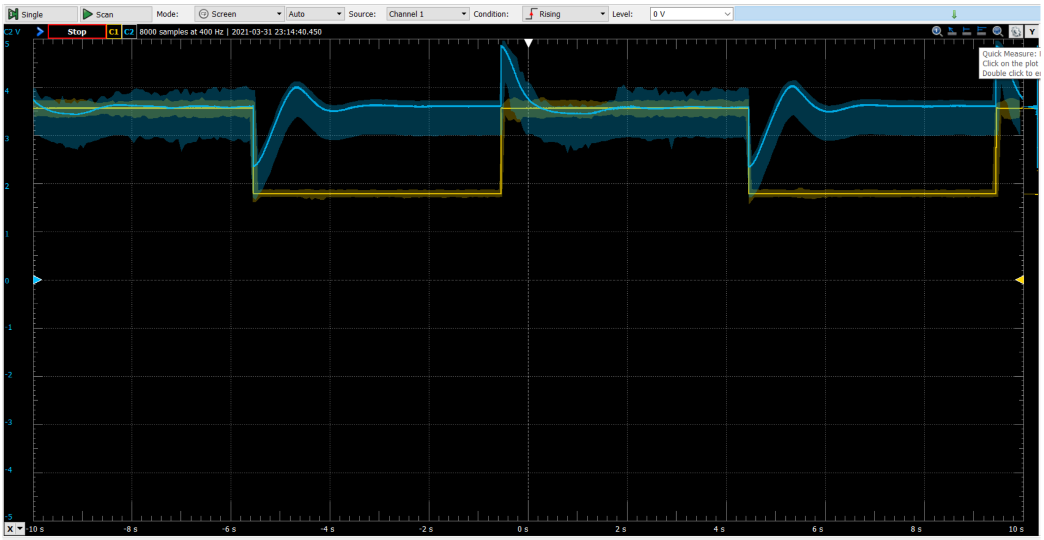


Figure 30: Ve (blue, C2) and Vref (yellow, C1) (TM2); shows the validity of the model with the triangular shape of the error voltage.

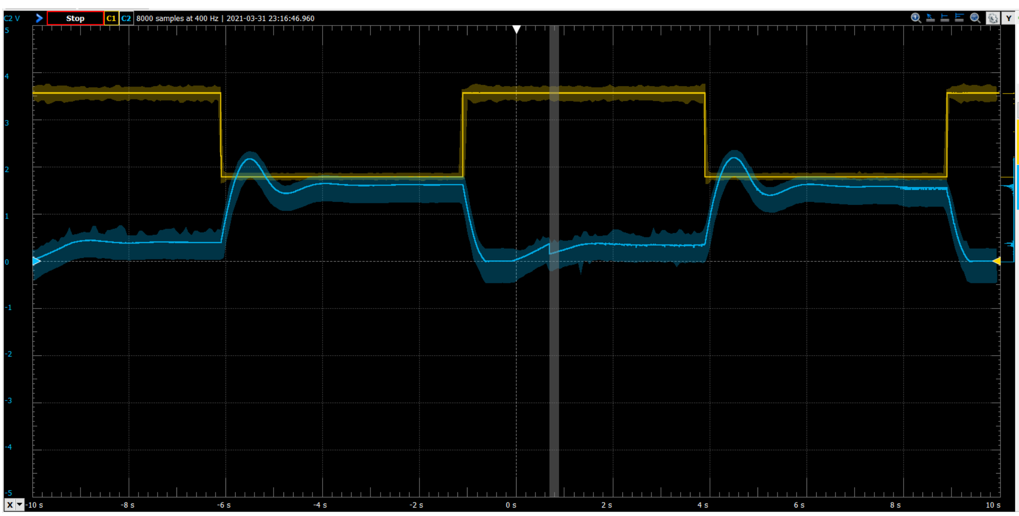


Figure 31: Vi (blue, C2) and Vref (yellow, C1) (TM2); shows the validity of the model with the accurate inverting integration expected.

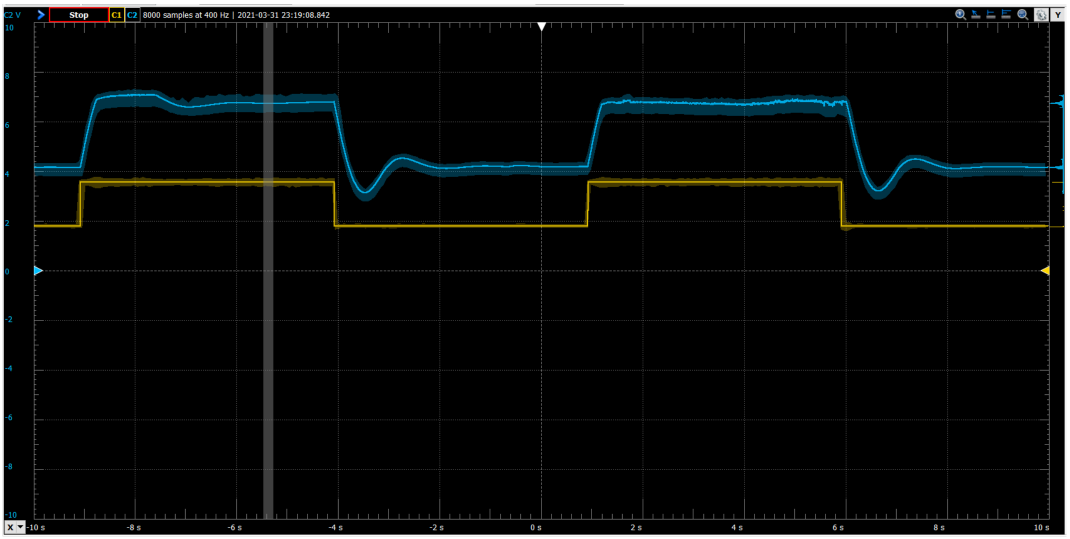


Figure 32: Vo (blue, C2) and Vref (yellow, C1); shows the validity of the model with the slight amplification of the reference voltage out of the Integral Compensator

Finished integral compensator circuit with direction control implementation below:

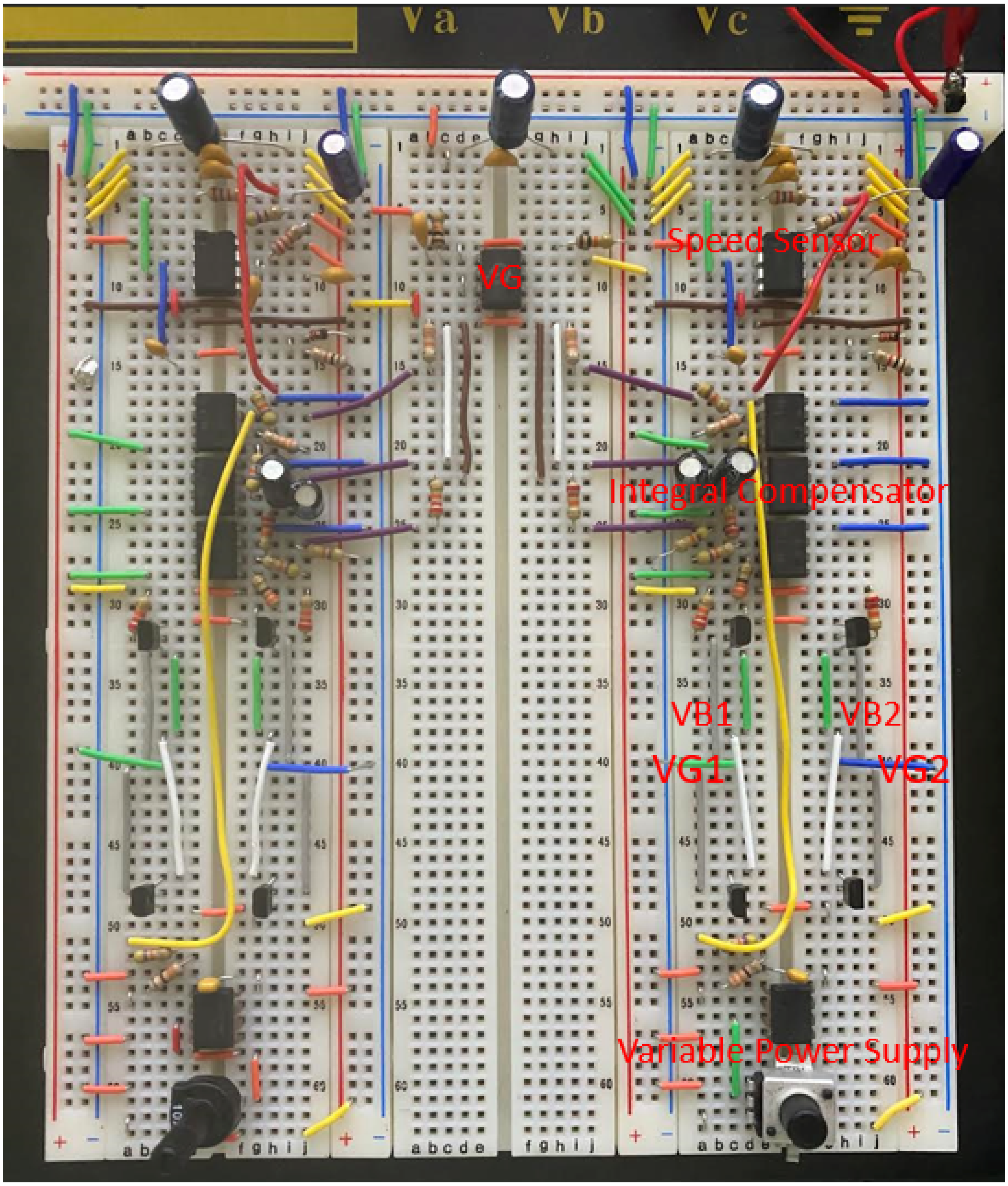


Figure 33: Finished Closed-Loop with Direction Control (TM3)

3. Discussion and Conclusion

This lab focused on constructing the closed loop consisting of an Integral Compensator, direction control, and the DC motor driver (H-bridge). We began by simulating the circuit in LTspice, and then building it on the actual breadboard. After we compared our results with our teammates, we found that our results are very similar to each other with some small disagreements, dependent on the varying calculated motor parameters and component values. The disagreements in our calculations created some relatively large difference in our measurements as our damping factors and time constants were changing a lot. The biggest challenge faced in this complex circuit was that if a team member ran into an issue, figuring out how to correct the mistake was often complicated and took a lot of time. As suggested during lecture, we believe that a FAQ section on Canvas would be very helpful for future labs, especially ones that are this complicated with several steps. We also think that some parts of this lab could have been spread out to Exp. 3A, which to us seemed relatively simple and take a lot less time than this lab. The primary thing we learned from this lab was the effect of the damping factor and how minor changes in one part of a circuit can cascade and effect the end results of a circuit tremendously.

4. Exploration Topic

1.What are some common examples of feedback control systems?

Positive Feedback System and Negative Feedback System.

2. How do the functions of positive and negative feedback systems differ?

Positive feedback Systems:

The set point and output values are added together by the controller as the feedback is in-phase with the input.

The effect of positive feedback systems is to increase the system gains.

The overall gain with positive feedback applied will be greater than the gain without feedback.

Negative feedback Systems:

The set point and the output values are subtracted from each other as the feedback is out of phase with the input.

The effect of a negative feedback system is to reduce the system gains.

Link to the source.

3. What is proportional, integral, and derivative control?

Proportional:

The proportional component depends only on the difference between the set point and the process variable. This difference is referred to as the Error term. The proportional gain determines the ratio of output response to the error signal.

Integral Response:

The integral component sums the error term over time. The result is that even a small the error term will cause the integral component to increase slowly. The integral response will continually increase over time unless the error is zero, so the effect is to drive the steady-State error to zero.

Derivative Response:

The derivative component causes the output to decrease if the process variable is increasing rapidly. The derivative response is proportional to the rate of change of the process variable. Increasing the derivative time parameter will cause the the control system to react more strongly to changes in the error term and will increase the speed of the overall control system response.

Link to the source

4.What is a good block diagram that shows the main principles of feedback control?

A block diagram provides a means to easily identify the functional relationships among the various components of a control system.

A good block diagram is that converting the time-domain electrical circuit into an s-domain electrical circuit by applying the laplace transform.

Link to the source.

5. What are advantages of feedback control systems?

1. Closed loop control systems are more accurate even in the presence of a non-linearity.
2. Highly accurate as any error arising is corrected due to the presence of a feedback signal.
3. The bandwidth range is large.
4. Facilitates automation.
5. The sensitivity of the system may be made small to make the system more stable.
6. This system is less affected by noise.

6.What are disadvantages of feedback control systems?

1. They are costlier.
2. They are complicated to design.
3. Required more maintenance.
4. Feedback leads to an oscillatory response.
5. Overall gain is reduced due to the presence of feedback.
6. Stability is the major problem and more care is needed to design a stable closed loop system.

Link to the source