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Line-Following Robot Report

Introduction: This project consisted of creating a line-following robot entirely out of analog components. It will follow a black line on white paper and must be battery-powered.

Description of operation:

<u>Calculations:</u>

1. Sensor Circuit(Photodiodes)
    a. Voltage Divider Calculation: The photodiodes will output a variable resistance based on the intensity of light falling on them. To determine the output voltage of the sensor circuit based on light intensity I began by measuring R_{LDR} by placing the photodiodes in dark and bright conditions and measuring its resistance using a multimeter. I found that R_{dark} = 50Kohms and R_{light} = 5Kohms. To maximize the voltage difference between light and dark conditions, R_{fixed} should be close to the average of R_{dark} and R_{light} which came out to be 15.8Kohms. Now V_{out} under dark conditions was 1.39V and V_{out} under bright conditions was 4.5V.

    $$V_{out} = V_{source} \cdot \frac{R_{fixed}}{R_{LDR} + R_{fixed}} \qquad \text{Dark: } V_{out} = 6 \cdot \frac{15000}{50000+15000} \approx 1.39V$$

    $$R_{dark} = 50K\Omega \quad R_{light} = 5K\Omega \quad V_{source} = 6V \qquad \text{Light: } V_{out} = 6 \cdot \frac{15000}{5000+15000} = 4.5V$$

    $$R_{fixed} = \sqrt{R_{dark} \cdot R_{light}} = \sqrt{(60000) \cdot (5000)} \approx 15.8K\Omega$$

    b. Biasing Resistor Calculation: The photodiodes need to operate in their active region for consistent output. I need a bias resistor(Rb) to set a small bias current. Based on my components' data sheet, the photodiode operated at I_b=10uA and V_{bias}=6V. I found that Rb=560Kohms or 680Kohms. This resistance is connected in series with the photodiode and a power supply sets a proper operating point so the photodiode generates a voltage or current proportional to light intensity.

    $$R_b = \frac{V_{bias}}{I_b} = \frac{6}{10 \times 10^{-6}} = 600K\Omega$$

    c. Sensor Response Time: The circuit's response time depends on the load resistor(Rload) and its capacitance(Csensor). My photodiodes' datasheet states that Csensor=10pF and Rload=Rfixed=15Kohms as calculated before. I calculated that the time constant for sensor response time is 150ns which assures me that the sensor can respond to rapid changes in light it will experience when detecting a black line on white paper.

    $$\tau = R_{load} \cdot C_{sensor} = 15000 \cdot 10 \cdot 10^{-12} \approx 150ns$$

2. Comparator Circuit(Op-Amp)
    a. Threshold Voltage Calculation: The op-amp comparator, LM358, will compare the photodiode's output against a set threshold voltage to differentiate between black and white surfaces. I began by measuring the photodiode output voltage(V_{sensor}) under both black and white conditions using a multimeter where I found that V_{sensor} is 1.5V on black and 1V on white. V_{ref} would be midway between these values, 1.25V. I set R_1 to be 10Kohms and R_2 to be 270ohms. So, the two

resistors R_1 and R_2 will be connected in series between V_{source} and GND to form a voltage divider.

$$V_{ref} = V_{source} \cdot \frac{R_2}{R_1+R_2}$$

$$V_{ref} = \frac{1+1.5}{2} = 1.25v \qquad R_1 = 1K\Omega$$

$$1.25v = \frac{R_2}{1k+R_2} \rightarrow R_2 \approx 270\ \Omega$$

b. Gain Calculation for Amplification: If the photodiode signal is too weak, I need to add an amplifier before the comparator to boost the signal. Using a non-inverting op-amp configuration, I need to pick a gain that ensures the photodiode signal spans a wide range. As found before my photodiode's output is 1V to 1.5V, to amplify it to my motor driver's input requirement found in its datasheet of 3V to 4.5V, A_v=3 if R_{in}=10Kohms R_f is calculated to be 20Kohms.

$$R_f = (A_v - 1) \cdot R_{in} = (3-1) \cdot 10000 = 20K\Omega$$

3. Motor Driver Circuit
    a. Transistor Base Resistor (R_b): I need to be in saturation mode which is necessary for my circuit to act as an efficient switch. The calculated base resistor(Rb) ensures that BJT operates in saturation region which ensures the transistor is driven fully on, minimizes heat dissipation, and prevents excessive current through the base, which could damage the transistor or upstream circuit. My motor's data sheet states that I_{motor} = 1.5A and β = 100. Because I have a power source of 6v, $V_{control}$ = 5V, and because I want to be in saturation region V_{BE} = 0.7V. After calculating a base resistance of 287 ohms, I found that my standard resistor value should be 270 ohms.

$$R_b = \frac{V_{control} - V_{BE}}{I_b} = \frac{(5) - (0.7)}{0.015} \approx 287\Omega$$

4. H-Bridge Design: An H-Bridge allows the motor to spin in both directions by controlling the polarity of the voltage applied to the motor. I will be using 2 MOSFETs so I need to make sure they provide sufficient current for the motors, achieve efficient switching, and operate within a safe limit. I need to choose a logic-level MOSFET that fully turns on(low $R_{DS,\ ON}$) at the control voltage. Since I am operating with 6V, my gate threshold($V_{GS,th}$) should be less than 2V, my 1motor should be less than IDS, max to stay within my MOSFET's drain current rating, and I must be within low RDS, ON to minimize heat dissipation. To do this, first I need to calculate the gate resistor(R_g) to prevent excessive current draw from the control circuit and reduce ringing at the gate. Because my charging current(I_g) = 60mA, R_g = 100 ohms. Next, I need to check that the MOSFET I chose can handle the heat generated during switching. Because my motor's data sheet states that I_{motor} = 1.5A and $R_{DS,\ ON}$ = 0.02 ohms is an assumed value based on my logic-level MOSFET, which means that P_{MOSFET} = 0.005 W for minimal heating. This proves my MOSFET can handle this heat. I will also be adding pull-down resistors(10K

ohms) to ensure my MOSFETs turn off completely when no control signal is present.

$$I_g = \frac{C_{GS} \cdot V_{source}}{t_{switch}}$$

$$I_g = \frac{(1 \times 10^{-6})(6)}{(100 \times 10^{-9})} = 60mA$$

$$R_g = \frac{6V}{60mA} = 100\Omega$$

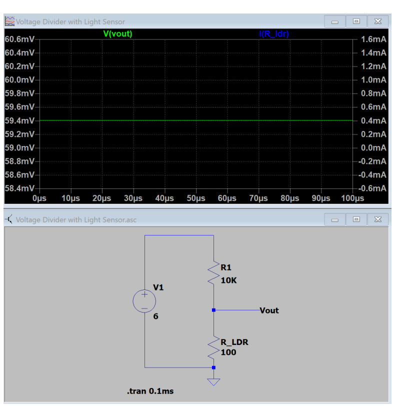
5. Feedback Control
    a. Proportional Gain(Av): To design a proportional control(Av) circuit for my line-following robot, I need to create an analog control signal based on the difference between the sensor outputs. My sensor outputs, $V_{sensor, left,}$ and $V_{sensor, right}$, are proportional to the intensity of light detected by the photodiodes. By experimentally measuring their ranges from black and white surfaces, I found that $V_{sensor, left}$ = 3.0V, and $V_{sensor, right}$ = 1.2V. Then, I found that $V_{difference}$ = 1.8V. The output $V_{control}$ should drive my H-Bridge and should be within the valid range for my motor driver which is 0-6V for my 6V battery pack. If $V_{control}$ exceeds this range, I need to adjust Av. I need $V_{difference}$ = 6V so I need to amplify it by 3. Since Av will be 3, my feedback resistor(Rf) = 300ohms while my ground resistor(Rg) = 100ohms. $V_{out} = \left(\frac{R_f}{R_g}\right) \cdot (V_{sensor,left} - V_{sensor,right}) = \left(\frac{300\Omega}{100\Omega}\right) \cdot (3.0V - 1.2V) = 5.4V$

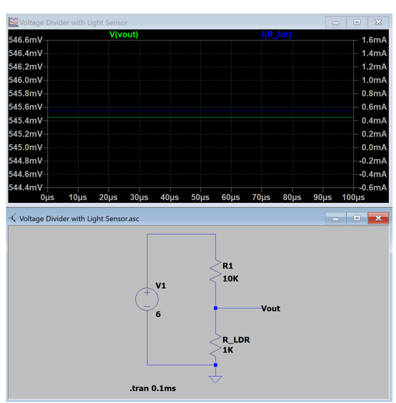
<u>LTSpice Models:</u>

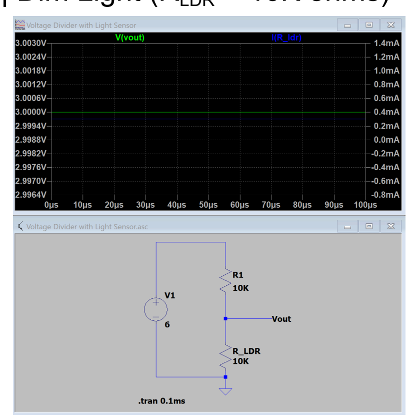
1. Light Sensor Circuit

Simulating a voltage divider with a phototransistor by sweeping light intensity to observe voltage changes at the output. We see that the output voltage of the light sensor circuit responds to the varying changes in light intensity. This shows me the sensor's behavior where a potentiometer will be necessary if I want to change the resistance within different lighting.

Bright Light (R_{LDR} = 100 ohms) | Midway Light(R_{LDR} = 1K ohms) | Dim Light (R_{LDR} = 10K ohms)



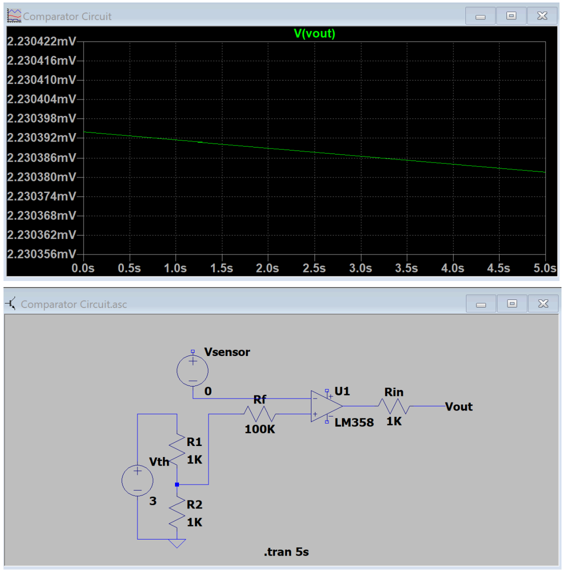


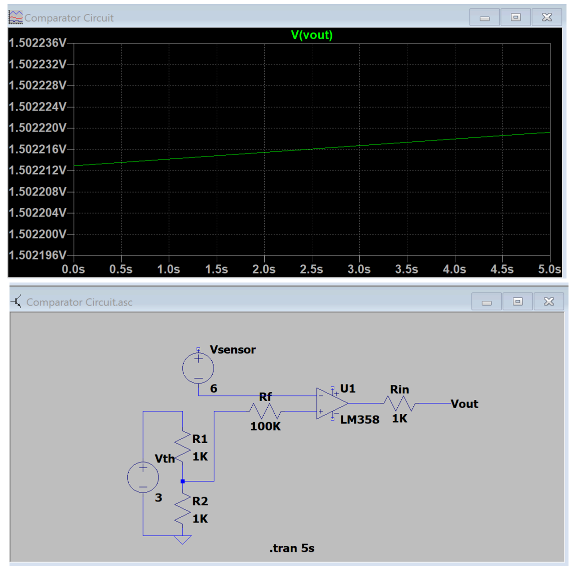


2. Comparator Circuit

I need to create a comparator circuit in LTSpice for comparing sensor outputs against a threshold voltage. A comparator compares two input voltages: one from the light sensor(V_{sensor}) and the other from a fixed threshold voltage(V_{TH}). I found that the output is high (logic 1) if the sensor voltage exceeds the threshold and low (logic 0) otherwise which will be useful for my op-amp. I also found that pull-up resistances such as R_f and R_{in} are necessary for noise handling such as stabilizing V_{out}. In the context of my robot, when $V_{TH} > V_{sensor}$, V_{out} is low representing the white surface. When $V_{TH} < V_{sensor}$, V_{out} goes to high which represents the black line. My calculation for R_f, R_{in}, and V_{TH}: $V_{threshold} = V_{cc} \cdot \frac{R_2}{R_1 + R_2} = 6v \cdot \frac{10k}{10K + 10K} = 3V$

$V_{TH} > V_{sensor}$ | $V_{TH} < V_{sensor}$



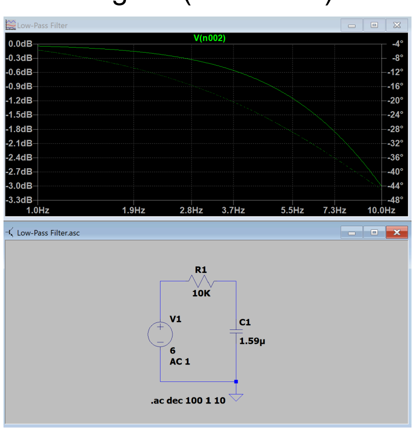


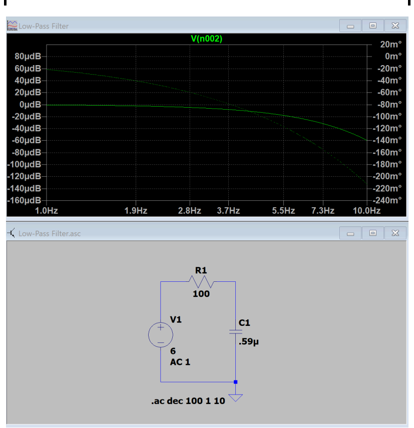
3. Signal Conditioning Circuit

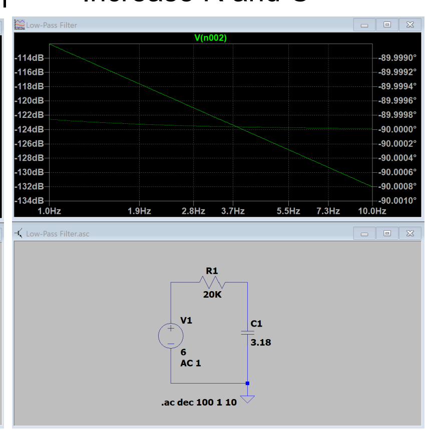
A low-pass filter is commonly used to smooth sensor signals by removing high-frequency noise. In this case, it will help process my photodiode's signals to ensure cleaner inputs for my op-amp comparator. My photodiode's data sheet states that its signal changes at a rate of up to 10Hz, so f_c = 10Hz. I found that decreasing R or C increases the cutoff frequency(f_c), making the filter respond more slowly and pass lower frequencies while increasing R or C increases the cutoff frequency(f_c), making the filter respond faster and pass higher frequencies.

$$C = \frac{1}{2\pi R f_c} = \frac{1}{2\pi(10)(10 \times 10^3)} = 1.59\mu F$$

Original (calculated) | Decrease R and C | Increase R and C



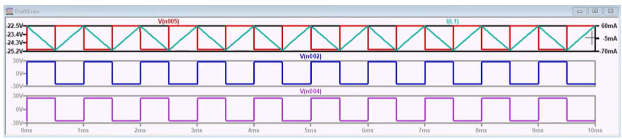


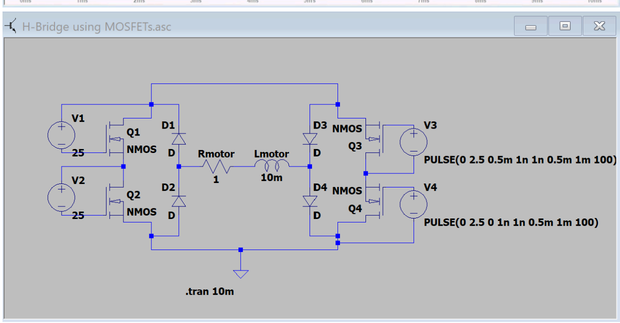


However, my photodiodes state, in their datasheet, an inherent capacitance of 2uF which is near the capacitance I calculated and need.

4. Motor Drive(H-Bridge)

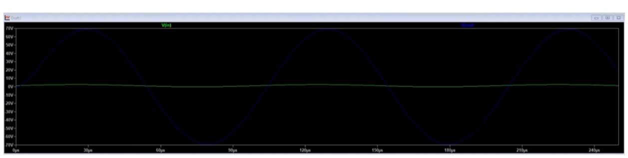
I will be using an L293D IC for my H-Bridge but first, I need to simulate how this IC works on LTSpice. I will simulate an H-Bridge using 4 MOSFETs because they are well-suited for higher frequencies and low drive loss. Including Rmotor, Lmotor, and flyback diodes control voltage spikes, and allow switching events in the H-bridge. In an H-Bridge circuit, polarity changes across the motor terminals determine the direction of the motor's rotation. By switching specific pairs of MOSFETs ON and OFF, the H-Bridge reverses the voltage polarity applied to the motor. This is critical for enabling both forward and reverse motion. In my simulation, I toggled Q3 and Q4 MOSFETs OFF using pulse signals and kept Q1 and Q2 MOSFETs ON to simulate how my robot would act. When my voltage goes to +V, the control signals are in a forward motion. In contrast, if my voltage were to go to -V, my control signals would be in reverse motion.

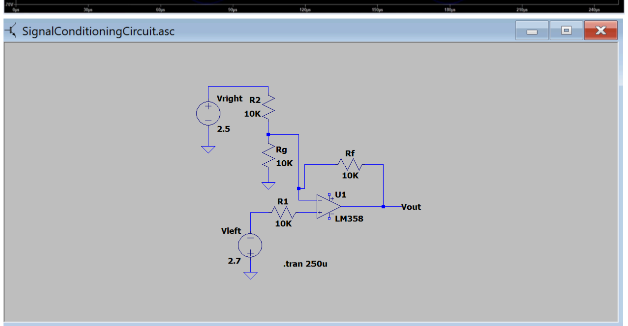




5. Proportional Controller

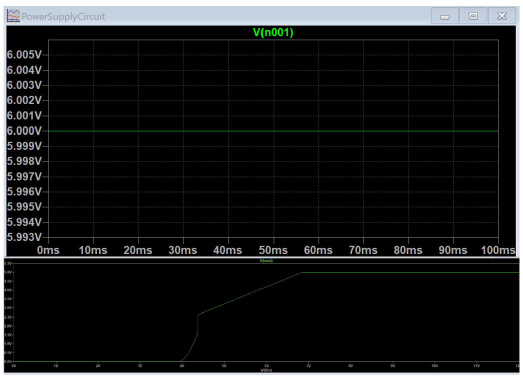
The proportional op-amp controller circuit generates a control signal proportional to the difference between two sensor outputs. Two input voltage sources simulate the left and right sensor outputs. The output follows the difference between the two inputs. If $V_{left} > V_{right}$, the output is positive but when $V_{left} < V_{right}$, the output will be 0 because of the LM358 op-amp configuration. For my robot, If my left sensor detected light it would go high and if my right sensor detected black it would be low which means that it would send an output voltage of 4.5v with the op-amp's A_v =3 gain. $V_{out} = A_v \cdot (V_{left} - V_{right}) = 3 \cdot (1.5v - 0v) = 4.5v$

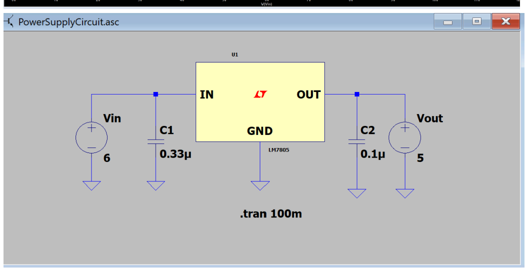




6. Power Supply Circuit

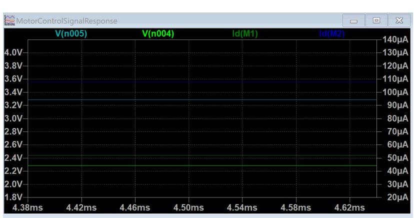
The analysis of the 7805 voltage regulator simulation in LTSpice helps verify that the circuit operates as intended and ensures a reliable power supply for my line-following robot. Because my motors may require a stable voltage to function properly, this regulator must correctly regulate the input voltage down to a constant 5V, regardless of small input fluctuations or changes in load. With this power supply, the regulator correctly regulates my V_{in} down to a constant 5V, regardless of small input fluctuations or changes in load, and my V_{out} may ramp up or have small ripples as simulated but it should quickly settle at exactly 5V with this 7805 regulator power supply.

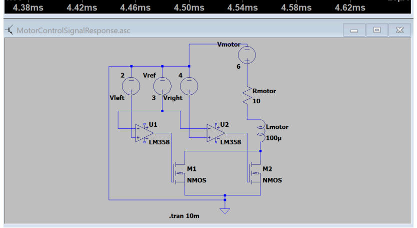




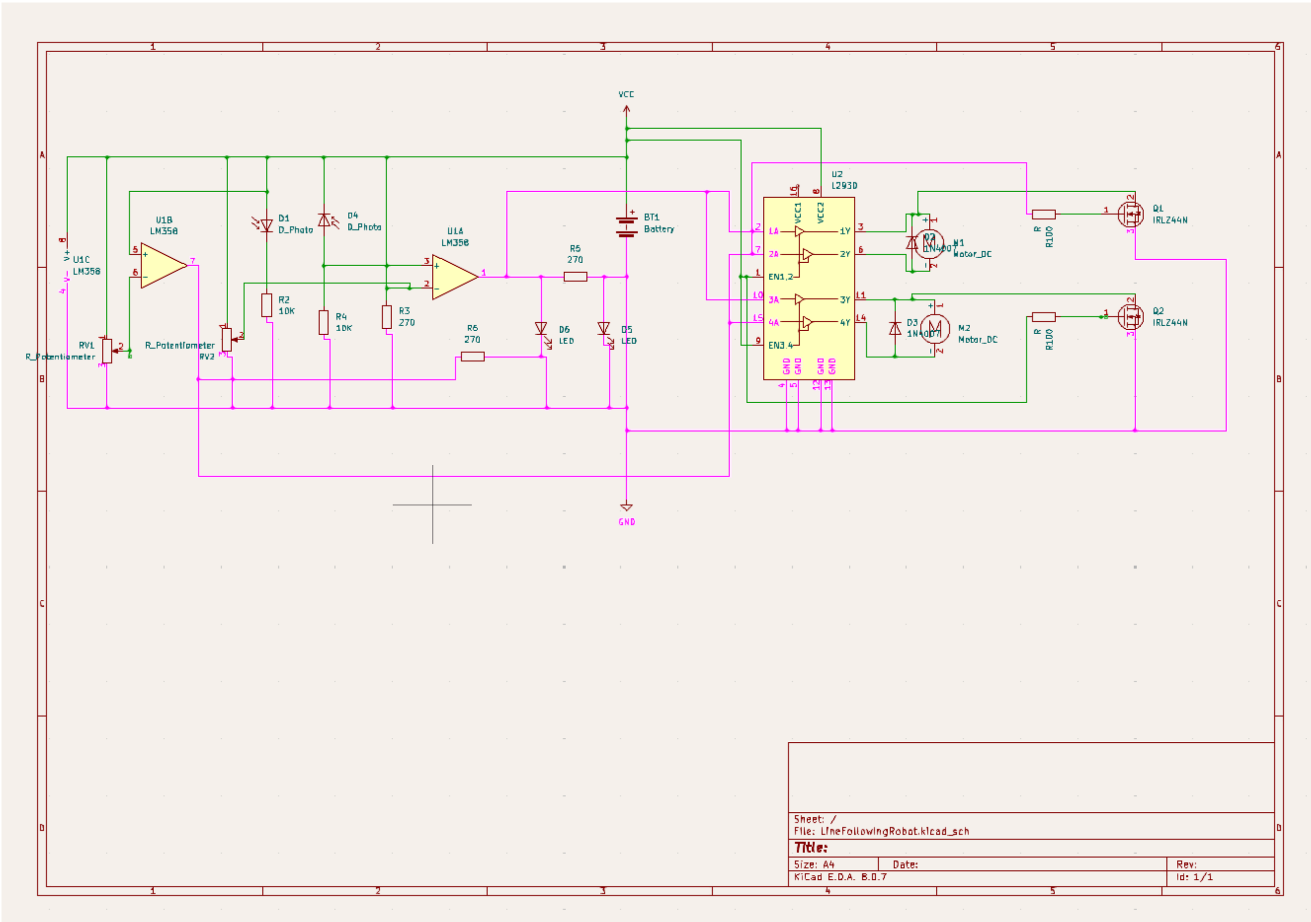
7. Motor Control Signal

For this simulation, I wanted to visualize how my MOSFETs would register different lighting such as white surface and the black line. I found that the outputs of the two comparators (U1 and U2) switch between HIGH and LOW states based on sensor readings relative to the reference voltage(V_{ref}). For example, if the left comparator output is LOW, $V_{left} < V_{ref}$, and if the right comparator output is HIGH, $V_{right} > V_{ref}$. The comparator outputs accurately indicate which sensor detects the line and which does not which sends signals that control the MOSFET gates.





Schematic:



Description of construction:

I began by following the scientific method steps to work effectively. Beginning with the question and research, I found inspiration online specifically in portfolios of individuals' projects of which I found four examples. I compared all four and noticed similar components they used, similar chassis structures they used, and even similar voltage sources. I found that phototransistors were necessary components to provide contrast in voltage levels when exposed to black versus white surfaces, an op-amp circuit would process sensor signals to generate a control signal, and the control circuit provides necessary adjustments to the motors to correct the robot's trajectory. After researching these components and finding them within my notes for CECS 311, I formed my hypothesis: A line-following robot can successfully detect and follow a black line on a white surface using a pair of photodiodes as sensors, a differential op-amp circuit to compare light intensity, and a proportional control circuit to adjust motor speeds. Then, I went on to test this experiment by building my robot. After testing and errors, these are the construction steps:

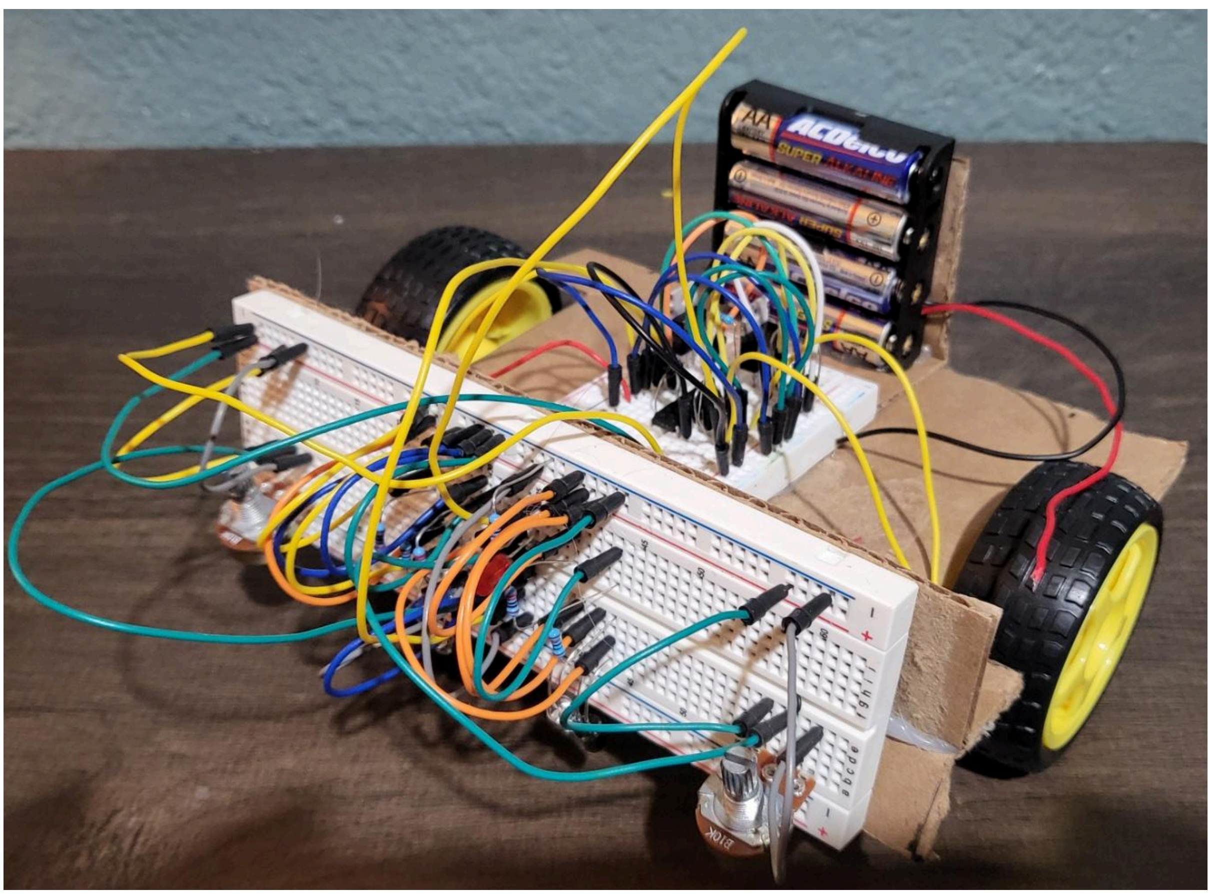
Begin by placing the InfraRed photodiode receiver on the breadboard. Connect the negative terminal of the InfraRed photodiode to the positive rail and its positive terminal to the negative rail with a 10K ohm resistor. Place the InfraRed photodiode transmitter beside the receiver photodiode. Connect its positive terminal to the positive rail and its negative terminal to the negative rail with a 270 ohm resistor. With this setup, the voltage is inversely proportional to the distance of an obstacle from the sensor. To explain more, as the obstacle gets closer to the sensor, the amount of InfraRed light that reflects and falls on the photodiodes increases, which causes more current to flow through the resistor, which then causes more voltage to flow. I want this output of voltage to reach my wheels which means I need to create a reference voltage(V_{ref}) using a comparator, the LM358 IC. This operational amplifier has two comparators and each comparator has two inputs, one is named inverting input and one non-inverting input. As found in my notes, if the voltage at the non-inverting input is greater than the voltage at the inverting input, the output goes HIGH and provides power to the wheels. Connect pin 4 of the LM358 to the negative rail and pin 8 to the positive rail. We are using the comparator to turn on the output whenever the voltage at the InfraRed photodiode is more than the reference voltage(V_{ref}). Because lighting at my home may be different from lighting in the classroom, I need to be able to adjust the reference voltage using the 10K potentiometer. Place the potentiometer on the breadboard and connect one extreme terminal to the negative rail and the other extreme terminal to the negative rail. The center would adjust the voltage using the knob, so connect the center terminal to the inverting input pin, pin 2 of the LM358 and connect the non-inverting input, pin 3, to the positive terminal of the InfraRed photodiode receiver. Now if an object is close, the non-inverting input is greater than the voltage at the inverting input and the output turns on. To visualize the actual recognition of the photodiodes, add an LED with its positive terminal connected to the output of the LM358 and the negative terminal connected to GND with a 270ohm resistor.

At this point, I decided to test my progress with the following cases. If you were to connect the 6v battery to the negative and positive rail, and you move an object close to the photodiodes, the LED would turn ON. Inversely, if the object moves away from the photodiodes, the LED would be OFF. Now I would repeat the same process for a second proximity sensor 3M away from the one I just constructed. For the second sensor, you would use the same resistors and potentiometer except you would use the pins across from the ones used before. You would use pin 7 of the LM358 for the second output/LED, pin 6 for the second inverting input, and pin 5 for the second non-inverting input. Now we need to connect these outputs to the motors.

For the second part of the construction, I focused on connecting the outputs of the IR proximity sensors to the wheels through a motor driver IC. To ensure smooth motor control and account for differences in motor speed and direction, I utilized the L293D H-Bridge driver IC, which allowed me to handle bidirectional motor movement while managing power distribution effectively. This decision was influenced by concepts learned in this class such as Bridge Rectifiers for power supplies. I began by connecting the output pins from the LM358 comparator to the input pins of the L293D IC. Specifically, the output of the first IR sensor was connected to the first motor's input pins (Pin 2 for Input 1 and Pin 7 for Input 2), while the second IR sensor's output was connected to the second motor's input pins (Pin 10 for Input 3 and Pin 15 for Input 4). These inputs determined the motor's direction based on the HIGH or LOW signals generated by the proximity sensors. The enable pins of the L293D (Pins 1 and 9) were connected to the positive voltage rail to activate both motor channels. Next, I connected the motors to the output pins of the L293D. For the first motor, its terminals were connected to Output 1 (Pin 3) and Output 2 (Pin 6), while the second motor's terminals were connected to Output 3 (Pin 11) and Output 4 (Pin 14). This configuration allowed each motor to respond independently to its corresponding sensor, ensuring that the robot could pivot or adjust its movement as needed when detecting the black line. To power the circuit, I incorporated two MOSFETs to ensure consistent operation and effective current handling. Next, I incorporated 100Ω gate resistors between the outputs of the LM358 comparator and the gates of the MOSFETs. These gate resistors reduce inrush current and help avoid noise/ringing. Additionally, I connected 10kΩ pull-down resistors between the gates of the MOSFETs and ground to ensure they turn off completely when no control signal is present. The outputs from the LM358 comparator were connected to the gates of the MOSFETs, allowing them to act as switches for the motors. The MOSFETs' sources were connected to the ground, and their drains were connected to the motor terminals, while the other motor terminals were connected to the positive terminal of the 6V battery. This setup allowed the MOSFETs to provide precise control over the motor power based on the signals from the IR sensors. To further protect the motors and L293D IC, I incorporated flyback diodes across the motor terminals. This precaution was essential to maintain the reliability of the circuit, as voltage spikes could potentially damage the L293D or the sensors. These diodes ensured that any back EMF generated by the motors was safely redirected, aligning with the principles of electromagnetic interference mitigation learned in class. The sensors should now successfully detect the black line and generate output signals processed by the L293D to control the motors.

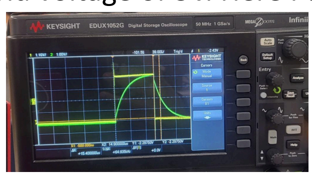
Pictures:

Completed Robot:



Video:
https://drive.google.com/file/d/1LY8CMUWOkdd8bt5ZUoRPknXECI9Cw-4v/view?usp=sharing

Waveforms:
Sensor Behavior: I built my IR sensor circuit and tested the output voltage when it detected black and white. As seen on my waveform, my photodiode's resistance will decrease under bright light (white surface) and increase under less light (black line). A white surface gives a lower resistance and higher output voltage while a black line gives a higher resistance and lower output voltage. 

Comparator Output: I simulated my LM328 IC behavior. I plotted the comparator's HIGH/LOW outputs relative to a fixed threshold voltage of 3V. Here I tested $V_{sensor} > V_{ref}$, which causes V_{out} to go HIGH and gives a square wave. 

Conclusion:
The robot successfully detected and followed the black line on a white surface, demonstrating that the sensors, comparators, and motor driver worked as intended. If given more time, I would replace the MOSFETs with 2N2222 BJTs for better efficiency in low-current scenarios. Using 270Ω base resistors calculated for proper motor current and voltage levels, the BJTs would ensure smoother operation. The 2N2222's low power dissipation (V_{CE} = 0.3V) ensures it operates well within its limits, enhancing reliability and efficiency.