Final Report

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1. Proposal (Author: Haochen)

The objective of this project is to design and implement a motor control system that utilizes an HC-SR04 ultrasonic sensor to measure distance and feedback to adjust motor speed. The system will incorporate a Proportional-Derivative (PD) controller to process the error between the current distance and a set reference value, which will be used to generate a Pulse-Width Modulation (PWM) signal through an NE555 timer. This PWM signal will then control a motor using a MOSFET.

Our plan for this project can be divided into three phases: Sensing, Processing, and Output

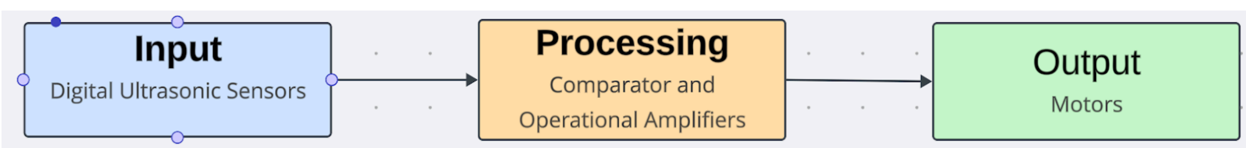


Fig. 1 Flowchart of the entire process

We selected the HC-SR04 ultrasonic sensor as our input device, which provides a digital echo signal. In the processing stage, this signal is converted into an analog error value using a counter and an R-2R resistor network. The output is then passed through a subtractor to maintain tracking with the set reference value. Next, the signal is fed into the PD controller, which processes the error and generates a corresponding output. This output is converted into a PWM signal using a NE555 timer. Finally, the PWM signal is used to drive a MOSFET, which controls the motor as the final output.

2. Milestones (Author: Bailiu)

Milestones No.	Task
1	PD controller
2	Trigger Signal for Ultrasonic Sensor HC-SR04
3	Processing Echo Signal
4	Counter and DAC
5	Subtracting Base Voltage
6	PD integration and Motor Control
7	Chassis Design

2.1 Milestone 1: PD controller

This circuit implements a Proportional-Derivative (PD) controller using operational amplifiers, The PD controller circuit responds to the input signal by providing both a proportional output (reacting to the signal's amplitude) and a derivative output (reacting to the signal's rate of change). The combined output of the summing amplifier is the PD control signal will then be processed to control the motor.

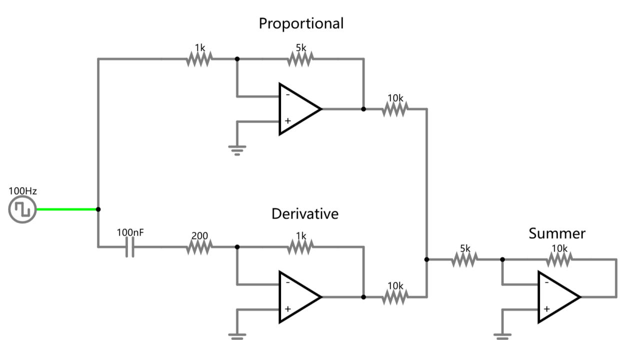


Fig. 2 Circuit diagram for PD controller

2.2 Milestone 2: Trigger Signal for Ultrasonic

According to the sensor's datasheet [1], the ultrasonic sensor requires a trigger signal consisting of a minimum 10µs TTL pulse. We took on this task by designing a pulse generator using a NE555 timer in astable mode.

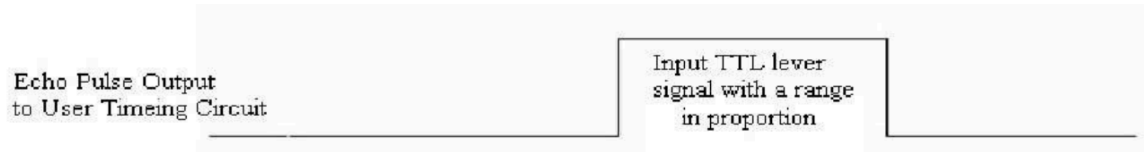


Fig. 3 Echo signal from HC-SR04

With the formula [2]:

$$T_h = 0.693(R_1 + R_2)C_1$$
$$T_l = 0.693 R_2 C_1$$
$$f = \frac{1.44}{(R_1 + R_2)C_1}$$

To meet the recommended 60ms interval between measurements, we selected R1 components to achieve the desired timing. Specifically, we used 100 kΩ for R1, 100Ω for R2, and a 1 µF capacitor. This configuration resulted in a high-level time of 69.37 ms, a low-level time of 0.07 ms, and an overall frequency of 14.37 Hz, then we fed it into a inverter so that we have a 69.3 µs TTL signal with 69.37 ms interval for trigger.

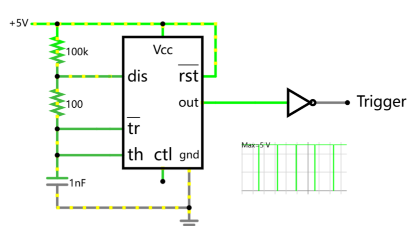


Fig. 7 Circuit diagram for trigger signal using NE555

2.3 Milestone 3: Processing Echo Signal

To convert the HC-SR04's output into a usable format, We implemented another NE555 timer in astable mode

We used a 100 nF capacitor and 100 Ω and 1 kΩ resistor implementations, generating a 6.9 kHz frequency, which results in a continuous square waveform with a much shorter period to the HC-SR04 echo signal.

By connecting the NE555 output and the HC-SR04 output to an AND gate. When the HC-SR receives a signal and generates a high level at the echo pin for a certain period, the gates will output a signal with the same duration as the frequency of the 555 and the same duration as the output of the ultrasonic transducer. Ideally, the gates will output

$$\frac{distance \cdot frequency}{170}$$

highs in each measurement.

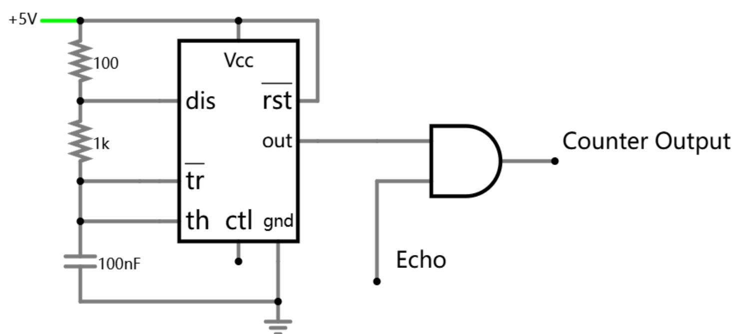


Fig. 8 Circuit diagram for processing echo signal

2.4 Milestone 4: Counter and DAC

To calculate the period, we connected the output to an AND gate. A 4-bit counter is used to sequentially count through a binary range from 0000 to 1111, which represents decimal values 0 to 15, with each clock pulse. The reset pin is connected to the trigger signal so that it refreshes the data in each cycle. We tested the counter's output using LEDs by placing obstacles at various distances from the sensor and comparing the results. After this, we removed the LEDs and implemented a digital-to-analog converter. We chose an R-2R ladder using several 1kΩ resistors, arranged in a ladder configuration to convert 4-bit binary input signals into proportional analog output voltages.

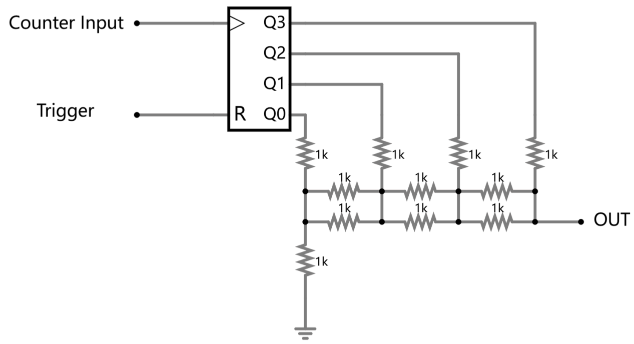


Fig. 9 Circuit diagram for counter's output and R-2R network

2.5 Milestone 5: Subtracting Base Voltage

For the subtractor, we configured the resistors as follows: R1=R2=10 kΩ and Rg=Rf=10 kΩ. This setup allowed us to accurately subtract the base distance signal, resulting in an output that reflects only the incremental distance beyond the baseline. We chose R1 = R2 and Rg = Rf to simplify calculations. The formula for the output of this subtracter can be expressed as:

$$V_{\text{out}} = \frac{R_f}{R_1}(V_2 - V_1)$$

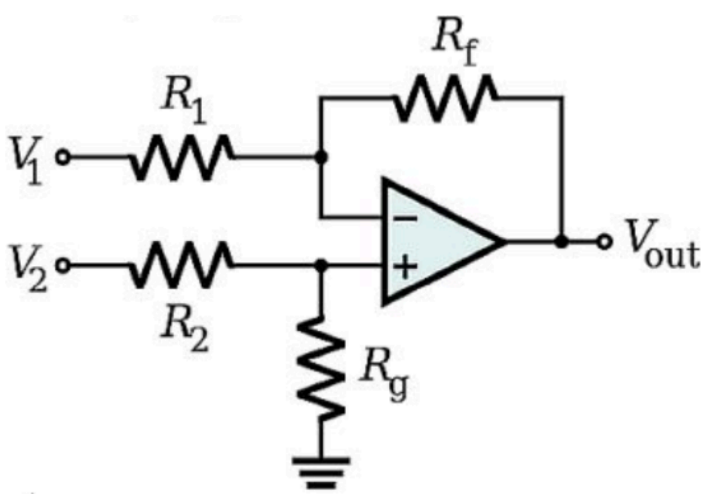
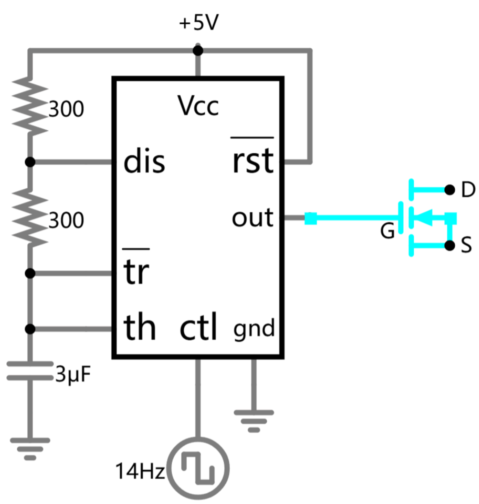


Fig. 10 Circuit diagram for subtractor [3]

2.6 Milestone 6: PD Integration and Motor Control

The Output of the subtracter will be fed into the PD controller, and the circuit below will process the output from the PD controller and encode a voltage using pulse-width modulation (PWM) through a 555 timer chip. The pulse width of the output varies based on a control voltage applied to the "CTL" input.

As the control voltage decreases, the timing interval shortens, causing the 555 timer to oscillate at a faster rate, thereby changing the duty cycle of the PWM output. This allows for precise modulation of the output signal's pulse width in response to the input voltage, thus controlling motor speed.



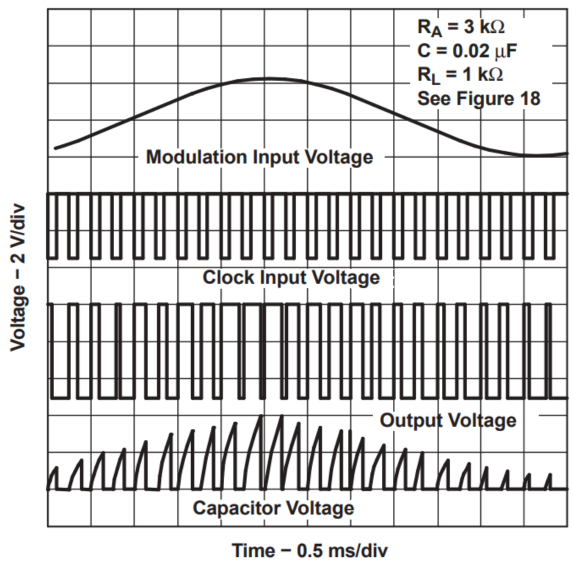


Fig. 11 Circuit diagram and expected output for Motor Control [4]

2.7 Chassis Design

For the chassis, we opted to use a breadboard as the main framework due to its flexibility and ease of prototyping. We designed and 3D-printed a custom mount using SolidWorks to securely attach the motors. Additionally, we created 3D-printed wheels and wrapped them with Teflon tape to ensure smooth and efficient movement. The back wheel was designed to be adjustable, allowing fine-tuning of its angle to ensure the vehicle moves in a straight line.

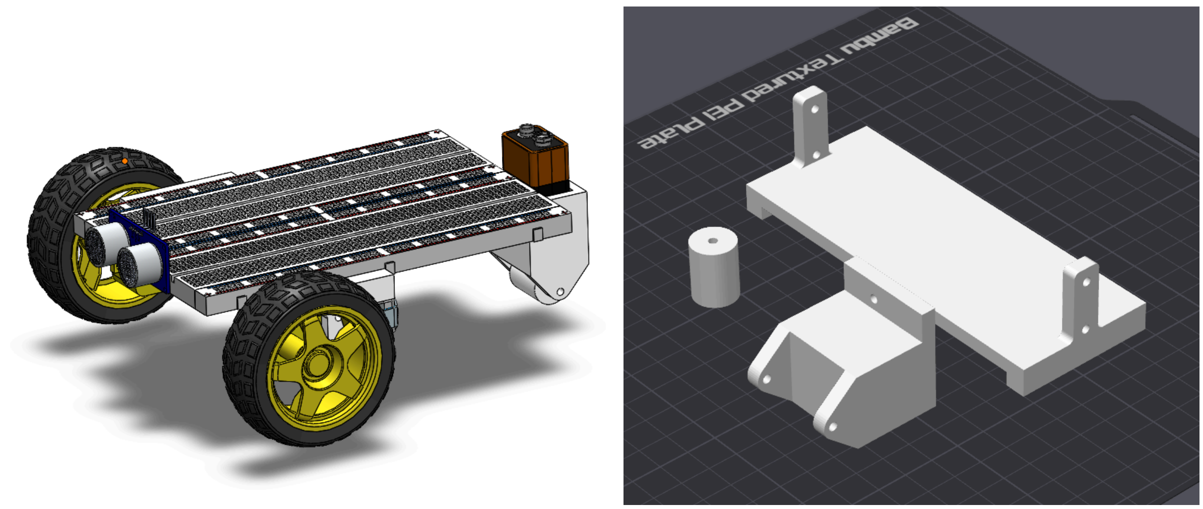


Fig. 12 3D models for chassis design

3. Operations & Verifications

(Author: Bailiu & Haochen)

3.1 PD controller

To verify the function of our PD controller, we used a 100 Hz, 50% duty cycle square wave signal as the input. The results are shown below. We observed a significant change in response when the phase shifted, corresponding to the D controller's effect. The smooth, proportional response reflects the P controller's influence, aligning with our circuit design.

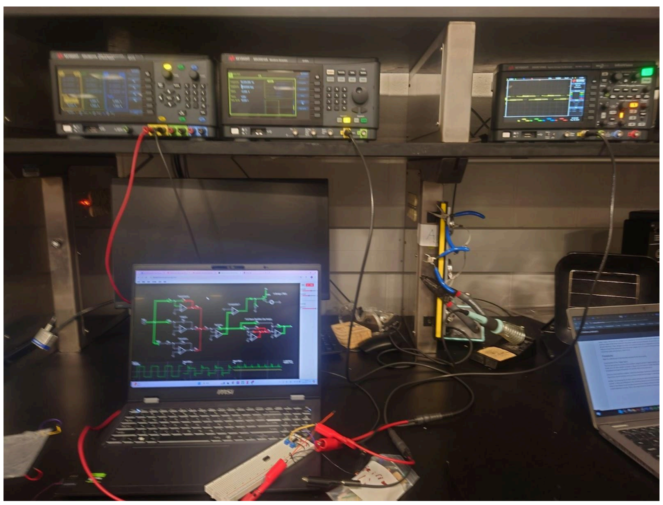


Fig. 13 Testing PD output with signal generator

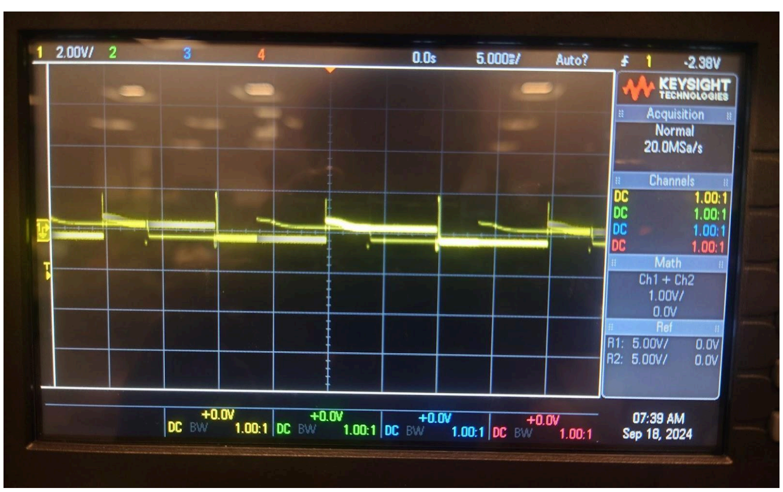


Fig. 14 Waveform of the PD ouput

3.2 Trigger Signal for Ultrasonic

Using the oscilloscope to monitor the output from the inverter, we observed a consistent, sharp pulse appearing at intervals of approximately 60 ms. This pulse had a distinct ridge shape, confirming the presence of a brief, high-level TTL signal at each interval. The timing of these pulses matched our calculated period of 60 ms, indicating that our NE555-based pulse generator, in conjunction with the inverter, reliably produces the required 10 µs TTL pulse for triggering the ultrasonic sensor. This outcome verifies that our design meets the timing specifications detailed in the sensor's datasheet, providing an accurate and consistent trigger signal essential for precise measurements.

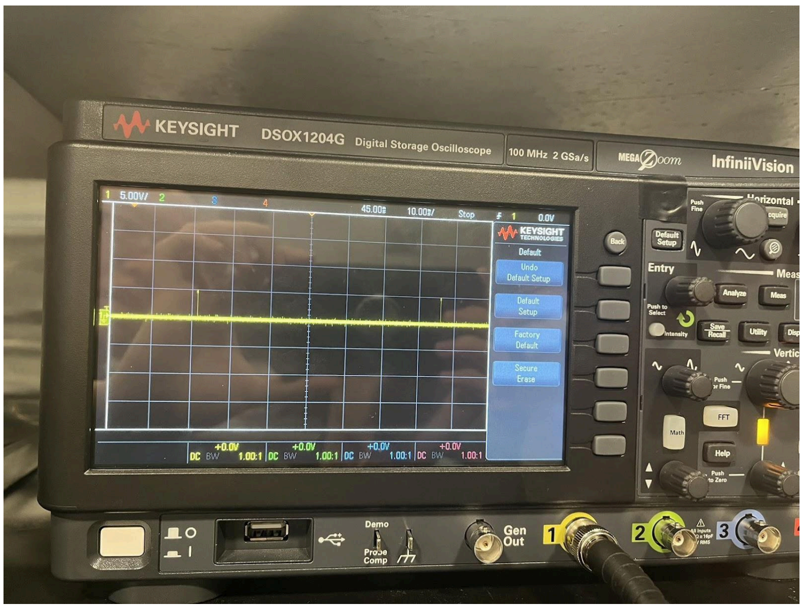


Fig. 15 Waveform of the trigger signal

3.3 Processing Echo Signal

The oscilloscope captures below show the input signals to the AND gate. The green trace (Channel 2) represents the output from the ultrasonic sensor’s echo pin, with its duration corresponding to the detected distance. The yellow trace (Channel 1) shows the output from the second NE555 timer, which consistently produces a square wave at approximately 7 kHz with a 50% duty cycle. After processing through the AND gate, the resulting output signal has the same 7 kHz frequency, matching the NE555 output, while the total duration aligns exactly with the echo signal from the sensor. This confirms that the AND gate successfully modulates the ultrasonic sensor’s output, encoding distance information in a format compatible with further digital processing.

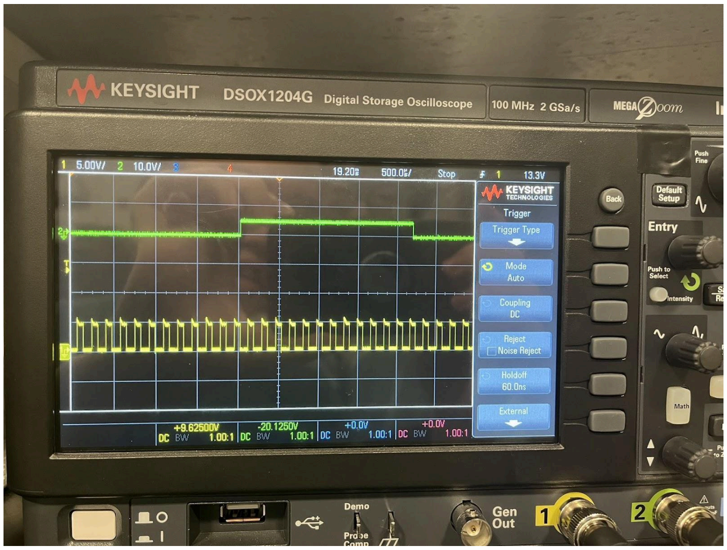


Fig. 16 Waveform of the AND gate’s inputs

Fig. 17 Waveform of the AND gate’s output

3.4 Counter and DAC

To better visualize the output of the counter, we used 4 LEDs to display the 4-bit binary code. As we moved the obstacle further from the sensor, the binary digits incremented by 1, accurately representing changes in distance. Occasionally, we observed an LED blinking between stages, which we attributed to minor acceptable sensor fluctuations. After this, we replaced the LEDs with an R-2R ladder and measured the output voltage levels at different stages, confirming proportional analog voltage outputs corresponding to the 4-bit binary input values.

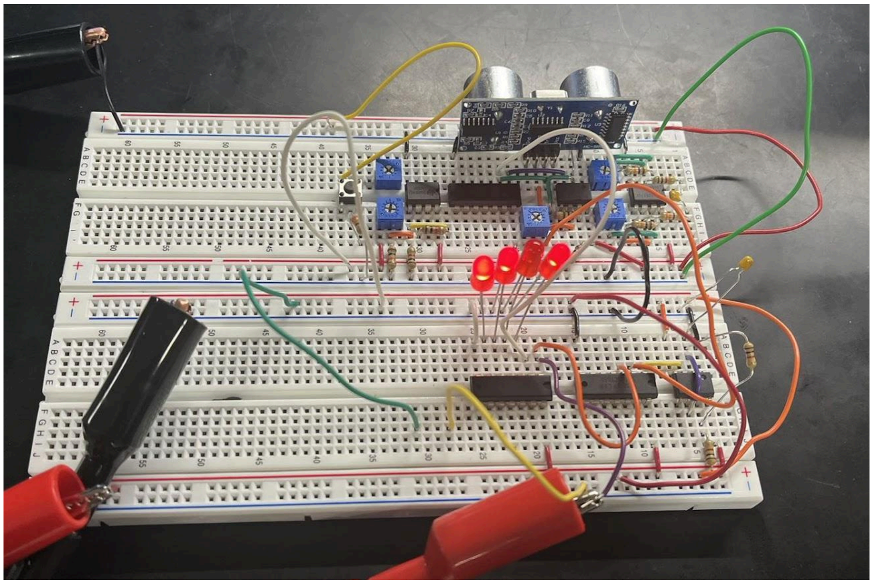


Fig. 18 Testing output with LEDs

3.5 Subtracting Base Voltage

After generating the analog voltage signal, we used an operational amplifier in a subtractor configuration to isolate the signal relative to a baseline distance. We fine-tuned the potentiometer to make sure that the voltage output at the base distance is near zero. The final results are shown below. The yellow trace (Channel 1) green shows the input and the green trace (Channel 2) represents Output.

Fig. 19 Waveform of the subtracter’s input and output

3.6 PD Integration and Motor Control

The output of the PD controller, which is shown below, will be used to produce the final PWM signal that controls the motor. We can see that the voltage produced is proportional to previous values. Since the voltage stays the same most of the time, we can only observe the effect of the D controller at the reset period.

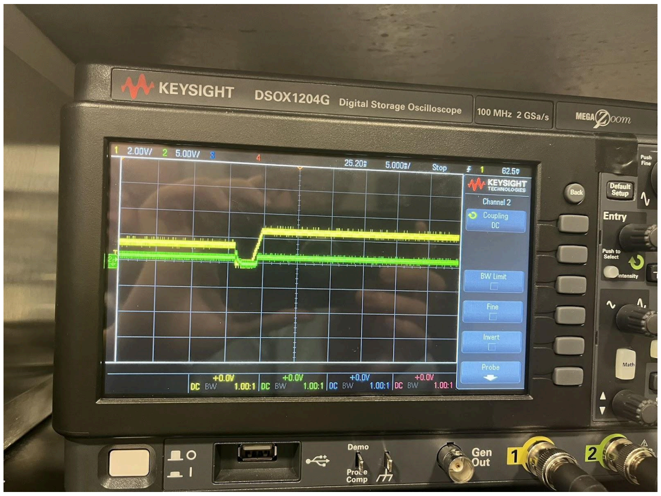


Fig. 20 Waveform of the PD controller's output (green, compared with input yellow)

We then feed the output of the PD controller into the differential amplifier, in which we used R1 = R2 = 3.3k ohm and Rg = Rf = 10k ohm, a setup that will amplify our output to be suitable for the trigger of NE555. We also fine-tuned the potentiometer to make sure that at our base distance, the input of the NE555 timer is zero.

The NE555 timer will produce a PWM signal whose duty cycle is proportional to the input voltage. Finally, we used an nMOS to control the motor. The output of the NE555 timer is shown below.

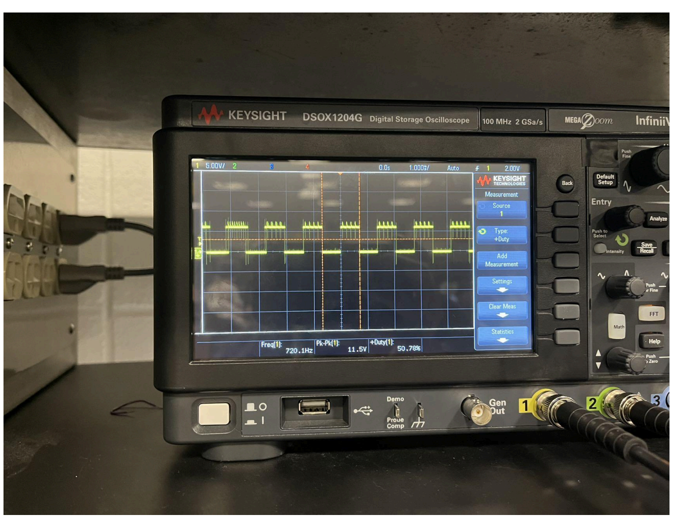


Fig. 21 Waveform of the motor's input signal generated by NE555

3.7 Chassis Design

After completing the 3D printing and removing the support structures, the printed components were mounted onto the breadboard. The motor and wheel support plates were attached to the back of the breadboard using double-sided tape for stability. The ultrasonic sensor was securely fixed in place with hot melt adhesive. The rear wheel assembly was attached to the breadboard using single M2 screws, allowing for angle adjustments. The wheels were mounted using a gap-fit mechanism, with M3 screws serving as the axles.

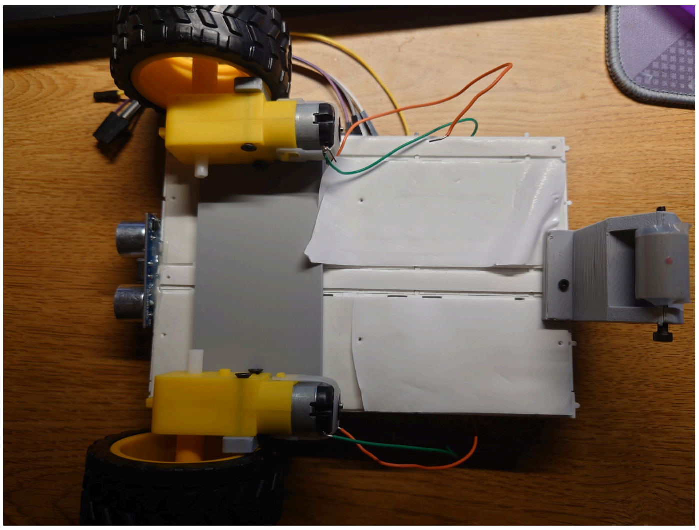


Fig. 22 Back view of the car

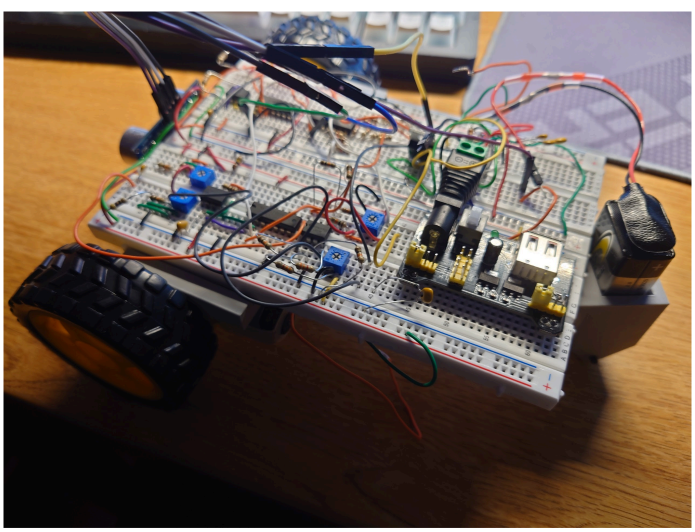


Fig. 23 Oblique view of the car

4. Challenges & Successes (Author: Bailiu)

Trigger Signal Problems: One of the main challenges we encountered was generating a reliable trigger signal for the ultrasonic sensor using the NE555 timer. Initially, we attempted to generate a square waveform with a 50% duty cycle and a higher frequency. However, upon reviewing the sensor's datasheet, we found that it recommended a measurement cycle of at least 60 ms to avoid interference between the trigger signal and the echo signal. After considering this, we decided to use a combination of the NE555 timer and an inverter, which allowed us to generate the required signal while minimizing potential interference.

RC-filters V.S. Counters: Another challenge was processing the echo signal. We first designed an RC low-pass filter to process the sensor's output. However, since the system operates at a relatively low frequency, we had to carefully select resistor and capacitor values to filter out the high-frequency components while preserving the integrity of the analog signal. We calculated the filter's cutoff frequency and tested several combinations of resistors and capacitors, but none of the configurations worked as expected. Some took too long to charge and discharge, while others failed to maintain a stable voltage with a fixed distance. After consulting with our TA, we ultimately decided to use digital counters and an R-2R resistor network to calculate the distance, even though this approach made the circuit design more complex.

Counter Reset Issue: The reset pattern for our counter is not functioning as expected, resulting in inaccurate output values when the obstacle is too close to the sensor. Currently, the reset pin is connected to the trigger of the ultrasonic sensor, but this configuration requires further adjustments and improvements to ensure correct resetting and accurate counting.

R2-R Circuit Problems: In the previous circuit, the LEDs used to indicate the counter's output were absorbing voltage, leading to lower-than-expected readings. When we removed the LEDs and switched to measuring the voltage with an oscilloscope, the readings returned to normal levels, confirming that the LEDs were interfering with the voltage levels.

Connection Issues: We noticed discrepancies between the expected voltage (1.875V) and the actual voltage at approximately 1.79V vs. 1.7V. This mismatch is likely due to the subtractor circuit having a relatively low impedance, which causes the input voltage at the subtractor to be lower than the output from the R2-R network. To address this, we used 10kΩ resistors to minimize the current draw from the subtractor and improve the voltage accuracy.

Output from PD Controller: The output from the PD controller has two issues: (a) there is noticeable noise, and even when we moved the barrier below the set distance, there is still a 200 mV signal; (b) the maximum amplitude of the controller output is approximately 2.2V, which is lower than expected and needs to be addressed for proper signal performance. After we redesigned the subtractor circuit and adjusted the Porpotional value, the noise decreased to roughly 20mV, and the output voltage from the PD controller was fed to another amplifier to solve the problem that output was lower than expected.

Base distance voltage issue: We configured a differential amplifier that amplifies the output signal of the PD controller and maintains zero output voltage at our base distance. However, after we use this output signal as the input of the NE555 timer that we used to generate the PWM control signal of the motor, the duty cycle of the final PWM control signal remains about 11% at the base distance for unknown reasons. After fruitless efforts to find solutions, we decided to utilize the weight of our car to achieve zero speed at an 11% duty cycle.

5. Conclusion and Final Product

(Author: Bailiu)

In this project, we have successfully developed a functional ultrasonic-based distance-measuring system that drives a trolley to follow objects in front of it using a PD control mechanism. We implemented various components, including the ultrasonic sensor, PD controller, NE555 timer circuits for triggering and echo processing, digital counters, differential amplifier, and DAC. Each of these components has undergone testing and verification, ensuring that the system performs as expected in many aspects. We have achieved all of the initial project milestones and tackled most of the challenges we encountered, such as generating a stable trigger signal, resetting the counter accurately, and resolving voltage discrepancies within the subtractor circuit.

To demonstrate our implementation, we 3D-printed a car chassis that can carry our board and tested our circuit in real-world circumstances. The car successfully showed full functionality as our design intended. In the future, the project can be further improved by enabling backward movement by configuring negative voltages in our control circuits and using an H-bridge.

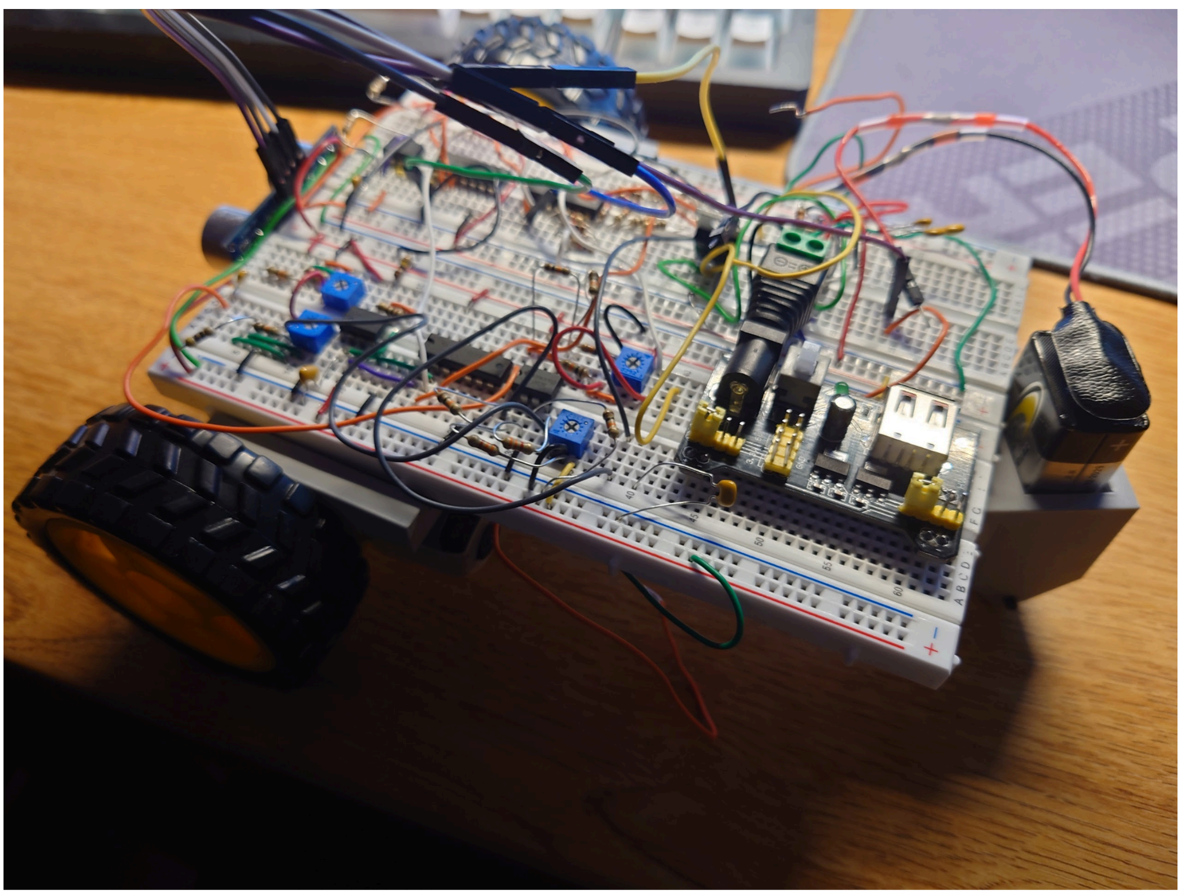


Fig. 24 Final Product

6. Team Work (Author: Haochen)

We (Haochen & Bailiu) collaborated on the project as well as the midterm report.

For the project, Haochen researched the project feasibility and configured the NE555 timer to generate trigger signals aligned with the ultrasonic sensor's specifications. He also assembled the digital calculator and R2-R ladder circuit, performing functional tests on the counter circuit to ensure accuracy and troubleshooting the R2-R output for optimal analog performance. Additionally, he adjusted resistance settings in the subtractor circuit to enhance performance. Bailiu focused on circuit implementation and simulation, designing the RC low-pass filter to convert PWM to analog voltage and implementing the NE555 timer as a clock generator with frequency set to project specifications. He also designed the subtractor circuit for future improvements and established baseline measurements, including base distance and expected voltage output, while testing and optimizing the PID controller for stability and accuracy.

For the report, Haochen recorded and edited the video. Haochen also wrote the Proposal and Teamwork section of the report. Bailiu was responsible for Milestones, Challenges and Future Plan sections of the report, and both team members collaborated on the Verification section.

Reference

[1] ElecFreaks, “Ultrasonic Ranging Module HC -SR04,” 2011. Available: https://cdn.sparkfun.com/datasheets/Sensors/Proximity/HCSR04.pdf

[2] “555 Timer Calculator | DigiKey Electronics,” *www.digikey.com*. https://www.digikey.com/en/resources/conversion-calculators/conversion-calculator-555-timer

[3] “Subtractor op-amp configuration to find the diference of 2 signals,” *Electrical Engineering Stack Exchange*, Aug. 08, 2020. https://electronics.stackexchange.com/questions/515490/subtractor-op-amp-configuration-to-find-the-difference-of-2-signals (accessed Nov. 11, 2024).

[4] www.alldatasheet.com, “NE555 datasheet(13/29 Pages) TI,” *Alldatasheet.com*, 2021. https://www.alldatasheet.com/html-pdf/355583/TI/NE555/358/13/NE555.html (accessed Nov. 11, 2024).