Zhejiang University/University of Illinois Urbana-Champaign Institute

Senior Design Final Report

AN IMMERSIVE HUMAN-DRIVEN ROBOT IN DETECTING FOREIGN MATTER IN TUBES

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Individual Report for Senior Design, Spring 2023

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Abstract

Our project, 'An Immersive Human-driven Robot in Detecting Foreign Matter in Tubes', focuses on the development of a multifunctional robot capable of detecting foreign matter in tube systems. we employ a hand recognition neural network based on a YOLO-like architecture to enable users to manipulate the direction of the robot by manipulating the position of their hands. The camera on the robot captures the user's hand gestures, which are then used to control the movement of the robot. A WiFi module is established to enable seamless communication between the robot control system and the hand. Moreover, the robot is equipped with sensors and a camera to collect environmental parameters. The infrared ray sensor, gp2y0e03, accurately measures the distance between obstacles and the front of the car, enhancing safety. The sg90 servo motor controls the camera's position, enabling a flexible perspective for improved detection and segmentation of foreign matter. A shell is also designed to protect the circuit inside. By combining these features, our robot assists the user in making informed decisions by providing real-time information about the environment.

Key words: *Immersive*, *Tube Detecting*, *Multifunctional Robot*

Content

1. Introduction

1.1 Problem

By the end of 2019, China's drainage network had a total length of more than 744,000 km, with the diameter of these pipes ranging from 32 mm to 2,000 mm. The aging of facilities and backward management technique are common problems in Chinese urban pipeline network. Defects such as pipeline rupture and corrosion lead to frequent accidents in urban pipeline operation and maintenance. At present, the operation and maintenance of urban drainage pipes mainly rely on manual work, which is difficult to operate, large amount of work and high risk. Traditional man-machine cooperation, such as pipeline desilting, requires workers to go down the well for operation, but the small and dark space in the downpipe makes it difficult for workers to work, and harmful gases such as hydrogen sulfide in the construction environment will seriously harm workers' health. Maintaining the operation of the drainage network has become an important and arduous task of urban governance.

1.2 Solution

We will design a human-driven robot but in an immersive context. We will use a self-design electric car as a model. People change the direction by manipulating the position of their hands as if there is a real steering wheel. This will be accomplished by a hand recognition neural network based on YOLO-like neural network. The camera captures the user's gestures and then uses them to turn the car around. The position of the car will be recorded and displayed on the screen in front of the driver or on the glass of the driver even though the actual car may be far away from the user. This will be implemented by a chip with a camera, esp32 and WiFi module. Robot control system and hand recognition neural network are connected by the WiFi module. The scene inside the sewer pipe is also transmitted by the camera on the car by WiFi module. In this way, the driver can drive the car in an immersive context and make precise and subtle operations when the "road" condition is very complex. The robot is able to detect the foreign matter as a recognition or segmentation problem and send back the information. We set the corresponding sensors and camera to collect the environmental parameters, helping the user to make a better decision. The infrared ray sensor gp2y0e03 can accurately measure the distance between the obstacle and the front of the car. The sg90 servor can control the position of the camera to support a more flexible perspective.

1.3 Visual Aid

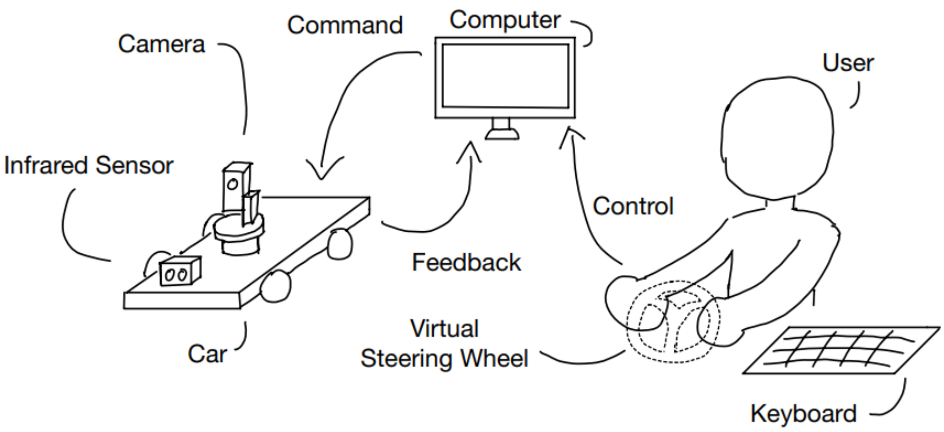

Figure 1 Visual Aid of the Project

2. Design

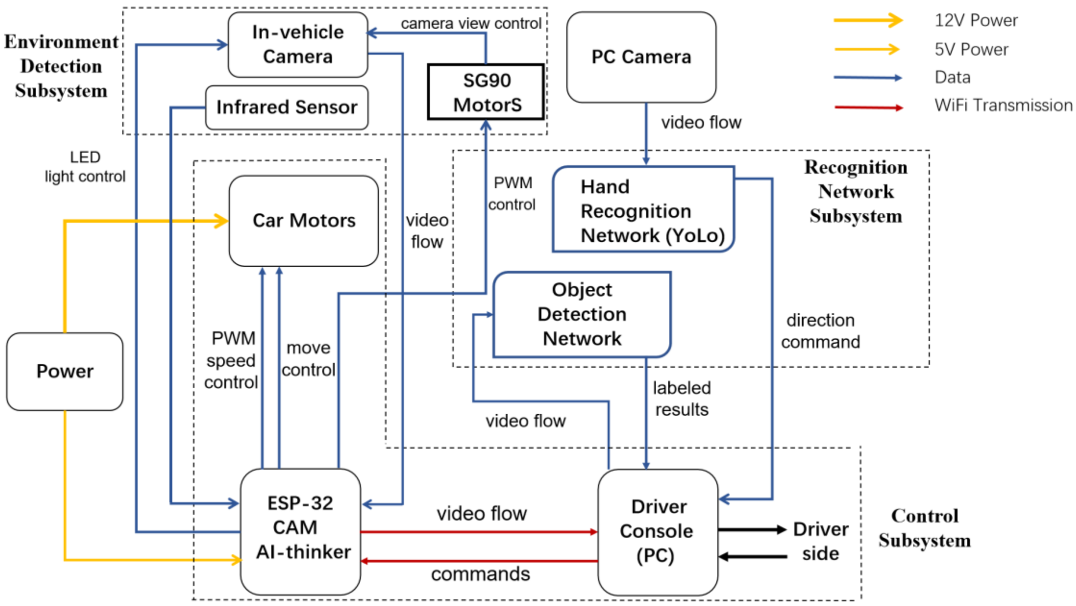

Figure 2 Overall Block Diagram of the Systems

Overview: In summary, we use the ESP-32 CAM chip to build our WiFi subsystem and environment detection subsystem. It can control the movement of the robot car, adjust the speed, turn up the flashlight, and support the camera monitor. We choose L298N Motor Driver Board to provide PWM signals and enough voltage to motors to achieve speed change. The whole system is powered by three 18650 batteries (3.7V each). The L298N Motor Driver Board can directly use batteries to support motors which have a rated voltage of 12V. Also, we use L298N to output a 5V power source to support ESP32 chips, a sg90 servo, and an infrared sensor simultaneously. ESP-32 CAM chip can autonomously record videos and directly sent them to the driver's PC. And the driver can also adjust the flashlight and control the robot car with the keyboard of the driver's PC and the hand recognition subsystem. What's more, we have one more ESP32 chip, which is still under WiFi remote control by the driver, to control this accessory hardware like servo and sensors.

2.1 Shell

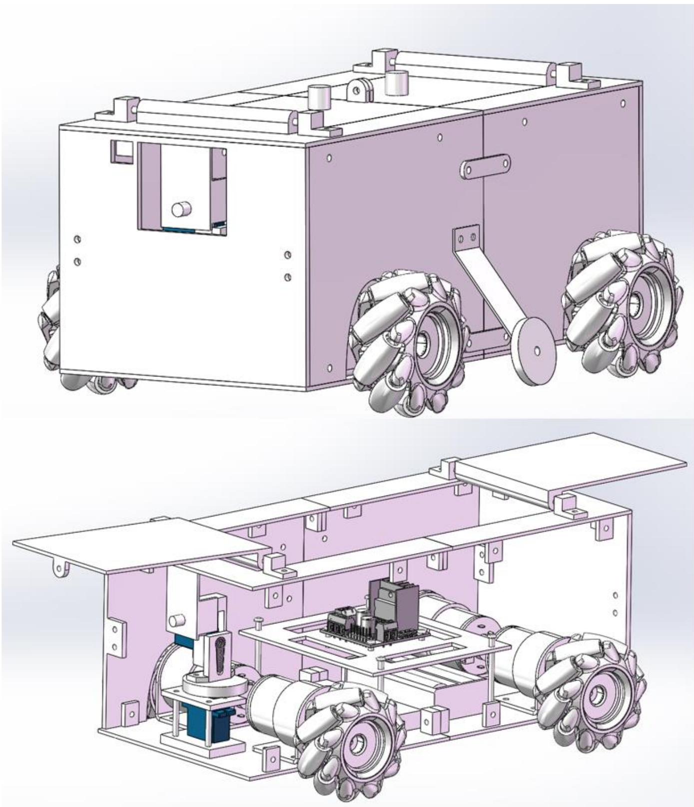

Figure 2.1 Shell CAD Model

Because our goal is to make a vehicle that could travel in a pipeline, our vehicle is supposed to be able to withstand the dangers from the environment. In addition to protecting the robot from external substances, the shell also prevents the robot from contaminating the tube environment. Besides, the shell provides structural support and rigidity to the robot, ensuring that it can withstand the physical stresses and strains encountered during its operation. It helps maintain the alignment and positioning of critical components, such as sensors and camera, which are essential for accurate data collection. Lastly, the shell should be designed to facilitate cleaning and maintenance of the robot.

Combined with the above three points, we designed such a completely closed box shell of the car to protect the internal circuit, and the top layer of the door can be opened, to facilitate our maintenance of the car, as figure 2.1.1 shown. The top layer can be opened by pulling on these two little handles. To lock the top layer, put a bolt through the holes in the middle and tighten the nut. Most of components of the shell are 3D printed with PLA (Polylactic Acid). In order to gurantee the strength and stability of the shell, we print the components with 95% percent density PLA. Although PLA is not as strong as some other materials like ABS or nylon, it still offers sufficient strength and rigidity for our project.

2.2 Camera Rotating Device & Distance detector

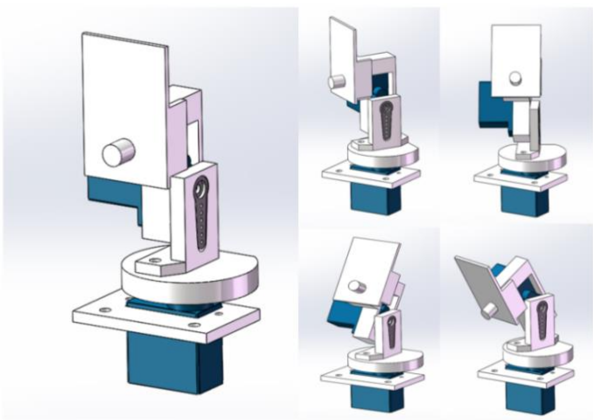

Figure 2.2.1 Camera Rotating Device with Different Rotating Angles

The environment is always dark and complex. In order to better deal with all kinds of emergencies that may happen in the pipeline and help the driver understand the situation in the pipeline more comprehensively, we designed a camera rotating device (shown in figure 2.2.1 with different rotating angles).

The most components of the device is also 3D printed with 95% percent PLA. 2 SG90 servo motors are respectively applied for horizontal rotation and forward and backward rotation, more design detail is shown in figure 2.2.2.

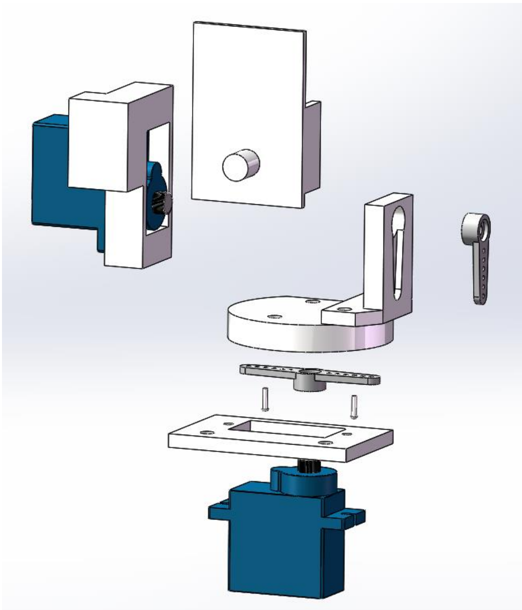

Figure 2.2.2 Explosion Diagram for Camera Rotating Device

The control system of servo motor is as follows: The servo is controled by PWM, which is controled by the digital signal ranging from 60 to 105 in the base 10 system(1024 bits). In reality, we use the 3.3v for clock, Vin, etc since the normal output of the esp32 chip is 3.3v without any voltage-lifting module. We adjust the range of the digital signal based on the car structure which Weng and Liu have implemented by making the board for distance sensor untouchable by the camera. The final decision we made is between 70 to 90 digital level for the PWM signal.

The distance detector we use is GP2Y0E03, which is a infrared sensor. We decided to use the ADC(Analog to Digital Converter) $GPIO_{34}$ to transfrom the Vout analog voltage to digital signal because we the esp-idf does not support serial transmission module for GP2Y0E03, which can be directly used to accept the SDA data(distance in centimeter).

The distance vs analog voltage graph has been shown qualitatively on the datasheet, which is a linear relation. This implies that digital signal versus distance function must also be linear. We take the hypothesis of the linear relationship and designed an experiment on the determining the k and b in the formula: $V = k * d + b$. We measured data and use quadratic loss to obtain the graph below.

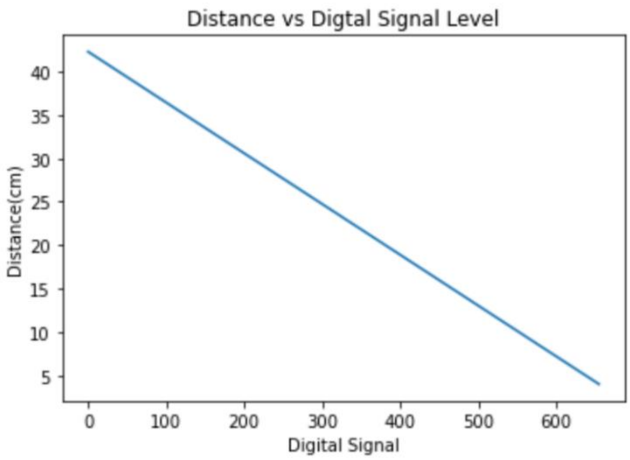

Figure 2.2.3 Distance vs Digital Voltage

2.3 Training Wheel

When the vehicle is running in the pipeline, sometimes it may encounter special circumstances that make the vehicle turn over. Once the rollover occurs, it will not only affect the stability of the internal circuits, but also make it difficult to get the car back to its original position. To avoid this, we designed training wheels (shown in figure2.3.1) on both sides of the car.

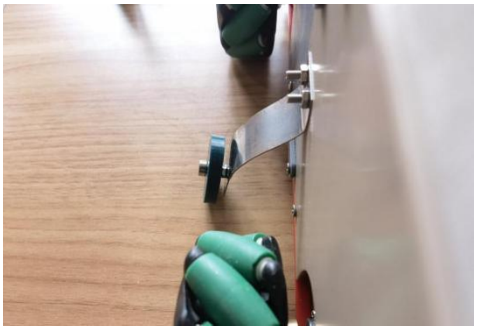

Figure 2.3.1 Training Wheel

It consists of steel plates, wheels, half-teeth screws and nuts. When the car is running normally, the training wheels will not be in contact with the ground. But when the car tilts, the training wheels make contact with the ground, keeping the car balanced for a while, giving the driver time to react and adjust the car's movement.

2.4 Environment Detection Subsystem

Our environment detection subsystem consists of an in-vehicle camera, an infrared ray sensor, and a servor. The camera is used to record videos and transmitted back to the PC. The infrared ray sensor is used to measure the accurate distance between the obstacle and the front of the car.

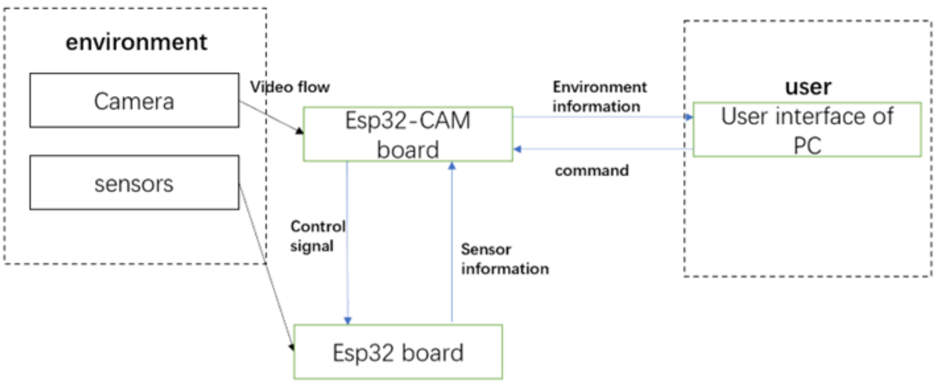

Figure 2.4.1. Environment Detection Flow Chart

2.5 WiFi Subsystem

The WiFi subsystem I built is based on WiFi connection and socket transmission. I use ESP32-CAM chip as a WiFi router to transmit signal between the driver's PC and the car by setting it to WiFi_AP mode. The other ESP-32 chip we use to control the servo and the infrared ray sensor is set to WIFI_STA mode. Because we use socket transmission, I implement information fetch algorithm to recognize jpeg format video and driver's commands in the socket string flow. We can support jpeg format video at 30 fps under 100ms. Each part of our subsystem, like the ESP-32 CAM chip and the PC, both serve as a client and a server in socket transmission. This means that each part both needs to receive and send messages during each round of algorithm running.

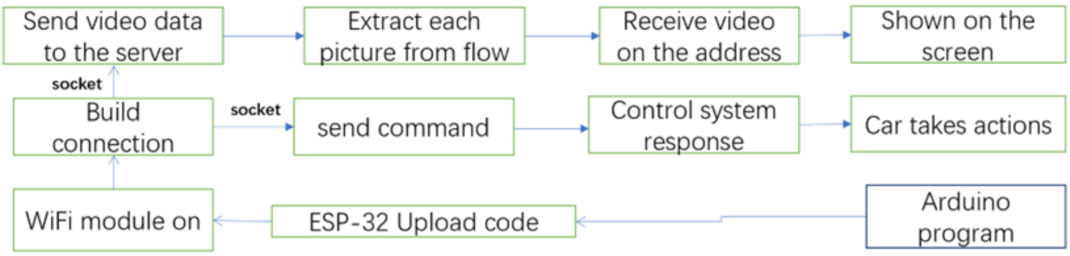

Figure 2.5.1. WiFi Subsystem Flow Chart

2.6 Control subsystem

This control subsystem includes the robot body of our remote-control car, which performs the main work of detecting. This part consists of motors we bought and car body which is 3D printed by my teammates. The rest of the subsystem is electronic devices (like chips and the board) that can start the motors, control the degree of the wheel and other operations. I built the electronic part of our control subsystem as I prepared in the design consideration part. The ESP-32 CAM chip will continuously be sending PWM signals to the L298N Motor Driver Board to control the speed of all motors to achieve the goal of move, stop, and change directions. All commands the driver made will go through the WiFi subsystem and entered our control subsystem to control the car or other components on our car like servo.

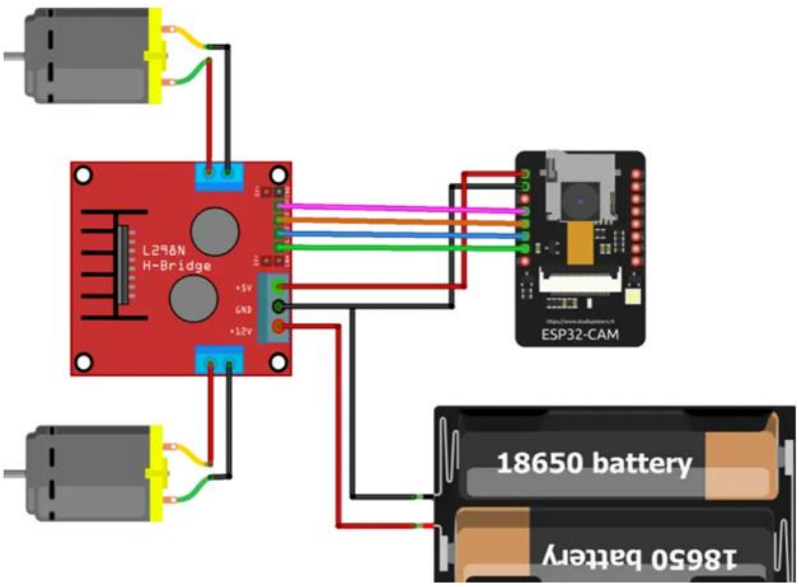

Figure 2.6.1. Control Subsystem Physical Diagram

2.7 Two Object detection Network

For our object detection network. We use custom dataset for collected around the campus. Here is one typical (image, label) pair.

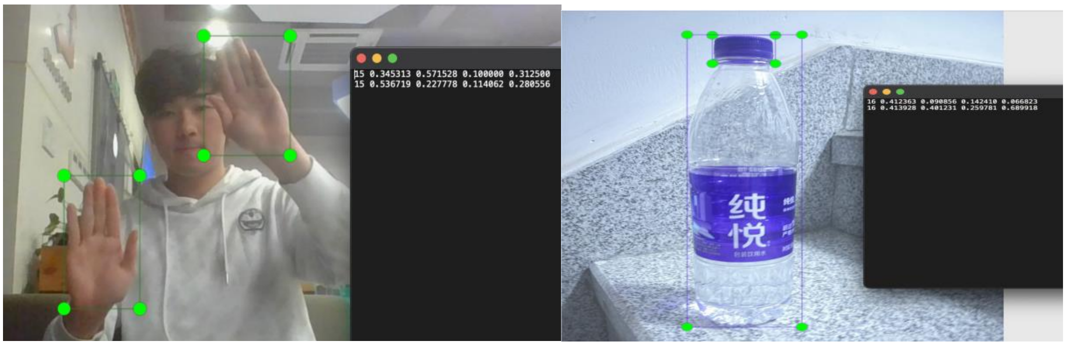

Figure 2.7.1 Typical (image, label) Pair for Our Data Set

After failure in training with our own network(2.7.2), the YOLO network turned out to be extremely powerful for our purpose. First of all, our dataset are all in YOLO-format, which serves right to YOLO. The output includes the coordinates of the bounding boxes and an graph instance which can be directly added to the video. There is a pre-trained model mode, which significant increase the confidence level of our hands detection model. The training result meets the high level requirement which is above 95% confidence. The modification process is more engineering. We tested the detection scheme in multiple environments including RC, classroom, stores, rooms of my friends, and even the toilet. When the output is not qualified or not stable, we add similar scenes to the training sets.

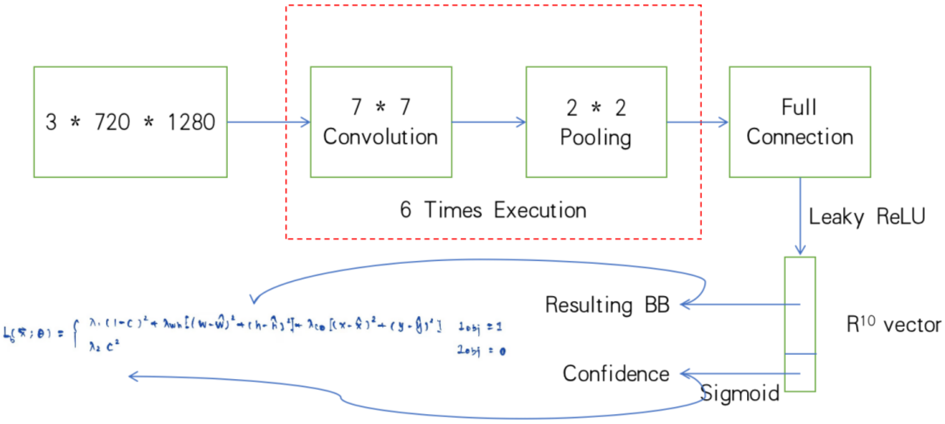

Figure 2.7.2 Our Failure Network

3. Design Verification

3.1 Motor Functionality Test

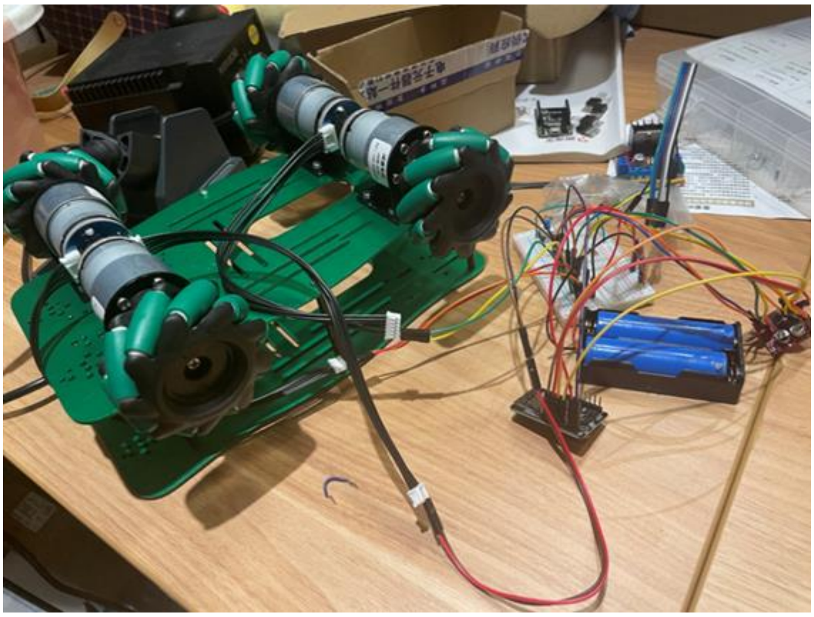

Figure 3.1.1. Motor Function Test

First of all, we need to test the normal function of the motors. With out this the environment detection subsystem can't work correctly. So, we had a test to check the functionality of the motors, like the figure 3.1.1 below. we found out that one motor could not work normally. So, we replace it with the new one after returning it to the seller.

3.2 Video Delay Test

Finally, after my car and chip can operate normally, we start to test the image quality and delay of my camera part. This part is a quantitative indicator of my environment detection subsystem. To make our driver drive in a relatively immersive context, our high-level requirements set the maximum delay of video transmission under 100ms. We need to make sure the environment information the car collects is specific and in time. Currently We can support jpeg quality 30 and 480x320 frame size. We calculate this by compare our movement and the camera video under a slow mode camera shotting at slow rate*10. Our test result of the delay of video is average 97.5 ms. So, the video we show on the driver's screen is fluent enough for our design purpose.

3.3 Simulation

Simulation plays a vital role in our project, particularly in ensuring the proper functioning and structural integrity of our robot car. Through static stress simulations, we can assess whether the car can operate within the tube without causing damage. This analysis allows us to identify potential weak points and make necessary design adjustments to enhance the car's durability. Additionally, by conducting static stress simulations alongside modal frequency simulations for the most vulnerable part, we can evaluate the car's performance and functionality. These simulations enable us to validate the car's ability to function properly and withstand the expected stresses and vibrations encountered during operation. Overall, the simulations provide valuable insights that inform our design choices and help us create a robust and reliable robot car for effective tube exploration and foreign matter detection.

3.4 Tube

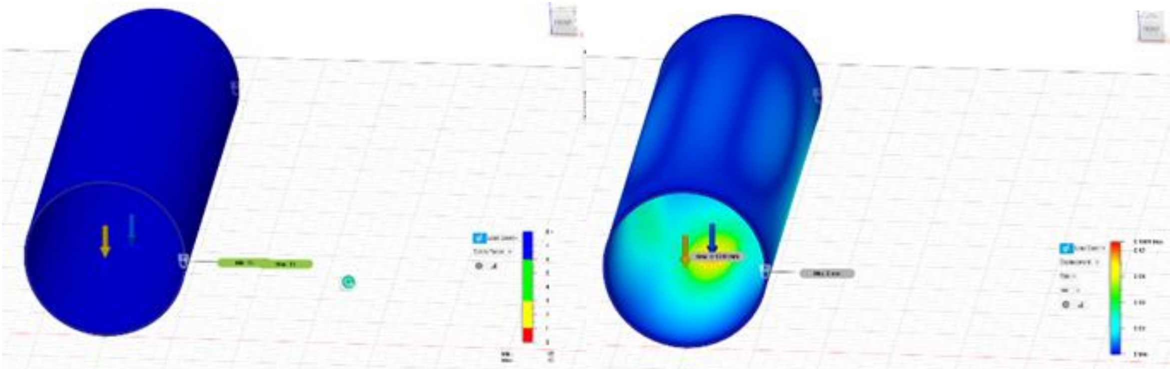

Figure 3.3.1: Static Stress Simulation for 300mm PP Tube

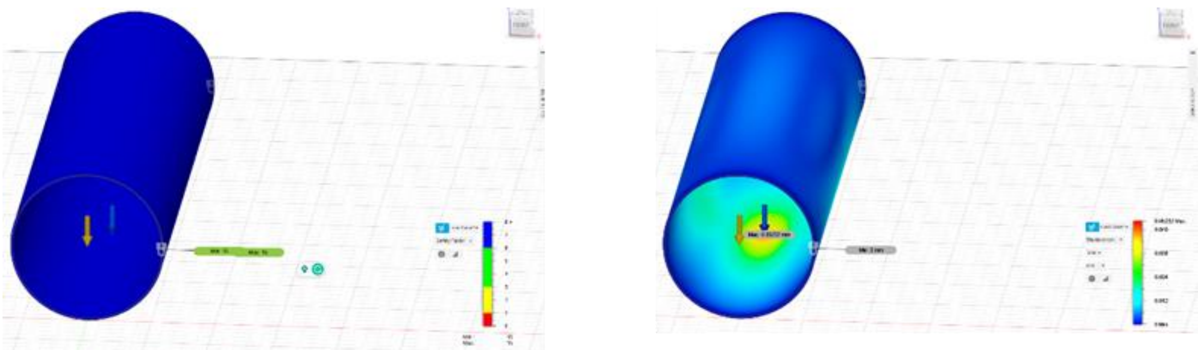

Figure 3.3.2: Static Stress Simulation for 300mm PVC Tube

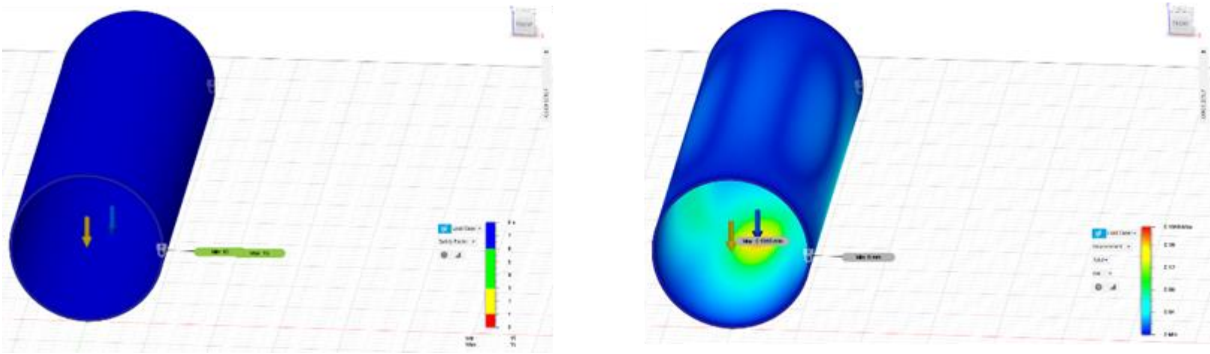

Figure 3.3.3: Static Stress Simulation for 300mm PEHD Tube

Assumption: Tube with 300 [mm] diameter and 1 [m] length; Consider the Safety Factor and Displacement here; The weight of the car is located on a circle with radius = 11.2838 [mm], whose area equals to the contact area of the car, because the only limited shape is circle; Fixed at both side; Consider gravity.

Result: The safety factors are all larger than 15 and the displacements are all smaller than 0.2 [mm], which are safe for the tube.

3.5 The Most Vulnerable Part of The Car

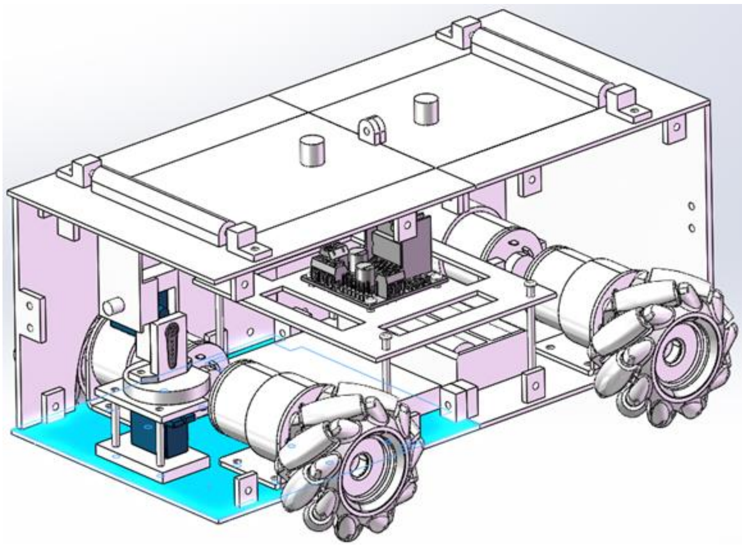

Figure 3.3.4: The Most Vulnerable Part

We chose this board as the most vulnerable part because it stands the most weight and it has to stand the vibration of the motor.

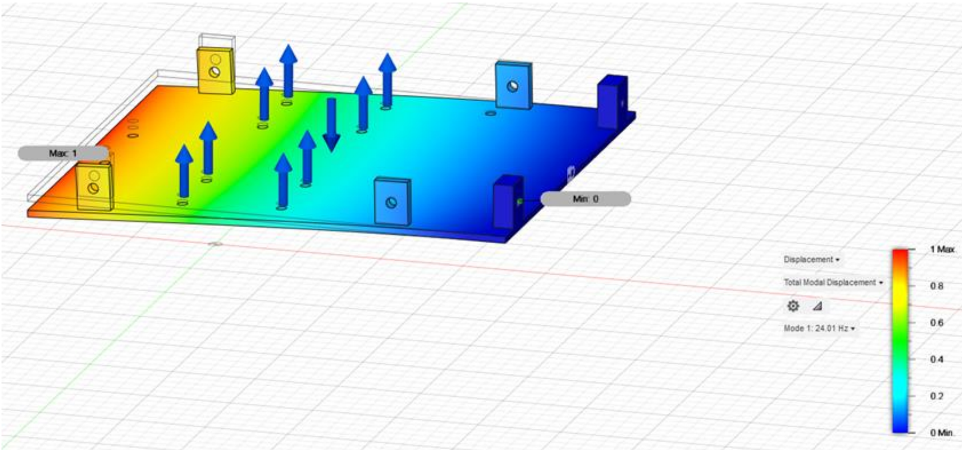

Figure 3.3.5: Modal Frequency Simulation

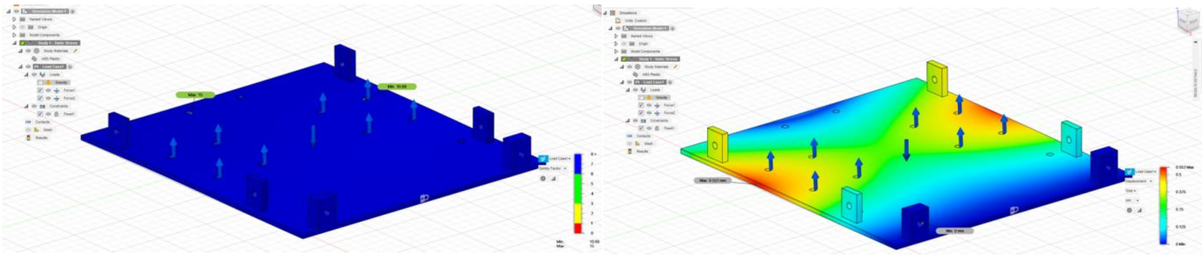

Figure 3.3.6: Static Stress Simulation

Assumption: Consider the Safety Factor and Displacement here; The load here is the normal force from the support of motor which directs upward, and the uniformly ditributed weight (10N); The fixed end is connected by bolt to the other board.

Result: The mode 1 frequency is 24 Hz, and from the property of motor (Figure 2.3.2), The maximum frequency from motors is 10 Hz, so there is no resonance. The safety factor is larger than 15 and the displacement is smaller than 0.2 [mm], which are definitely safe.

3.6 Servo and Distance Sensor

The servo controlled by PWM signal can be turned within range (50, 130) degree. 46% of the tube scene can be captured by the camera which is enough for our scenario. A bit larger turning scale is also available by tuning digital signal range. The distance detector can detect a range between 2.5cm to 44.3cm which is a little bit different from the scale on its datasheet, but is accurate enough for our case. The car can find the right-angle corner which can compensate for the deficiency of 2D video--cannot determine the exact distance and therefore unable to know where to turn the car. The distance detector will not heat up with our configuration and works properly even with warm air conditioner.

3.7 Two detection model

Using YOLO model, the hands detection confidence level is above 0.95, at around 0.97, which satisfied our high-level requirement. The false positive confidence are all below 0.85 which can be filtered out using 0.85 threshold. The driving data(e.g angle, speed) can be transmitted to esp32 server with delay of less than 180ms second, which cannot be noticed. The garbage detection confidence is quite low, about 0.40 for most of the garbage like plastic bottle or card board. However, this can still satisfy our goal since what we need is to identify the objects. The garbage detection is an auxiliary tool to help us identify them, so we can tolerate certain amount of false negative. Under dark environment inside the tube, the detection works quite well with the help of on-car light.

4. Costs

4.1 Parts

Table 4.1 Parts Costs

item	Cost(in total)	Cost(bulk)	explanation
Google Colab VIP membership	¥280	¥70	Online GPU leasing Fees
battery	¥8	¥8	
Frame of car& motors	¥429		Include Macnum wheels
L298N Motor Driver Board	¥7.5	¥7.5	
Esp32-CAM chip + OV2640 camera	¥37.5	¥37.5	
Dupont Line	¥6.6	¥3.3	
Resistors	¥2.1	¥2.1	
Battery box	¥3	¥3	
HC-SR04 distance sensor	¥4.8	¥4.8	

PLA (Polylactic Acid)	423.81g		3D printing material
Total	¥770.5		

4.2 Labor

For each member in our group, we spent about 10 hours per week on this project. And we scheduled to finish this project in 3 months (15 weeks). We estimate our salary per hour as ¥100/hour and we believe that everyone should be paid the same wage for the same level of work they put in.

Table 4.2 Labor Costs

Name	Hourly Rate	Hours	Total	Total×2.5
Shixin Chen	¥100	150	¥15000	¥37500
Ziyuan Lin	¥100	150	¥15000	¥37500
Pengzhao Liu	¥100	150	¥15000	¥37500
Tianle Weng	¥100	150	¥15000	¥37500
Total				¥150000

5. Conclusion

5.1 Accomplishments

Firstly, we implement the basic moves of the car and the PWM speed change control of motors. Also, we achieved the goal of building a WiFi subsystem of the robot car. Now we can watch the jpeg format video which is transmitted by the in-vehicle camera on PC in low delay. At the same time, we can use this subsystem to remote control the car by the driver’s PC while not influencing the fluency of video transmission. By the way, for the environment detection subsystem, we equipped the ESP32-CAM chip with an OV2640 camera and use ESP library to fetch video flow. And we use a GPIO pin on ESP-32 CAM chip to control the LED light for camera working in dark environment.

What’s more, we assembled the sg90 servor and infrared ray sensor. We measured different distance and corresponding value of the digital signal of the infrared sensor and calculated the relationship between them to finally build our infrared ray detecting function. A YOLO based hand position recognization system is developed to enhance the immersive experience of the driver. Lastly, in order to protect the circuit inside and adapt the tube environment, a shell is designed. We also did some simulation to guarantee its environmentally friendly feature.

5.2 Uncertainties

For physical design part, the assumption for those simulations are also uncertainties since we cannot guarantee they are always true, so we have to take them into account. By the way, PLA is commonly used for 3D printing due to its ease of use and affordability, it may have limitations in terms of strength and durability compared to other materials like ABS or nylon.

For network connection stability, utilizing a WiFi connection for controlling the cart and transmitting camera video introduces the potential for network connection instability. Challenges such as signal interference, transmission delays, or interrupted connections may arise, which could impact the real-time nature and overall stability of remote control. For battery life and power supply, employing three 18650 batteries to power the motor raises considerations regarding battery life and power management. Ensuring sufficient power supply for the motor's runtime and implementing measures to prevent over-discharging is crucial. Exploring alternative power sources for improved stability may be beneficial. By the way, for control algorithm and sensor accuracy, the movement and navigation of the cart are influenced by the control algorithm and the accuracy of the sensors employed. Varied terrains, lighting conditions, and sensor precision may introduce errors, potentially resulting in unexpected cart behavior. Lastly, for software programming, uncertainties can arise due to different versions of Arduino and associated software. This encompasses the development of code to establish communication with the ESP32-CAM chip, network transmission, and image processing algorithms. During the development process, challenges such as errors, debugging complexities, and software compatibility issues may emerge.

5.3 Ethical considerations

Based on the IEEE Code of Ethics, here are some ethical considerations that should be applied to my work. Firstly, we should consider the environmental impact of my project. Minimize waste and optimize resource utilization during the 3D printing process. Strive to design the robot and its components in a manner that promotes sustainability and minimizes adverse environmental effects. Conduct several simulation tests to minimize the damage to the pipeline itself when the car runs in the pipeline.

Secondly, as we mentioned in the design document before, the photos our car takes may violate someone's right of privacy. According to the first part of the IEEE code of Ethics, we need to protect the privacy of people [4]. So, the video resource we take is not stored on our computer. And the training photos we use are also our own hand pictures which are shot by us.

Lastly, we should continuously strive to enhance my professional ability in the areas relevant to the project. Stay updated with the latest advancements, techniques, and best practices in 3D printing, robotics, and related fields to ensure the highest level of technical proficiency.

5.4 Future work

For physical design part, refining the design to reduce weight without compromising structural integrity will be crucial. Additionally, continuous improvement and iterative testing will be necessary to ensure the car's reliable performance and adaptability to various tube environments, especially for slope/vertical tube.

For control part, presently, our car does not meet the high-level requirement of moving at a speed of 1m/s. Given that our car operates within a lengthy pipeline, it is crucial for it to achieve a relatively fast speed to effectively reach its designated workspace. To accomplish this objective, we intend to utilize a high-voltage power source and high-rotation speed motors. By the way, in order to address connectivity issues, we aim to implement a WiFi reconnection protocol, eliminating the need to restart the car every time a connection is lost. This feature proves particularly valuable when the car needs to navigate deep inside a pipe, where human access is challenging. Additionally, we recognize the importance of a steadier and lighter power source. Under the current version, my plan involves testing and optimizing battery life and power supply. This will ensure an adequate power supply while implementing appropriate power management measures. In our future work, four cores chip implementation is necessary. We can replace esp32 with some other cores to enable scheduling among multiple processes to enlarge concurrency. We will also do collection of garbage. We can further improve our robot by adding gesture recognition function to control the robot arm to grab the garbage or other foreign objects.

References

[1] Kamegawa, Tetsushi, et al. "Development of the snake-like rescue robot kohga". IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004. Vol. 5. IEEE, 2004.

[2] Redmon, Joseph, et al. "You only look once: Unified, real-time object detection." Proceedings of the IEEE conference on computer vision and pattern recognition. 2016.

[3] Ieee.org, "IEEE Code of Ethics", 2020. [Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html. Accessed May 2023.

[4] Ieee.org, "IEEE Code of Ethics", 2020. [Online]. Available: http://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 07-Mar-2023].

Appendix Requirement and Verification Table

Table 2 System Requirements and Verifications

Requirement	Verification	Verification status
The shell should provide safeguard for the car in the pipeline. Protect the internal circuit from being damaged by the material in the pipe. Have the ability to withstand impact.	Simulate the performance of the robot under different stresses on the software Fusion. Simulate the torque of robot in different diameters of pipe. After the physical assembly is completed, drive the robot in the pipeline to test the stability.	Yes
The camera rotating device should provide a wide field of view to enhance the driver's visibility. The device should be stable and not easy to shake when driven by SG90 servo motor	Measure the maximum angle of rotation and verify that the camera can cover a desired range, ensuring a wide field of view as intended. The parts are reinforced with bolts and nuts.	Yes
The training wheel should prevent the robot from tipping over during operation.	Simulate the performance of the training wheel on the software Fusion. Perform stability tests by applying controlled lateral forces to the robot and verify that the training wheel maintains stability and prevents tipping over.	Yes
12V power supply to support car motors. 5V power supply to support ESP32-CAM	Measure the voltage of the two outputs of L298N board by the voltmeter. Found out	

chip, sg90 and infrared ray sensor.	the two voltages perfectly meets the requirement (one is 12.1V and the other is 5.0V)	Yes
The robot should be equipped with a WiFi module to receive and send WiFi signals under regular internet protocol. It should support stable video transmission at low frame rate.	The WiFi module we have on ESP32 has advantages of small size, low power consumption, low heat generation, WiFi, network port transmission performance is stable. It supports UDP/IP protocol and has maximum PA output power 15dBm under 72.2 Mbps, maximum PA output power 20.5dBm under 11b mode.	Yes
Video transmission delay lower than 100ms	Compare our movement and the camera video under a slow mode camera shotting at slow rate*10. Calculate the average delay: 97.5ms	Yes
Sensors that can measure other variables both about the car and the environment.	Tracking sensors like gp2y0e03 infrared ray sensor, temperature sensors like ds18b20. These sensors can transform collected information into electric signal	Yes
A SD camera with low power consumption that can work for a long time under normal environment and support high frame rate WiFi transmission.	The OV2640 Color CMOS UXGA(2.0 MegaPixel) Camera Chip with Omnipixel2 Technology we use can be activated and work normally at both 125mW and 140mW. It can also tolerate temperatures between	Yes

	0℃ to 50 ℃. It has at most 1600*1200 definition, 60fps and can compress image for faster transmission.	