ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Autonomous Vehicle with Sign Recognition and Obstacle Clearing through Wi-Fi

Team #19

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Abstract

Autonomous vehicles have become popular in industrial research and daily life for a long time, with advanced functions like reading signal lights and giving ways to pedestrians. In recent years, many efforts have been devoted to introducing autonomous vehicles to urban traffic and domestic life. However, among those universalized autonomous vehicles like Tesla and Cruise, they are seldom brought to campus as shuttle buses or trash carts due to high costs. It would bring much convenience to students' campus life if some low-cost and efficient autonomous vehicles help students commute and provide some safety guarantees in obstacle detection and self-speed control by reading speed limit signs. We aim to develop the core of such low-cost autonomous vehicles to potentially take the responsibilities of commuting and obstacle-clearing, enabling wireless transmission to provide efficiency via campus Wi-Fi.

Contents

1 Introduction

In the following sections, we will elaborate on the problem and offer our solutions, including visual aids and high-level requirements.

1.1 Problem

Based on our personal life experience and class schedules on campus, we observe that most undergraduate students have a tight class schedule, resulting in insufficient time to transfer from one classroom to another between consecutive classes. Some choose to ride a bicycle for commuting. However, the number of bicycles around each teaching building is often limited and unevenly distributed. Classrooms with a large student current might be matched to an area with only a few available bicycles. Consequently, manually moving and re-distributing those bicycles to support student commuting needs places an additional burden on campus staff. In the meanwhile, we also notice that the ratio of cleaning staff and the campus area is quite low. The campus is too vast compared to the number of personnel responsible for cleaning, laying down a heavy workload to clean trash and obstacles on the campus, especially in the leaf-falling season or rainy and snowy weather.

According to two observations mentioned above, we came up with the idea of incorporating autonomous driving systems into our campus life and study as shuttle buses or trash carts. However, the most popular autonomous driving vehicles in the market are expensive and suitable for more complex situations other than campus life. Therefore, considering the special properties of the campus (everywhere Wi-Fi coverage and relatively simple road conditions), we aim for a low-cost autonomous vehicle designed and constructed using basic mechanical and electronic components like Arduino board, Wi-Fi modules, robot arms, etc.

1.2 Solution and Visual Aid

Specifically, our solution of an autonomous vehicle supporting speed limit sign recognition and obstacle-clearing elaborates as follows with a brief overview in Fig 1. Considering that the speed limit on campus is usually 30 km/h and a safe distance of 2 meters, the camera contained in the Raspberry Pi captures an image every other 0.24 seconds (i.e. at a frequency of 4.167 Hz). Another specific factor on the campus is Wi-Fi signals and availability. Each time the camera snaps a shot, we consider two following cases:

- When Wi-Fi is available, the captured image is sent to the remote server for thorough powerful image analysis and obstacle/speed limit sign recognition. After the remote server returns the corresponding obstacle type or the speed in km/h, such information is sent to the microcontroller (Arduino Uno R3) via Wi-Fi again. On receiving obstacle or speed information, Arduino Uno R3 transmits it to the vehicle motors or the robot arm for self-speed adjustments or obstacle clearing via UART protocols and Wi-Fi modules respectively. For visual aid of this situation, please refer to Figure 3 and Figure 2a.

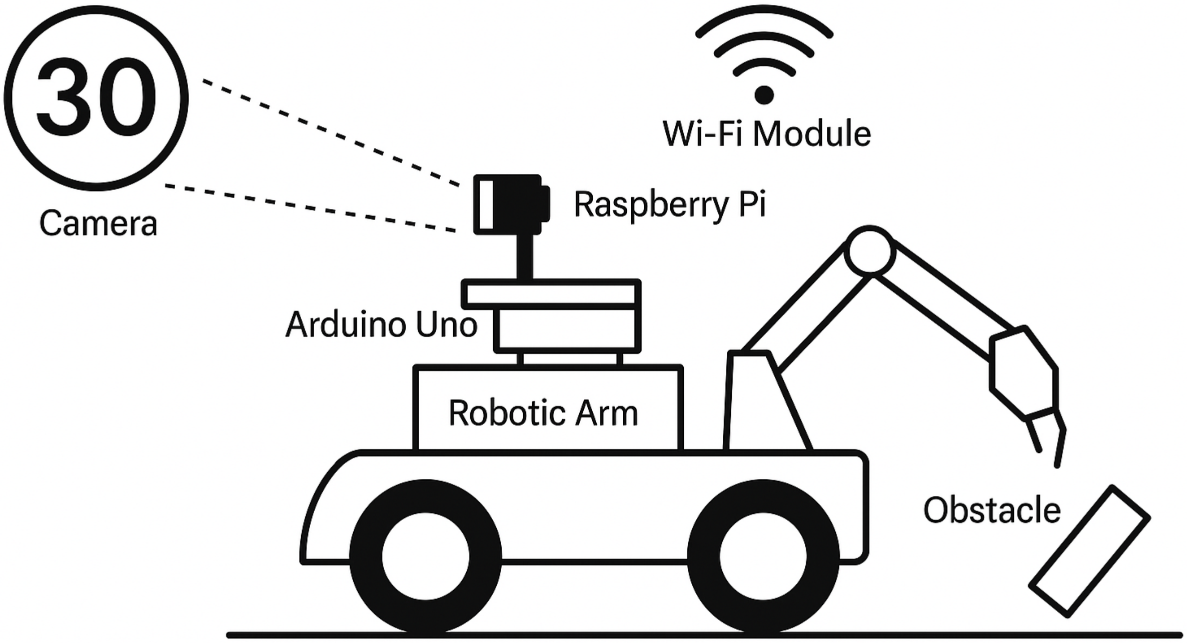


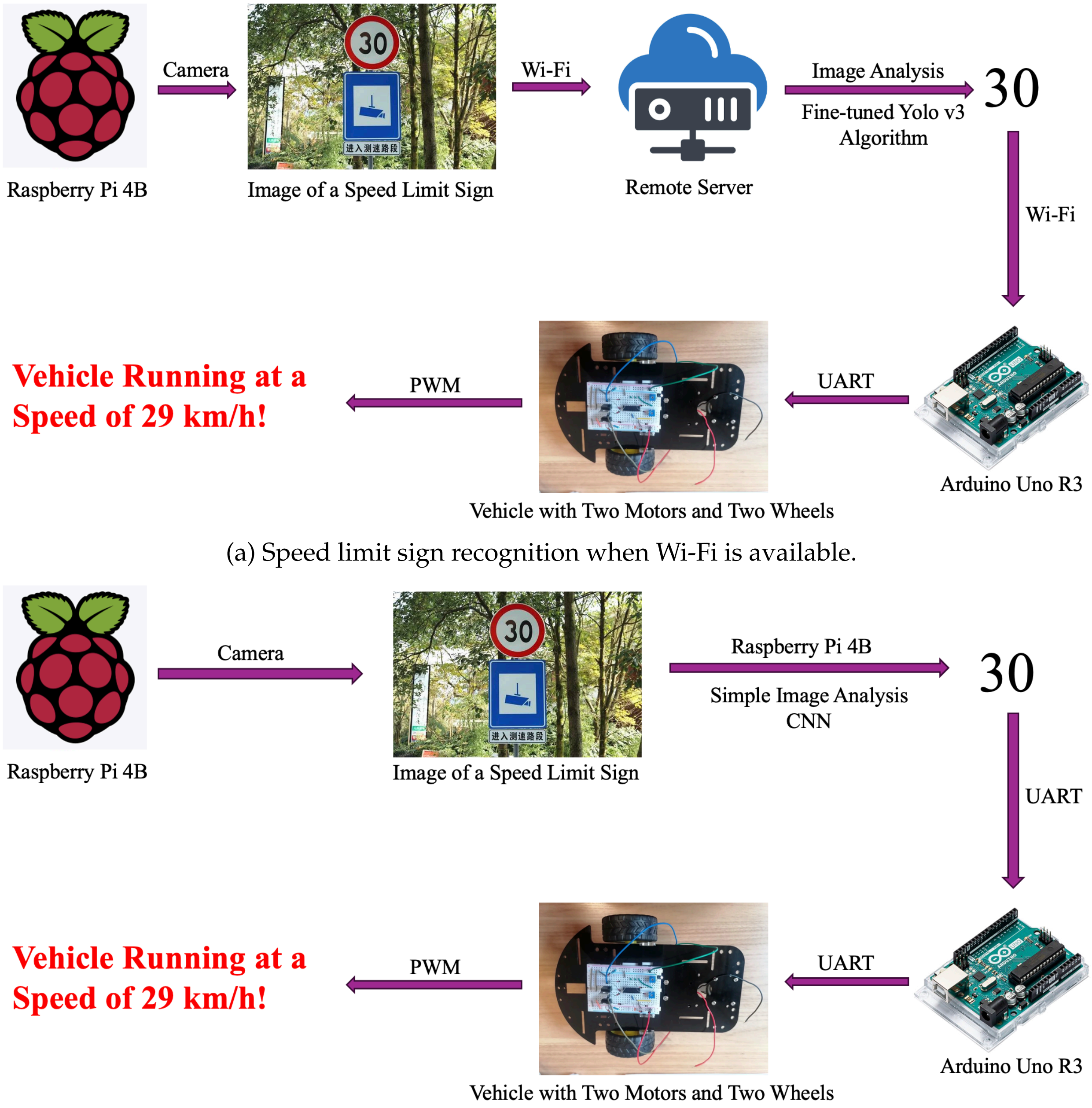
Figure 1: A visual aid of our general solution.

- When Wi-Fi is unavailable 2b, the Raspberry Pi takes the responsibility to analyze the image using simpler computer vision algorithms like CNN [1] compared to the remote server due to limited GPU capability. After the Raspberry Pi returns the corresponding speed in km/h, such information is sent to the microcontroller (Arduino Uno R3) via UART protocols. On receiving speed information, Arduino Uno R3 transmits it to the vehicle motors for self-speed adjustments via UART protocols again.

1.3 High-level Requirements

Here are four quantitative high-level requirements for our proposed solution, aiming to solve students' commuting issues and the heavy workload of trash clearing on the campus:

- The vehicle must navigate autonomously with the aid of speed limit signs only on the campus, for at least 30 minutes.
- Total time of each image capturing, image analysis, and information transmission must be less than 0.24 seconds, the time interval between two shots of the Raspberry Pi camera.
- The robot arm must clear an obstacle within 0.24 seconds, which is the time interval between two shots of the Raspberry Pi camera.
- The accuracy of recognizing speed limit signs and obstacles must be above 80%.


Raspberry Pi 4B
Camera
Image of a Speed Limit Sign
Wi-Fi
Remote Server
Image Analysis
Fine-tuned Yolo v3 Algorithm
30
Wi-Fi
Arduino Uno R3
UART
Vehicle with Two Motors and Two Wheels
PWM
Vehicle Running at a Speed of 29 km/h!
Raspberry Pi 4B
Camera
Image of a Speed Limit Sign
Raspberry Pi 4B
Simple Image Analysis CNN
30
UART
Arduino Uno R3
UART
Vehicle with Two Motors and Two Wheels
PWM
Vehicle Running at a Speed of 29 km/h!

(a) Speed limit sign recognition when Wi-Fi is available.

(b) Speed limit sign recognition when Wi-Fi is not available.

Figure 2: A visual aid of speed limit sign recognition.

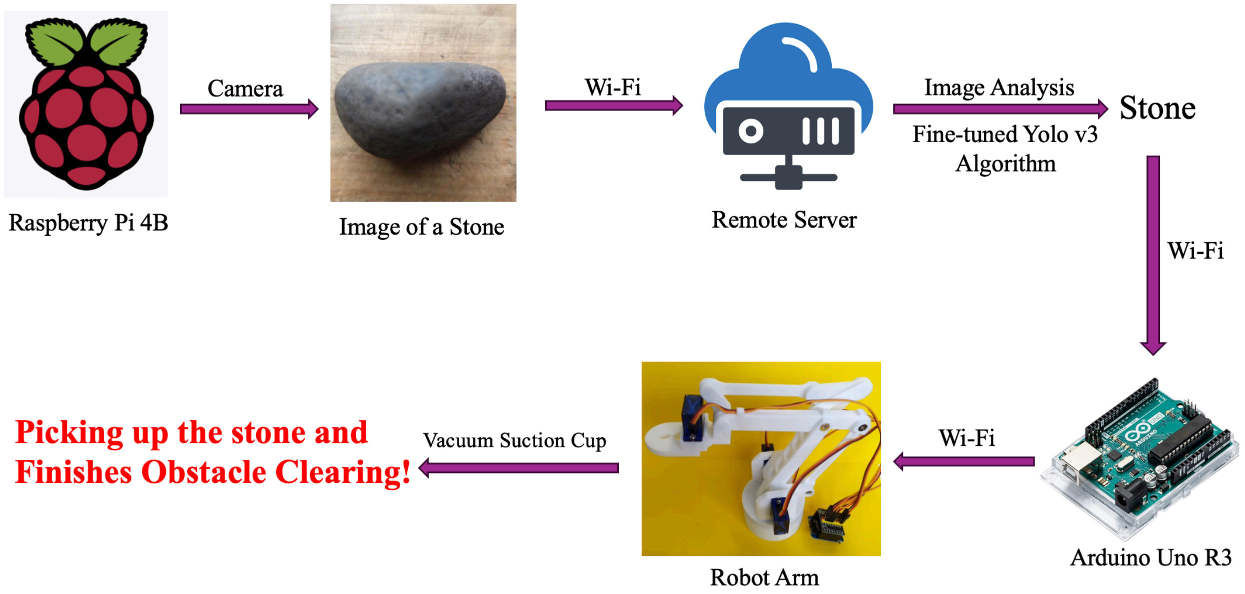


Figure 3: A visual aid of obstacle clearing.

2 Design and Requirements

Our design is based on Arduino Uno R3 (as the microcontroller), with the aid of the Raspberry Pi 4B as the camera and simple image analyzer, the Wi-Fi module ESP8266 as the information transmission media, a 4-axis 4-degree robot arm as the obstacle-clearing tool, and a vehicle with two DC motors carrying all components as an autonomous driving system. The detailed workflow, block diagram, and the physical design of our design can be found in Figure 4.

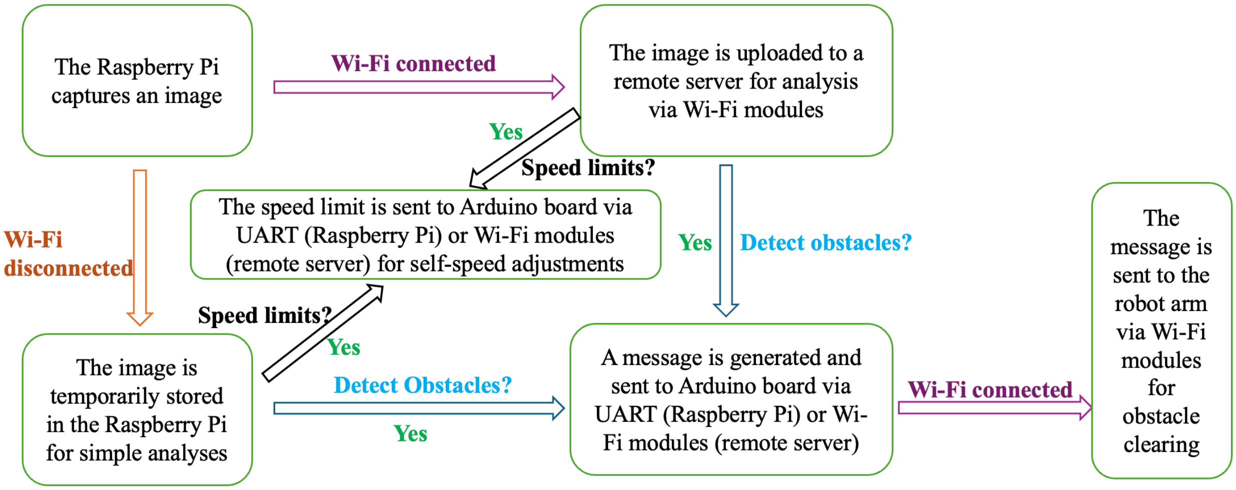
2.1 Image Capture and Simple Analysis Subsystem

2.1.1 Subsystem Overview

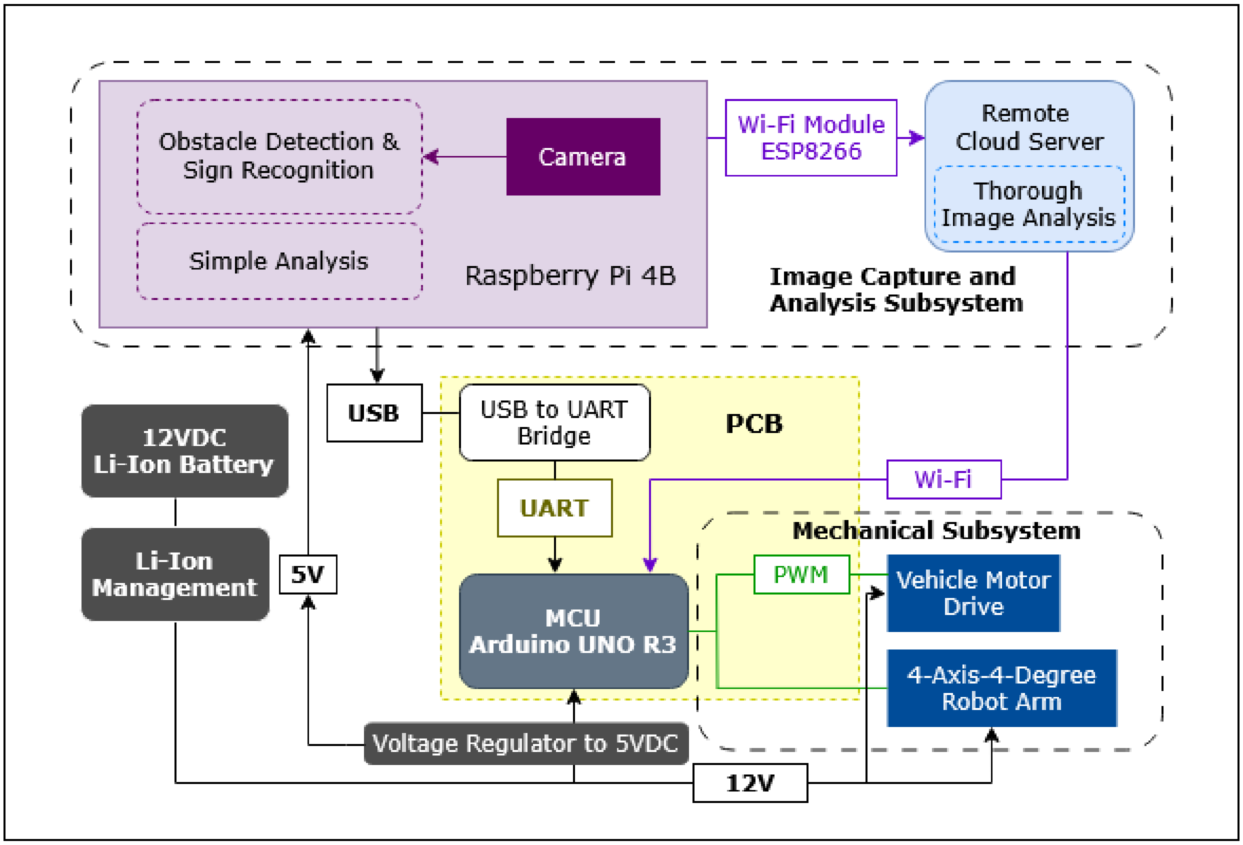
The main component in the *Image Capture and Simple Analysis Subsystem* is the Raspberry Pi 4B. With a camera of high resolutions and wide angles, it captures images of the speed limit signs and obstacles every 0.24 seconds to ensure safety and promptness. When Wi-Fi signals are unavailable, it can also take the responsibility of simple image analysis to ensure the self-speed adjustment of the autonomous vehicle. This subsystem is closely related to the *Microcontroller Subsystem* as the Raspberry Pi 4B communicates with the microcontroller Arduino Uno R3 via UART for image and speed information transmissions.

2.1.2 Acceptance Requirements

- *Requirement 1*: The accuracy of speed limit sign recognition must be larger than 80%.
- *Verification 1*: Generate images of different speed limits ranging from 0 to 30 km/h


The Raspberry Pi captures an image
Wi-Fi connected
The image is uploaded to a remote server for analysis via Wi-Fi modules
Yes
Speed limits?
The speed limit is sent to Arduino board via UART (Raspberry Pi) or Wi-Fi modules (remote server) for self-speed adjustments
Wi-Fi disconnected
Yes
Detect obstacles?
The message is sent to the robot arm via Wi-Fi modules for obstacle clearing
Speed limits?
Yes
The image is temporarily stored in the Raspberry Pi for simple analyses
Detect Obstacles?
Yes
A message is generated and sent to Arduino board via UART (Raspberry Pi) or Wi-Fi modules (remote server)
Wi-Fi connected

(a) Workflow of our proposed solution.



(b) Block diagram of our proposed solution consisting of four subsystems and a power supply module.

Figure 4: Block Diagrams in Hardware and Software Design.

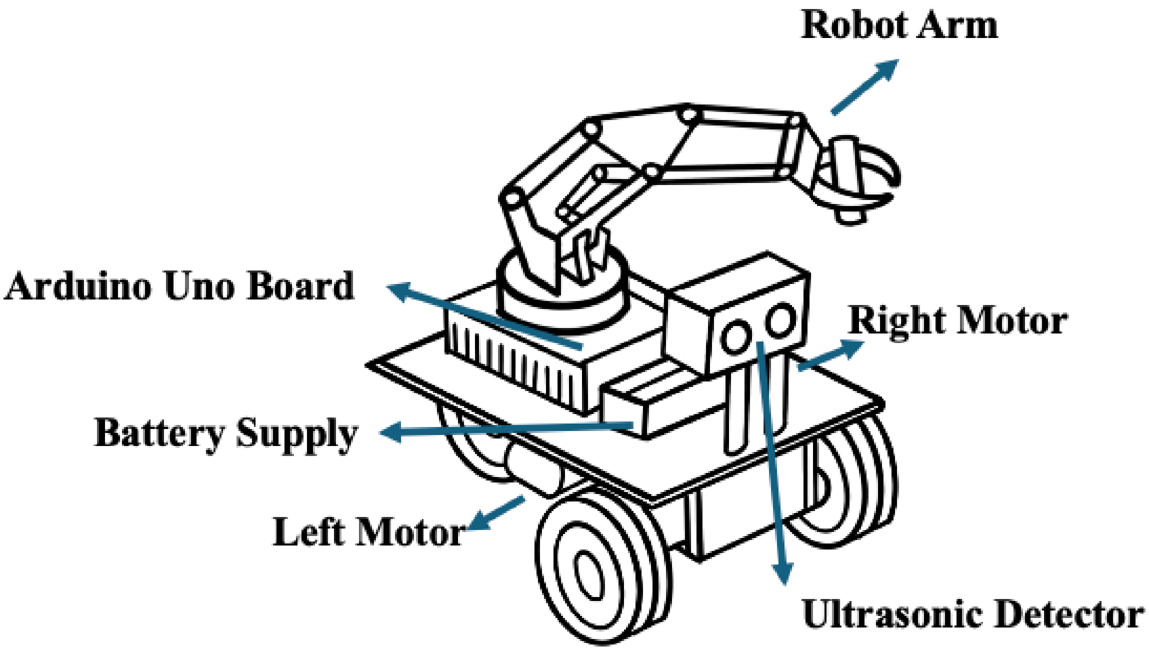


Figure 5: Physical Diagram in Hardware and Software Design.

(according to the rules on the campus) to test the recognition algorithm on the Raspberry Pi 4B and record the accuracy of recognition.

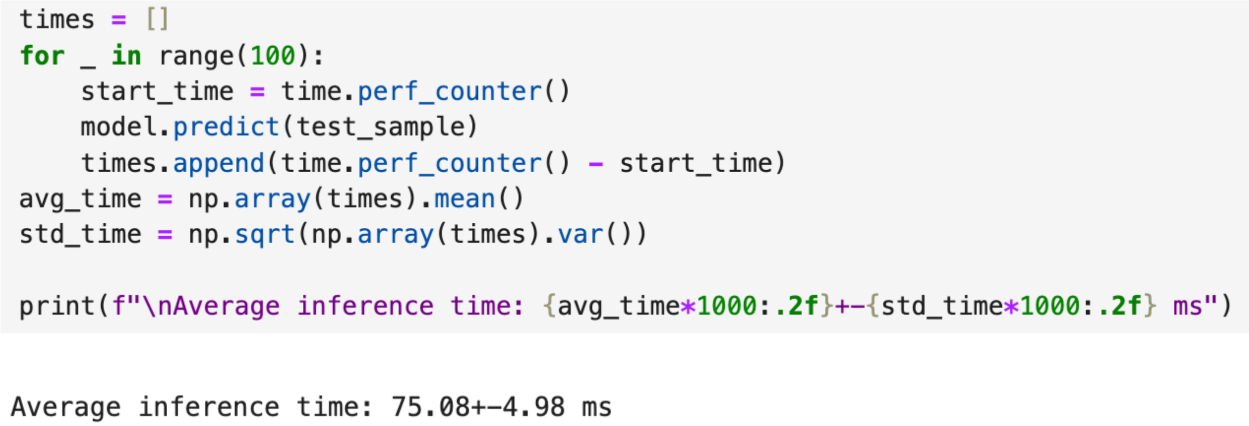
- *Requirement 2*: The time of speed limit sign recognition must be less than 0.08 seconds, one-third of the time interval between two shots of the Raspberry Pi camera.
- *Verification 2*: Generate images of different speed limits ranging from 0 to 30 km/h (according to the rules on the campus) to test the recognition algorithm on the Raspberry Pi 4B and record the average recognition time.

2.1.3 Difficulty and Risk Analysis

Since the GPU capability and storage space of the Raspberry Pi 4B is limited (4 GB), finding and finetuning a CNN-based algorithm to detect obstacles and speed limit signs while satisfying the accuracy requirement of 80% might take some time of careful consideration.

2.1.4 Tolerance Analysis

We use accuracy and time to evaluate the performance of this subsystem. If the time of speed limit sign recognition is less than 0.08 ± 0.001 seconds and the accuracy of speed limit sign recognition is larger than $80\% \pm 0.1\%$, we consider this subsystem to be successfully constructed and functioning. The tolerance scale is derived from the following experimental conclusions by averaging the classification results of 100 test samples on the remote cloud server with a RTX 3090 GPU, as shown in 6.



```
times = []
for _ in range(100):
    start_time = time.perf_counter()
    model.predict(test_sample)
    times.append(time.perf_counter() - start_time)
avg_time = np.array(times).mean()
std_time = np.sqrt(np.array(times).var())

print(f"\nAverage inference time: {avg_time*1000:.2f}+-{std_time*1000:.2f} ms")
```

```
Average inference time: 75.08+-4.98 ms
```

Figure 6: Average recognition time is 0.075 ± 0.005 seconds.

2.2 Microcontroller Subsystem

2.2.1 Subsystem Overview

The main component in the *Microcontroller Subsystem* is the Arduino UNO R3 with a schematic 7. With a power supply of 5 volts direct current, it connects the components of the Raspberry Pi 4B, the remote cloud server, the robot arm, and the vehicle across all other subsystems. It enables simultaneous reading and writing via UART to receive information from the Raspberry Pi 4B in the *Image Capture and Simple Analysis Subsystem* and delivers it to the vehicle to adjust motor speed via PWM. It also enables Wi-Fi transmission with the remote cloud server in the *Thorough Image Analysis Subsystem* by controlling the Wi-Fi module.

2.2.2 Acceptance Requirements

- *Requirement 1*: The time of UART transmission must be less than 0.08 seconds, one-third of the time interval between two shots of the Raspberry Pi camera.
- *Verification 1*: Record the average UART transmission time by recording the time when the Raspberry Pi 4B generates the result and the time Arduino receives.
- *Requirement 2*: The time of Wi-Fi transmission must be less than 0.08 seconds, one-third of the time interval between two shots of the Raspberry Pi camera.
- *Verification 2*: Record the average Wi-Fi transmission time by recording the time when the remote cloud server returns the result and the time Arduino receives.

2.2.3 Difficulty and Risk Analysis

Since the microcontroller links all other subsystems and components in this design, it is essential to avoid any potential misusing or misleading practices on the Arduino Uno

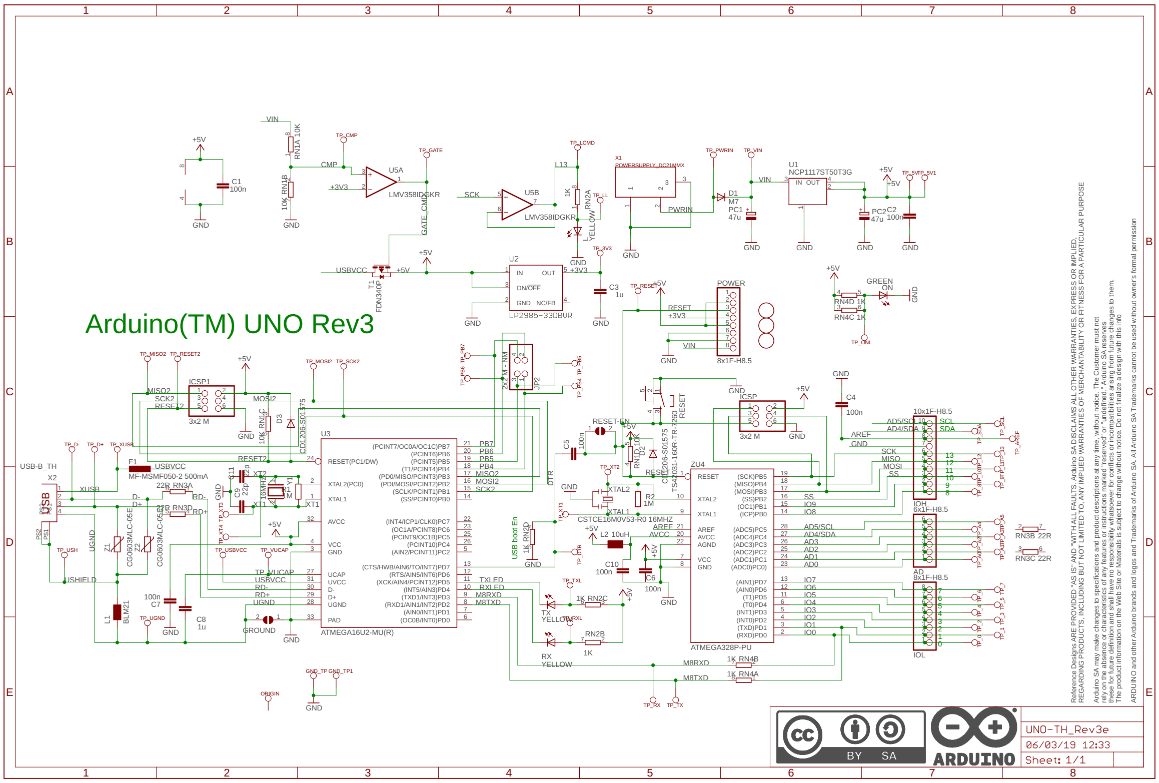


Figure 7: Arduino Uno Schematic Diagram referring to official Arduino Board information website [2].

R3.

2.2.4 Tolerance Analysis

We use time to evaluate the performance of this subsystem. If the time of Wi-Fi transmission is less than 0.08 seconds and the time of UART transmission is also less than 0.08 seconds, we consider this subsystem to be successfully constructed and functioning.

2.3 Thorough Image Analysis Subsystem

2.3.1 Subsystem Overview

The main component in the *Thorough Image Analysis Subsystem* is the remote cloud server containing a powerful GPU to perform more complex and more accurate image analysis and object detection. When Wi-Fi signals are available, it can also take the responsibility of thorough image analysis to ensure the self-speed adjustment and obstacle detection of the autonomous vehicle. This subsystem is closely related to the *Microcontroller Subsystem* as the remote cloud server communicates with the microcontroller Arduino Uno R3 via Wi-Fi modules for image and speed/obstacle information transmissions. The software algorithm used by both the remote cloud server can be generalized and summarized in Figure 8.

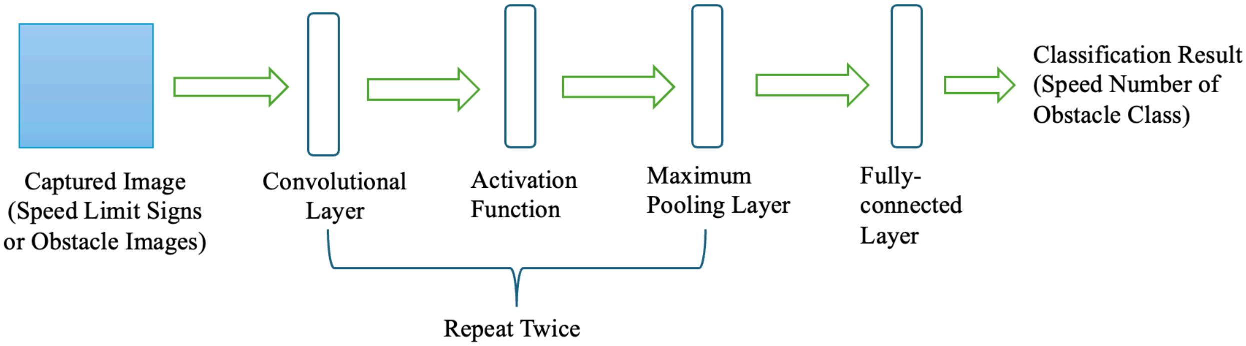

Captured Image (Speed Limit Signs or Obstacle Images)
Convolutional Layer
Activation Function
Maximum Pooling Layer
Fully-connected Layer
Classification Result (Speed Number of Obstacle Class)
Repeat Twice

Figure 8: The training flow chart of speed limit sign and obstacle recognition.

2.3.2 Acceptance Requirements

- *Requirement 1*: The accuracy of speed limit sign recognition must be larger than 80%.
- *Verification 1*: Generate images of different speed limits ranging from 0 to 30 km/h (according to the rules on the campus) to test the recognition algorithm on the remote cloud server and record the accuracy of recognition.
- *Requirement 2*: The time of speed limit sign recognition must be less than 0.08 seconds, one-third of the time interval between two shots of the Raspberry Pi camera.

- *Verification 2*: Generate images of different speed limits ranging from 0 to 30 km/h (according to the rules on the campus) to test the recognition algorithm on the remote cloud server and record the average recognition time.

2.3.3 Difficulty and Risk Analysis

Since the computer vision algorithms implemented on the remote cloud server might be complex to enhance the accuracy of object and speed sign detection, finding and finetuning a powerful algorithm like Yolo v3 [3] to detect obstacles and speed limit signs while satisfying the time constraint of 0.08 seconds might take some time of careful consideration.

2.3.4 Tolerance Analysis

We use accuracy and time to evaluate the performance of this subsystem. If the time of speed limit sign recognition is less than 0.08 seconds and the accuracy of speed limit sign recognition is larger than 80%, we consider this subsystem to be successfully constructed and functioning.

2.4 Microcontroller Subsystem

2.4.1 Subsystem Overview

The main component in the *Microcontroller Subsystem* is the Arduino UNO R3. With a power supply of 5 volts direct current, it connects the components of the Raspberry Pi 4B, the remote cloud server, the robot arm, and the vehicle across all other subsystems. It enables simultaneous reading and writing via UART to receive information from the Raspberry Pi 4B in the *Image Capture and Simple Analysis Subsystem* and delivers it to the vehicle to adjust motor speed via PWM. It also enables Wi-Fi transmission with the remote cloud server in the *Thorough Image Analysis Subsystem* by controlling the Wi-Fi module.

2.4.2 Acceptance Requirements

- *Requirement 1*: The time of UART transmission must be less than 0.08 seconds, one-third of the time interval between two shots of the Raspberry Pi camera.
- *Verification 1*: Record the average UART transmission time by recording the time when the Raspberry Pi 4B generates the result and the time Arduino receives.
- *Requirement 2*: The time of Wi-Fi transmission must be less than 0.08 seconds, one-third of the time interval between two shots of the Raspberry Pi camera.
- *Verification 2*: Record the average Wi-Fi transmission time by recording the time when the remote cloud server returns the result and the time Arduino receives.

2.4.3 Difficulty and Risk Analysis

Since the microcontroller links all other subsystems and components in this design, it is essential to avoid any potential misusing or misleading practices on the Arduino Uno R3.

2.4.4 Tolerance Analysis

We use time to evaluate the performance of this subsystem. If the time of Wi-Fi transmission is less than 0.08 seconds and the time of UART transmission is also less than 0.08 seconds, we consider this subsystem to be successfully constructed and functioning.

2.5 Output Subsystem

2.5.1 Subsystem Overview

The main component in the *Output Subsystem* is a 4-axis 4-degree robot arm and a vehicle with two DC motors. With a power supply of 12 volts direct current, both are controlled by the Arduino Uno R3 in the *Microcontroller Subsystem*. On receiving the clearing command from the Arduino Uno R3 via the Wi-Fi module, the robot arm picks up the obstacle via a vacuum suction cup and completes the obstacle-clearing task. If the command of speed adjustment is received via UART protocols, the vehicle adjusts the speed of its DC motors via PWM.

2.5.2 Acceptance Requirements

- *Requirement 1*: The time of obstacle clearing by the robot arm must be less than 0.24 seconds, the time interval between two shots of the Raspberry Pi camera.
- *Verification 1*: Record the obstacle picking and clearing time.

2.5.3 Difficulty and Risk Analysis

Since the vehicle carries all other subsystems and components in this design, it is essential to avoid any potential misusing or misleading practices on the DC motors.

2.5.4 Tolerance Analysis

We use time to evaluate the performance of this subsystem. If the time of obstacle clearing is less than 0.24 seconds, we consider this subsystem to be successfully constructed and functioning.

Component	**Cost**	**Cost Type**
Raspberry Pi 4B	$54.6224	Electronic Consumables
ESP8266 Wi-Fi Module	$4.5165	Electronic Consumables
Arduino Uno Board with Vehicle Components	$85.9914	Electronic Consumables
Robot Arm Components	$28.8828	Mechanical Consumables
4 Persons with Equal Contributions	$30 per hr * 30 hr/week * 20 week/person * 4 persons = $72000	Labor
Summary	$72174.0131	Total

Table 1: Detailed cost analaysis including Consumables and Labor Costs

3 Costs and Schedules

3.1 Costs

3.2 Schecules

4 Ethics and Safety

4.1 Ethical Issues

For the privacy part, image capturing might inevitably incorporate students' faces, which requires us to manually blur or remove such private information to protect students (Term I. 4 of IEEE Code of Ethics [4]). For the social effects, the introduction of autonomous cleaning vehicles might reduce the needs of cleaning staff on the campus, which requires us to collaborate with campus administration to reassign affected staff to other roles or help them become the technical controller of such autonomous vehicles [5], [6].

In our solution, we will not leak any images with students' faces, even the blurred one. And our algorithm will not misuse the images except from speed limit sign and obstacle recognition. We will immediately delete the images once the analysis is done and the action is delivered to either the vehicle or the robot arm. This avoids information misconduct and abusing images from the source. In the future, anti-attack techniques will also be added to the vehicle to prevent any abnormals' attacks.

4.2 Safety Issues

Since this autonomous vehicle is under testing, it might cause some injuries or destroy to the students or the buildings if it is out of control (Term II. 9 of IEEE Code of Ethics [4])., which requires our designers to watch it carefully when testing and preemptively identify and mitigate potential hazards [7].

In our solution, we will test several times in different weather conditions, including extreme weather conditions. And our algorithm will not test the autonomous vehicle in the real campus unless it passes all tests in diverse weather conditions. In the future, anti-attack techniques will also be added to the vehicle to avoid any attacks negatively influencing its functioning.

Time	**Pai Zhang**	**Rui Zhang**	**Wendi Wang**	**Pengyu Zhu**
Feb 24th-28th, Mar 3rd-7th	Get familiar with the project topic.	Get familiar with the project topic.	Get familiar with the project topic.	Get familiar with the project topic.
Mar 10th-14th, Mar 17th-21th	Start searching suitable computer vision algorithms for speed limit sign recognition.	Start searching suitable components for constructing the robot arm.	Start searching suitable components for the autonomous vehicle and the microcontroller.	Start searching suitable computer vision algorithms for obstacle detection.
Mar 24th-28th, Mar 31th-Apr 4th	Start testing suitable computer vision algorithms for speed limit sign recognition.	Start constructing the robot arm.	Start constructing the autonomous vehicle.	Start testing suitable computer vision algorithms for obstacle detection.
Mar 31th-Apr 4th, Apr 7th-11th	Modifying computer vision algorithms for speed limit sign recognition.	Testing the robot arm to pick up obstacles and controlled by the Arduino Uno Board (the microcontroller).	Testing the autonomous vehicle to change its speed and instruct the robot arm's behavior.	Modifying computer vision algorithms for obstacle detection.
Apr 14th-18th, Apr 21th-25th	Collecting real images of speed limit signs to attain 80% recognition accuracy.	Enabling data transmission between the robot arm and the microcontroller.	Enabling data transmission among the robot arm, the vehicle, and the microcontroller.	Collecting real images of diverse obstacles to attain 80% recognition accuracy.
Apr 28th and after	Unifying all functions and preparing for the demo.	Unifying all functions and preparing for the demo.	Unifying all functions and preparing for the demo.	Unifying all functions and preparing for the demo.

Table 2: Detailed Schedule and Task Plan

References

[1] R. Girshick, "Fast r-cnn," in *Proceedings of the IEEE international conference on computer vision*, 2015, pp. 1440–1448. [Online]. Available: https://openaccess.thecvf.com/content_iccv_2015/papers/Girshick_Fast_R-CNN_ICCV_2015_paper.pdf (visited on 04/14/2025).

[2] "Arduino uno rev3 documentation," Arduino. (2019), [Online]. Available: https://content.arduino.cc/assets/UNO-TH_Rev3e_sch.pdf (visited on 04/14/2025).

[3] J. Redmon and A. Farhadi, "Yolov3: An incremental improvement," *arXiv preprint arXiv:1804.02767*, 2018. [Online]. Available: https://ask.qcloudimg.com/draft/2661027/i16j8zgndj.pdf (visited on 04/14/2025).

[4] "Ieee code of ethics," IEEE. (2025), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 04/14/2025).

[5] A. Martinho, N. Herber, M. Kroesen, and C. Chorus, "Ethical issues in focus by the autonomous vehicles industry," *Transport reviews*, vol. 41, no. 5, pp. 556–577, 2021. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/01441647.2020.1862355 (visited on 04/14/2025).

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[7] J. Wang, L. Zhang, Y. Huang, and J. Zhao, "Safety of autonomous vehicles," *Journal of advanced transportation*, vol. 2020, no. 1, p. 8 867 757, 2020. [Online]. Available: https://onlinelibrary.wiley.com/doi/pdf/10.1155/2020/8867757.