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The Design and Testing of a Novel Leader-following Automatic Guide Vehicle

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Abstract

Vehicle following technology is essential for the autonomous operation of intelligent electric vehicles under the current net-zero objective. This paper presents an innovative automated vehicle following a system based on Raspberry Pi and multi-sensors. The study introduces a mathematical model of a platoon of vehicles and the creation of a linear controller. The experiments were conducted in a practical setting simulating an RC vehicle with an optimal speed range of 25 cm/s to 50 cm/s. The results indicate that the built RC vehicle adapts completely to the control model of the vehicle platoon, and the controller is stable and reliable. The distance between the trolley and the obstruction reveals a linear relationship with and without load. The Raspberry Pi was utilized to successfully integrate many sensors, regulate steering, and move forward. Through the wireless network, all sensor states are synchronized with the PC. The experimental results show the dynamic performance of the car and the tracking of objects with values demonstrating the mathematical model's reliability. It also contributes to future contact-less courier services, whose importance has and will increase during emergency situations such as the COVID-19 pandemic in addition to the existing autonomous vehicle research.

Keywords: Intelligent transportation; Vehicle platoon; Car-following; RC Vehicle; Raspberry Pi.
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1. Introduction

The deployment of networks and autonomous vehicles changed people's inherent thinking about road transport.[1]. Numerous companies and institutes are currently working to develop an Intelligent Traffic System (ITS), such as Uber.[2] The car-following system is a sub-branch of the ITS study, which aims to increase the efficiency of road traffic.[3] The Tracked Electric Vehicle (TEV) Project, in which electric cars travel at 200 km/h in specified lanes in a platoon,[4] is an example of a vehicle that doesn't require much steering. Car-following describes the interactions between a car and its preceding vehicles or objects within the same lane.[5] However, in the existing robot car research, only the stop-and-go function of a motor is being used, which currently lacks the control of the speed of the motor for obstacle avoidance,[6] vehicle image processing,[7], *etc*. Due to this, there exists a significant gap in the development of automated vehicles that can reliably deal with everyday traffic situations.

Leader-following automatic guide vehicles (AGVs) is an important development in the field of automation and robotics. These vehicles are designed to follow a designated leader vehicle, which can be either an AGV or a manually driven vehicle, without the need for human intervention. This technology is widely used in manufacturing and warehousing operations, where it can improve efficiency, safety, and productivity. Leader-following AGVs are typically equipped with sensors and communication systems that enable them to maintain a safe and accurate distance from the leader vehicle, while also adjusting their speed and direction in real time based on the leader's movements. Vehicle platooning is a concept in which a group of vehicles travels together in a tight formation, with one vehicle acting as the leader and the others following closely behind. This technique can help to reduce fuel consumption,[8,9] improve traffic flow,[10] and increase safety on the road. Leader-following AGVs use similar technology to vehicle platooning, but they are typically used in closed environments such as factories and warehouses. In the research area of the vehicular platoon system and AGV,[11] is concerned with the adaptive intelligent backstepping

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longitudinal control (AIBLC) system for the vehicle-following control of a platoon of automated vehicles. The aim of[12] is to present a control system that can optimally control a convoy of closely following vehicles for the stop-and-go type of traffic.[13] investigate the control problem for leader-following (LF) vehicle platoons with a constant-spacing policy, where the information of the leader is broadcast to each follower via vehicular ad hoc networks (VANETs) subject to varied communication ranges. This limits existing Cooperative Adaptive Cruise Control (CACC) strategies as most of them assume a fixed information flow topology (IFT). To address this problem[14] introduce a CACC design that considers a dynamic information flow topology (CACC-DIFT) for CAV platoons.[15] show, how a longitudinal controller based on distributed consensus can, at the same time, guarantee stability and performance in regime platoon operations, and be at the hearth of maneuvering protocols and algorithms, as it remains stable in face of changes in platoon topology and control gains.[16] present a control structure designed to autonomously guide two of-the-shelf quadrotors navigating in outdoor environments, as a leader-follower formation. This contribution of [17] is to characterize the empirical car-following behaviors of a commercial ACC system and understand how ACC behaves in different conditions and the underlying impact mechanism.

In the study of vehicle platoon above, plenty of theoretical literature already exists. However, the design of the actual hardware is absent. Experiments on vehicle platoon control design are especially difficult in terms of the number of vehicles, communication, and roads. Therefore, this paper begins with the construction of a mathematical model for vehicle platoon control leading to the design of a linear controller using a Raspberry Pi for software control. Other new control strategies that could be explored include sliding mode control,[18] fuzzy logic control,[3] and adaptive control.[11] These approaches can help to address the limitations of linear controllers and improve the performance of complex control systems. So, linear controllers in this paper may be preferred because they are more interpretable and easier to tune compared to more advanced controllers. Additionally, the increased complexity of advanced control strategies may not be justified by the performance improvements they offer. It is Raspberry Pi was developed by the Raspberry Pi Foundation, a charity registered in the United Kingdom in available as an open-source platform, both open in software and hardware and has rich hardware interfaces such as Inter-Integrated Circuit (I2C) and General-Purpose Input/Output (GPIO), which makes it suitable for electronic design.[19] Raspberry Pi is an obvious choice to study Vehicle to Infrastructure (V2I) communication for researchers owing to its wireless communication and low design cost.[20] Table 1 provides a comparison of the advantages and disadvantages of several recent studies in the field of RC vehicle control, including our proposed approach. Each study is briefly described and evaluated based on key features such as control method, communication protocol, and energy efficiency.

Table 1. Comparison of Raspberry Pi-based remote control vehicle systems: advantages and disadvantages.

Research	Approach	Advantages	Disadvantages
[21]	Smartphone-controlled car	Easy to control using a smartphone app, small and portable.	Limited speed and power, limited range due to Bluetooth connectivity
[22]	Arduino-based RC car	Customizable and programmable, versatile control system	Limited speed and power, limited range due to Bluetooth connectivity
[23]	Neural network-based autonomous car	High level of autonomy and accuracy, efficient use of energy	High cost and complexity, limited flexibility for customization
[24]	FPGA-based RC car	High speed and power, low latency control system	High cost and complexity, limited flexibility for customization
This paper proposed a method[25]	Raspberry Pi-based autonomous car	Customizable and programmable, efficient use of energy	Limited speed and power, limited range due to Wi-Fi connectivity

In this paper, the design of a remote control (RC) vehicle based on the concept of a commercial toy car is proposed. The planned vehicle is low-priced, multi-functional, and compact with a genuine electrical vehicle structure. The primary novel outcomes of this effort are that it:

- Proposes a mathematical model of the vehicle platoon and designs a controller for the simulation.
- Design of an RC vehicle using Raspberry Pi and multiple sensors with the proposed controller to control the car's speed dependent on the object's distance.
- A low-cost solution for future experimental vehicle platoon design and the compilation of vehicle design code in Python for public access.

2. System modeling

2.1 Vehicle dynamic model

Numerous studies demonstrate that the upper controller determines the appropriate acceleration for the mechanical components, including the brake and throttle.[4,26] For theoretical analysis, the linear model is provided as equation (1):

$$\tau\dddot{x}_i(t) + \ddot{x}_i(t) = u_i(t) \tag{1}$$

In this equation, the output is the desired acceleration $x_i(t)$, which represents the vehicle's position with respect to time, and τ is the vehicle's time delay. It then transforms into a stable space model, which is given by equations (2) and (3):

$$\dot{x}_i(t) = A_i x_i(t) + B_i x_i(t), i \in N \tag{2}$$

$$\dot{x}_i(t) = \begin{bmatrix} p_i \\ v_i \\ a_i \end{bmatrix}, A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/\tau \end{bmatrix}, B_i = \begin{bmatrix} 0 \\ 0 \\ -1/\tau \end{bmatrix} \tag{3}$$

2.2 Spacing policies

The main control objective of a platoon system study is to maintain the desired spacing and velocity consistency. CD and CTH policies are vehicle-following policies used in automated driving and specifically in platooning systems. The Constant Distance (CD) policy specifies that the following vehicle should maintain a constant distance from the lead vehicle, while the Constant Time Headway (CTH) policy specifies that the following vehicle should maintain a constant time gap with the lead vehicle. Both policies are important in ensuring the safe and efficient operation of platooning systems.[26] When employing a CD policy, it is essential to keep a close but safe distance, hence increasing traffic efficiency. In the CTH policy, distance has a linear relationship with self-velocity.[27] This is similar to the behavior of a driver, although the space between cars is larger. Consequently, it cannot provide the same level of efficiency as the CD policy. This paper investigates the CD policy for the purpose of enhancing traffic efficiency. As seen in Fig. 1, the inter-vehicle spacing of CD policy is determined by equation (4):

$$\epsilon_i = x_{i-1} - x_i - l_{i-1} \tag{4}$$

where ϵ_i is the inter-vehicular spacing of vehicle i, x_i and x_{i-1} are the vehicle head position for the vehicle *i* and vehicle *i-1*. l_{i-1} is the vehicle length of vehicle *i*. Then the spacing error for a vehicle *i* can be defined as equation (5):

$$\delta_i = D_{des} - \epsilon_i \tag{5}$$

where D_{des} is the desired spacing between vehicles and δ_i is the spacing error of the vehicle *i*.

2.3 Controller design

Each fuzzy control[3] and sliding mode control[18] has its own design logic flow to leverage its local information. This study focuses on the design of the linear controller for complex hardware as it is the most common and traditional controller which the researchers utilize to examine the stability of platoon systems. The linear controller is then expressed by the following equation (6):[28]

$$u_i(t) = -\sum\left[k_{ij,p}\left(p_i(l - r_{ii}) - p_j(l - r_{ij}) - d_{i,j}\right) + k_{ij,v}\left(v_i(l - r_{ii}) - v_j(l - r_{ij})\right) + k_{ij,a}\left(a_i(t - r_{ij}) - a_j(t - r_{ij})\right)\right] \tag{6}$$

where the $k_{ij,x}$ (x = *p*,*v*, *a*) is the control gain, r_{ii} is the time delay that vehicle i to obtain the data from itself. $p_{i,j}$, $v_{i,j}$ and $a_{i,j}$ donate the position, velocity, and acceleration of vehicle i and j in this platooning. r_{ij} is the time delay from vehicle j to the vehicle i. Since this equation has the time delay and the platoon node-set, which is i, j. It should be noted that the study mainly utilized the controller shown in equation (6) to design the cart following the system. However, due to the limitations of the sensor settings, the following object may not broadcast its acceleration, velocity, and other relevant information, which in turn resulted in the simplification of the controller. As a result, simulations were conducted to validate the effectiveness of the simplified controller. The simulation of the controller's performance depended on the setting of the parameter tau, as referenced in Ref. [26], The results of the simulations were then validated through experimental testing to ensure the reliability of the control algorithm in real-world scenarios. The combination of simulations and experimental testing was critical in optimizing the vehicle's performance and validating the effectiveness of the control algorithm.

3. Vehicle design for car-following system

3.1 Power supply configuration

The RC vehicle is designed with a Raspberry Pi 4B as the control unit, a chassis with 4 wheels, a forward drive motor and steer servomotor, and a 9.6 V lithium battery. Fig. 2 shows the overall configuration diagram of the car. This section describes the functions of this car. The dimensions of the car are 30 cm × 16 cm × 10 cm, and it weighs 700 g (including the battery). A battery of 9.6V is supplied directly to the motor. This battery can be reduced to 5 V for the Raspberry Pi, sensors, A/D converter, steer servomotor, and 3.2 A Step-down voltage regulator to meet their requirement. The servo logic and motor enable pin is controlled using Pulse Width Modulation (PWM), by Raspberry Pi. All controlled components use Raspberry Pi General-purpose Input/Output (GPIO) port for data transmission. In addition to selecting an appropriate voltage regulator, this paper also explored ways to

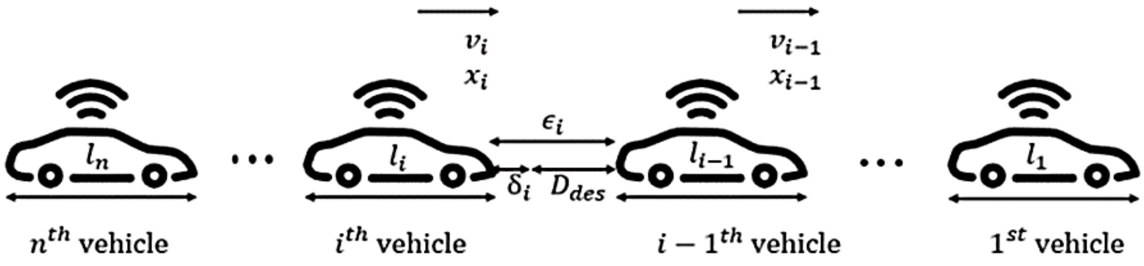

Fig. 1 Vehicles platoon system geometry.

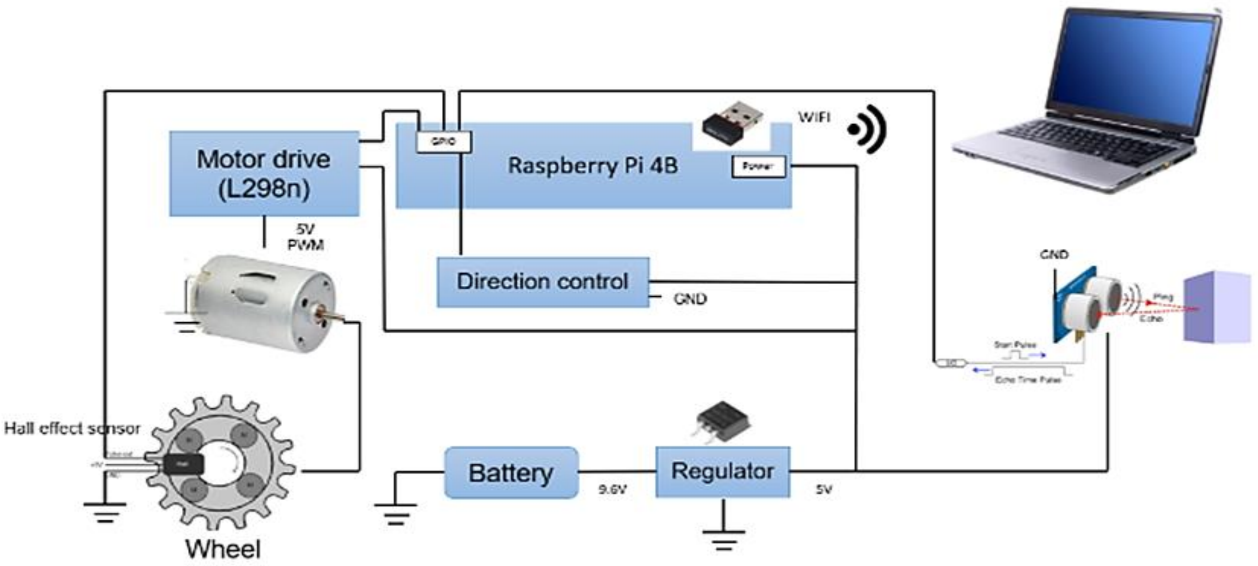

Fig. 2 Remote control vehicle assembly diagram.

Table 2. Introduction of main components.[29]

Main components and prices

Name	Model	Use	Price
Ultrasonic Sensor	HC-SR504	Used for measuring the distance in front	£3.16
Raspberry Pi	Raspberry Pi4 Model B 2GB	Center controller	£35.71
Motor Driver	L298n	Use PWM to control the motor	£4.99
WIFI Model	Ralink 5370	Wireless connects to PC	£7.99
Hall Sensor	A1120EUA-T	Measure the wheel speed	£0.71
Regulator	D36V28F5	Supply 5V,3.2A step-down voltage to power the vehicle	£11.47

reduce the weight of the RC vehicle to save energy. By minimizing the weight of the vehicle's components, we were able to extend the battery life and increase the efficiency of the vehicle. However, the size and capacity of the battery cannot be changed, as it is an essential component that comes with the car.

The power consumption of Raspberry Pi 4B is reduced to 2.1 W at the idle time and to 6.41 W with the load. The ultrasonic sensor and the hall sensor consume less than 1 W. Therefore, the step-down regulator can supply 15 W, which is enough for the sensors and the raspberry pi. The L298n motor drive and the motor are powered by a 700 mAh battery. This paper used a D36V28F5 step-down voltage regulator to reduce the battery voltage to 5V, which provides a maximum output current of 1A. The regulator is designed to be highly efficient and minimize power losses, which is important for extending the battery life of the vehicle. The servo logic and motor enable pin is controlled using Pulse Width Modulation (PWM) signals generated by the Raspberry Pi. We used the RPi.GPIO Python library to configure the Raspberry Pi's GPIO pins for PWM output, which allowed us to precisely control the motor and servomotor speeds. By providing more details about the power supply components and control signals, this paper shows the inner workings of the RC vehicle. The advantage of this design set is that when the power supply is replaced, all components can work normally making the entire design flexible. The selection of these components was also guided by considerations of cost-effectiveness, which makes the overall experimental setup less expensive. The individual components of the vehicle along with their usage and costs are listed in the following table.

3.2 Lateral control

This part involves keeping the vehicle on a straight path. Also illustrated is the general approach to steering control. In this system, the Raspberry Pi acts as the center of the system. The left and right electromagnetic sensors have different voltages induced in them, depending on their distance to the center of the track, as shown on the head of the vehicle in Fig. 2. The track is a 5V, 10KHz AC loop wire from a signal generator. Then the analog signal is picked up by the electromagnetic sensors and transferred to a digital signal from the A/D converter. The Raspberry Pi cannot accept analog signal input, but the Raspberry Pi can receive digital signals from the I2C interface, which is a synchronous serial protocol used to transfer data between two devices. The Raspberry Pi obtains this difference input to a PID controller, and then directs the steering of the servos and modifies the speed of the motors to ensure that the buggy remains in the center of the track.

3.3 Longitudinal control

The longitudinal control/block diagram is shown in Fig. 3. It

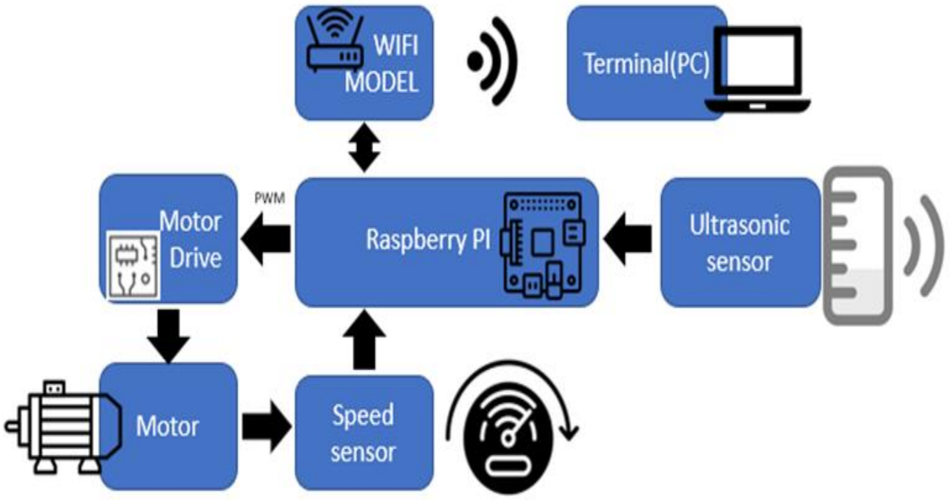

Fig. 3 System block diagram.

consists of two sensors which are the ultrasonic and the speed sensor, which provide the input distance and velocity signals to the Raspberry Pi. The raspberry pi then uses this data to calculate the duty-cycle output to be forwarded to the motor drive. This allows the motor to start or to change its speed. The overall closed-loop structure of the longitudinal control is monitored by a PC, via a Wireless Fidelity (Wi-Fi) network. The following mathematical equation is used to derive a basic longitudinal linear control as a change to equation (6):

$$D = k_1 \cdot d + k_2 \cdot \Delta v \tag{7}$$

where D is the duty cycle of the PWM signal to the motor drive, d is the distance from the preceding object, Δv is the velocity difference from the following object (condition: if the following can broadcast velocity), and k_1 and k_2 are the setting parameters, depending on the actual physical environment of the car.

This work installed a small magnet on the edge of the wheel. The hall sensor will generate a voltage when the magnet passes the sensor, due to the Hall effect.[30] It will transfer the signal to the Raspberry Pi. The Raspberry Pi can calculate the speed of the vehicle using the time interval $\Delta t = 0.1s$ as follows equation (8).

$$\frac{2\pi r}{\Delta t} = v \tag{8}$$

where v is the car speed and r is the wheel radius. The Wi-Fi module allows the car data to be instantly uploaded to the computer for display by connecting to the same Wi-Fi network. The computer can also control the starting and stopping of the car, as well as the wheel speed at any time.

3.4 Control algorithm

The control program of this car is compiled in Python using a 4G cellular network as a communication method. The Raspberry Pi and the PC are connected to the same 4G network to ensure the interconnection of computers and RC vehicles. As algorithm 1 shows, the Raspberry Pi enables the GPIO, the I2C channel, and each sensor *i.e.*, speed sensor, ultrasonic sensor, etc. With the values from the sensors, the Raspberry Pi will calculate the output to the motor which is the PWM duty cycle. The program will then repeat this process until the user exits the program.

Algorithm 1: Car-following Algorithm for Raspberry Pi

```
Set the vehicle speed sensor and the ultrasonic sensor, the distance $d$, the speed $v$, and the frequency of the PWM wave.
While True do
    The sensors collect all the state information from the vehicle.
    Raspberry Pi uses distance $d$ to calculate the PWM duty cycle $D$.
    Send $D$ the motor drive board.
    Obtain the speed v from the wheel speed sensor and record it.
end while the user interrupts the program.
```

In this study, a Raspberry Pi was used as the control unit for the RC car, and communication between the Raspberry Pi and a PC was established using Wi-Fi. The Raspberry Pi was configured as an access point, while the PC was connected to this access point as a client. The IP addresses of both devices were assigned manually to ensure proper communication. During testing, the network setup was found to be reliable, with no major issues encountered.

4. Car performance test

The dynamic performance of the car was tested at the Sports Centre, Newcastle University using the mobile phone's 4G cellular network to provide a hot spot for the PC and RC vehicle to connect. The first experiment was the speed performance when the vehicle has no load. The speed results are shown in Fig. 4. In this case, this paper defines the RC with load and without load as running the car on the ground and lifting the car with the wheels idling, respectively. This paper addresses the limitations of the components used in the design. While the size and capacity of the battery cannot be changed, we explored ways to minimize the weight of the RC vehicle's components to save energy. By minimizing the weight of the vehicle, we were able to extend the battery life and increase its

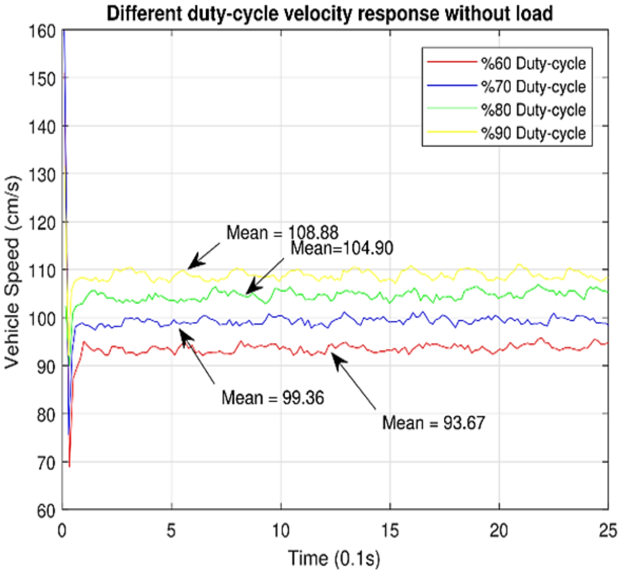

Fig. 4 Velocity response when the wheels idling.

efficiency of the vehicle. However, it's worth noting that there are still limitations to the performance of the RC vehicle given the constraints of the battery and components used in the design. The sampling time is the time for the wheel to make one revolution and was set to 0.1 s. The paper describes a vehicle following system that uses multiple sensors to gather data and control the movement of an RC vehicle. The maximum time required to gather and send data was found to be 80 ms when the vehicle was stationary and had no object in front of it. However, the delay between transmissions could increase up to 145 ms when the vehicle was moving slowly and with maximum bad timing, due to the way magnets hit the Hall effect sensors at inopportune moments. The update frequency under this condition was approximately 7 Hz, which was found to be lower than the system requirement. Taking into account the complication of static friction and the instantaneous nonlinear dynamics of the vehicle during start-up, the static friction in the mechanical process is ignored during the first 1 s, as depicted in Fig. 4. During the experiments, this paper tested the performance of the RC vehicle in car-following scenarios at various speeds ranging from 10 to 60 cm/s and distances ranging from 2 to 10 meters in the straight lane. A total of 10 trials were conducted for each speed and distance combination to ensure statistical significance. This paper did observe some variability in the results, particularly at higher speeds and longer distances. We plan to conduct further analysis to investigate the causes of this variability and identify any trends in the data. This additional analysis will provide valuable insights into the limitations of the current system and how it can be improved for real-world applications. These results then allowed us to calculate the mean speed with different PWM duty-cycle outputs. Finally, the experimental results were obtained so that the speed is constant under different PWM duty cycles.

Under the same conditions, the experimental car was placed on the ground to test its dynamic performance of the car. The results are shown in Fig. 5. The figure shows the car has speed noise due to the static friction in the first 10 s, which is not expected due to its complex mechanical dynamics. Spaces from 10 s to the end, the speed is relatively constant with 50%, 60%, and 70% PWM duty-cycle. When the duty cycle is under 50%, the car remains stationary.

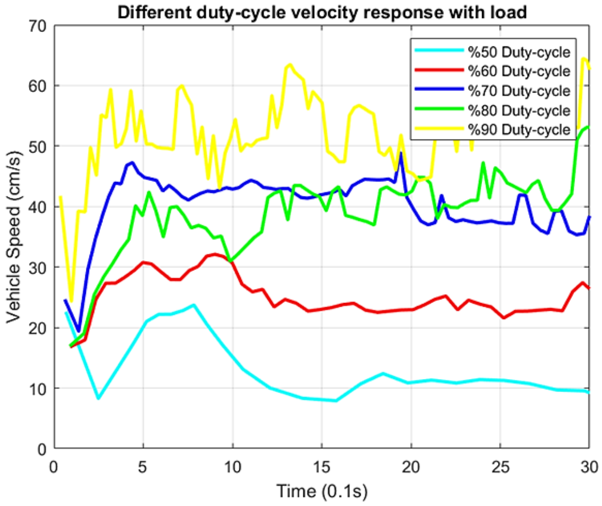

Fig. 5 Different duty-cycle when the car running on the ground.

As shown in Fig. 6, it then determines the link between velocity and duty cycle based on the mean speed after 10s, derived from the experimental findings. In this graph, the connection between 50%, 60%, and 70% PWM duty cycle and speed is linear. In the subsequent stage of the method, the output duty cycle may therefore be determined based on these data.

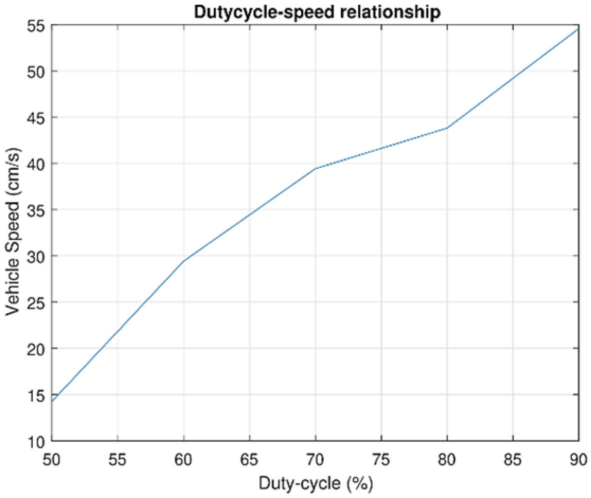

Fig. 6 Relationship between velocity and duty cycle.

5. Car-following experiment

Considering the precision of the ultrasonic sensor, the tracked item should ideally have a regular form. Therefore, a square box serves as the simulation's target vehicle in this experiment. Therefore, this paper used the RC-designed vehicle to track a box. The size of the storage box is approximately 38 cm × 30 cm × 25 cm with 0.2 kg. This experiment only requires the size of the box to be monitored by the sensor. In equation (7), k_1 is set to 1 and k_2 is set to 0, since the box cannot broadcast the dynamic information. When setting the values of k_1 and k_2, it was important to consider the weight of the distance to the box and the potential for the car to accelerate too rapidly or lose track of the box. In this experiment, a value of k_1= 1 and k_2 = 0 were chosen to minimize these risks. A larger value of k_1 would result in a larger signal to the motor, causing the car to accelerate more quickly and potentially react violently, while a smaller value of k_1 would result in the car losing track of the box. Therefore, based on these considerations, k_1= 1 was deemed a suitable choice for this experiment. Typically, the vehicle determines the PWM duty-cycle output for the motor based on the distance to the box. This section indicates that static friction is a significant problem. Therefore, it eliminated the car's operation against static friction. When the car is in motion, a box is positioned approximately 50 cm to 80 cm in front of it and is activated under variable speed movement. The vehicle can then track the AC loop wire using 5V at 10 KHz to ensure that it travels in a straight line. This study carried out repeated trials and compared the findings.

In the experiment, an attempt was made to change the box within a restricted range so that the automobile would move at variable speeds over a variable distance. However, when the distance is less than 50 cm, the friction causes the vehicle to remain immobile, as depicted in Fig. 7. Due to static friction, the speed-distance relationship is nonlinear after a restart. Fig. 7 demonstrates that the distance and velocity are essentially linear. When the distance is shorter than 40 cm, there is a significant reduction in velocity. This is because the vehicle lacks a braking function, thus it must rely on friction to stop. Therefore, the connection between speed and distance cannot remain linear.

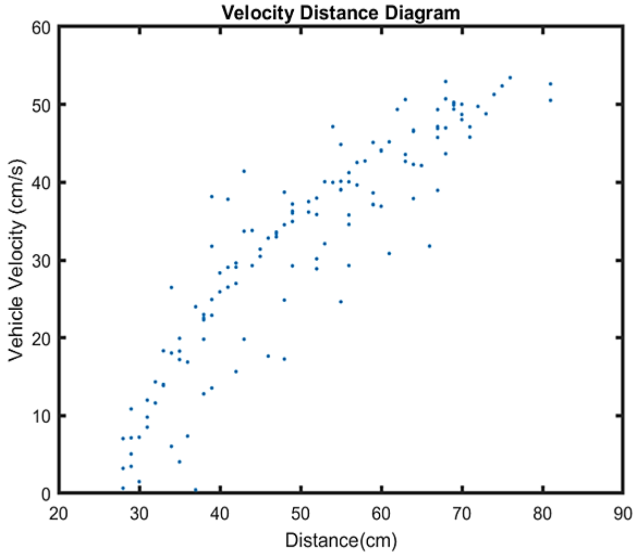

Fig. 7 The relationship between velocity and distance.

6. Conclusions

In this paper, the built RC vehicle adapts completely to the control model of the vehicle platoon and controls the vehicle's forward movement based on the objective's dynamic data. The Raspberry Pi was utilized to successfully integrate many sensors, regulate steering, and move forward. Through the wireless network, all sensor states are synchronized with the PC. It designed an RC car-following system for research, where the optimal speed range is 25 cm/s to 50 cm/s. It shared the design of the control algorithm and the hardware acquisition for the use of other researchers. The findings of this study have significant implications for real-world applications, particularly in the field of autonomous driving. The control program and hardware configuration developed in this study could be modified to improve the performance of the RC vehicle in car-following scenarios. For example, more advanced sensors, such as LiDAR or radar, could be used to improve the accuracy of distance measurements and enhance the vehicle's ability to follow a target vehicle. Additionally, more sophisticated control algorithms could be developed to account for complex driving scenarios, such as lane changes or intersections. Overall, the results of this study demonstrate the potential of low-cost hardware and simple control algorithms in the development of autonomous vehicle systems. Additionally, the platform can be simply augmented with an Inertial Measurement Unit (IMU) and GPS to provide acceleration and location. To validate the model and controller design, future work might incorporate this system into a vehicle platoon.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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