Design of the following car based on FreeRTOS and UWB

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ABSTRACT

This paper mainly studies and designs an indoor autonomous tracking vehicle system based on FreeRTOS real-time operating system and UWB ultra-wideband ranging technology. The system integrates advanced wireless positioning technology and embedded control algorithm to achieve intelligent following function with high accuracy, low delay and strong robustness. Firstly, the characteristics and advantages of FreeRTOS are introduced, and how to apply it to the design of the car control system is described to meet the requirements of real-time control and ensure the stable and efficient operation of the system. Secondly, the principle of UWB ranging technology and its application in precise positioning are discussed. Combining the above two key technologies, a vehicle following strategy based on FreeRTOS and UWB ranging information was proposed. Using high-precision ranging capabilities and excellent task control capabilities, the vehicle can track the preset target object in real time and maintain a safe distance. Finally, the effectiveness and feasibility of the designed system are verified by experiments.

Keyword: UWB positioning technology, incremental PID control algorithm, FreeRTOS real-time operating system

1. INTRODUCTION

With the rapid development of Internet of things technology, wireless positioning technology and embedded systems, autonomous mobile robots have shown great application potential in many fields such as industrial production, logistics and transportation, and service industries. Among them, the car system with precise following function has attracted particular attention. They can realize efficient and accurate object handling and personnel guidance, which greatly improves operation efficiency and safety.

In this paper, FreeRTOS real-time operating system and Ultra-Wideband (UWB) positioning technology are integrated to design a scheme of intelligent following car system with high performance and precision. Firstly, the characteristics and advantages of FreeRTOS real-time operating system were analyzed, focusing on its task scheduling, memory management and interrupt handling mechanism. Then, the basis of UWB technology is deeply analyzed, especially the ranging method and principle based on Time of Flight (ToF)[1].

On the basis of theoretical analysis, the design scheme of intelligent following car system based on FreeRTOS and UWB technology is proposed. Firstly, the system architecture was constructed from the perspective of hardware, the main control unit, UWB positioning module, drive motor and other key components were selected and integrated, and the physical connection and communication protocol were clarified. At the software level, the system module design logic is detailed, and the corresponding algorithm is designed. Finally, the performance of the system was verified by experiments, and the key performance indicators were comprehensively tested and evaluated to ensure the effectiveness and integrity of the design.

2. RELATED TECHNOLOGY INTRODUCTION

2.1 Introduction and applicability analysis of FreeRTOS real-time operating system

Real-time operating System (RTOS), as a special type of operating system, has become a key component in the design of modern embedded system because of its highly efficient processing ability of multi-task. The so-called real-time system refers to the response level of the control system to the change of external related information, which requires not only the calculation results with high precision, but also the results with timeliness[2]. Figure 1 is the system architecture diagram of FreeRTOS, which shows the peripheral equipment and various functions that the system can support, so it is not difficult to see that the system is suitable for various embedded systems. It provides a small and efficient kernel that

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can run on microprocessors and microcontrollers to provide functions such as multitask management, task scheduling, timers, semaphores, and message queues for embedded applications.

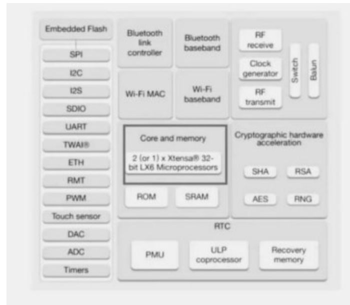

Figure 1. Schematic of the FreeRTOS system architecture.

FreeRTOS, with its strong real-time performance, low resource occupation, excellent multi-task management and synchronous communication mechanism, as well as good scalability and compatibility, shows a high degree of applicability in the following car control system. An intelligent truck based on FreeRTOS[3] gives an example of applying the real-time system to the intelligent vehicle, which can show that the FreeRTOS real-time operating system can and is suitable for the design.

2.2 Introduction and working principle of UWB ranging technology

Ultra-Wideband (UWB) technology, as a revolutionary means of wireless communication, has a number of significant advantages, including high-speed data transmission, excellent penetration ability, and strong resistance to multipath fading phenomena. This makes UWB an ideal choice to solve the problem of complex indoor environment and short-range accurate ranging[4].Unlike traditional narrowband communication, UWB technology does not rely on continuous carrier or specific frequency, but by sending nanosecond or even picosecond level pulse signals, and by accurately measuring the propagation time of these signals in space, that is, the time of flight (ToF) to calculate the accurate distance between the signal source and the receiver.

The principle is as follows:

In the Two Way Time of Flight (TW-TOF) method, the UWB module A at the transmitter emits a pulse with a timestamp at a specific time (T_{a1}). When UWB module B at the receiver receives this pulse, it marks it as T_{b1} on its own timestamp. After receiving, possibly after some processing and delay, receiver B sends A response pulse to transmitter A, and the sending time of this response signal on B is denoted as T_{b2}. Transmitter A receives this response pulse and records the reception time T_{a2}. By comparing the above four timestamps, the round-trip time of the pulse from A to B and back to A can be calculated $[(T_{a2} - T_{a1}) - (T_{b2} - T_{b1})]$. Since the propagation speed of electromagnetic waves in air is close to the speed of light, the straight-line distance D between two points can be calculated by equation (1):

$$\mathrm{D} = \frac{1}{2} \times \mathrm{c} \times [(T_{a2} - T_{a1}) - (T_{b2} - T_{b1})] \quad (1)$$

where c is the speed of light (or approximately the speed at which an electromagnetic wave travel in the current medium).

In practical applications, in order to improve the ranging accuracy, the system should consider and compensate for the influence of factors including but not limited to: clock synchronization error, signal attenuation and phase variation during signal propagation.

The schematic diagram of the ranging principle is shown in Figure 2.

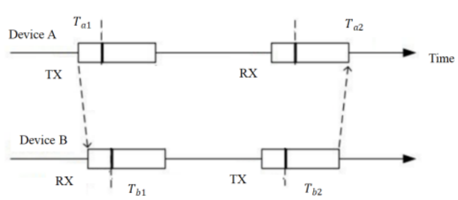

Figure 2. Schematic diagram of UWB ranging principle.

UWB ranging technology is widely used in indoor positioning, Internet of things node positioning and other fields to provide centimeter level location information because of its advantages of high accuracy and low power consumption.

3. DESIGN OF THE HARDWARE IN THE SYSTEM

3.1 Hardware system architecture design

The design is divided into two devices: the follower carries a UWB base station, and the small car installs two UWB tags. The battery is connected to the LM2596S DC-DC buck module to reduce the voltage to 5 V, and the ESP32, UWB module, motor drive module, Hall sensor and the relevant port of the motor are connected to the load end of the buck module. In addition, the relevant data pins of UWB module, Hall sensor module and motor drive module are connected to the corresponding pins of ESP32 microcontroller. The block diagram of the hardware structure is shown in Figure 3, where the arrow indicates the direction of data or energy transmission, and the dashed arrow indicates that the UWB base station and the tag transmit data wirelessly.

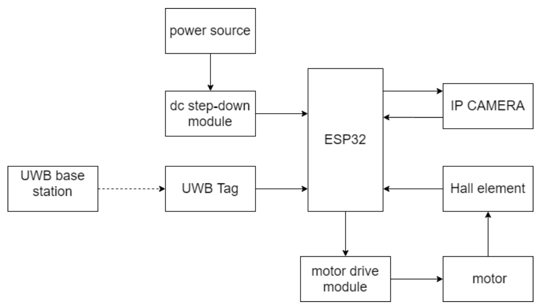

Figure 3. Block diagram of hardware structure.

3.2 UWB module

The UWB ranging module is the core component of the positioning and tracking function of the following car, which accurately measures the distance to the target object by sending and receiving ultra-wideband pulse signals and calculating the Time of flight (ToF) of the signals. The module is capable of transmitting and receiving at the same time and has a high-precision clock to record the timestamp of the signal transmission.

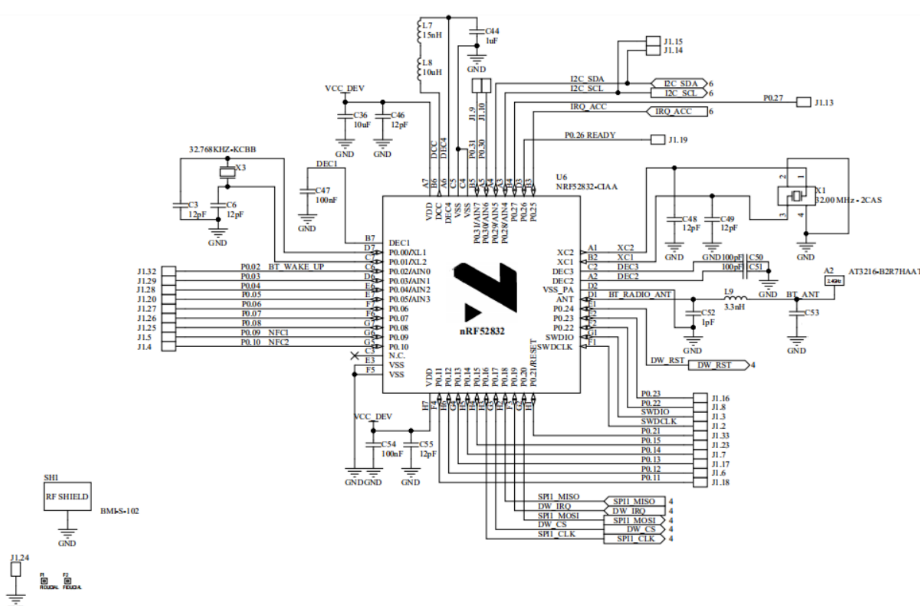

Figure 4. DW1000 circuit schematic.

In this design, SWM1000 UWB ranging module is used, which is used in all kinds of UWB research and design. The module uses DW1000 UWB chip of Decawave company. The schematic diagram of DW1000 circuit is shown in Figure 4.

3.3 Main control unit

As the control center of the system, the main control unit adopts a high-performance microprocessor or embedded controller. In this design, the ESP32-WROOM-32E model single chip microcomputer produced by ESpressin Company is used (Figure 5 shows the patch type physical diagram of the chip, the schematic diagram of the minimum system board and the schematic diagram). FreeRTOS real-time operating system has a wide range of applications in ESP32 series microcontroller. All kinds of designs based on ESP32 series microcontroller apply FreeRTOS system, which is responsible for running FreeRTOS operating system and data processing and decision-making control. It integrates rich communication interface to connect UWB module and other sensor devices, and docking drive unit to realize real-time control of motor and other actuators.

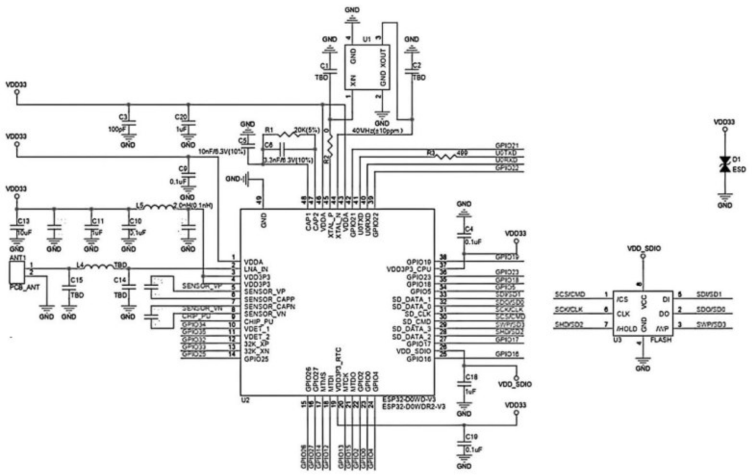

Figure 5. ESP32-WROOM-32E circuit schematic.

ESP32 development board is a controller with integrated WiFi and Bluetooth functions. WiFi support 802.11 b/g/n, the highest speed of 150 Mbps, also compatible with Bluetooth v4.2 complete standard which contains low power (BLE), 32-bit dual-core processor, CPU normal working speed of 80 MHz, built-in 448 KBROM, built-in 520 KB SROM[5].

3.4 Motor drive unit

In this design, the double H-bridge circuit is used to drive the motor. The double H-bridge circuit, also known as the full bridge drive circuit, is a circuit commonly used in DC motor control, especially for the occasion of positive and reverse control. The circuit consists of four power switching components (such as MOSFET or IGBT) to form two inverter bridge arms. By reasonably switching the conduction state of the upper and lower bridge arms, the voltage polarity at both ends of the motor can be changed, so as to realize the forward rotation, reverse rotation and speed regulation of the motor.

Combined with UWB positioning information and FreeRTOS real-time operating system, the working state of each motor is accurately controlled to ensure that the car can accurately track the target and maintain a stable following distance. Figure 6 shows the dual-channel H-bridge motor driver module and the schematic diagram used in the design, which is named TB6612.

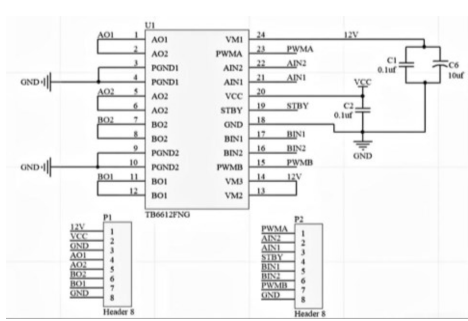

Figure 6. TB6612 circuit schematic diagram.

3.5 Power management section

In this design, the power source of the following car is 7.4 V energy-efficient lithium polymer battery. The battery has the characteristics of high energy density and stable discharge performance, which can provide sufficient and continuous energy support for the whole following car system.

The LM2596S DC-DC buck module is used to meet the requirements of multiple operating voltages inside the following car. This module can reduce the voltage from 3.2 V to 40 V to the required voltage according to the actual situation. Figure 7 shows the schematic diagram and pin diagram of this module, which can meet the power supply requirements of microcontroller, UWB module, motor drive unit and other sensor devices. In the design process, the conversion efficiency, thermal dissipation and dynamic response speed are considered, and the electronic components with low on-resistance and high switching frequency are selected to ensure that the output voltage is adjusted quickly when the load changes, and the power consumption is minimized.

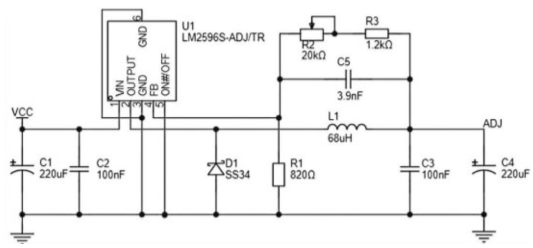

Figure 7. LM2596S DC-DC buck module schematic diagram.

3.6 Hardware circuit design

The circuit connection diagram of each module is shown in Figure 8. The two PWM output pins of the MCU are connected to the signal line of TB6612 and MG995 steering gear. The positive and negative output of TB6612 is connected to the DC gear motor, and the power supply of the battery is connected to the power end of each module after the step-down module, the UWB module and Hall sensor module are not drawn. In practice, only the corresponding pins need to be connected.

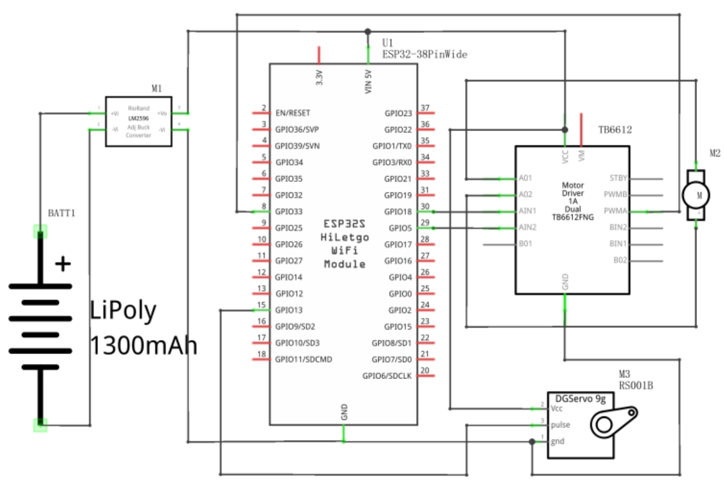

Figure 8. Circuit connection diagram of each module.

4. SOFTWARE PROGRAMMING

4.1 Task scheduling based on FreeRTOS

In the following car design based on FreeRTOS and UWB, we divide the task into multiple independent task entities according to the system functional requirements:

(1) UWB positioning information processing task: This task is responsible for receiving and analyzing the target position

data sent by the UWB module, calculating the distance and direction of the car to be adjusted, and generating the corresponding control instructions.

(2) Motor drive control task: Based on the received control instructions, this task accurately controls the speed and steering of each motor through the double H-bridge circuit, and realizes the real-time adjustment of the motion state of the car.

(3) Communication and feedback tasks: responsible for wireless communication with the host computer or other devices, real-time upload car status information, receive remote instructions, and feedback the execution results as needed.

The flow chart of the system program is shown in Figure 9.

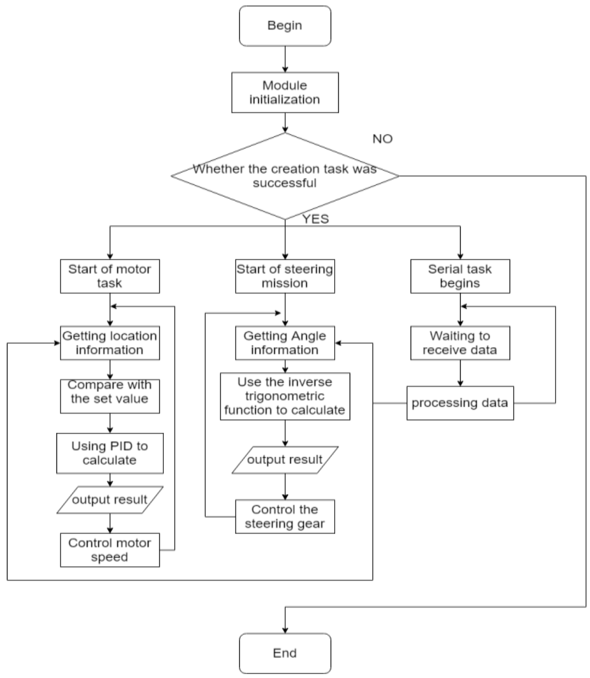

Figure 9. Program flow chart.

4.2 Motor speed control algorithm

For the program design of the following car, the core is the motor drive algorithm, In the design of intelligent car speed control system based on incremental PID[6], a scheme of motor speed closed-loop control is introduced. On this basis, the design is further optimized, making the control algorithm simpler and more efficient.

In this design, the Incremental PID control algorithm is used to accurately control the trajectory and speed of the following car. Compared with the traditional PID control algorithm, the incremental PID control algorithm is an improved algorithm for the optimization of real-time control system characteristics, especially suitable for fast response and high-precision control occasions[7].

The incremental PID control algorithm focuses on the change of the control output rather than the absolute value. It calculates the incremental value of the current control output relative to the previous output according to the change of the current error and the previous error, and then accumulates the last output value to form a new control output.

How it works: The core of the incremental PID controller is to update the control output based on the change between the error at the current time and the error at the previous time. The basic formula can be expressed as equation (2):

$$\Delta u(k) = K_p * \Delta e(k) + K_i * \sum \Delta e(k) + K_d * [\Delta e(k) - \Delta e(k-1)] \tag{2}$$

$\Delta u(k)$ is the increment to be added to the control output this time.

K_p, K_i and K_d are the proportional, integral and differential coefficients, respectively.

$\Delta e(k)$ is the change in error at the current time, which is $[e(k) - e(k-1)]$, where $e(k)$ is the current error (the difference between the target and the actual measurement).

$\sum \Delta e(k)$ denotes the integral term and will usually have an upper bound to prevent integral saturation.

$[\Delta e(k) - \Delta e(k-1)]$ represents the differential term, which reflects the trend of error variation.

In the actual application process, we only need to use the C language method to realize the above formula, let the ranging information obtained by the UWB ranging module as the actual value, and set the set value artificially, and call the corresponding C language function with the two values as parameters to obtain the output result.

4.3 Car steering control algorithm

MG995 servo is used in this design scheme. It is a high-performance analog servo motor with strong torque output capability. The rated torque is up to 13 KG force/cm (13 kg/cm)[8], which makes it very suitable for applications with high requirements of diagonal position accuracy and load bearing. Such as manipulator joint drive, model aircraft control, remote control vehicle orientation adjustment and other application scenarios.

In the design of intelligent handling trolley based on STM32 and UWB communication[9], the author realized the following function according to the corresponding algorithm. In this design scheme, the corresponding algorithm is improved to make it simpler and more efficient. In this scheme, three UWB modules are used, two of which are used as base stations and the other one is used as tags, the interim tags are carried by the follower, and the two base stations are located on both sides of the car head. In this way, the three tags can form a triangle arrangement, and then a mathematical model can be constructed (Figure 10), so as to determine the Angle between the follower and the movement direction of the car, so as to drive the servo to turn.

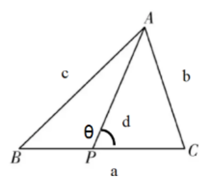

Figure 10. Schematic of the mathematical model.

Let AB have length c, AC have length b, BC have length a and AP have length d in the graph, where p is the midpoint on the edge of BC. Then we only need to try to find the Angle θ between AP and BC. Equation (3) is obtained from the theorem of cosines:

$$\angle ABC = \frac{c^2+a^2-b^2}{2ac} \tag{3}$$

and since it's in the triangle ABP:

$$\angle ABC = \frac{c^2+\frac{a^2}{2}-d^2}{ac} \tag{4}$$

and:

$$\theta = \frac{d^2+\frac{a^2}{2}-b^2}{ad} \tag{5}$$

The above three equations can be solved simultaneously to determine the Angle between the target and the equipment, and then control the servo through the program to realize the steering operation of the equipment.

In this design, it is necessary to obtain the PWM wave of the corresponding duty cycle according to the offset Angle to control the servo and realize the steering function, but each sensor has its own dimension and value[10], so it is necessary to carry out the scale transformation of the offset Angle obtained by the above method (the digital quantity is converted into a dimensional value before data processing, analysis and visual representation. This transformation is the scaling transformation[11]), which converts the corresponding Angle into the corresponding duty cycle. The general formula of linear scaling transformation is as follows:

$$A_X = A_0 + \frac{(A_m - A_0)}{(N_m - N_0)} \times (N_x - N_0) \tag{6}$$

A_X is the actual engineering quantity value obtained after scaling transformation.

A_0 is the lower limit (minimum) of the range of the measuring instrument.

A_m is the upper limit (maximum value) of the range of the measuring instrument.

N_x is the digital quantity output by the sensor.

N_0 is the numerical quantity lower bound corresponding to A_0.

N_m is the upper limit of the number corresponding to A_m.

Bring in the corresponding maximum output duty cycle, minimum output duty cycle, set following Angle and actual following Angle to obtain the duty cycle data that should be output by the system after scale transformation, and then output the corresponding duty cycle waveform according to the data, so as to realize the control of the servo and make the car run according to the specified following Angle.

5. SYSTEM DEBUGGING AND PERFORMANCE EVALUATION

5.1 Motor closed-loop control verification

In order to verify the effectiveness of the motor closed-loop control, we first build a car hardware platform including UWB positioning module, microcontroller and motor. At the software level, a special task for motor closed-loop control is designed by using the task scheduling mechanism of FreeRTOS. The task reads the target position information transmitted by the UWB module in real time, and generates the corresponding motor control instructions according to the pre-designed control algorithm.

Firstly, the closed-loop control of the car speed is verified. The experimental verification was carried out in the suspended state of the driving wheel of the car, and the parameters in the PID were set as $K_P = 25, K_I = 0.1$ and $K_D = 0.1$. At this time, the motor speed response curve is shown in Figure 11, where the red line is the motor speed curve, and the green line is the given speed signal curve.

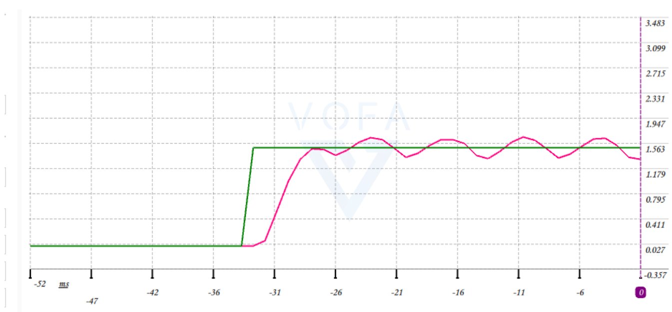

Figure 11. Motor speed response curve.

Because a fast response speed is not required for the car following system, it is only necessary to make the system in an overdamped state. Figure 12 shows the response curve of the motor speed when each parameter of PID is changed.

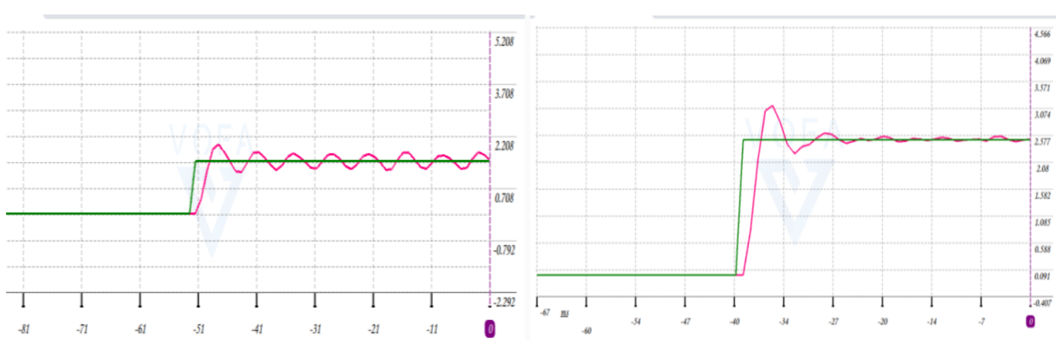

Figure 12. Motor speed response curves corresponding to different parameters.

A conclusion can be drawn from the comparison of the two figures, when the system is stable, there will be a constant amplitude oscillation with the same frequency, and the oscillation period is 5 ms (the vertical coordinates of the two figures are not equal, so the amplitude is different in the visual, and the actual value is equal). In order to explore the reasons for this problem, experiments are carried out by changing the relevant parameters of PID for many times (Figure 13).

By comparing the two dynamic response curves of the system, we can clearly observe that after the system reaches the stable state, there is a constant amplitude oscillation with the same frequency, and the oscillation period is 5 ms.

In order to further reveal the root cause of such oscillatory behaviors, we have carried out in-depth and detailed experimental studies. By adjusting the parameters of PID controller many times to find the cause of this problem. Figure 13 shows the results of one of these experiments.

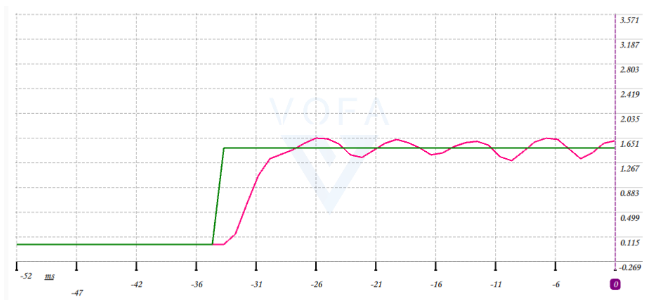

Figure 13. The response curve obtained from the test.

According to the research results, whether the system works in the underdamped state or the overdamped state, the step response curve of the motor speed will have the same frequency of constant amplitude oscillation. Finally, it is concluded that the cause of this problem is due to the problem of the mechanical structure design of the motor part of the car model, that is, the friction between the gear and the tire edge, which affects the motor speed, resulting in this phenomenon. Since the following system is a servo system rather than a custom control system, the set point will change with time, so the constant amplitude oscillation generated in the above experiment has little influence on the following effect, and the following experiment is shown in the next subsection.

After many experiments, the PID related parameters are finally selected as $K_P = 30$, $K_I = 10$ and $K_D = 0.1$. The corresponding control effect is shown in Figure 14, which has good static and dynamic characteristics.

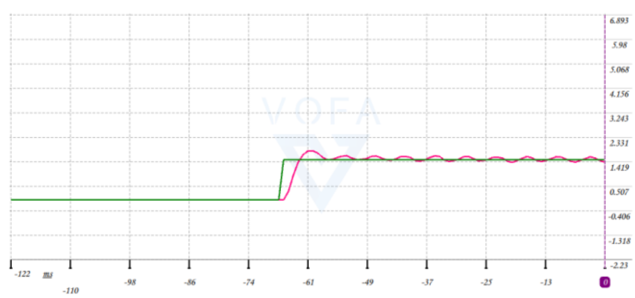

Figure 14. The dynamic characteristics corresponding to the final selected parameters.

5.2 The system follows the functional verification

The function is verified in an indoor environment, and the UWB tag is carried by the follower to obtain the distance and speed information of the car in real time through the serial port and send it to the computer. The relevant information is processed and displayed by the PC software. The results are shown in Figure 15. The green line represents the speed value that the car should have after calculating the actual distance and the set distance, and the red line is the actual value, which is the current speed information of the car.

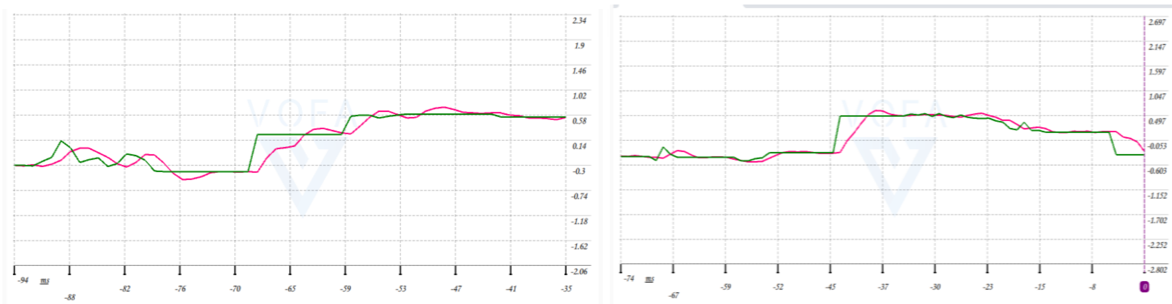

Figure 15. Changes in the speed of the car in different scenarios.

From the above experimental results, it is easy to see that the system has a good follow-up effect on the speed control. Next, the real-time distance information of the car is collected and displayed to evaluate the function of the car following.

This is shown in Figure 16, where the green color is the set following distance and the red line is the actual distance between the trolley and the follower. The following distance was set to 1.5 m in the experiment. It can be seen from the figure that the actual distance will fluctuate up and down, which is because the accuracy range of UWB ranging module is 10 cm, so the measurement distance will have a random error of 10 cm. Due to the accumulation of integral action, the actual distance will fluctuate irregularly, but in the practical application process, this fluctuation will not have an excessive impact on the system.

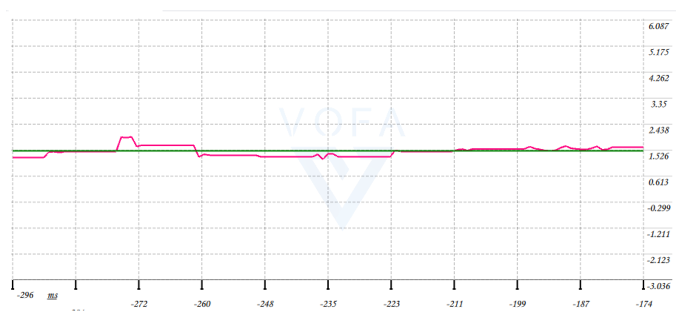

Figure 16. The changing law of the actual distance and the set distance in the system operation.

6. CONCLUSION

In this paper, FreeRTOS real-time operating system as the software core platform, ESP32 series single-chip microcomputer as the main controller, combined with advanced ultra-wideband ranging technology, the design of the following car has carried out a full range of research and practice. An efficient, accurate and responsive following control system is constructed to improve the autonomous navigation ability and task execution efficiency of the following vehicle in complex environments.

In terms of hardware, ESP32 meets the design requirements with its excellent performance, diverse peripheral interfaces, high integration, and built-in Wi-Fi and Bluetooth functions, which provides flexibility and great potential for future expansion of the system. Combined with the application of high-precision UWB ranging technology, cm-level accurate positioning can be achieved, and strong anti-interference and excellent penetration ability can be maintained even in complex environments. In terms of software, the lightweight, highly customizable and efficient real-time advantages of FreeRTOS are used to provide stable support for the efficient execution of the algorithm. Through fine task scheduling and multi-thread management, the seamless collaboration between core tasks such as UWB data processing, positioning algorithm execution and motor control is ensured, and the overall performance of the system is improved.

In the experimental verification, the designed car shows good following performance in different scenarios. It not only maintains stable distance tracking on the straight path, but also can quickly respond and adjust the driving state when tracking dynamic targets. Experiments show that the design scheme based on FreeRTOS and UWB ranging technology can effectively reduce the power consumption and complexity of the system while improving the following accuracy and enhancing the robustness of the system.

Overall, this research innovates to combine FreeRTOS with UWB technology, contributes an efficient and accurate design paradigm to the field of indoor autonomous navigation and intelligent robotics, and broadens the path of technical practice.

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