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Principles and Applications of Ultrasonic Waves Based on Single-chip Microcontroller

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Abstract: Ultrasonic ranging is a technology for measuring distance based on the characteristics of ultrasonic waves, which is widely used in fields such as robot obstacle avoidance, industrial inspection, and automotive parking sensors. This paper aims to design an intelligent vehicle experiment based on ultrasonic ranging. The ultrasonic module is used to achieve ranging, enabling the intelligent vehicle to perform obstacle avoidance functions. By analyzing the voltage regulation function of the power supply module and the principle of the DC motor drive module, the voltage regulation and drive modules are designed. The single-chip microcontroller is meticulously designed to receive information from the Wi-Fi module and output corresponding control signals to generate PWM waveforms, thereby controlling the rotation and speed of the motor.

Keywords: Ultrasonic waves; Single-chip microcontroller; Wireless Local Area Network (WLAN)

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1. Introduction

Ultrasonic ranging is a distance measurement technology based on the propagation characteristics of ultrasonic waves in the air. Compared with other ranging methods, ultrasonic ranging has advantages such as strong anti-electromagnetic interference ability, high accuracy in short-distance measurement, and excellent longitudinal resolution. It has a strong directivity and a wide coverage range, making it suitable for various complex environments. Currently, ultrasonic ranging technology has been widely applied in fields such as obstacle avoidance, positioning, and navigation of mobile robots, demonstrating broad application prospects [1].

In the field of motor control, speed regulation technologies are mainly divided into two categories: DC motor speed regulation and AC motor speed regulation. Among them, DC motors have significant advantages in precision control scenarios due to their excellent operating characteristics and controllability. Pulse Width Modulation (PWM) technology, as an efficient digital control method, adjusts the duty cycle of pulse signals to control analog circuits, showing remarkable energy-saving effects in motor speed regulation. PWM technology has features such as strong anti-interference ability, small space occupation, and high cost-effectiveness, with obvious advantages over traditional analog control methods.

Traditional analog control circuits have many limitations, such as problems like circuit parameter drift over time, high heat loss, and sensitivity to noise. The PWM technology adopted in this paper effectively overcomes these defects through digital control methods. It not only reduces the power consumption and cost of the system but also improves the control accuracy and reliability, and has been widely used in motor control and other analog signal processing fields.

2. Theoretical analysis

2.1. Ultrasonic module

This system uses the HC-SR04 ultrasonic ranging module for distance measurement. This module communicates with the main system through the IO port, emitting ultrasonic waves and receiving reflected signals to achieve accurate ranging. The HC-SR04 module is triggered by the TRIG pin. After sending a high-level signal for at least 10 μs, it emits 8 ultrasonic pulses with a frequency of 40 kHz. When the ultrasonic waves encounter an obstacle, they are reflected back to the receiver along the same path. After reception, the ECHO pin outputs a high-level signal, and its duration is proportional to the distance [2, 3]. The duration of this high-level signal is the time from the emission to the reception of the ultrasonic waves, as shown in formula (1).

$$d = \frac{1}{2}vt \tag{1}$$

Where v represents the speed of ultrasonic waves. The range of the HC-SR04 is from 2 cm to 400 cm, with an accuracy of 3 mm. It has a fast response and low power consumption (15 mA). The main system judges the distance to the obstacle based on the received information and selects an appropriate motor movement plan to achieve the obstacle avoidance function.

2.2. DC motor drive module

The L298N is a high-voltage and high-current motor drive chip produced by ST Company. It is the core component of DC motor drives and is suitable for various complex control systems. This chip is packaged in a 15-pin format, supporting a working voltage of up to 46V, with a peak current of 3A, a continuous current of 2A, and a rated power of 25W. Its core feature is the integration of two H-bridge drivers inside, which can independently control two DC motors or one two-phase/four-phase stepper motor. It is widely used in fields such as robotics, intelligent cars, and industrial automation.

The L298N is compatible with TTL and CMOS levels and can be directly connected to microcontrollers. Its logic power input terminal isolates the logic circuit from the high-voltage drive part, allowing the internal logic circuit to operate at a low voltage, improving system safety. The two enable terminals can independently control the start and stop of the H-bridge without being affected by the input signal, enhancing control flexibility. In addition, the L298N supports an external detection resistor to provide real-time feedback on the motor current for over-current protection or torque control.

By using two L298Ns and adding a small number of external components, the drive of the DC motor can be achieved.

2.3. Voltage conversion module

The TPS54331 is a high-performance asynchronous buck converter designed by TI Company. It supports an input voltage of up to 28V and an output current of 3A. It integrates a high-side MOSFET with a low on-resistance (RDS(on)), and is suitable for industrial control, automotive electronics, consumer electronics, and battery-powered devices.

This device automatically activates the pulse-skipping Eco mode under light loads, reducing switching losses and improving efficiency. Its shutdown supply current is only 1μA, making it suitable for battery-powered scenarios and extending the device's battery life. It adopts an internal slope-compensated current-mode control, which simplifies the external compensation design, reduces the number of components, and improves system stability. It supports ceramic output capacitors, reducing the circuit volume and cost.

The TPS54331 has input under-voltage lock-out (UVLO) and over-voltage transient protection functions to ensure the safe operation of the system under insufficient input voltage or transient conditions. The frequency foldback and thermal shutdown protection functions reduce the switching frequency under overload conditions, and the cycle-by-cycle current limiting scheme protects the device and the load from damage.

2.4. PWM speed regulation principle of DC motors

Compared with the speed regulation principle of AC motors based on frequency modulation, DC motors change their rotational speed utilizing amplitude modulation. PWM speed regulation adjusts the pulse width of the drive voltage and, in conjunction with energy-storage components in the circuit (such as capacitors and inductors), changes the voltage amplitude delivered to the motor armature, thereby achieving precise control of the motor speed.

The core of PWM speed regulation lies in the adjustment of the duty cycle. The duty cycle refers to the ratio of the high-level time to the entire cycle time in a PWM cycle. For example, a PWM signal with a 15% duty cycle means that the high-level duration is 15% of a cycle, and the low-level duration is 85%. A PWM signal with a 70% duty cycle means that the high-level duration is 70% and the low-level duration is 30%. The larger the duty cycle, the longer the high-level time, and the higher the output average voltage. Conversely, the smaller the duty cycle, the lower the average voltage. When the duty cycle is 0%, the output voltage is 0, and the motor stops running. When the duty cycle is 100%, the output voltage reaches the maximum value, and the motor runs at the highest speed. By continuously adjusting the duty cycle, stepless and continuous control of the motor speed can be achieved.

Pulse Width Modulation (PWM) is a highly advantageous control technology [4-6]. It aims to control analog circuits with digital outputs by adjusting the pulse width. Compared with other control technologies, PWM control has the following advantages:

(1) Energy-saving and efficient: PWM uses fast switching to adjust the voltage, reducing energy losses in linear regulation and improving system efficiency. Moreover, the PWM speed-regulation circuit has a simple structure and requires few components, greatly saving space and reducing system costs.

(2) Strong anti-interference ability: Digital signals, compared with analog signals, do not rely on the characteristics of components in the circuit. They have strong noise resistance, greatly reducing the sensitivity of analog circuits to noise. At the same time, they are not affected by the aging and drift of resistance and capacitance values, making them more stable.

3. Design scheme of single-chip microcontroller

3.1. Structure scheme of the hardware system

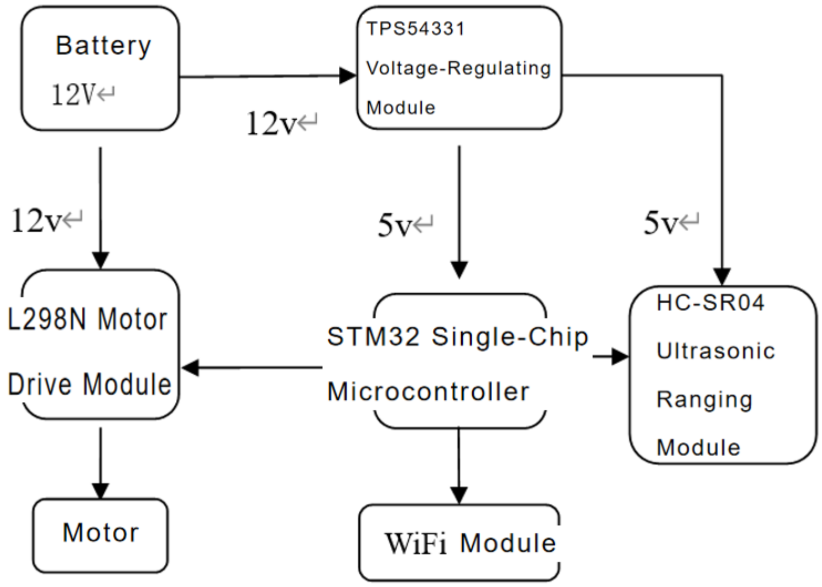

Figure 1. Circuit design framework.

In the overall design framework (**Figure 1**), the battery serves as the main power source. On the one hand, it directly supplies 12V power to the motor drive module. On the other hand, it is regulated to 5V through the TPS54331DR chip to power the STM32F407 single-chip microcontroller and other modules (such as the WiFi module and the ultrasonic ranging module). The STM32F407 single-chip microcontroller minimum system board acts as the main controller, responsible for the control and data processing of the entire system. It is connected to multiple modules, including the WiFi module, the ultrasonic ranging module, and the DC motor drive module. When the single-chip microcontroller receives a signal from the upper computer through the WiFi module, it will modify the high and low-level states of the corresponding IO ports and the PWM signal according to the instructions. In this way, the single-chip microcontroller can accurately control the rotational speed and direction of the DC motor. At the same time, the single-chip microcontroller continuously detects the distance information returned by the ultrasonic ranging module. The ultrasonic ranging module periodically emits ultrasonic waves and receives the reflected waves. By calculating the round-trip time of the waves, it determines the distance to the obstacle. Based on this distance information, the single-chip microcontroller can perceive and judge the surrounding environment. If the single-chip microcontroller needs to report information to the server during the program operation, it will send the relevant data to the upper computer through the WiFi module [7–11].

In the actual circuit design, to improve the integration level and space utilization rate, we integrated the entire system circuit onto a single circuit board and adopted a four-layer board design to further reduce the space occupied by the circuit board.

3.2. Main program of the single-chip microcontroller and ultrasonic ranging

After the single-chip microcontroller is powered on, system initialization is carried out, including the initialization settings of timer interrupts, serial port interrupts, external interrupts, and the initialization configuration of PWM GPIO [12–14]. First, the status of the reception flag bit is judged. If the reception flag bit is “no”, the system enters the corresponding interrupt handling process. If it is “yes”, the received message handling process is executed. When the reception flag bit is “no”: if a serial port interrupt is triggered, the system receives instructions from the WiFi module and modifies the state of motor action according to the instructions. When a timer interrupt is triggered, the system outputs corresponding high- and low-level states and PWM values according to the current state of motor action to control the motor’s operation. When an external interrupt is triggered, the system receives the signal from the ultrasonic module, decodes it, and then sets the reception flag bit to 1, indicating that a signal has been received. When the reception flag bit is “yes”, the system enters the received message handling process. At this time, the system sends the received message to the WiFi module and sets the reception flag bit to 0 in preparation for the next signal reception. The flow chart is as follows [15,16].

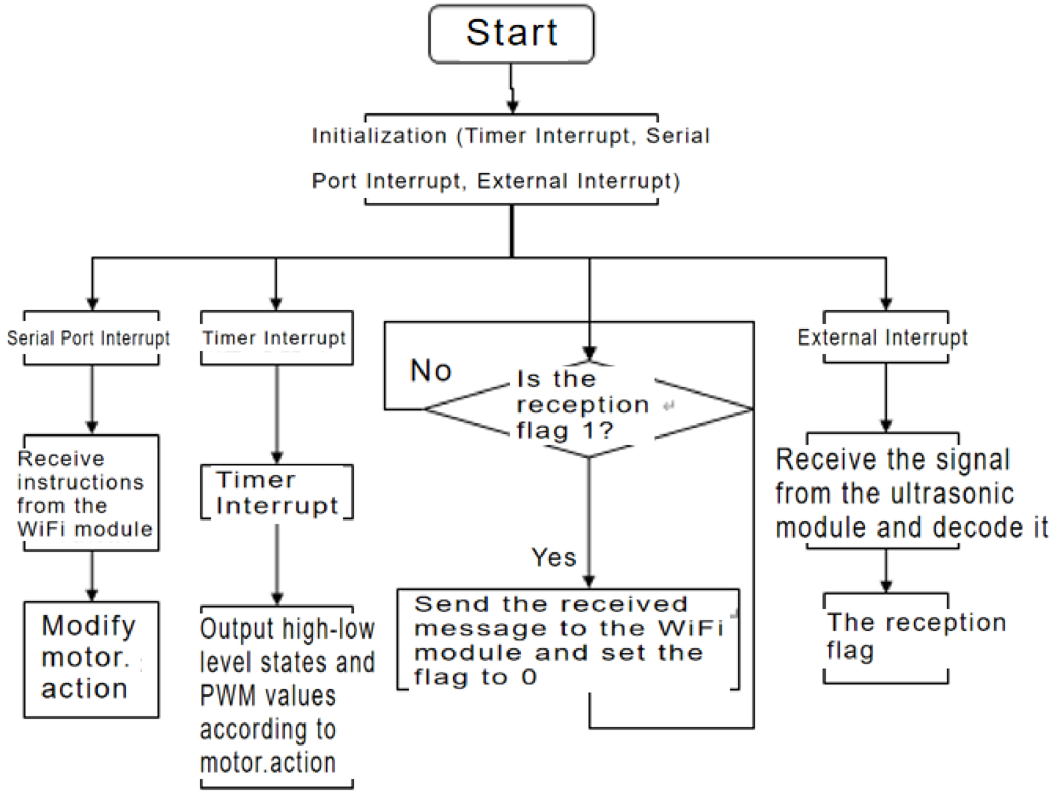

Figure 2. Main program of the single-chip microcontroller.

A high-level signal with a duration of not less than 10 μs is sent through the TRIG pin to trigger the ranging function. The module then automatically emits 8 ultrasonic pulse signals with a frequency of 40 kHz. When the ultrasonic signals encounter a target object and are reflected back to the receiver, the ECHO pin outputs a high-level signal. The duration of this high-level signal starts from the emission of the ultrasonic waves and ends when the reflected signal is received. Based on the propagation speed of sound waves in the air (340 m/s), the distance between the target object and the ranging module can be calculated by calculating the time difference (**Formula 1**). The final ranging result is processed by the system and displayed in real-time on the liquid-crystal display. The ultrasonic program flow is shown in **Figure 3**.

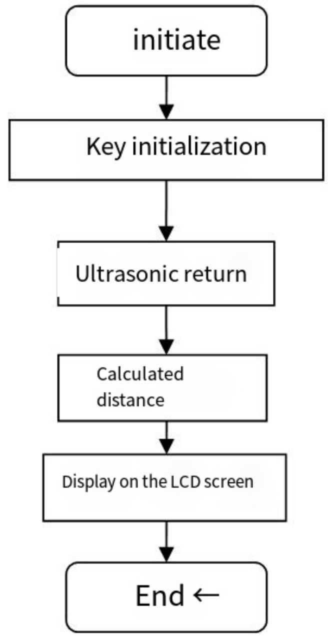

Figure 3. Main program of ultrasonic ranging.

4. System test results and analysis

The study applied the fabricated system to an intelligent vehicle. After connecting the battery, a voltage regulation module test was conducted, and the output voltage was recorded. It was stable at 4.95V. After connecting the single-chip microcontroller, the single-chip microcontroller output high- and low-level signals. According to the magnitude of the PWM on the ENABLE pin, an output of 5V-10V could be detected at the output pins of the L298N, indicating that the DC motor drive part was in good condition. The ultrasonic module was connected (**Figure 4**), and an ultrasonic ranging test was carried out. Black occlusions were placed at different distances, and the distance between the occlusion and the vehicle was calculated through ultrasonic ranging and the data was displayed on the liquid-crystal screen, obtaining relatively accurate data.

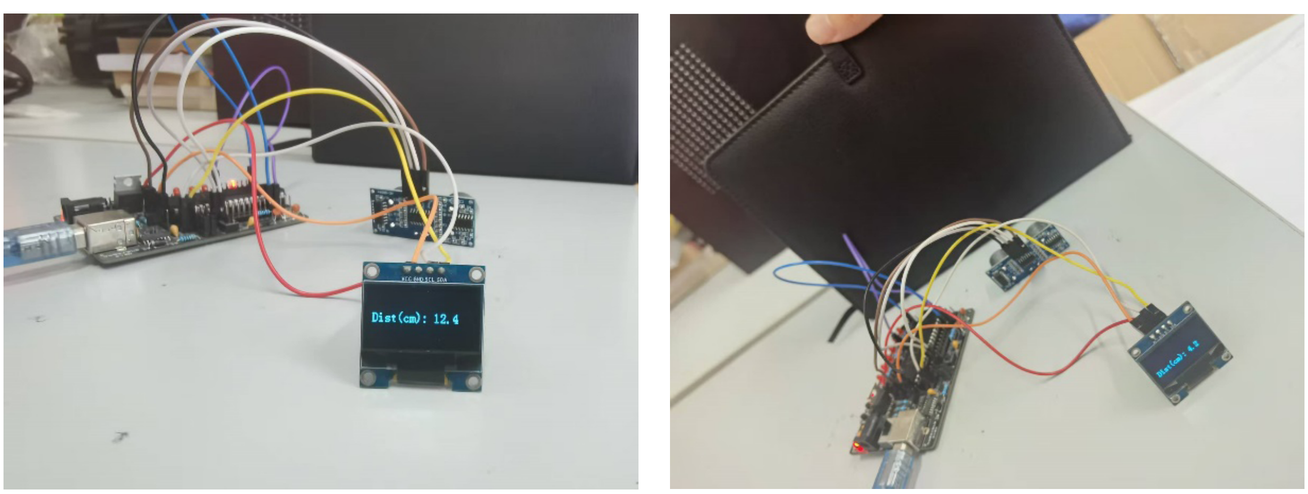

Figure 4. Ultrasonic ranging results.

5. Conclusion

This paper designs and implements an ultrasonic intelligent vehicle system based on a single-chip microcontroller, mainly achieving functions such as power supply voltage regulation, DC motor drive, PWM speed regulation, and ultrasonic ranging. Through the design of the hardware circuit and the development of the software program, the system successfully realized the control of the speed and direction of the DC motor and used the ultrasonic module to achieve obstacle detection and avoidance functions. The entire intelligent vehicle system meets the requirements of low-latency control, has complete functions, and the design of the client and server makes it more user-friendly. In terms of further applications, it enables scene visualization.

Disclosure statement

The author declares no conflict of interest.

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