Design and implementation of an automatic charging system for intelligent patrol robot

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ABSTRACT
This paper is concerned with the design and implementation of an automatic charging system for the intelligent patrol robot. An economic and practical method combined with the infrared sensor and laser sensor is developed to realize the accurate automatic charge docking. The phase-shifted full-bridge ZVS-PWM converter is adopted to design an automatic charging pile, which uses a constant voltage limited current charging mode and improve the efficiency of the charging. Several simulations and experiments are implemented to test the automatic charge docking system, and the results could demonstrate the effectiveness and superiority of the system.

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1. Introduction
With the rapid development of artificial intelligence technology, the intelligent patrol robots have been increasingly widely used in various fields, such as chemical plants, substations and coal mines (Song, Wang, & Sheng, 2016; Song, Wang, & Zou, 2017), to name a few. In the patrol robot system, the design of charging system is a vital problem which has attracted lots of attentions. However, the manual charging method is still widely used in practice, which would subject to several disadvantages, e.g. low degree of intelligence, low efficiency and manual intervention, etc. Hence, a lot of researchers have paid their attentions to the issue of automatic charging, where the development of automatic charge docking methods and the design of charging piles are still two difficult and complicated problems for the charging system of the intelligent patrol robot (Fang, Guo, Li, & Sun, 2011; Wang, Hou, Li, & Zhou, 2017).

Up to now, a lot of methods have been developed for the automatic charge docking of the mobile robot. For instance, the first robot with automatic charging function can be traced back to the robot named Tortoise that is invented by Grey Walter (Silverman, Nies, Jung, and Sukhatme, 2002). By installing a light source at the charging station, the robot with photosensitive components could trace this light source and dock itself on the charging station. In Cassinis, Tampalini, and Bartolini (1999), the visual sensors are used to determine whether the heights of two different light sources are aligned so as to achieve charge docking. In Nourbakhsh et al. (1999), the map of the surrounding environment is exploited to help the robot to locate the charging piles. In Yuta and Hada (1998), CCD and three dimensional road signs are employed to guide the robot to complete the task of charge docking. In Hao and Hong (2005), the laser sensors are used to guide the robot to connect with the charging piles. However, there are several disadvantages in the aforementioned docking methods. For example, the light sources are prone to be affected by the light of external environment especially in the daytime, the electronic map will become invalid when there are some changes in the environment, and the laser sensors are not accurate enough to locate the charging piles. In addition, the design of the charging pile is not only an indispensable part for an automatic charging system, but also a very crucial factor to achieve effective charge docking. Therefore, this paper is concerned with the design and implementation of an automatic charging system for the intelligent patrol robots, where a kind of phase-shifted full-bridge ZVS-PWM converter is adopted to design the charging system and an approach combined with infrared sensor and laser sensor is developed to realize the accurate automatic charge docking of the patrol robots. The main contributions of this paper can be summarized as follows.

(1) An economic and practical method is developed for the automatic charge docking of the intelligent patrol robot. (2)
An automatic charging pile is designed based on the phase-shifted full-bridge ZVS-PWM converter, which could improve the efficiency of the charging. (3) The effectiveness and superiority of the automatic charge docking system are tested and verified by several comprehensive experiments.

The remainder of this paper is outlined as follows. In Section 2, the method for the automatic charge docking is introduced, including the hardware design and the algorithm design. In Section 3, the development of the charging pile is addressed, including the charging mode, ZVS-PWM converter and simulation experiments. In Section 4, several experiments are implemented on the automatic charge docking system to verify its performance. Finally, the paper is concluded in the last section.

2. Automatic charge docking method

2.1. Outline of the intelligent patrol robot

To accomplish the automatic charge docking, an approach combined with infrared sensor and laser sensor is developed in this section. The robot control system concerned in this paper is composed of two controllers, i.e. the main controller and the chassis controller, both of them could communicate with each other by Ethernet bus. The main controller developed based on the iMX6Q is mainly used to run the ROS operating system, which is cooperated with the laser sensors to accomplish the autonomous navigation. The chassis controller developed based on STM32F429 is mainly used for respectively the motion control of the robot, the SOC management of the battery and the signal processing of the sensors, e.g. laser sensor and infrared sensor.

When the SOC of the battery is lower than the required minimum power for the operation of the robot, the chassis controller will send a charging instruction to the main controller, which will then order the chassis controller to drive the robot back to the docking area by using the laser sensor-based autonomous navigation. When the infrared signal from the charging pile is received, an automatic charge docking will be implemented by the chassis controller based on the information of infrared signal. Considering that the autonomous navigation based on the ROS operating system has been extensively studied in recent literatures, we will focus on the analysis and design of the infrared sensor-based automatic charge docking system in the remainder of this section.

2.2. Hardware design

The infrared communication technology has a lot of advantages, such as high cost performance, simple implementation and high transmission rate, so that it is very suitable for the low cost and point to point high speed data transmission in the embedded system. In this paper, the infrared communication system of the intelligent patrol robot is composed of the receiving terminal and the transmitting terminal. The infrared receiving terminal consists of a decoding controller, an infrared receiver and the power supply. The infrared transmitting terminal consists of a coding controller, an infrared emitter, a triode amplifier circuit and the power supply.

To improve the anti-interference performance of the infrared emission, the binary data of the infrared signal are usually modulated by a kind of carrier wave in the practical applications. In this paper, a charging pile controller (STM32F103) is used to modulate the binary data into a 38 kHz carrier wave, which is then sent to the infrared-emitting diode to be converted to the transmitted infrared signal. The transmitted data are composed of 32 bits pulse signal as shown in Figure 1, including the boot code, user code, user anti-code, data code and anti-code, where the data anti-code is used to ensure the correctness of the data coding. Each bit of the data code can be a ‘1’ bit or a ‘0’ bit, which are distinguished by the time interval of the pulse, i.e. the pulse position modulation mode (PPM). In this paper, four infrared transmitters are designed on the charging pile, and their transmitted data are denoted as A, B, C and D, respectively. In the coding of the four groups of data, the user code are the same one and the data codes are different so as to distinguish themselves. For the infrared receiving terminal, the chassis controller (STM32F429) is used as the decoder controller, which is cooperated with four infrared receivers (H50038B) to carry out the infrared decoding process, see Figure 2 for more details.

To make an exact docking of the robot, four infrared receivers are set on the robot chassis, as shown in Figure 3. Meanwhile, an automatic charging interface is also set at the same side of the robot. The charging interface consists of four same copper plates denoted as Power+, Power−, Signal+ and Signal−, as well as an iron plate that could be attracted by the magnet on the charging pile. To handle the inevitable errors of the automatic charge docking system, there are some redundances on the length of the four copper plates to ensure some fault tolerances. For example, the automatic charge docking system allows a docking error of ±5° and ±5 cm.

2.3. Algorithm design

The schematic diagram of the infrared automatic charge docking system has been described in Figure 4. When the robot starts to carry out the automatic charge docking, the four infrared receivers installed on the robot will receive different signals from the infrared emitters if
the robot is at different positions. Thus, the operation of the automatic charge docking could be divided into two steps, i.e. the rough adjustment and the fine adjustment.

In the step of rough adjustment, the robot is driven to turn left or right for the automatic charge docking based on the signals of the four pairs of infrared receivers and emitters. For example, when the receiver \( d \) receives the transmitted signal \( A \), which means that the robot is on the right front side of the charging pile, the chassis controller has to drive the robot to move to the left. On the contrary, the controller will drive the robot to move to the right if the receiver \( a \) receives the transmitted signal \( D \), which means that the robot is on the left front side of the charging pile. When the step of rough adjustment is completed, the receivers \( a \) and \( d \) will receive respectively the transmitted signals \( A \) and \( D \).

In the step of fine adjustment, the robot will resort to the two receivers \( b \) and \( c \) to complete a fine adjustment to ensure the success of automatic charge docking. Similarly, when the receiver \( b \) and \( c \) receive the transmitted signal \( A \) and \( B \) respectively, the robot will be driven to move slightly to the left. Otherwise, when the receiver \( b \) and \( c \) receive the transmitted signal \( C \) and \( D \) respectively, the robot will be driven to move slightly to the right. Finally, the robot will be driven to move straightly to complete the charge docking when the four pairs of infrared transceivers have just face to each other.

When the automatic charge docking has been accomplished, the charging pile will send a high level signal to the robot, and meanwhile, drive an electromagnet to generate a magnetic force to hold the robot so as to prevent the poor contact between the robot and the charging pile. Then, the charging pile will send a low level signal to the robot and cut off the electromagnetic force after the battery is fully charged.
3. Development of the charging pile

3.1. Charging mode of the lithium battery

Nowadays, the lithium battery is the most widely used battery for the patrol robot because of its high energy density, which determines the service life of the robot. Thus, it is important to choose a suitable charging method for the lithium battery. Generally, there are three common used battery charging modes for the lithium battery, including constant current charging, constant voltage charging and constant voltage limited current charging, which are depicted in Figure 5–7.

For the constant current charging mode, the charging current is constant and the charging voltage is variable in the charging process. Contrarily, the charging voltage is constant and the charging current is decreasing for the constant voltage charging mode. These two modes are easy to be implemented and frequently used in the charging of lithium battery. However, these two modes are likely to cause the over-voltage or over-current faults, which would reduce the working life of the battery and increase the potential risk. While, there are two periods for the mode of constant voltage limited current charging. At the beginning of the charging, the charging board recharged the battery with a constant current. When the charging is about to be completed, the battery is turned into a constant voltage limited current charging. Then, the charging pile is automatically closed if the battery is fully charged. Comparatively, the control algorithm of this mode is more complicated than others, but it can increase the working life of the battery and reduce the potential risk. So that, the constant voltage limited current charging mode is adopted in this paper.

3.2. Phase-shifted full-bridge ZVS-PWM converter

In this paper, the phase-shifted full-bridge ZVS-PWM converter is adopted to achieve the constant voltage limited current charging. In the converter, the junction capacitance of the power switches and the leakage inductance of the transformer are used as the resonant elements, so the four power switches of the full-bridge power supply are sequentially tuned on at zero voltage (ZVS) to achieve the constant frequency soft switching, which would improve the overall efficiency and power density of the power supply.

In this paper, the power supply is AC 220V, which will be rectified into a DC voltage $V_{in}$ by a rectifier circuit and then put into a phase-shifted full-bridge circuit. As shown in Figure 8, $Q_1$–$Q_4$ are the four main power switches, $D_1$–$D_4$ are the antiparallel diodes of the main power switches, the transformation ratio of the output transformer is $1:n$, $D_5$ and $D_6$ are the output rectifier diodes, $L_f$ and $C_f$ are respectively the inductance and capacitance of the output filter, $R$ is the load with the output DC voltage $V$. For the phase-shifting control of the switches, the duty cycle of them is 50% and the driving voltages are complementary on the same bridge with a phase difference of $180^\circ$. The output voltage is adjusted by the phase angle,
which is defined as the phase difference of the two arms. To achieve the soft switching, the absorption capacitor can be connected parallel with the switches.

To control the aforementioned converter, the internal reference voltage $U_{ref}(s)$ is compared with the output voltage to generate a voltage error. Then, a PI regulator of the voltage outer loop is used to produce the reference value $i_{ref}(s)$ for the current inner loop. The error between $i_{ref}(s)$ and the output current of the filter inductance is exploited by another PI regulator to achieve the modulation wave of the PWM driven circuit. The structure of the control loops are shown in Figure 9, where $G_i(s)$ and $G_v(s)$ represent the transfer function of the regulator for the current inner loop and the voltage outer loop respectively; $K_i$ and $K_v$ denote the gain of the current and voltage measurement circuits; $K_c$ is the triangular carrier coefficient of PWM, $K_c = 1/U_c$ and $U_c$ is the peak of the triangular carrier; $G_{id}(s)$ stands for the transfer function of the power level of the current loop and $Z_o(s)$ indicates the transfer function of the output load, where the transfer functions of $G_{id}(s)$ and $Z_o(s)$ are expressed as follow:

$$G_{id} = \frac{U_0/n}{s^2L_fC_f \left( 1 + \frac{R_c}{\pi} \right) + s \left[ \frac{L_f}{\pi} + R_cC_f \left( 1 + \frac{R_c}{\pi} \right) \right] + 1 + \frac{R_d}{\pi}},$$

(1)

$$Z_o(s) = \frac{R_cC_fs + 1}{C_f \left( 1 + \frac{R_c}{\pi} \right) s + \frac{1}{\pi}}.$$

(2)

For the voltage and current double closed loop control system, the parameters of the inner loop are firstly designed to obtain a stable inner loop, and then the voltage outer loop is designed based on the transfer function of the current inner loop.

### 3.3. Simulation experiment

It has been verified by several experiments that the voltage of a single node of the lithium battery is 3.7 V and the charging voltage is 4.2 V. Taking into account of the parameters of the load and the working life of the battery, the total normal voltage of the patrol robot is 48 V and the SOC of the battery is 30 Ah. To guarantee the working life of the battery, the maximum charging voltage is 54.6 V and the charging current is limited to 10 A.

To verify the performance of the phase-shifted full-bridge ZVS-PWM converter, which is used to accomplish the constant voltage limited current charging, the simulation experiment is carried out and the simulation model of the charging system with aforementioned parameters is shown in Figure 10, where the voltage and current of the charging pile are controlled by two PI controllers, and the PWM generating circuit and full-bridge circuit are shown respectively in Figures 11 and 12.
Figure 10. Simulation model of the charging system.

Figure 11. Simulation model of the PWM generating circuit.

Figure 12. Simulation model of the Full-bridge circuit.
The outputs of the voltage and current of the charging pile are shown in Figures 13 and 14. In the simulation experiment, the initial SOC is set as a high value to save the simulation time and reflect the process of charging. It is clear that the charging performance is compatible with the mode of constant voltage limited current charging and could satisfy the requirements of the voltage and current for the charging of the lithium battery.

4. Experiments

In this section, several experiments have been implemented to test the automatic charge docking system of the intelligent patrol robot.

In the first experiment, the initial angle between the robot and the charging pile is set as 40°, and the distances between them will vary from 60 to 200 cm with an interval of 20 cm. In the second experiment, the initial distance between the robot and the charging pile is set as 100 cm,
Figure 15. Charging pile of the intelligent patrol robot.

Table 2. Docking with different initial angles.

| Angle (°) | Successful docking | Success rate (%) |
|----------|--------------------|------------------|
| −30      | 49                 | 98               |
| −20      | 49                 | 98               |
| −10      | 50                 | 100              |
| 0        | 50                 | 100              |
| 10       | 50                 | 100              |
| 20       | 50                 | 100              |
| 30       | 48                 | 96               |

Figure 16. Variation of SOC with time.

and the angles between them will vary from −30° to 30° with an interval of 10°. To evaluate the performance of the automatic charge docking system, each of the experiments is repeated 50 times, and their results are listed in Tables 1 and 2. It is clear that all of the experiments could achieve very high success rates in spite of the different initial distances or angles between the robot and the charging pile, which can demonstrate that the automatic charge docking system developed in this paper is effective and robust for the intelligent patrol robot with various initial conditions.

To test the performance of the charging pile as shown in Figure 15, the lithium battery is charged based on the phase-shifted full-bridge ZVS-PWM converter and the SOC data of the lithium battery is recorded. The variation of the SOC is depicted in Figure 16, which could achieve the desired performance of the charging mode.

5. Conclusion

In this paper, the design and implementation of an automatic charging system is investigated for the intelligent patrol robot. An economic and practical method based on the infrared sensor and laser sensor is developed for the automatic charge docking of the intelligent patrol robot. And the phase-shifted full-bridge ZVS-PWM converter is adopted to design the charging system. Several simulations and experiments have been implemented to test and verify the effectiveness of the automatic charging system.

In the future work, we will focus on some more complicated topics of the intelligent patrol robot, e.g. the precise control of the robot, the fault diagnosis of the power electronic switch (Sheng, Zhang, & Gao, 2014; Xu, Song, Zhang, and Xu, 2018; Xu et al., 2018; Zhang, Song, and Zhao, 2017; Zhao, Song, Zhang, & Xu, 2017), etc.

Disclosure statement

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