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*Low-resolution Hall Sensor-based Automatic Assisted Pollination Device for Hybrid Rice**

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Abstract: Auxiliary pollination for hybrid rice seed production is a time-sensitive and labour-intensive task, so exploring efficient auxiliary pollination methods is key to improving the efficiency and quality of rice seed production. In this paper, a low-resolution Hall sensor-based permanent magnet synchronous motor drive system is proposed for the electrification of assisted pollination and the feasibility of the scheme is verified in Matlab/Simulink software. Finally, the software and hardware design of this automatic auxiliary pollination device is completed based on the SC32F5664 platform, and its effectiveness is verified through practical tests to realise the automation of auxiliary pollination. The automatic pollination device can replace manually assisted pollination, which helps to facilitate the automation of the entire seed production process.

1. Introduction

Rice (Oryza sativa L.) is one of the most important dietary staples and feeds more than half of the world's population [1,2]. Since 1973, when China first realized the "three lines" of indica hybrid rice, after years of research and development, the use of rice hybrid advantage has made remarkable achievements [3,4]. As the world's largest rice producer, China also consumes and imports more rice than any other country, meaning that even small changes in China's rice production will strongly affect the global rice market [5]. The high yield of hybrid rice seed production is determined by the high rate of maternal heterosis, and the number of effective pollen available from the parent is the key to determining the high rate of maternal heterosis, because rice self-pollination does not have a beautiful corolla and glumes, pollen grains are small, is a wind-borne flowers, natural way to pollinate hybrid rice is difficult to meet production requirements [6], so rice seed production requires auxiliary pollination, auxiliary pollination is another key to ensure high seed production [7]. To increase seed production and obtain good quality seeds, it is essential that the parent pollen is adequately dispersed and spreads to the stigma of the parent in time to increase the heterozygous fertility of the parent [8,9]. Some studies have shown that assisted pollination during seed production can increase yields by at least about 10% [10]. The flowering period of rice is about 10d, and the daily flowering time is short, about 10:00-12:00 every day. In fine weather, pollination is usually done 3-4 times a day, and each pollination time is 20-30min. Auxiliary pollination for hybrid rice seed production is a time-sensitive and labour-intensive task [11-13], therefore, exploring efficient auxiliary pollination methods is the key to improving the efficiency and quality of rice seed production.

Manual pollination is the traditional pollination technique widely accepted by farmers in Asian countries due to its high feasibility. However, it is very time-consuming and labor-intensive with low efficiency [14]. Moreover, migration to urban areas reduces the supply of rural labour and raises labour costs [15]. Other auxiliary pollination methods, such as spray pollinators, collision pollinators, pneumatic pollinators or agricultural drones, cannot be operated without a human operator and even increase their pollination manpower costs due to operational difficulties. For this reason, the automation of pollination devices is of great importance.

2. Material and Methods

2.1. Rice Auxiliary Pollination Equipment

In this paper, an auxiliary pollination trolley is used instead of a manual traction rope to complete the auxiliary pollination process of rice, as shown in Figure 1.

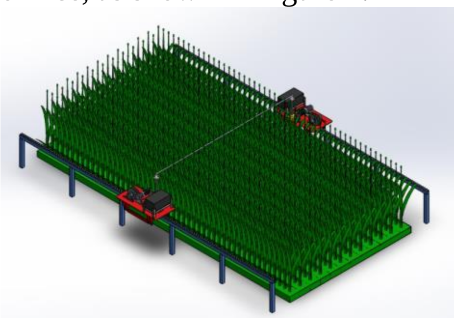

Figure 1: 3D model of assisted pollination process.

2.1.1. Mechanical Hardware Design for Assisted Pollination Trolleys

The mechanical hardware composition of the auxiliary pollination trolley is shown in Figure 2.

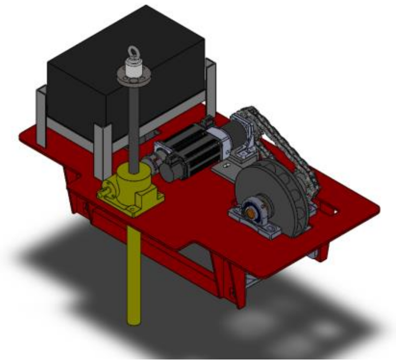

Figure 2: Mechanical hardware components of the auxiliary pollination trolley.

The overall equipment is powered by a lithium battery, which drives two permanent magnet synchronous motors through a permanent magnet synchronous motor drive system. The first permanent magnet synchronous motor has a sprocket fixed to the end of the motor, which is connected to the drive wheel through a chain drive, and the drive wheel rotates on the rack on the track to achieve horizontal operation of the auxiliary pollination trolley on the track; the second permanent magnet synchronous motor is connected to the screw lift through a coupling to achieve vertical movement of the screw, which drives the traction rope connected to the top to lift.

2.1.2. Hardware Design for Permanent Magnet Synchronous Motor Drive Systems

In order to ensure the stability and reliability of the operation of the permanent magnet synchronous motor, the hardware structure of the permanent magnet synchronous motor drive system is designed as shown in Figure 3.

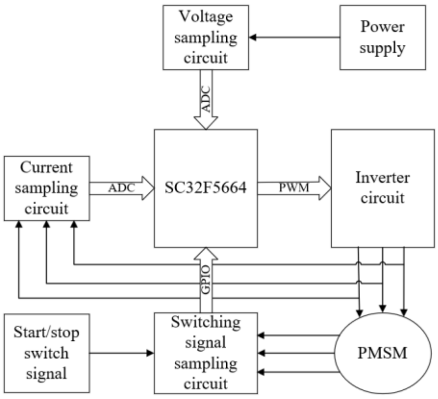

Figure 3: Hardware diagram of the drive system.

2.1.3. Mechanical Hardware Design for Assisted Pollination Trolleys

The main function of the control software is to receive analogue voltage signals such as busbar voltage, busbar current and three-phase current from the sensors via the ADC sampling interface, and after dividing and filtering the conditioning circuit inputs, these signals are reduced to their actual values. The pins are also configured to receive digital switching signals for low-resolution Hall position sensors and tacho sensors.

The main structure of the control software is to regulate the position loop, speed loop and current loop by means of the real-time current received from each sensor and the rotor position interval and speed signal obtained through the Hall sensor, and to output voltage to the quantitative, control system principle as shown in Figure 4.

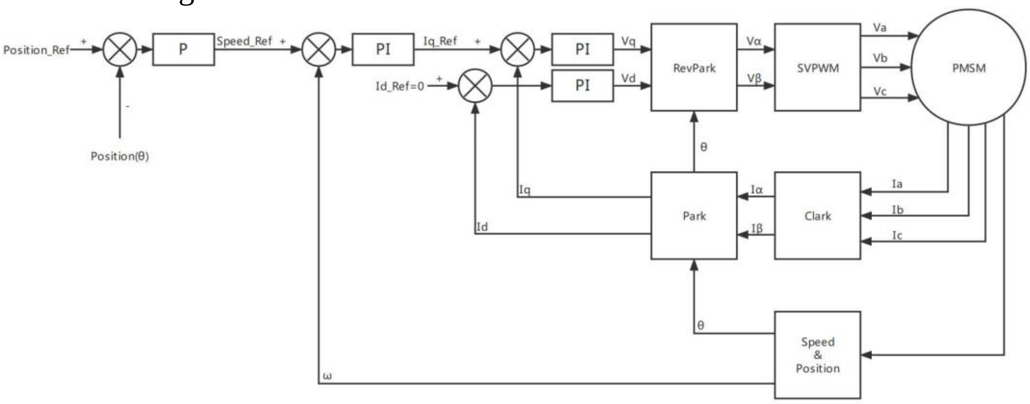

Figure 4: Block diagram of the drive system control software.

2.2. Low Resolution Position Sensor Algorithm

The implementation of vector control algorithms requires real-time rotor position and speed information, and the accuracy of the rotor position detection determines the performance of the vector control algorithm to a certain extent. Therefore, accurate detection of the motor rotor position is essential. In the current motor rotor position detection, rotor position detection devices with high resolution such as optical encoders and resolvers are generally used. However, these position detection devices are not only expensive, but also have high requirements for the working environment. When the operating environment of the auxiliary pollination trolley is harsh, the work of these devices may be seriously affected, reducing the adaptability and reliability of the auxiliary pollination trolley for a variety of environments. In addition, additional signal conditioning circuits and corresponding decoding circuits are required to achieve a more stable transmission of speed information. These circuits add a degree of complexity to the circuit design and are not conducive to reducing the size of the motor controller. In order to reduce the cost of PMSM control systems and to obtain accurate speed and rotor position information, low-cost, low-resolution Hall position sensors are often used to achieve efficient and reliable rotor position estimation.

2.2.1. Hall Switch Position Signal Analysis

When using switching Hall position sensors for rotor position estimation, there are three types of sensors depending on their number: single switching, two-phase quadrature switching and three-phase symmetrical switching. Obviously, the greater the number of Hall position sensors, the higher the estimation accuracy. In this paper, three Hall position sensors are used to detect the rotor position of the PMSM, which theoretically gives a high accuracy position signal, especially during the start-up phase when speed fluctuations are obvious.

The mounting of Hall sensors based on three-phase symmetrical switching is either 60 ° mounting or 120 ° mounting. In this paper, Hall sensors are mounted at 120 ° intervals. This is the most common and effective method of low-resolution position sensing, where three switching Hall sensors are mounted at suitable locations on the PMSM stator to detect the rotor position. As shown in Figure 5, Ha, Hb and Hc are the three switching Hall sensors.

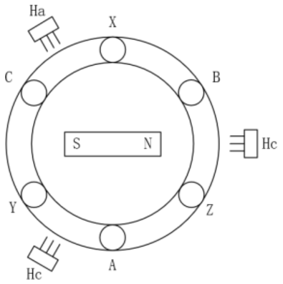

Figure 5: Installation diagram for Hall position sensors.

After the motor rotor has rotated for one week, the Hall position sensor outputs three Hall signals h_a, h_b and h_c, which are square wave signals with a phase difference of 120 °and an effective position angle of 180 °, these signals divide an electrical cycle into six 60 °intervals on average, and the position corresponding to the jumping edges (rising and falling edges) of the Hall signals is the starting position of each interval, which can be obtained by using the This can be obtained by capturing the edges, as shown in Figure 6.

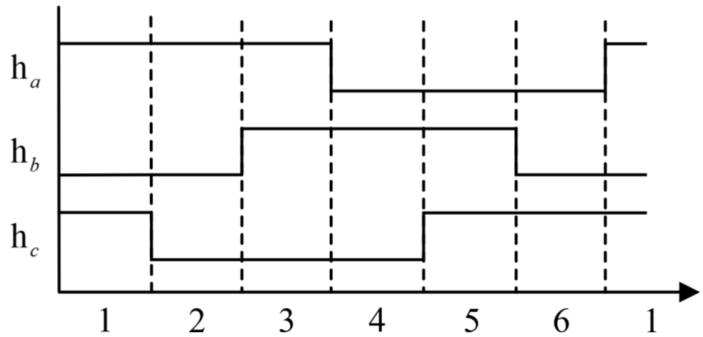

Figure 6: Diagram corresponding to Hall switch position signal and Hall interval.

The combination of the output Hall signals shows that there are a total of 8 position signals, of which 6 are valid non-zero signals and the other 2 are invalid signals. By detecting the state of the Hall interval, the direction of rotation of the motor can be determined. The relationship between the Hall switch position signal and the rotor position when the motor is in forward rotation is shown in Table 1.

Table 1: Hall switch signal in relation to rotor position.

Interval	Hall switch signals $h_a h_b h_c$	Range of intervals
1	101	270 ~330 °
2	100	-30 ~30 °
3	110	30 ~90 °
4	010	90 ~150 °
5	011	150 ~210 °
6	001	210 ~270 °

As can be seen from the table above, by detecting the state of the Hall interval, the current Hall interval of the rotor can be determined in real time and accurately. When the Hall signal jumps, the time interval between the adjacent jump edges of the three Hall signals is detected and the average rotor speed in the interval is calculated. As the motor rotor continues to rotate, a new position value is obtained when the next interval is reached, and this value can be used as the starting position for the current interval, and can also be used to correct the rotor position for the current Hall interval.

2.2.2. Hall Switch Position Signal Analysis

With low-resolution position sensors only 6 discrete position signals can be obtained, which cannot be better implemented for vector control. Therefore, linearisation of the discrete position signals is the key to low-resolution position sensor technology.

When the Hall sensor detects that the rotor pole is running into a new interval, its rotor electrical angle $\theta(t)$ is

$$\theta(t) = \int_{t_k}^{t} \omega(t)dt + \theta_k \tag{1}$$

Where $\omega(t)$ is the instantaneous angular velocity of the motor in the current interval; t_k is the moment when the motor rotor enters the kth (k = 1,2,3,4,5,6) interval; and θ_k is the initial angle of the rotor in the kth Hall interval.

In order to meet the requirements of PMSM vector control, combined with the relationship between motor speed and rotor angle, the (1) is expanded using Taylor's formula, which is given by

$$\theta(t) = \theta_k + \frac{d\theta}{dy}(t - t_k) + \frac{1}{2!}\cdot\frac{d^2 t}{dt^2}(t - t_k)^2 + \cdots \tag{2}$$

If the order in the above equation is higher, the more accurate the result of its rotor position estimation, but it will add a large amount of calculation and is more difficult to implement specifically. Therefore in this paper the first two terms of the above equation are taken to obtain the basic formula for the zero-order algorithm to be analysed next.

2.2.3. Zero-order Algorithms

Considering that the electrical time constant of the PMSM is much smaller than the mechanical time constant, the PMSM is considered to run at a constant speed or with little variation in speed during one Hall interval and the motor speed is considered to have similarly little variation in speed during adjacent Hall intervals. Based on this, the average speed of the previous Hall interval is used in the estimation of the motor speed and rotor angle for the current interval of the rotor.

From the characteristics of the Hall switch position signal, the average speed of the rotor during this interval is calculated by detecting the time interval between the jumping edges of the three Hall signals, which is given by

$$\omega = \frac{\pi / 3}{\Delta t} \tag{3}$$

Where ω is the average speed of the motor rotor during this Hall interval and Δt is the rotation time of the motor rotor during the interval.

The estimation principle of the zero-order algorithm is shown in Figure 7, assuming that the motor rotor runs to a certain position in the interval k.

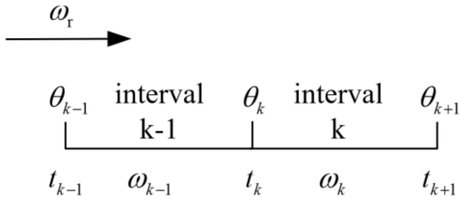

Figure 7: Schematic representation of the estimation of the zero-order algorithm.

Based on the previous assumptions, the relevant formula is as follows

$$\begin{cases} \omega_{k-1} = \dfrac{\pi / 3}{\Delta t} = \dfrac{\pi / 3}{t_k - t_{k-1}} \\ \theta = \theta_k + \omega_{k-1} \Delta T \\ \theta_k \le \theta \le \theta_{k+1} \end{cases} \tag{4}$$

where ω_{k-1} is the average speed of the motor rotor in interval k-1, t_{k-1} and ω_k are the start and end moments of the rotor in interval k-1 respectively, θ is the rotor position in the current interval, ΔT is the rotor rotation time in interval k, and θ_k and θ_{k+1} are the boundaries of the current Hall interval used to come to correct the rotor position, i.e. the forced correction angle.

3. Results

3.1. Simulation Analysis

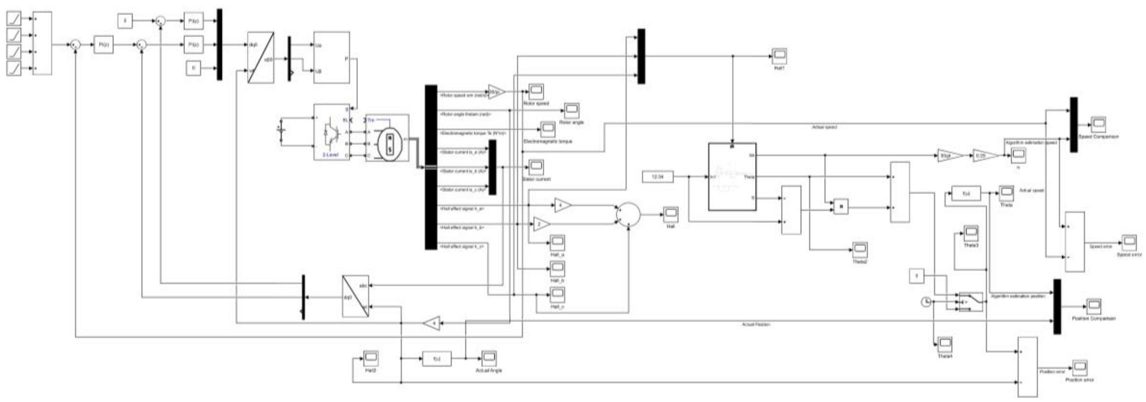

Figure 8: PMSM simulation model.

In order to verify the correctness and effectiveness of the three rotor position estimation algorithms based on Hall interval time detection, a simulation model of convex-polar PMSM vector control was built in Matlab/Simulink software, using a control strategy with $i_d = 0$. The motor speed and rotor position induced by the measurement port of the motor simulation model were used as actual values and compared with the estimated values, as shown in Figure 8 shows.

In order to make the rice auxiliary pollination equipment simulate manual auxiliary pollination, we set its speed to 0.5m/s. According to the designed mechanical transmission ratio, the speed of the motor can be obtained that is 490rpm, using this speed as the maximum speed to simulate this system, and obtain the speed, position tracking curve and its error curve as shown in Figure 9 and Figure 10.

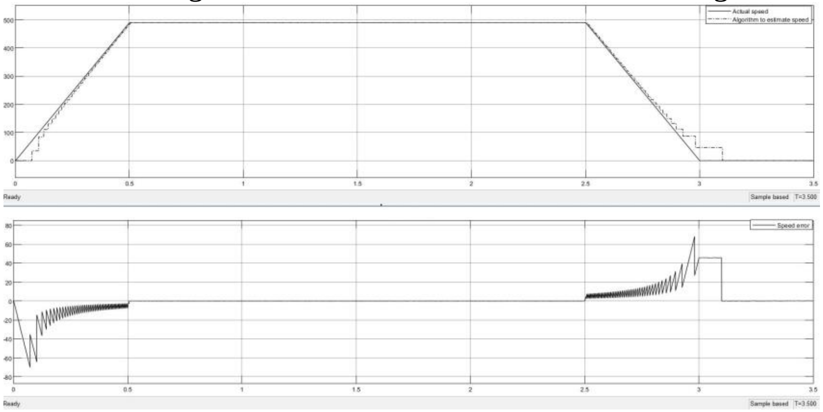

Figure 9: Speed tracking curves and error curves.

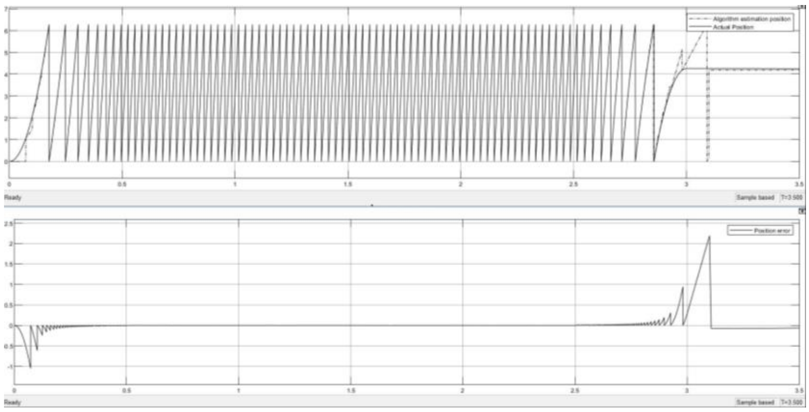

Figure 10: Position tracking curves and error curves.

From Figure 9 it can be seen that during the zero speed start of the motor, the estimated speed during the first Hall interval of motor operation is basically 0. The estimated speed rises in steps, with a maximum error of -69.55r/min during the speed rise, and its speed fluctuates slightly after reaching a steady state. The maximum error in rotor position is approximately 1.05rad as can be seen in Figure 10, which drops to 0.58rad in the second Hall interval and decreases as the motor rotates to almost zero at 0.372s. At the moment the motor stops, the Hall interval never changes and therefore the speed and position deduced from the algorithm are incorrect, so a threshold of 100ms is given in the program and when the Hall interval does not change for 100ms, the motor is considered to have stopped completely.

3.2. Test Analysis

To verify the feasibility of this rice assisted pollination device, it was tested in a rice trial field where assisted pollination was required, as shown in Figure 11.

Figure 11: PMSM simulation model.

In order to facilitate the control and monitoring of the rice auxiliary pollination equipment, the system connects the equipment to the IoT platform, where the control and data monitoring is shown in Figure 12 and the video monitoring is shown in Figure 13.

Figure 12: IoT platform control and data monitoring.

Figure 13: IoT platform video surveillance.

Through the test, the rice auxiliary pollination equipment can operate according to the design requirements, and its starting as well as stopping process are close to the uniform acceleration and deceleration motion with constant acceleration. In order to avoid the overcurrent situation when the motor is zero-started and stopped sharply, the acceleration and deceleration process is about 500ms, and the final system operating bus voltage, bus current and motor speed are shown in Figure 14.

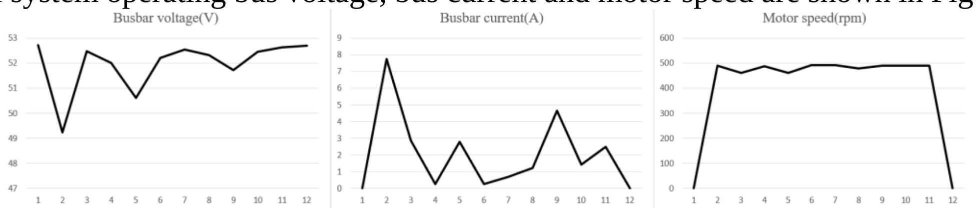

Figure 14: System operating busbar voltage, busbar current and motor speed.

Finally, comparing the actual auxiliary pollination effect of the auxiliary pollination equipment with the manual pollination effect, it can be found that the actual effect can fully meet the actual effect of manual auxiliary pollination because the auxiliary pollination equipment has a more uniform auxiliary pollination speed and strength compared with manual pollination.

4. Conclusion

Auxiliary pollination for hybrid rice seed production is a time-sensitive and labour-intensive task, so exploring efficient auxiliary pollination methods is key to improving the efficiency and quality of rice seed production. This paper presents a low-resolution Hall sensor-based automatic assisted pollination device for hybrid rice, the practical effect of which can replace manual assisted pollination. Because of its use of IoT technology, it has a low barrier to operation, can be operated from a mobile phone or computer, has start and end buttons for assisted pollination and can be monitored on the IoT platform or via a camera, so the process requires little human involvement.

At present, this automatic pollination aid has its shortcomings. For example, rice flowers from approximately 10:00-12:00 each day and the timing of flowering is dependent on a number of factors, so the device still requires human intervention to determine the right time for assisted pollination. If you go by the operator's experience, you may have reduced rice yields because the timing of the assisted pollination was not optimal. If you artificially go to the rice field to observe the flowering before deciding on the timing of the assisted pollination, you are again wasting manpower and not truly automating the process.

Subsequently, if a clearer camera can be installed so that the state of flowering of the rice can be observed via the IoT platform and the timing of the assisted pollination can be decided, then perfect automation can be achieved. If this is combined with artificial intelligence and other technologies, the IoT platform can be used to predict the time of flowering through weather and other conditions, or to independently determine the time of assisted pollination through high-definition cameras that capture the flowering state of the rice, i.e. to achieve assisted pollination intelligence.

Acknowledgment

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