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Design of 4UM-120D Electric Leafy Vegetable Harvester Cutter Height off the Ground Automatic Control System Based on Incremental PID

Wenming Chen [1,2], Lianglong Hu [1,*], Gongpu Wang [1], Jianning Yuan [2], Guocheng Bao [3], Haiyang Shen [1], Wen Wu [1,2] and Zicheng Yin [1]

[1] Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China; chenwenming199806@163.com (W.C.); wanggongpu37@163.com (G.W.); 82101221060@caas.cn (H.S.); zwnthyx@163.com (Z.Y.)
[2] Nanjing Institute of Technology, Nanjing 211167, China; jnyuan961@126.com
[3] China Academy of Agricultural Mechanization Sciences Group Co., Ltd., Beijing 100083, China; 82101196209@caas.com
* Correspondence: hurxbb@163.com; Tel.: +86-153-660-92972

Abstract: In this study, a 4UM-120D electric leafy vegetable harvester was employed as the research object. An automatic control system was created to maintain the cutter's height above the ground within ±2% of the desired value. The intention was to reduce the operators' work intensity while improving the leafy vegetable harvester's working quality. The automatic control system for the cutter height from the ground was explained, along with its structure and operating philosophy. MATLAB was used to establish the two-phase hybrid stepper motor's mathematical electrical equation and mechanical equation models. An analysis was carried out on the fundamentals and differences between position PID and incremental PID control algorithms. Utilizing incremental PID in combination, the control strategy for the harvester cutter height from the ground was built, and an automatic control system was produced under the corresponding control strategy. The stability, accuracy, and rapidity of the automatic control system of the cutter height from the ground under the incremental PID control strategy were analyzed by simulating different actual working conditions with MATLAB/Simulink and taking the steady-state transition time as the evaluation index. The test results show that when the deviation between the current value and the set value was greater than 2%—that is, when the harvester was in the condition of suddenly crossing the ditch or suddenly climbing the slope—the automatic control system based on the incremental PID control strategy had a good dynamic response performance and stability. This resulted in the automatic control function of the harvester cutter height off the ground being achieved. When the rotation angle PID control algorithm's proportional coefficient is Kp = 4.665, the rotation speed PID control algorithm's proportional coefficient is Kp = 5.65 and its integral coefficient is Ki = 3.86, and the current PID control algorithm's proportional coefficient is Kp = 0.5455 and its integral coefficient is Ki = 30.4578. The harvester abruptly crossed a ditch while operating steadily, and the automatic control system's steady-state transition time for the height of the cutter off the ground was 1.0811 s. The harvester abruptly climbed a slope while operating steadily, and the automatic control system's steady-state transition time for the height of the cutter off the ground was 1.1185 s. Data from the field tests revealed a degree of reliability in the simulation test results. The study offered a strategy for raising the harvester quality for leafy vegetables while lowering the operator workload.

Keywords: leafy vegetable harvester; height of cutter from the ground; automatic control system; incremental PID control strategy; design

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1. Introduction

China has the widest range and greatest variety of vegetable planting in the world, and its output accounts for nearly 50% of global production [1–3]. According to the Ministry of

Agriculture and Rural Affairs' estimates for 2023, the national vegetable-producing area would be 22.375 million hectares, yielding a total of 787 million tons. With a short growing cycle and a highly labor-intensive harvesting process, leaf vegetables are a type of vegetable that often uses fresh and sensitive leaves, petioles, and stems as edible portions [4]. The collection of leafy vegetables is primarily carried out manually [5] because of the broad diversity of leafy vegetables that are cultivated in China as well as the clear disparities between planting densities, planting modes, and growth characteristics of various leafy vegetables. The picking of leafy vegetables is a labor-intensive sector due to the ongoing fall in the number of rural workers. Accelerating the development of harvesting equipment for leafy vegetables and realizing the mechanized and intelligent harvesting of leafy vegetables are crucial to lowering the cost of producing leafy vegetables, lowering labor intensity, and fostering the growth of the leafy vegetable harvesting industry [6].

There have been many leafy vegetable harvesters used recently, but the level of intelligent technology is not very high and there have been many operational issues [7]. The majority of domestic leafy vegetable harvesters are currently unable to automatically adjust the height of the cutting blade from the ground according to the height of the ridge surface (border surface), so they must instead manually adjust it based on the height of the leafy vegetables' stubble before harvesting. The quality of the leafy vegetable harvest will be impacted if the height of the ridge surface (boundary surface) changes, which would result in varied leafy vegetable stubble heights. Regardless of how high or low the cutter is above the ground, the operators' professionalism during the actual operation process is typically inadequate, making it difficult to keep the leafy vegetable harvester in a stable operational state for an extended period. The intensity of the operators' labor as a result and the quality of the harvest of leafy vegetables are both significantly impacted.

In developed nations, research on the height adjustment device for leaf vegetable harvester cutters from the ground has already begun. These countries have also substantially improved the mechanization of this equipment through the use of sensors, machine vision, and automatic control technology [6,8]. A leafy vegetable harvester was created by Ortomec Agricultural Equipment Co., Ltd., Italy. It primarily consists of a cutting device, conveying device, automated cutting height adjustment device, and gathering device [9]. A photoelectric sensor-based automatic cutting height adjustment mechanism is used. The cutting blade's real height above the ground is determined by the photoelectric sensor, which outputs a pulse signal under that measurement. The primary controller receives the output pulse signal and manages the mechanism that automatically adjusts the cutting blade's height above the ground. However, this device uses a diesel engine [10], which will pollute the atmosphere in some ways. According to Figure 1, the hydraulic auxiliary steering and electric interim stop device are features of the SLIDE FW leaf vegetable harvester created by HORTECH, Italy. Following a brief stop and recovery, the machine can resume walking at the same pace. A hydraulic control device can autonomously adjust the cutting height after being detected by sensors [11]. In China, harvesting equipment for green vegetables has advanced significantly in recent years [12–15], and the sophistication of intelligent technology has also risen somewhat. Jian Zhang and colleagues developed a control system that measures the height of the cutting tool above the ground using ultrasonic sensors and inputs the detection signal to the main controller to automatically manage that height. The appropriate amount of pulse signals is output after being processed by the main controller. The DC motor, electric hydraulic cylinder, and other actuators are controlled to automatically vary the height of the cutting device from the ground to guarantee that it is always within $\pm5\%$ of the preset figure. To correspond with the actual height of the ground for growing green vegetables, the system can automatically adjust the height of the harvester's cutting tool [16]. A machine-vision-based system was developed by Yuanyuan Wu et al. to collect information on the header height and navigational parameters of leafy vegetable harvesters in order to further the harvesters' technological intelligence. A long time and high price are the drawbacks, making them unsuitable for widespread application and promotion [17]. The 4UGS2 double-row sweet potato harvester was created by Tao Li et al.

and is depicted in Figure 2. An automatic depth control system on this machine is installed. The digging depth of the digging shovel can be automatically modified during the harvest of sweet potatoes depending on the real conditions of the ridge surface [18].

Figure 1. SLIDE FW leafy vegetable harvester.

Figure 2. 4UGS2-type double-row sweet potato harvester.

Yang Long created closed-loop pressure control by integrating pressure control architecture with the position-based PID control algorithm. MATLAB simulation confirmed that the design achieved the desired control aim, but its control effect is only applicable to pressure control circumstances with less stringent accuracy requirements [19]. Tan Baocheng et al. proposed a new incremental PID control approach by enhancing and optimizing the traditional incremental PID control algorithm in order to assure the safe and dependable driving of autonomous cars along a predetermined course. Experimental findings show that the new incremental PID control technique reduces the unmanned vehicle's route tracking rise time and adjustment time, increases response speed, reduces overshoot, and results in quick and stable path tracking [20]. Xiao Wenjian et al. described the procedure for using an incremental PID control algorithm to steer an intelligent vehicle. The experiment shows that using an incremental PID control method enhances the cart's stability and speed as well as the responsiveness and speed of the intelligent vehicle servo [21].

The 4UM-120D electric leafy vegetable harvester served as the research subject for this study, which aimed to develop an automatic control system for the height of the cutter above the ground so that it is always within ±2% of the predetermined value. First, the structure and operation of the automatic control system for the cutter's height above the ground are described. The two-phase hybrid stepper motor's mathematical electrical equation and mechanical equation models were then created in MATLAB. The principle and difference between the position PID and the incremental PID control strategy were analyzed. The incremental PID was used to establish the control strategy of the harvester cutter height off the ground. The automatic control system of the harvester cutter height off the ground under the corresponding control strategy was built. Finally, in order to conduct simulation testing and field tests, MATLAB/Simulink was utilized to model various real-world operating circumstances. The stability, accuracy, and rapidity of the automatic control system of cutter height off the ground under the incremental PID control method were examined using the steady-state transition time as the evaluation index.

2. Materials and Methods

2.1. Machine Structure and Working Principle

2.1.1. Machine Structure and Technical Parameters

The main components of the newly created 4UM-120D electric leaf vegetable harvester are the cutting mechanism, reel mechanism, cutter height adjustment device, conveying mechanism, control box, 48 V lithium battery, differential, reducer, travel drive motor, control panel, gear switch knob, brake knob, wheel, etc. Its basic layout is shown in Figure 3. The parts of the cutter height adjustment device are slide rails and electric push rods. The main structural and technical information about the machine is shown in Table 1.

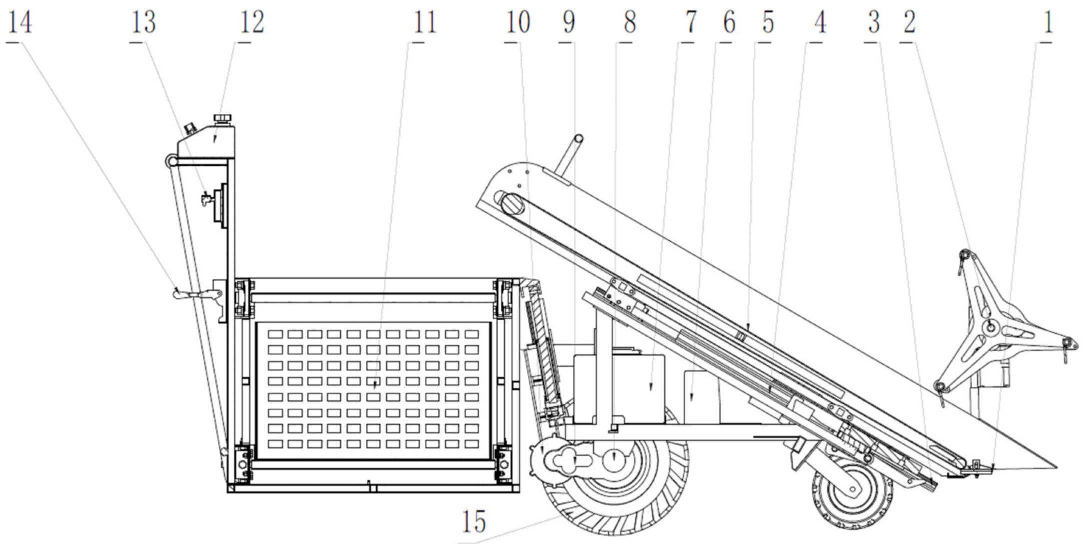

Figure 3. Sketch of the structure of the 4UM-120D electric leafy vegetable harvester. 1. Reciprocating double-acting cutter 2. Reeling mechanism 3. Slide rail 4. Electric push rod 5. Conveyor mechanism 6. Control box 7. Forty-eight-volt lithium battery 8. Differential 9. Reducer 10. Traveling drive motor 11. Collection basket 12. Control panel 13. Gear shift knob 14. Brake knob 15. Wheel.

Table 1. Technical and structural specifications for the 4UM-120D electric leafy vegetable harvester.

Parameters	Values
Whole machine size (length × width × height)/(mm × mm × mm)	2180 × 1500 × 1200
Battery capacity/Ah	50
Working width/mm	1200
Cutter height adjustment range/mm	0~100
Conveyor belt width/mm	1200
Conveyor belt installation inclination/°	30
Wheelbase/mm	550
Wheel radius/mm	175
Minimum ground clearance/mm	70
Productivity/hm^2/h	0.04~0.08

2.1.2. Working Principle

In order to cut at a precise pace, the reciprocating double-acting cutter was powered by a DC brushless motor when the electric leafy vegetable harvester was in operation. The device for height adjustment allowed the cutter's height from the ground to be changed to a range that was reasonable for the height of leafy vegetable stubble. The chopped green vegetable was first moved from the reel to the conveying mechanism, which, in turn, delivered to the rear outlet, before the collecting basket was used to cover the outlet and complete the collection operation.

2.2. Composition and Control principle of an Automatic Control System for Cutter Height from the Ground

2.2.1. Composition of an Automatic Control System for Cutter Height from the Ground

Based on the invented 4UM-120D electric leafy vegetable harvester, the automatic control system of cutter height from the ground was made up of a touch screen, a photoelectric sensor, PLC, stepper motor and its driver, ball screw device, proximity switch, etc., as shown in Figure 4.

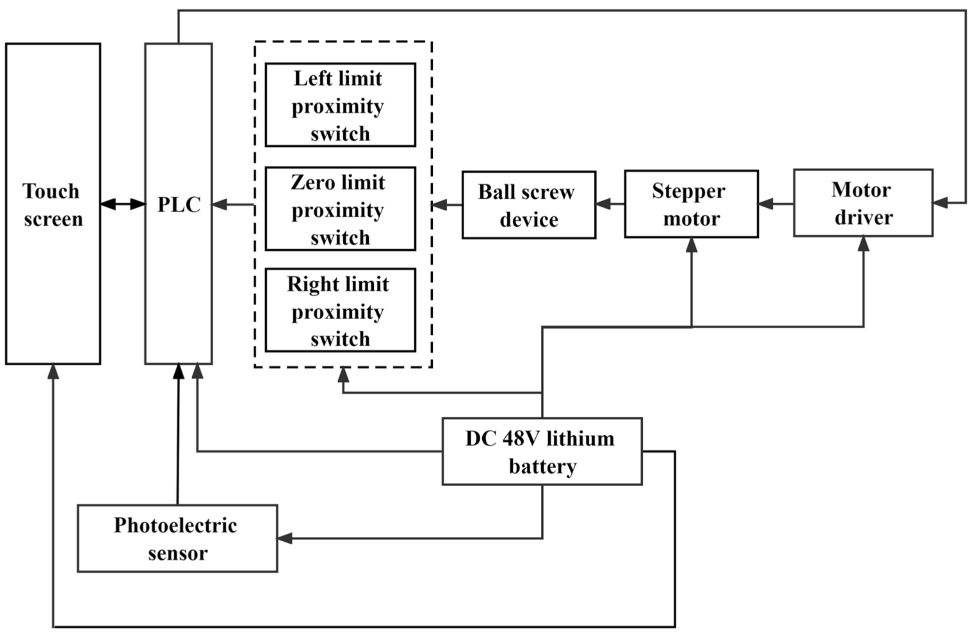

Figure 4. Automatic adjustment system of cutter height from the ground.

2.2.2. Control Principle

The system program flow chart is shown in Figure 5, and it largely completes the functions of measuring, showing, and regulating the cutter height above the ground. The setting value for the height of the cutting blade above the ground (stubble height of leafy vegetables) is determined by the type of leafy vegetable. When harvesting the same type of leafy vegetable, the setting value for the height of the cutting blade above the ground remains unchanged. The zero limit proximity switch was set as the first reference point, the setting value for green vegetable stubble height was entered into the touch screen, and then the first parameter search was initiated. The slider in the ball screw device would not move at this time if the distance-measuring photoelectric sensor determined that the height of the cutting blade from the ground was always within ±2% of the set leafy vegetable stubble height, i.e., the leafy vegetable harvester did not have the phenomenon of ditch crossing or slope climbing. When the photoelectric sensor determined that the height of the cutting blade from the ground was less than 98% of the predetermined height of the leafy vegetable stubble, the leafy vegetable harvester entered the climbing condition, and the PLC calculated the difference between the current value of the cutting blade from the ground and the predetermined value to obtain the deviation and calculated the number and frequency of pulse signals that the stepper motor driver should receive through the control strategy. Thus, the stepper motor was rotated to drive the lead screw device to adjust the height of the cutter from the ground at a specific speed. When the height of the cutter from the ground was within ±2% of the preset stubble height of leafy vegetables, the stepper motor stopped rotating. Additionally, when the stepper motor rotated to adjust the height of the cutter from the ground, if the left limit switch was on, the stepper motor also stopped rotating to prevent the slide block from hitting the stepper motor and causing motor damage. Thus, the automatic control of the height of the cutter from the ground when climbing was realized. The leafy vegetable harvester was in the situation of a ditch crossing when the photoelectric sensor determined that the height of the cutting blade from the ground was greater than 102% of the predetermined height of the leafy vegetable stubble. The PLC determined the deviation by calculating the difference between the cutting blade's current value and its set value from the ground. It then determined how frequently the stepper motor driver should receive pulse signals, as well as the amount of pulse signals, through the control strategy. Consequently, the stepper motor was driven to move the slider at the appropriate speed to change the height of the cutter from the ground. When the height of the cutter from the ground was within ±2% of the preset stubble height of leafy vegetables, the stepper motor stopped rotating. Additionally, when the stepper motor rotated to adjust the height of the cutter from the ground, if the right limit switch was on, the stepper motor also stopped rotating to prevent the cutter from being damaged by touching the ground due to the low height of the cutter from the ground. Thus, the automatic control of the height of the cutter from the ground when crossing a ditch was realized.

2.3. Model of Cutter Height from the Ground Adjustment System

2.3.1. Cutter Height from the Ground Adjustment Motor Model

A two-phase hybrid stepper motor was utilized to adjust the cutter height above the ground on the 4UM-120D electric leaf vegetable harvester. This motor's rotation angle and speed could be changed by altering the quantity and frequency of pulse signals received by the stepper motor driver. As a result, the two-phase hybrid stepper motor mathematical model was developed [22]. Consider as an example a two-phase permanent magnet hybrid stepper motor [23] and assume that: (1) hysteresis and eddy current effects were not taken into consideration; (2) only the average component and fundamental component of air gap permeability were taken into consideration; and (3) the mutual inductance between two phase windings was ignored [24–26]. Equation (1) depicts the voltage balance equation of the phase a winding of the two-phase hybrid stepper motor. Equation (2) depicts the equivalent circuit expression of the phase a winding. Equation (3) depicts the phase a winding's back electromotive force u_a. Equation (4) depicts the electromagnetic torque of the two-phase hybrid stepper motor.

$$U_a(t) = R_a I_a(t) + \frac{dL_s I_a(t)}{dt} \quad (1)$$

$$U_a(t) = R_a I_a(t) + L_s(\theta)\frac{dI_a(t)}{dt} + I_a(t)\frac{\partial L_s(\theta)}{\partial \theta}\frac{d\theta}{dt} \quad (2)$$

$$u_a(\theta) = -p\Psi_m \sin(p\theta)\frac{d\theta}{dt} \quad (3)$$

$$T_e = -p\Psi_m\left[I_a(t)\sin(p\theta) - I_b(t)\sin\left(p\theta - \frac{\pi}{2}\right)\right] - T_{dm}\sin(2p\theta) \quad (4)$$

where U_a is the winding voltage of motor stator phase a(V); R_a is the resistance of phase a winding of motor stator (Ω); I_a is the phase a winding current of motor stator (A); I_b is the phase b winding current of motor stator (A); L_s is self-induction (H); θ is mechanical position angle (rad); u_a is the back electromotive force of phase a winding of motor stator (V); p is the number of magnetic pole teeth; Ψ_m is the maximum magnetic flux of the motor (Wb); T_e is the electromagnetic torque (N·m); T_{dm} is the detent torque (N·m).

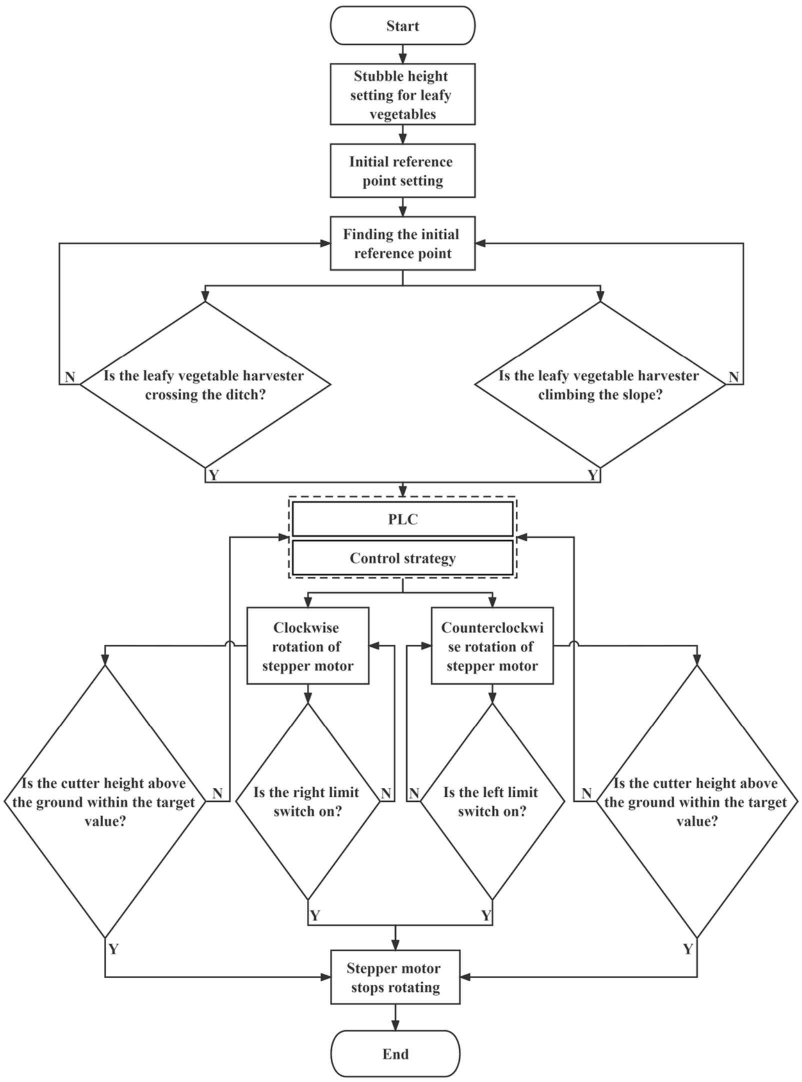

Figure 5. Flow chart of the automatic adjustment program of the cutter height off the ground.

The two-phase hybrid stepper motor's mechanical dynamics equation is displayed in Equation (5).

$$\begin{cases} T_e = J\frac{d\omega}{dt} + B\omega + T_L \\ \omega = \frac{d\theta}{dt} \end{cases} \quad (5)$$

where J is the total rotational inertia of motor body and load (kg·m^2); ω is the motor angular speed (rad/s); B is the viscous friction coefficient of motor body and load (N·m·s); T_L is the load torque (N·m).

2.3.2. Drive System Model

A motor driver, stepper motor, screw rod, slider, cutter, etc., make up the driving system for the system that allows the cutter height to be adjusted from the ground. Stepper motor–screw rod–cutter make up the drive path. The following is the transfer function between the cutter adjustment height and the stepper motor's rotation angle:

$$G_1(s) = \frac{l(s)}{\theta(s)} = \frac{\frac{1}{2}L_{slider}}{\frac{6.28L_{slider}}{L_{pitch}}} = \frac{L_{pitch}}{12.56} \quad (6)$$

where G_1(s) is the transfer function between the cutter adjustment height and the rotation angle of the stepper motor; $l(s)$ is the cutter adjustment height (mm); $\theta(s)$ is the rotation angle of stepping motor (rad); L_{slider} is the slider moving distance (mm); L_{pitch} is the screw pitch (mm).

The Simulink model for the adjustment system for harvester cutter height from the ground was created as illustrated in Figure 6.

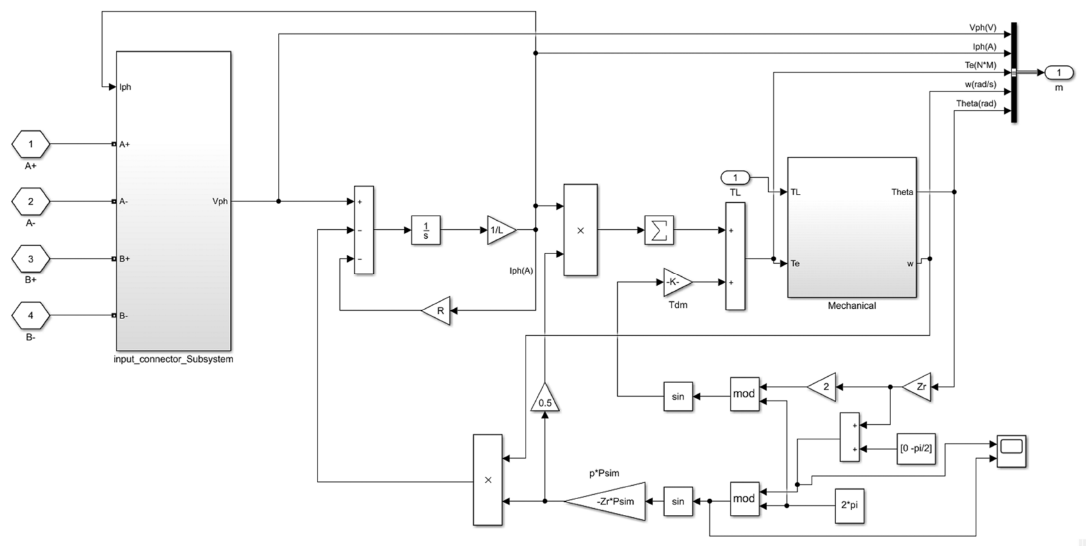

Figure 6. Model of cutter height adjustment system from the ground.

2.4. Control Strategy Establishment

2.4.1. Analysis of Position PID Control Strategy

The position error of a stepper motor position PID control was calculated as the difference between the set value of the motor rotation angle and the actual rotation angle. The proportional, integral, and differential coefficients were then multiplied by this position error, and the three were then summed to provide the control quantity [27]. After that, the stepper motor received the control quantity, which caused it to adjust its rotation angle to match the predetermined value. Figure 7 depicts the operation of position PID control. The transfer function of a positional PID controller is shown in Equation (7). Assuming that $u(k)$ was the output value of the controller at the kth sampling moment, the discrete positional PID was calculated as shown in Equation (8).

$$G(s) = \frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s \tag{7}$$

$$u(k) = K_P e(k) + K_I \sum_{j=0}^{k} e(j) + K_D[e(k) - e(k-1)] \tag{8}$$

where $G(s)$ is the transfer function of a positional PID controller; $U(s)$ is the output of the controller; $E(s)$ is the input of the controller; K_P is the proportional coefficient; K_I is the integral coefficient; K_D is the differential coefficient; $u(k)$ is the output value of the controller at the kth sampling moment.

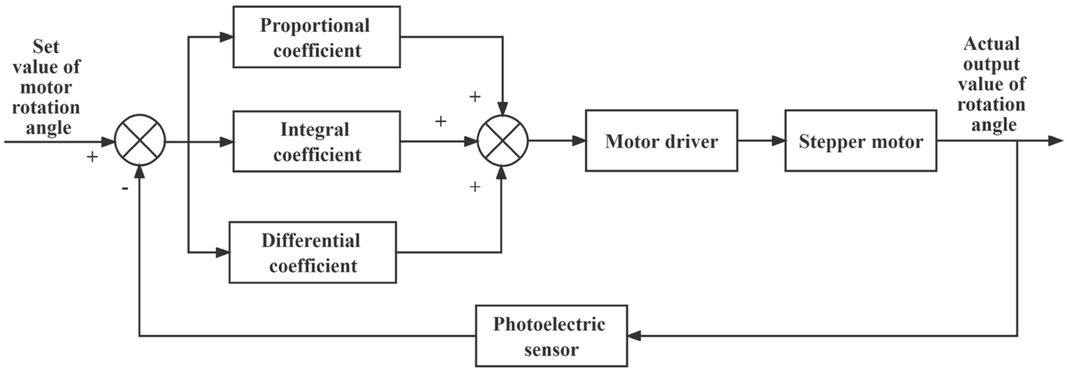

Figure 7. Position-based PID control schematic.

2.4.2. Analysis of Incremental PID Control Strategy

In order to perform incremental PID control of the stepper motor, one has to first calculate the position error e(k), the position error $e(k-1)$ of the previous generation, and the position error $e(k-2)$ of the previous two generations. Next, one has to calculate the difference between $e(k)$ and $e(k-1)$ and then multiply it by the proportional coefficient. $e(k)$ was multiplied by the integral coefficient, and the final differential coefficient was multiplied by $(e(k) - 2e(k-1) + e(k-2))$ [28]. The stepper motor's rotation angle was adjusted by the control quantity, which was the total of the three, to bring it into compliance with the predetermined value. Incremental PID control was used to take the increment of position PID control. The difference between the positions of the two adjacent sampling periods was the output of the control system at this time, and the control amount was the increment, which meant increasing the control amount based on the previous control amount (negative value meant reducing the control amount). The incremental PID control was calculated as shown in Equation (9).

$$\begin{aligned} \Delta u(k) &= u(k) - u(k-1) \\ &= K_P \Delta e(k) + K_I e(k) + K_D[\Delta e(k) - \Delta e(k-1)] \\ &= K_P[e(k) - e(k-1)] + K_I e(k) + \\ &K_D\{[e(k) - e(k-1)] - [e(k-1) - e(k-2)]\} \\ &= (K_P + K_I + K_D)e(k) - (K_P + 2K_D)e(k-1) + K_D e(k-2) \end{aligned} \tag{9}$$

2.4.3. Difference between Position and Incremental PID Control

(1) Incremental PID control optimizes the accumulation calculation so that the control increment no longer needs to accumulate the previous values several times, but only needs to process the most recent value 3 times, further reducing error0s. It is simple to manufacture significant accumulation errors because the position PID control is tied to the error accumulation value [29].

(2) Incremental PID control optimizes the output, and, in order to ensure that the actual output had a minimal impact on the variability of the system, only the control increments are output here, making the impact of faults minimal, i.e., the occurrence of a fault with only minor problems does not seriously affect the system process. The output of the position PID control is in perfect agreement with the output of the controlled item, which significantly affects the system [30,31].

Hence, incremental PID was used in the automatic adjustment control technique for cutter height above the ground.

2.5. Control Model Establishment and Simulation

Figure 8 depicts the model of the automatic control system for the cutter's height off the ground under the incremental PID control technique. PID was used to regulate the stepper motor's rotational angle, rotational speed, and current regulation. These include the proportion coefficient Kp = 4.665 in the rotation angle PID control, the proportion coefficient Kp = 5.65 in the rotation speed PID control, the integral coefficient Ki = 3.86 in the rotation speed PID control, the proportion coefficient Kp = 0.5455 in the current PID control, and the integral coefficient Ki = 30.4578 in the current PID control.

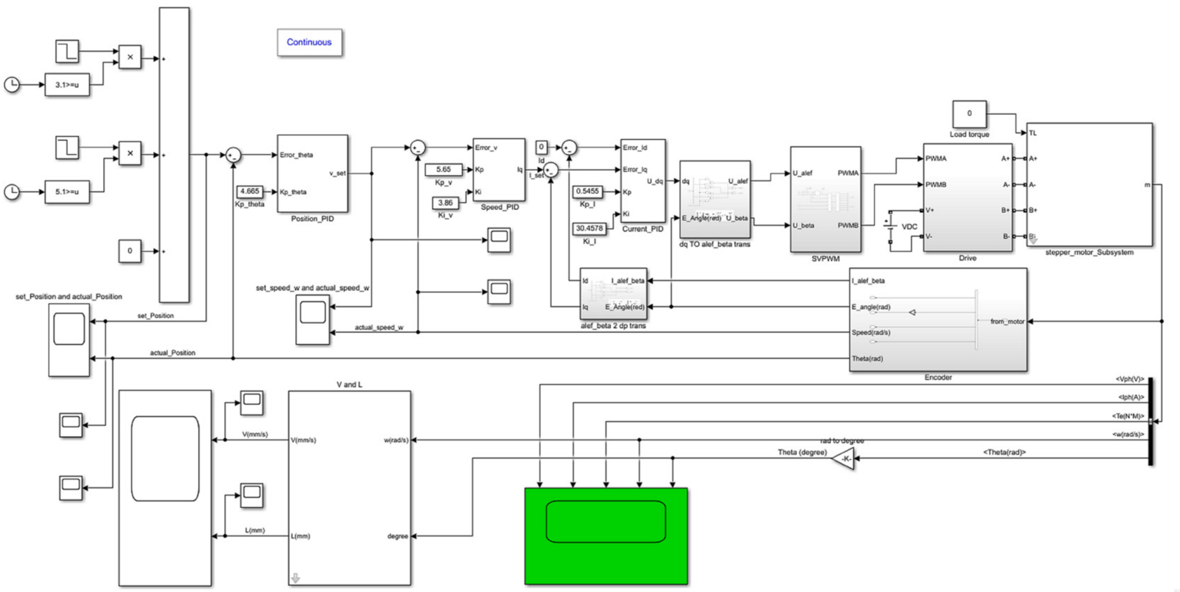

Figure 8. Incremental PID-based model for automatic control system of cutter height off the ground.

3. Results

3.1. Results of the Simulation Tests

The automatic control system model of the cutter height off the ground based on incremental PID was established in MATLAB in accordance with the previously established adjustment system model of the cutter height off the ground and control strategy model. This model includes the stepper motor rotation angle PID control module, stepper motor rotation speed PID control module, stepper motor current PID control module, cutter height off the ground adjustment motor transfer function, and other components. The real-time measurement of the stepper motor's rotational speed, rotational angle, and current was conducted throughout the harvesting process of the leafy vegetable harvester. This motor controls how high the cutter is above the ground. Then, a simulation was conducted for the two working conditions of the harvester: suddenly crossing the ditch and suddenly climbing the slope during the harvesting operation. Table 2 displays the test simulation circumstances.

Table 2. Simulation test conditions.

Working Condition Numbers	Names	Specific Situations
Working condition 1	The harvester suddenly crossed the ditch	A narrow strip of lower ground was in front of the harvester, which led the sensor to believe that the cutter was too high, and therefore should be lowered.
Working condition 2	The harvester suddenly climbed the slope	A narrow strip of higher ground was in front of the harvester, which led the sensor to believe that the cutter was too low, and therefore that it should rise.

(1) The sudden ditch crossing of the harvester: a narrow strip of lower ground was in front of the harvester, which led the sensor to believe that the cutter was too high, and therefore should be lowered. The simulation of the harvester suddenly crossing the ditch: it was assumed that the set value of the height of the cutter from the ground corresponding to the rotation angle of the stepper motor was 0(rad), so when the height of the cutter from the ground was within $\pm 2\%$ of the set value, the rotation angle of the stepper motor should be within the range of -0.02~0.02. It was assumed that the pitch of the ball screw device was 20 mm, and that the harvester suddenly crossed the ditch in 1 s; at this time, it was necessary to lower the cutter, assuming that the height of the cutter from the ground could be within $\pm 2\%$ of the set value. The corresponding stepper motor should rotate clockwise with a rotation angle of 6.28. The clockwise direction of motion of a stepper motor is positive. Due to the connection between the cutting blade and the conveying platform, the system actually lowers the cutting blade by driving the ball screw device to lower the conveying platform through the clockwise rotation of the stepper motor. The simulation results are shown in Figure 9. The rotation angle of the stepper motor increased from 0 to the end and remained within the range of -0.02~0.02. The time it took for the harvester to abruptly cross a ditch and return to stable operation, or the steady-state transition time of the automatic control system of the cutter height off the ground based on the incremental PID, was 1.0740 s. The dynamic reaction performance and stability of the automatic control system of the cutter height off the ground under the incremental PID control approach were thus good when the harvester abruptly crossed the ditch.

(2) The sudden slope climbing of the harvester: a narrow strip of higher ground was in front of the harvester which led the sensor to believe that the cutter was too low, and therefore that it should rise. The simulation of the harvester suddenly climbing the slope: it was assumed that the set value of the height of the cutter from the ground corresponding to the rotation angle of the stepper motor was 0(rad), so when the height of the cutter from the ground was within $\pm 2\%$ of the set value, the rotation angle of the stepper motor should be within the range of -0.02~0.02. It was assumed that the pitch of the ball screw device was 20 mm, and the harvester suddenly climbed the slope in 3 s. At this time, it was necessary to lift the cutter. If the cutter was raised by 20 mm, the height of the cutter from the ground could be within $\pm 2\%$ of the set value. The corresponding stepper motor should rotate counterclockwise with a rotation angle of 6.28. The counterclockwise direction of motion of a stepper motor is negative. Due to the connection between the cutting blade and the conveying platform, the system actually raises the cutting blade by driving the ball screw device to raise the conveying platform through the counterclockwise rotation of the stepper motor. The simulation results are shown in Figure 10. The rotation angle of the stepper motor decreased from 0 to the end and remained within the range of -0.02~0.02. The time it took for the harvester to stabilize after suddenly climbing a slope, or the steady-state transition time of the automatic control system of the cutter height off the ground based

on the incremental PID, was 1.0345 s. The dynamic reaction performance and stability of the automatic control system of the cutter height off the ground under the incremental PID control strategy were thus good when the harvester abruptly climbed the slope.

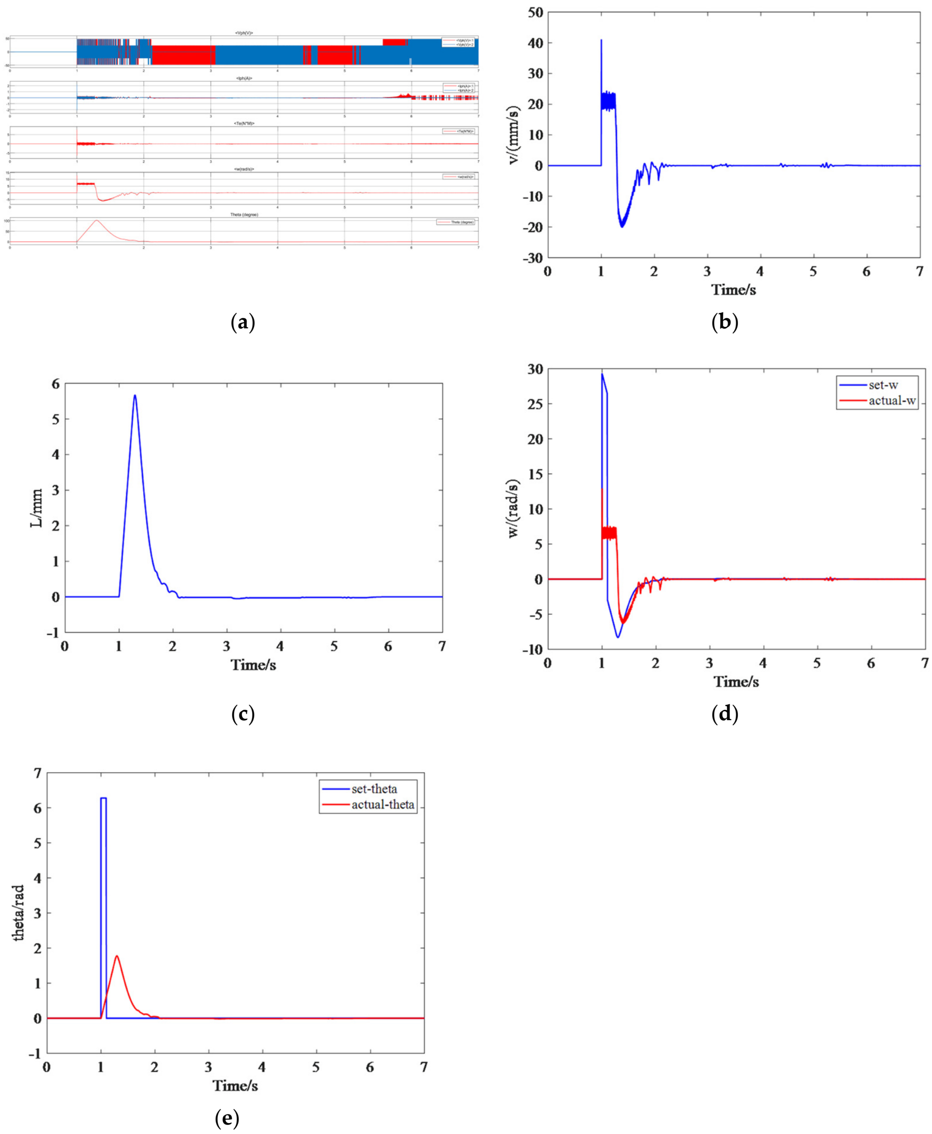

Figure 9. The simulation results of stepper motor with sudden over-groove in smooth condition under incremental PID control strategy for automatic control system of cutter height off the ground. (**a**) The simulation results of stepper motor voltage, current, electromagnetic torque, rotation speed, and rotation angle with sudden over-groove in smooth condition under incremental PID control strategy for automatic control system of cutter height off the ground; (**b**) the simulation results of stepper motor rotation speed (mm/s) with sudden over-groove in smooth condition under incremental PID control strategy for automatic control system of cutter height off the ground when the pitch of ball screw device is 20 mm; (**c**) the simulation results of stepper motor rotation distance (mm) with sudden over-groove in smooth condition under incremental PID control strategy for automatic control system of cutter height off the ground when the pitch of ball screw device is 20 mm; (**d**) the simulation results of stepper motor setting rotation speed and actual rotation speed with sudden over-groove in smooth condition under incremental PID control strategy for automatic control system of cutter height off the ground; (**e**) the simulation results of stepper motor setting rotation angle and actual rotation angle with sudden over-groove in smooth condition under incremental PID control strategy for automatic control system of cutter height off the ground.

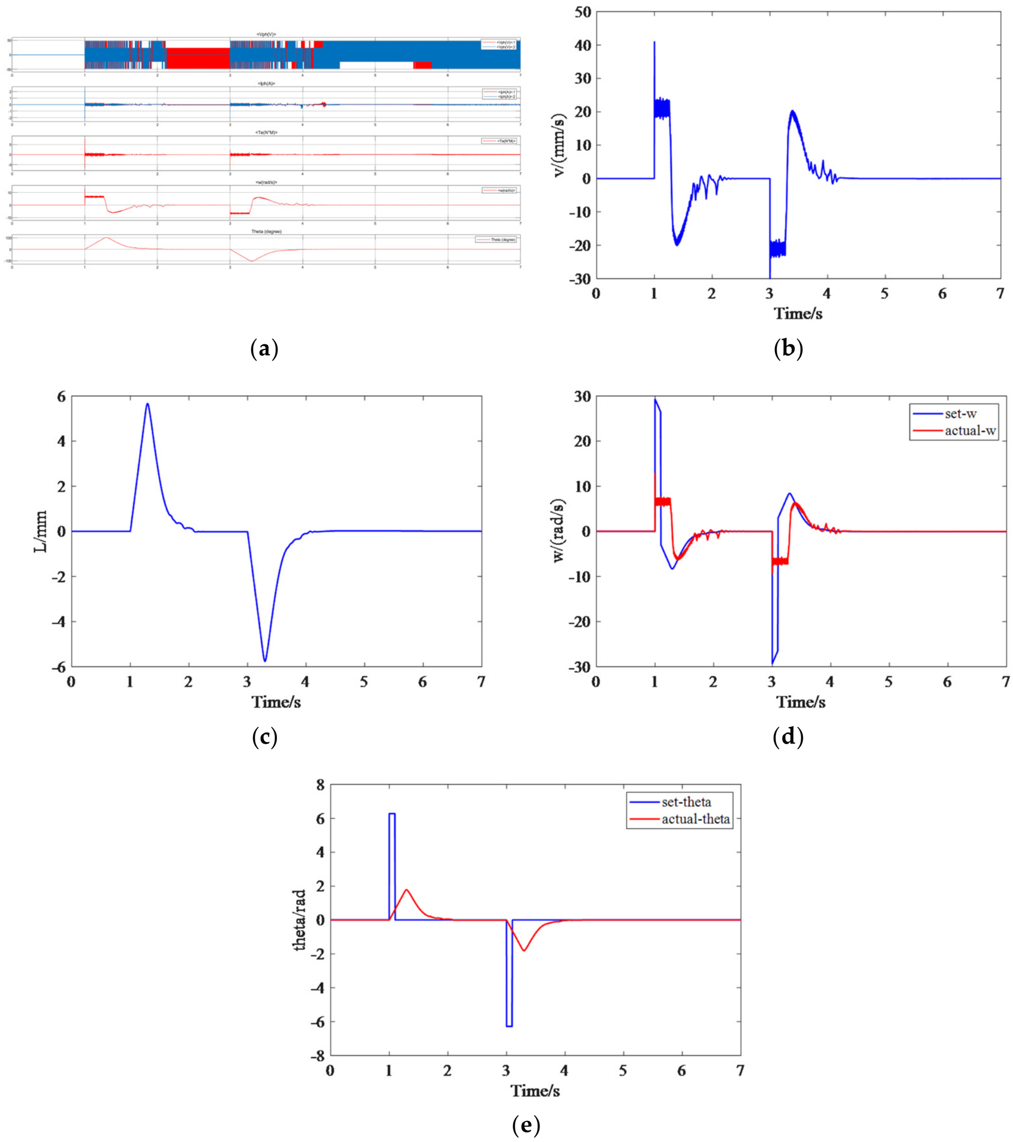

Figure 10. The simulation results of stepper motor with abrupt climbing in smooth condition based on incremental PID control strategy for automatic control system of cutter height off the ground. (**a**) The simulation results of stepper motor voltage, current, electromagnetic torque, rotation speed, and rotation angle with abrupt climbing in smooth condition based on incremental PID control strategy for automatic control system of cutter height off the ground; (**b**) the simulation results of stepper motor rotation speed (mm/s) with abrupt climbing in smooth condition based on incremental PID control strategy for automatic control system of cutter height off the ground when the pitch of ball screw device is 20 mm; (**c**) the simulation results of stepper motor rotation distance (mm) with abrupt climbing in smooth condition based on incremental PID control strategy for automatic control system of cutter height off the ground when the pitch of ball screw device is 20 mm; (**d**) the simulation results of stepper motor setting rotation speed and actual rotation speed with abrupt climbing in smooth condition based on incremental PID control strategy for automatic control system of cutter height off the ground; (**e**) the simulation results of stepper motor setting rotation angle and actual rotation angle with abrupt climbing in smooth condition based on incremental PID control strategy for automatic control system of cutter height off the ground.

To summarize, the automatic control system of the cutter height from the ground based on the incremental PID control strategy had the advantages of a fast response and stability and could achieve the expected goal of automatically adjusting the cutter height from the ground when the deviation between the current value and the set value of the cutter height from the ground was greater than 2%; that is, when the harvester was in the condition of suddenly crossing the ditch or suddenly climbing the slope.

3.2. Results of Field Trials

At the vegetable sweet potato base of the Nanjing Institute of Agricultural Mechanization of the Ministry of Agriculture and Rural Affairs, an electric leafy vegetable harvester based on the incremental PID cutter height from the ground control mode was tested and verified in order to confirm the accuracy of the simulation test results. Figure 11 depicts the components of the automatic control system for the cutter height from the ground based on incremental PID. In the automatic control system of the cutter height from the ground using the incremental PID control strategy, the proportional coefficient Kp of the rotation angle PID control algorithm was set to 4.665. For the PID control technique to regulate rotation speed, the integral coefficient Ki was set to 3.86 and the proportional coefficient Kp was set to 5.65. For the current PID control scheme, the proportional coefficient Kp was set to 0.5455 and the integral coefficient Ki was set to 30.4578. The results of the field test, which was conducted under the two conditions of the harvester abruptly crossing the ditch and abruptly climbing the slope (Figure 12), are presented in Figures 13 and 14.

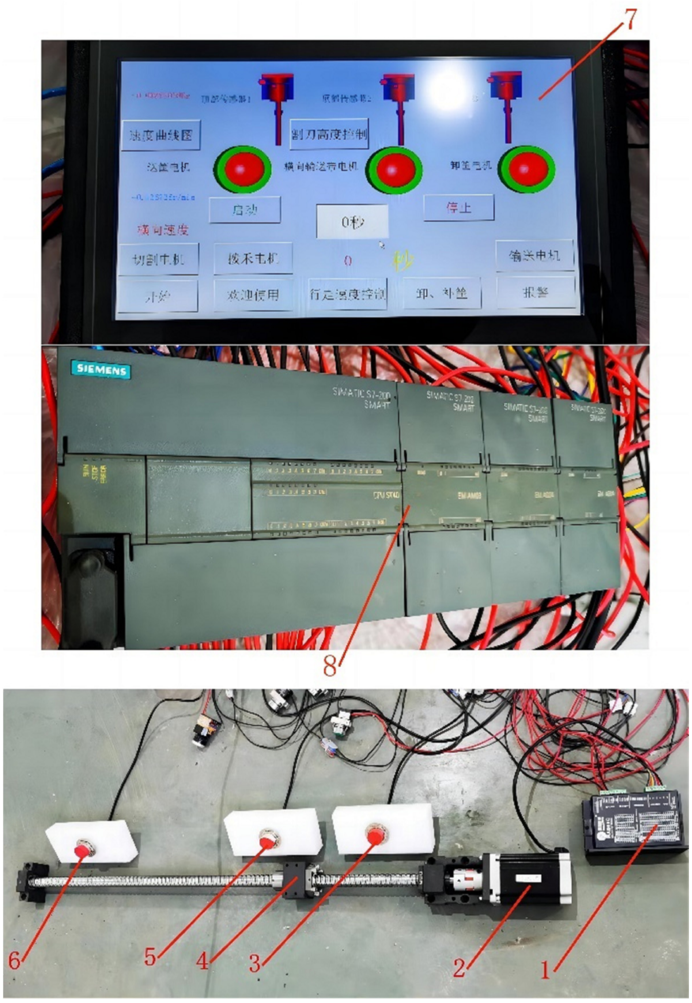

Figure 11. Cutter height off the ground automatic control system device based on incremental PID. 1. Stepper motor driver 2. Stepper motor 3. Left limit proximity switch 4. Slider 5. Zero limit proximity switch 6. Right limit proximity switch 7. Touch screen 8. PLC.

Figure 12. Field operation diagram for the 4UM-120D electric leafy vegetable harvester.

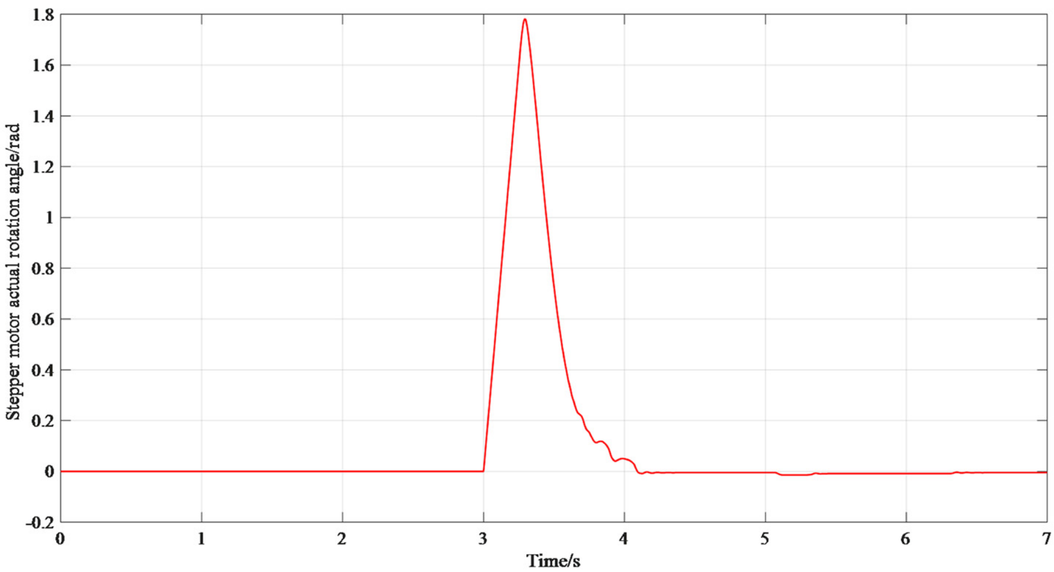

Figure 13. Response effect of incremental PID-based automatic control system of cutter height off the ground when the harvester suddenly crosses a ditch.

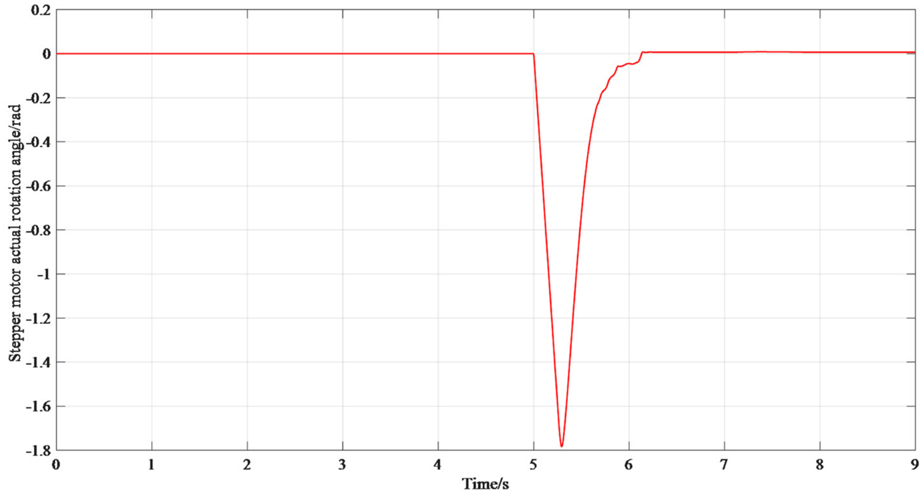

Figure 14. Response effect of incremental PID-based automatic control system of cutter height off the ground when the harvester suddenly climbs a slope.

It can be seen from Figure 13 that, when the harvester suddenly crossed the ditch under the stable operation state, the time from when the rotation angle of the stepper motor increased from 0(rad) to the first time it entered the range of −0.02~0.02 and no longer exceeded it was recorded as the steady-state transition time. Therefore, when the harvester abruptly crossed the ditch, the incremental PID control algorithm's steady-state transition time for the automatic control system of the cutter height off the ground was 1.0811 s. It could be seen from Figure 14 that, when the harvester suddenly climbed a slope under stable operation, the time from when the rotation angle of the stepper motor decreased from 0(rad) to the range of −0.02~0.02 for the first time and no longer exceeded it was recorded as the steady-state transition time. Therefore, when the harvester abruptly climbed a slope, the steady-state transition time of the automatic control system of the cutter height off the ground based on the incremental PID control method was 1.1185 s. In other words, the dynamic response performance and stability of the automatic control system of the cutter height off the ground based on the incremental PID were good when the harvester was in the condition of suddenly crossing the ditch or suddenly climbing the slope, so the simulation test results were reliable.

4. Discussion

If the left limit switch of the automatic adjustment system of the cutter height from the ground was on, the system would issue a warning and the stepper motor would stop rotating to prevent the slide block from hitting the stepper motor and causing motor damage. If the right limit switch of the automatic adjustment system of the cutter height from the ground was on, the system would also issue a warning and the stepper motor would stop rotating to prevent the cutter from being damaged by touching the ground due to the low height of the cutter from the ground. As the automatic control system for the height of the cutter off the ground was a semi-closed loop system, i.e., sampled from the motor, there must be an error in accuracy, and it was an order of magnitude difference compared to a closed loop system; however, at this stage, the "yes" and "no" problems were first ensured, and the rest were left for later. However, there was a need to acknowledge the errors and recognize the problems involved, as well as to provide a basis for further research on the subject to improve accuracy.

5. Conclusions

(1) In this research, the use of an incremental PID control method to automatically modify the height of the electric leafy vegetable harvester's cutter from the ground was

proposed. The mathematical model of the motor for regulating the height of the cutter from the ground was built based on the physical properties of the stepper motor. An approach utilizing incremental PID control technology was created to achieve the automatic adjustment of the height of the electric leafy vegetable harvester's cutter from the ground.

(2) Through the use of theoretical analysis, simulation analysis in various working environments, and field testing, the results of the simulation study were validated. When the deviation between the current value and the set value of the cutter height from the ground was greater than 2%—that is, when the harvester was in the condition of abruptly crossing the ditch or abruptly climbing the slope—it was demonstrated that the dynamic response performance and stability of the automatic control system of the cutter height from the ground based on the incremental PID control strategy were good. This was accomplished to automatically control the harvester's cutter height from the ground.

(3) When Kp = 4.665 is used as one of the incremental PID control strategy's parameters—the rotation angle PID control algorithm's proportional coefficient—the rotation speed PID control algorithm's proportional coefficient and integral coefficient values are 5.65 and 3.86, respectively. The current PID control algorithm's integral coefficient Ki = 30.4578 and proportional coefficient Kp = 0.5455. The automatic control system's steady-state transition time for the height of the cutter off the ground was 1.0811 s when the harvester abruptly crossed the ditch while operating steadily. The harvester's automatic control system's steady-state transition time of the cutter height from the ground was 1.1185 s when the machine abruptly climbed a slope while it was operating steadily.

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References

1. Jun, W.; Dongdong, D.U.; Jinbing, H.U.; JianXi, Z. Vegetable Mechanized Harvesting Technology and Its Development. *Trans. Chin. Soc. Agric. Mach.* **2014**, *45*, 81–87.
2. Yue, J.; Hongru, X.; Suwei, X. Research Statue and Development Trendency on Leaf Vegetable Harvesting Technology and Equipment. *J. Agric. Sci. Technol.* **2018**, *20*, 72–78.
3. Pei, T.; Xin, L.; Peiben, W. Design of power system of electric leaf vegetable harvester. *J. Chin. Agric. Mech.* **2019**, *40*, 72–76.
4. Yuanjuan, G.; Yulong, F.; Chuangye, L. Research Actuality of Leek Harvester and its Developing Countermeasures. *J. Agric. Mech. Res.* **2018**, *40*, 262–268.
5. Gongwei, S.; Gongpu, W.; Lianglong, H.; Jianning, Y.; Yemeng, W.; Teng, W.; Xiaodong, C. Development of harvesting mechanism for stem tips of sweet potatoes. *Trans. Chin. Soc. Agric. Eng.* **2019**, *35*, 46–55.
6. Peng, M.; Zhiyu, Z.; Hanping, M. Research on Automatic Alignment Control System of Electric Leaf Vegetable Harvester. *J. Agric. Mech. Res.* **2022**, *44*, 84–89.
7. Li, J.; Shang, Z.; Li, R.; Cui, B. Adaptive Sliding Mode Path Tracking Control of Unmanned Rice Transplanter. *Agriculture* **2022**, *12*, 1225. [CrossRef]
8. Bai, S.; Yuan, Y.; Niu, K.; Shi, Z.; Zhou, L.; Zhao, B.; Wei, L.; Liu, L.; Zheng, Y.; An, S.; et al. Design and Experiment of a Sowing Quality Monitoring System of Cotton Precision Hill-Drop Planters. *Agriculture* **2022**, *12*, 1117. [CrossRef]
9. Nang, V.N.; Yamane, S. Development of prototype harvester for head lettuce. *Eng. Agric. Environ. Food* **2015**, *8*, 18–25. [CrossRef]
10. Guo, Y.; Dong, S.; Tian, S.B. Design on Control System of Seedling Vegetable Harvester Based on Single Chip. *Adv. Mater. Res.* **2013**, *721*, 656–660. [CrossRef]

11. Chen, J.; Zhang, H.; Pan, F.; Du, M.; Ji, C. Control System of a Motor-Driven Precision No-Tillage Maize Planter Based on the CANopen Protocol. *Agriculture* **2022**, *12*, 932. [CrossRef]
12. Honglei, J.; Yun, L.; Jiangtao, Q. Photoelectric sensors combined with rotary encoders to detect the suction performance of suction metering devices. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2018**, *34*, 28–39.
13. Chengqian, J.; Feiyang, G.; Jinshan, X. Optimization of working parameters of soybean combine harvester. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2019**, *35*, 10–22. (in Chinese with English abstract)
14. Jie, H.; Jingguang, Z.; Zhizhang, Z.; Xiwen, L.; Yang, G.; Lian, H. Design and experiment of automatic operation system for rice transplanter. *Trans. Chin. Soc. Agric. Mach.* **2019**, *50*, 17–24.
15. Lixin, Z.; Zenghui, Z.; Chengyi, W.; ShiChun, J.; Tong, L.; DongYun, C.; XiaoLing, D. Design of integrated monitoring system for wheat precision seeding and fertilization based on variable distance photoelectric sensor. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2018**, *34*, 27–34.
16. Xincheng, L.; Jian, Z.; Yuliang, Y. Design and Experiment on an Intelligent Control System for Small Electric Leafy Vegetable Harvester. *J. Agric. Mech. Res.* **2020**, *42*, 83–87.
17. Yuanyuan, W. *Design of Greenhouse Celery Harvester*; Ningxia University: Yinchuan, China, 2018.
18. Tao, L.; Jin, Z.; Wenyi, X.; QingLong, L.; Hua, Z.; XiTian, Q.; Na, L.; WeiHua, L.; DaYong, G. Development of 4UGS2 type double-row sweet potato harvester. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 26–33.
19. Long, Y. Design and MATLAB simulation of pressure control based on positional PID algorithm. *Electron. Technol. Softw. Eng.* **2018**, *146*, 27.
20. Baocheng, T.; Bin, W. Incremental PID control for unmanned vehicle path tracking. *J. Xi'an Univ. Technol.* **2016**, *36*, 996–1001.
21. Wenjian, X.; Yongke, L. Intelligent vehicle design based on incremental PID control algorithm. *Inf. Technol.* **2012**, *36*, 125–127.
22. Yifei, Z. *Simulation of Stepper Motor Control System Based on Simulink*; Southwest Jiaotong University: Chengdu, China, 2014.
23. Lei, W.; Donghao, L. Optimal design and simulation of acceleration and deceleration curves of stepper motors. *Autom. Appl.* **2021**, *26*, 21–24.
24. Wenqiang, X.; Jianhong, Y. Derivation of transfer function model for two-phase hybrid stepper motor. *Space Electron.* **2011**, *8*, 50–53.
25. Lin, Y.; Yunlong, J.; Yang, L. Modeling and simulation of short arc removal rivet system. *Electr. Process. Tool.* **2022**, *366*, 24–29.
26. Zhenya, Q.; Qianqian, Q.; Liying, W. Simulation study of constant current subdivision drive control for two-phase hybrid stepper motor. *Microtechnology* **2022**, *50*, 48–52.
27. Zaimang, W.; Juan, P.; Jie, H. Development of rice precision hole direct seeding machine sowing monitoring system. *Trans. Chin. Soc. Agric. Eng. (Trans. CSAE)* **2020**, *36*, 9–16.
28. Caiyun, L.; Weiqiang, F.; Chunjiang, Z.; Hebo, M.; Zhijun, M.; Jianjun, D.; Nana, G.; Xiu, W.; Liwei, L. Design and experiment of real-time monitoring system for wheat sowing. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 32–40.
29. Dongye, S.; Datong, Q.; Yuxing, W. Study on fuzzy control strategy of CVT system for automatic vehicles. *Trans. Chin. Soc. Agric. Mach.* **2001**, 7–10.
30. Tian, F.; Wang, X.; Yu, S.; Wang, R.; Song, Z.; Yan, Y.; Li, F.; Wang, Z.; Yu, Z. Research on Navigation Path Extraction and Obstacle Avoidance Strategy for Pusher Robot in Dairy Farm. *Agriculture* **2022**, *12*, 1008. [CrossRef]
31. Zhang, B.; Chen, X.; Zhang, H.; Shen, C.; Fu, W. Design and Performance Test of a Jujube Pruning Manipulator. *Agriculture* **2022**, *12*, 552. [CrossRef]