RESEARCH ON THE DESIGN OF MULTIFUNCTIONAL AUTOMATIC SPINACH HARVESTING MECHANICAL DEVICE BASED ON SOIL SHAKING TYPE

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This study targets the key challenges in current spinach harvesting, including low mechanical efficiency, high labor costs, and poor cleanliness. To address these issues, a multifunctional automatic soil-shaking spinach harvester is designed, integrating automatic cutting, soil shaking and cleaning, transportation, collection, and intelligent cruise harvesting control. This system can facilitate efficient harvesting while automatically removing soil and residual leaves of spinach. In addition, this multifunctional harvester can be remotely controlled through a smartphone and use an onboard electronic control screen for autonomous path planning and constant speed cruise harvesting within a specified range.

Keywords: Spinach harvesting; mechanical design; soil shaking device; multifunctional integration; intelligent cruise harvesting

1. Introduction

Spinach is rich in various essential nutrients [1-3]. Its tender and fragile stems and leaves have long hindered mechanized harvesting. Spinach harvesting in China mainly relies on manual labor, and is labor-intensive and inefficient [4-6]. As agricultural labor shortens and market demand increases, developing low-damage, high-efficiency spinach harvesting equipment has become an urgent need in the industry. The SLIDE ECO model from Hortech in Italy uses vertical gripping and conveying with high efficiency, but limited applicability [7-9]. Although it cutroots during harvesting, it still uses a disordered harvesting approach. Wen Yongtao et al. optimized gripping parameters based on spinach rheological properties using a Burgers viscoelastic model, reducing damage rates to 6.7% [2]. The Nanjing Institute of Agricultural Mechanization, under the Ministry of Agriculture and Rural Affairs, pioneered ordered harvesting techniques for stem and leaf vegetables. Through flexible gripping with extraction and conveying devices, the commercialization rate can increase 30%, reaching internationally leading levels [10-15]. However, existing equipment has several limitations: cutting devices typically use fixed root-cut shovels, causing high soil resistance and energy consumption; harvesters lack versatility and require specialized machines to process

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different leafy greens; multi-row harvesting results in a large horizontal structure that is difficult to adapt to small plots of land in facility agriculture. Therefore, we propose a longitudinal reciprocating vibration root-cutting device based on crank-link mechanism to reduce energy consumption through low-resistance subsurface cutting. We also design an innovative soil-shaking ordered conveying system that uses a soil shaking mechanism to clean spinach. This structure can significantly improve quality rate and reduce damage of spinach.

2. Theoretical Model

2.1 Structure and working principle of the whole machine

The Shaking Spinach Multi-Functional Automatic Harvester consists of five modules: walking system, cutting system, shaking system, conveying system and intelligent control system, which jointly complete the cutting, clearing, conveying and collecting operations of spinach. The machine adopts a lightweight aluminum frame (density 2.7 g/cm³) to ensure the structural strength and reduce the mass of the machine to 42 kg, which significantly improves the pass ability in the field. The structure of the machine is shown in Fig.1.

Fig. 1 The overall mechanism diagram of the Shaking soil spinach multifunctional automatic harvester

According to the design requirements, the structural parameters of the main parts of the harvester are determined. Three-dimensional modeling is carried out using Solidworks software, and a 1:1 prototype of spinach cutting and shaking soil cleaning device is established based on the simulation analysis. Functions and parameters of main components are shown in Table 1.

Table 1

Core components and parameters

System Modules	***Core Components***	***Functional Description***
Travel System	Rubber Wheels x 4[a]	Differential Steering and Ground Adaptation
Cutting System	Crank Slider Mechanis	Transverse Reciprocating Cutting
Soil Shaking System	Double Crank Shaking Claw	Soil Stripping and Directional Conveying
Conveyor System	Synchronous Belt	Elevator Spinach Directional Conveying
Control System	ESP32 Master Control	Multi-Motor Co-Schedulin.

3. The workflow of shaking soil spinach multifunctional automatic harvester

The workflow of shaking spinach multifunctional automatic harvester is shown in Fig. 2. It contains four consecutive phases: cutting, cleaning, conveying, and collecting.

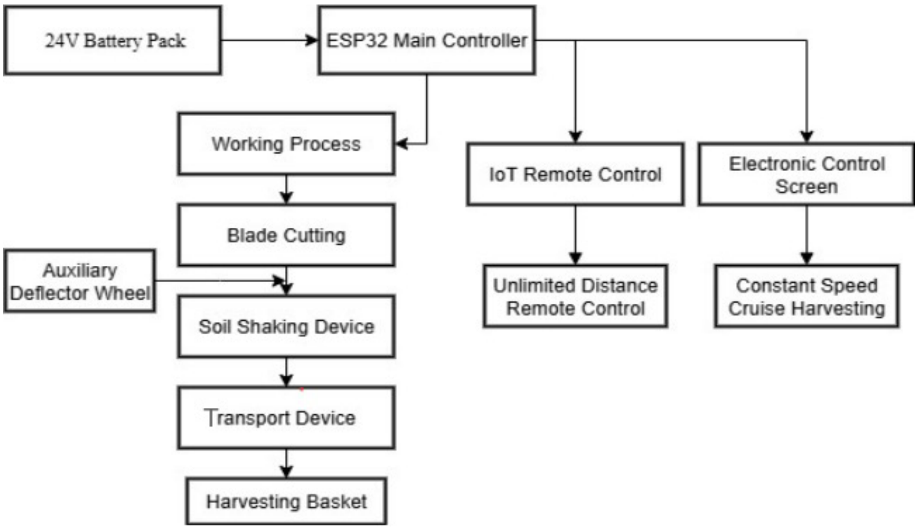

Fig.2 Flowchart of shaking soil spinach multifunctional automatic harvester

3.1 Cutting stage

The harvester travels at a constant speed of V_{mmax} =0.015m/s, and the crank-slider mechanism drives the cutting blades to reciprocate transversely (stroke L_c =80mm, frequency f_c=1.33Hz) and complete the cutting of spinach roots (stubble height h_s=15mm). After cutting, the spinach falls to the harvester frame under the action of gravity.

3.2 Soil clearing stage

The fallen spinach enters the double crank soil shaking device, and the moving shaking claw (amplitude A_d=30mm, frequency f_d =1.48Hz) and the fixed shaking claw form periodic squeezing and releasing, achieving soil stripping (stripping rate $\eta_s \geq$ 85%). At the same time, the eccentric movement of the soil shaking claw generates an upward component V_u=9.74cm/s, which pushes the spinach to slide to the conveyor belt.

3.3 Conveying stage

The cleaned spinach is conveyed upward by a 39.94° inclined conveyor belt with a belt speed of V_l=0.204m/s (active shaft speed n_l=3.083r/s). The surface of the conveyor belt is designed with anti-slip pattern (friction coefficient μ=0.3) to ensure the spinach does not slip during transportation.

3.4 Collection stage

Spinach enters the collection box at the end of the conveyor belt in the form of free fall (fall difference H_f=200mm) to complete a single operation cycle. The entire process is coordinated by the ESP32 main control system to coordinate the timing of each motor, with an action delay of t_d<50ms.

4. Key subsystem design and construction

4.1 Transmission system design

The forward speed of the spinach harvester, the speed and inclination of the conveyor belt, and the installation position of the cutter all affect the cutting and conveying effect of spinach plants. Cutting in a forward state is a necessary condition to ensure the orderly conveying of spinach.

When vegetables are cut, spinach may show uncertain postures such as tilting forward or backward due to the pulling of the conveyor belt and the forward movement of the machine. The absolute speed V of the conveyor belt is the synthesis of the machine forward speed V_m and the conveyor belt inclined upward movement speed V_l, as shown in Fig.3.

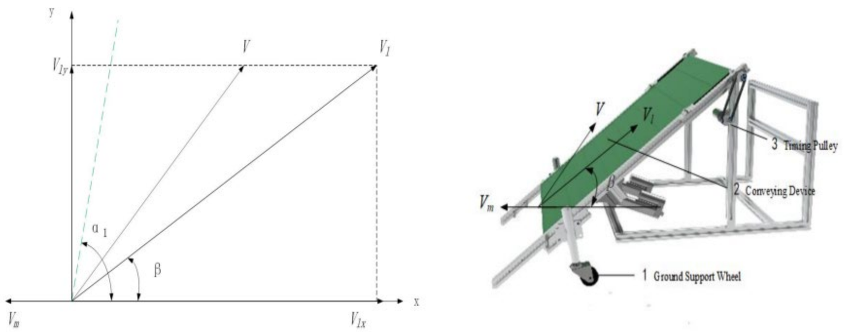

Fig. 3 Speed analysis of spinach harvester conveyor process

Due to the fixation of plant roots in the soil, spinach stems and leaves will tilt backwards under the influence of machine advancement and cutters, forming a clip α_1 with the ground. According to the geometric relationship shown in Fig. 3, it can be known that the angle of the plant attitude $\alpha_1$during conveyance is expressed as follows:

$$\alpha_1 = \arctan \frac{v_{ly}}{v_{m} - v_{lx}} \tag{1}$$

where

$$\begin{cases} v_{lx} = v_l \cos \beta \\ v_{ly} = v_l \sin \beta \end{cases} \tag{2}$$

where v_{lx} is the horizontal partial velocity of spinach at the delivery point, m/s; v_{ly} is the vertical partial velocity of spinach at the delivery point, m/s.

The speed of conveyor belt line is calculated as follows:

$$v_l = n_l \pi d_l / 60 \tag{3}$$

where d_l is the synchronous wheel shaft diameter, 0.02m; n_l is the speed of the synchronous belt drive motor, 185r/min.

The absolute speed V of the conveyor belt is backward to ensure smooth backward conveying of spinach without pushing down the spinach plant. That is, the speed of the conveyor belt in the horizontal direction at the spinach cutting point is greater than the forward speed of the synchronous wheel axle diameter of the harvester. The speed of the synchronous belt drive motor isexpressed as follows:

$$v_l \cos \beta \geq v_{\mathrm{mmax}} \tag{4}$$

where v_{mmax} is the maximum forward speed of the harvester, designed as 0.015m/s.

Due to the conveyor belt being too fast, spinach will be transported backwards before cutting, causing damage to the spinach. To ensure smooth cutting and transportation of spinach in a stable state, the direction of machine movement during the cutting process is analyzed. As shown in Fig.4, assuming that the conveyor belt is stationary, spinach moves at $V_m$relative to the conveyor belt and reaches point C where it is cut. A Cartesian coordinate system is established with the intersection point O between the initial stage of the spinach plant root system and the ground horizontal line as the coordinate origin. The height of the conveyor point F from the ground isH_0; the depth of the spinach cut root depth ish_0; the angle between the cutting plant and the ground is α, and the time from clamping to cutting spinach is t.

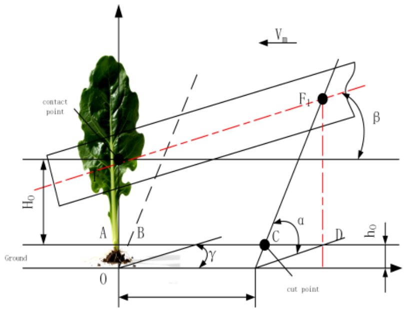

Fig. 4 Analysis of spinach attitude change during transportation

According to the relationship between the conveyor belt speed and the forward speed of the machine, the displacement of the cutting stage pointF1relative to the stage point F isexpressed as follows:

$$\begin{cases} x_{l'} = v_l t \cos \beta \\ y_{l'} = v_l t \sin \beta \end{cases} \tag{5}$$

In △CDF1, combining Eq. (6) yields

$$\tan \alpha = \frac{v_l t \sin \beta + H_0 + h_0}{v_l t \cos \beta - v_m t} \tag{6}$$

It can be seen that the attitude change of the spinach after cutting is related toα.The closerα to π/2, the more ideal the conveying state. The height of the conveying point is determined by the height of the electric pusher and cutter. The main parameters affecting α are the forward speed of the machine V_m,the linear speed of the conveyor belt V_l, and the angle of the conveyor belt β. It can be seen from Eq. (6) that the smaller β, and the smaller α, that is, the more the conveyor belt is inclined to the position of the stalks of the plant, the more unstable the conveying is and the greater the possibility of damage to the stalks and leaves. If β is too small, the height of the whole machine is too low. Considering the structural size of the machine and the harvesting characteristics, β is 39.94°.

The dynamic characteristics of the traveling system directly affect the field passability and energy efficiency of the harvester. Based on the Bekker ground mechanics theory, the active wheel torque $T_w$and drive $F_t$satisfy:

$$T_w = F_t \cdot r_w = (F_{rr} + F_g + F_a) \cdot \eta_t \cdot r_w \tag{7}$$

where F_t is the traveling driving force (N); F_{rr} is the rolling resistance (N); f_r=0.3 is the rolling resistance coefficient of dry loamy soil; F_g is the slope resistance (N); θ = 8°is the maximum design slope; Fa is the air resistance (N); C_d=0.8 is the wind resistance coefficient, ρ=1.2kg/m^3, and η_t=0.92 is the transmission efficiency.

4.2 Design of Angle Adjustment Motorized Actuators

Two motorized actuators are selected as the model PFDE24, with specific parameters shown in Table 2.

Table 2

Specific parameters of motorized actuators

Model Specification	***Operating Voltage***	***Working Stroke***	***Maximum Thrust***	***Speed***
PFDE24	24V	100mm	700N	5mm/s

After the theoretical model deduction, the lifting requirements for spinach harvesting ramp is about 10cm. Therefore, the calibration design of the electric actuator is aimed at 10. The stroke of the electric actuator is selected to be 0-100mm. We can use the graphical method in Fig.5 to solve the maximum lifting height of the electric actuator. With the help of computer-aided mapping, the results can be obtained as follows:

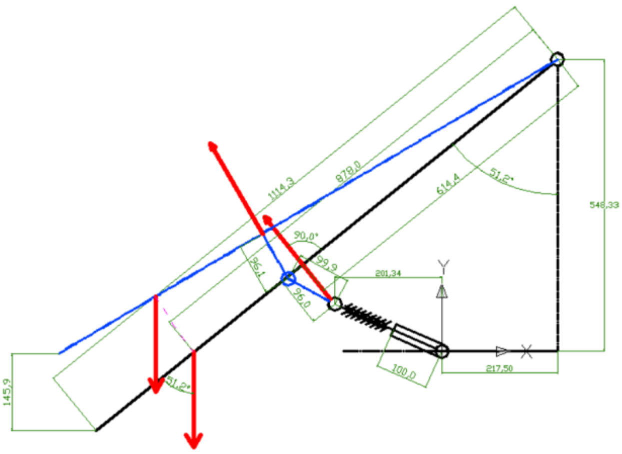

Fig.5 Electric actuator design of the solution schematic diagram

The electric actuator with a stroke of 100mm can be lifted to a maximum height of the inclined plane H_t=145.69mm>100mm. The selected electric actuator can meet the design requirements and use the specifications of the electric actuator.

4.3 The design of the soil shaking device

The soil shaking device includes a frame, a synchronous belt drive motor, a synchronous wheel, a synchronous belt, a crank, crank shaft, a short shaft, a crank bearing seat, a fixed shaft, a fixed soil shaking claw, and a movement soil shaking claw.The function of the soil shaking device is to first shake off the spinach soil and soil particles that have just been shaken out of the soil, so as to achieve better cleaning. In addition, the rotation of the hyperbolic handle mechanism is used to achieve upward conveying. The schematic diagram of the shaking device is shown in Fig. 6.

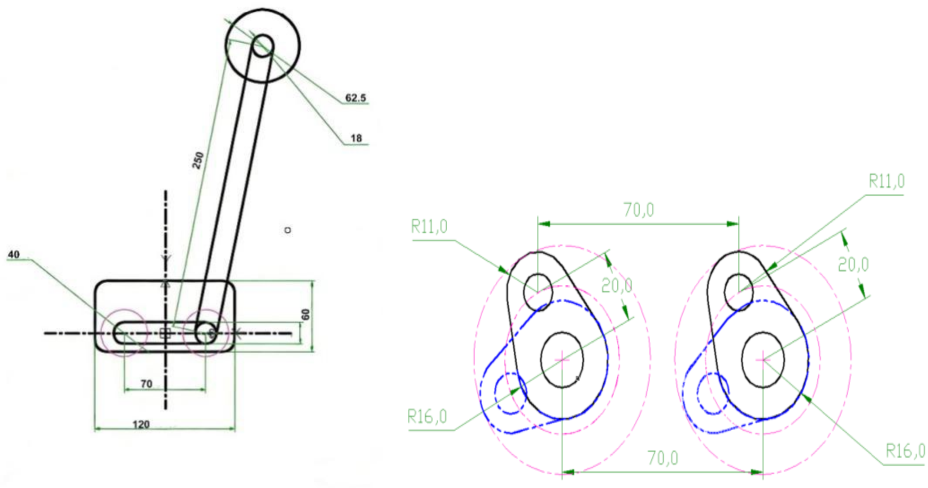

Fig. 6 Schematic diagram of soil shaking device

The vibrating soil claw drive motor, two crank bearing housings, and two fixed shafts are mounted on the frame. The fixed vibrating soil claws are evenly spaced along the two fixed shafts. The synchronous belt drives the short shaft below the frame, which is fixed to the frame through a crank bearing box. The two short shafts rotate through a synchronous pulley and belt mechanism. The crank is fixed at the other end of the short shaft and connected to the crankshaft. The movable vibrating soil claws are evenly distributed along the crankshaft and move in coordination with the crank. Finally, the movable claws rotate around the fixed claws for soil shaking. This vibrating soil device can achieve efficient soil removal during leafy vegetable harvesting by using the rotation of the dual-crank mechanism, significantly improving the soil shaking efficiency during picking.

4.4 Conveying appliance

The conveyor system achieves a slope transportation of 39.94°through the design of a drive motor, transmission shaft, and synchronous belt. This mechanism can adjust harvesting angles while maintaining stable slope support.The system utilizes dual-angle adjustable electric actuators to maintain the blade height at 1.5cm above the ground, allowing fordynamic adjustment of cutting blade elevation relative to the inclined surface. This height adaptation ensures optimal performance at different terrain elevations. The front-end adopts two adjustable auxiliary support wheels, which improves the slope stability without compromising structural integrity.

The conveyor system consists of a conveyor belt, a drive shaft, an idler, and a motor. This mechanism mainly transports vegetables upward into the harvesting frame. The system operates through a drive shaft driven by a motor that rotates at a constant angular velocity. The drive shaft (main shaft) is connected to the driven shaft (secondary shaft) at its lower end. The rotation of the shaft drives the secondary shaft through friction between the conveyor belt and shaft components, thereby achieving upward material conveying.

4.5 Control system design

We use the ESP32-DevKitC-32E development board. ESP32-DevKitC-32E is a powerful and widely used multifunctionalWiFi+BT+BLE MCU module. It can be used in low-power sensor networks and high-demand tasks such as voice encoding, audio streaming, and MP3 decoding.ESP32 is a cost-effective, low-power microcontroller developed by Espressif Systems (ESPRESSIF) in China, following the ESP8266 chip, with integrated Wi-Fi and Bluetooth capabilities. It serves as a management module that combines an antenna, RF balun, power amplifier, low-noise amplifier, filter, and power management. This solution occupies minimal space on the printed circuit board. This boarduses the 40nm low-power technology of TSMCand incorporates a 2.4GHz dual-mode Wi-Fi and Bluetooth chip,providing optimal power and RF performance. It can ensure secure, reliable operation and scalability, making it suitable for a wide range of applications.

This module is powered by the ESP32-DOWDO6 chip and has scalable and adaptive capabilities. The dual CPU cores can be controlled or poweredseparately. The clock frequency is in the range of 80MHz -240MHz. Users can disable the CPU power supply and utilize the low-power coprocessor to continuously monitor peripheral status changes or detect analog signal thresholds.ESP32 also integrates a variety of peripherals, including capacitive touch sensors, Hall sensors, low-noise sensor amplifiers, SD card interfaces, Ethernet interfaces, high-speed SDI/O SPI, UART, I2S, and I2C.

For software development, we use ArduinoIDE for programming and remote IoT control by using the Blinker Lighting Technology APP on mobile devices in Wi-Fi mode. The ArduinoIDE program integrates functions including serial port command reception, motor control through buttons and sliders, and automatic cruise control tasks. The system operates in two modes: Wi-Fi control and screen control. In Wi-Fi mode, the program retrieves connection details from the Taojingchi serial port screen and initiates remote control through Blinker after confirming the connection. In screen control mode, the program continuously reads 10-byte data packets from the serial port screen for device control. The first byte is the frame header (0x55), and the last three bytes form the frame footer (0xff 0xff 0xff).Frame header/footer verification is used to enhance serial communication accuracy. It is worth noting that the screen control mode has autonomous cruise function. Users can customize the plowing range by inputting length and width measurements on the screen. This program can automatically calculate straight-line cruise duration and steering frequency based on input data, starting position, and cruise speed, thereby enabling self-guided harvesting. Partial control code is as follows.

```
intcruising_time;
inttrun_times;
int length;
int width;
float Max_speed = measure;
cruising_time =
length/(ubuffer[6]/255*Max_Speed)*1000;
lines = width/Body width;
void trun_right()
{
mcp.digitalWrite(0,HIGH);
mcp.digitalWrite(2,HIGH);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
analogWrite(,);
analogWrite(,);
delay();
mcp.digitalWrite(0,LOW);
mcp.digitalWrite(2,LOW);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
}
void trun_left()
{
mcp.digitalWrite(0,HIGH);
mcp.digitalWrite(2,HIGH);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
analogWrite(,);
analogWrite(,);
delay();
mcp.digitalWrite(0,LOW);
mcp.digitalWrite(2,LOW);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
}
void AutoCrusing_ByRight(intcruising_time,int
lines)
{
inti = 0;
while(i＜lines)
 {
mcp.digitalWrite(0,HIGH);
mcp.digitalWrite(2,HIGH);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
analogWrite(,ubuffer[6]);
analogWrite(,ubuffer[6]);
delay(cruising_time);
mcp.digitalWrite(0,LOW);
mcp.digitalWrite(2,LOW);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
i++;
if(i＜lines){
trun_left();
}
mcp.digitalWrite(0,HIGH);
mcp.digitalWrite(2,HIGH);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
analogWrite(,ubuffer[6]);
analogWrite(,ubuffer[6]);
delay(cruising_time);
mcp.digitalWrite(0,LOW);
mcp.digitalWrite(2,LOW);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
```

```
i++;
if(i<lines){
trun_right();
}
 }
}
void AutoCrusing_ByLeft(intcruising_time,int lines)
{
inti = 0;
while(i<lines)
 {
mcp.digitalWrite(0,HIGH);
mcp.digitalWrite(2,HIGH);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
analogWrite(,ubuffer[6]);
analogWrite(,ubuffer[6]);
delay(cruising_time);
mcp.digitalWrite(0,LOW);
mcp.digitalWrite(2,LOW);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
i++;
if(i<lines){
trun_right();
}
mcp.digitalWrite(0,HIGH);
mcp.digitalWrite(2,HIGH);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
analogWrite(,ubuffer[6]);
analogWrite(,ubuffer[6]);
delay(cruising_time);
mcp.digitalWrite(0,LOW);
mcp.digitalWrite(2,LOW);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
i++;
if(i<lines){
trun_left();
}
 }
}
void AutoCruising_ByLine(intcruising_time){
mcp.digitalWrite(0,HIGH);
mcp.digitalWrite(2,HIGH);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
analogWrite(,ubuffer[6]);
analogWrite(,ubuffer[6]);
delay(cruising_time);
mcp.digitalWrite(0,LOW);
mcp.digitalWrite(2,LOW);
mcp.digitalWrite(1,LOW);
mcp.digitalWrite(3,LOW);
}
if(lines<=1){
AutoCruising_ByLine(cruising_time);
}
else{
}
```

5. Conclusion

The designed soil shaking spinach multifunctional automatic harvester integrates automatic cutting, soil shaking and cleaning, conveying and spinach collection, and has a high degree of functional integration. Only one machine is needed to achieve full process harvesting of spinach. The soil shaking device transmits the output torque to the double crank mechanism through a synchronous wheel drive assembly. This mechanism drives the shaking claws to rotate around the fixed shaking claws, effectively removing soil and residual leaves from the harvested spinach.At the same time, the assembly conveys the spinach upward onto the conveyor belt. The through-shaft design of the single motor ensures a more stable and reliable conveying process.

The multifunctional automatic soil-shaking spinach harvester can significantly reduce labor costs and manual input in the cultivation of spinach and other leafy vegetables. Through enabling full automation of the harvesting process, it helps minimize labor expenses while improving harvesting efficiency. At the same time, the harvester can collect vegetables and adjust the cutter height above the ground, allowing it to accommodate the harvesting of various vegetable types.

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