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Design of a Small Pure Electric Tracked Tillage Machine

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Abstract

To address the challenges of complex terrain, fragmented plots, varying slopes, and low levels of agricultural mechanization in hilly and mountainous areas of my country, a small, all-electric tracked tillage machine suitable for unmanned aerial vehicle (UAV) lifting and transportation was designed. Based on the characteristics of the hilly and mountainous operating environment, design requirements for the machine in terms of slope stability, passability, lightweight design, and intelligent operation were proposed. Through comparative analysis of the walking system and rotary tillage system structures, a triangular tracked walking device was selected to improve the machine's adhesion and adaptability to complex terrain. The selection and calculation of track parameters, drive motor, and reducer were completed, and the power of the rotary tillage motor and battery capacity were rationally matched. Based on this, the finite element method was used to model and simulate the vehicle frame structure. The model was reasonably simplified and shell element meshing was adopted to improve computational efficiency and accuracy. The results show that the tillage machine, while meeting lightweight requirements, possesses good slope stability and obstacle-crossing ability, effectively adapting to the complex operating environment of hilly and mountainous areas. This research provides a reference for the electrification and intelligent development of agricultural machinery equipment in hilly and mountainous areas.

Keywords

Hilly and Mountainous Areas; Pure Electric Tillage Machine; Tracked Chassis; Structural Design.

1. Introduction

Hilly areas account for 34.62% of the country's arable land and are important production bases for grain, oil, fruits, vegetables, and tea. However, they also represent the biggest weakness in my country's agricultural mechanization and modernization. Constrained by complex geographical conditions, fragmented farmland, continuously varying slopes, and undulating terrain, coupled with an aging population and the migration of young laborers to cities for work, the level of agricultural mechanization in this region lags far behind that of the plains. It has long faced prominent problems such as a lack of available machinery, difficulty in using organic machinery, and challenges in accessing the hilly areas and fields.

Currently, the most commonly used tillage machinery in hilly and mountainous drylands in China is small mountain tractors and micro-tillers. For example, Jia Guangpan et al. [1] designed a fuel-powered single-wheel micro-tiller, which is compact in shape and improves the ability to move and

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pass through narrow terrains such as mountainous areas. However, the single-wheel structure has the disadvantage of poor lateral stability. Yang Xiao et al. [2] designed a wheeled electric micro-tiller, which integrates the start/stop, speed adjustment, electric steering and rotary tillage function buttons into the handrail area, which improves the machine's control performance and intelligence level compared with traditional wheeled micro-tillers. However, the operator still needs to hold the handrail and walk to follow during operation, and the level of automation is limited. Chen Pinglu et al. [3] designed a vertical micro-tiller composed of a spiral blade, reducer, tillage depth control mechanism and fertilization mechanism to address the problems of high machine body and unstable tillage depth of traditional micro-tillers. The average tillage depth can reach 106mm, but the overall power is small and it is only suitable for orchard operations in hilly and mountainous areas.

Hilly and mountainous dry land is mostly sloping, and the working area of each plot is usually small. Continuous rotary tillage often requires frequent transfers between plots, which may involve crossing terrain obstacles such as field ridges and irrigation ditches. Wheeled machinery has a small contact area with the ground, posing a risk of tipping over when crossing obstacles such as field ridges and ditches. Traditional fuel-powered tillage machinery has problems such as high noise levels and continuous emission of environmental pollutants during operation. To solve the above problems, this paper designs a small, pure electric rotary tiller, a deep rotary tiller, which can adapt to the complex terrain of hilly and mountainous areas and can tillage to a depth of up to 8 cm.

2. Design Requirements for Tillage Machines

The small, pure electric tillage machine designed in this paper, which can be transported by drone, is mainly used in hilly and mountainous areas where the development of agricultural mechanization in my country is relatively lagging. This region suffers from fragmented and scattered land plots, significant topographic relief, and underdeveloped agricultural infrastructure [4], making it difficult for agricultural machinery to pass through and relocate. Furthermore, sloping farmland accounts for a large proportion of the cultivated land in this region; for example, in Sichuan Province, sloping land with an angle of 6° to 15° accounts for as much as 43.61%. Therefore, based on the project requirements and the conditions of cultivated land in hilly and mountainous areas, the following requirements are proposed for the design of the pure electric tracked tillage machine:

(1) Good stability on slopes. The tillage machine should have good driving performance on farmland with a slope angle not exceeding 20°, without the risk of overturning or slipping.

(2) High passability. The tillage machine should have a compact structure, move quickly, and be flexible in steering, with high passability and a small ground pressure, possessing a certain ability to overcome obstacles and ditches to adapt to the complex operating environment of hilly and mountainous areas.

(3) Lightweight design. The project stipulates that the weight of the agricultural machinery module in a single drone transport mission cannot exceed 115 kg.

(4) Improved intelligence and ease of operation. Operators can use a remote control while standing in the work area to control the movement, steering, speed adjustment, and rotary tillage of the agricultural machinery, reducing the labor intensity of farmers in agricultural production.

2.1 Overall Structure and Working Principle of Tillage Machine

2.1.1 Overall Structure of Tillage Machine

Based on the design requirements of tillage machines and referencing other types of tillage machines on the market, a small, pure electric tracked tillage machine suitable for drone lifting was designed. Figure 1 shows the overall structure of the tillage machine, which mainly consists of two working modules: a tracked power chassis and a rotary tiller. The power chassis provides the power required for vehicle movement. There are three attachment points between the rotary tiller and the tracked power chassis. The lower attachment points are connected by flat-headed, perforated pins, while the

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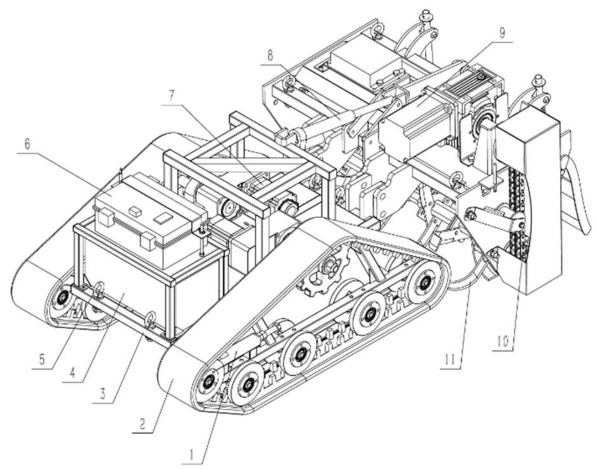
upper attachment points are connected via an electric push rod. To meet the needs of drone lifting and transportation, both the power chassis and the rotary tiller are equipped with lifting rings.



1) Track tensioning device; 2) Track; 3) Chassis frame; 4) Power battery; 5) Eye bolts; 6) Electrical control box; 7) Travel motor; 8) Electric push rod; 9) Rotary tiller motor; 10) Chain; 11) Rotary tiller blades

Figure 1. Small Pure Electric Tracked Tillage–Land Preparation Machine Suitable for UAV Lifting

2.1.2 Working Principle of Tillage Machine

The tillage machine employs a distributed motor drive, resulting in smoother power output. The walking motors on both sides of the power chassis achieve speed reduction and torque increase through reducers, driving the drive wheels to wrap around the tracks. The machine moves using the reaction force of the ground on the tracks. Compared to tillage machines using traditional power take-off shafts (PTO), the tillage machine designed in this paper features an independent motor drive for the rotary tiller, enabling independent control of the walking system and the rotary tillage system. The tillage machine operates in two modes: non-operational driving and operational driving. In non-operational driving, the operator sends corresponding commands to the control module in the tillage machine's electrical control box via remote control to control the machine's forward, reverse, steering, and gear shifting. During this time, the rotary tiller retracts upwards due to the retraction of the electric push rod, and the rotary tiller motor remains stationary. During operation, the rotary tiller motor drives the cutter shaft to rotate, and the speed control knob allows the output speed to be adjusted within the range of 0-300 r/min. The electric push rod extends, causing the rotary tiller to be slowly lowered and gradually come into contact with the soil. When it is lowered to the appropriate soil depth, the machine is moved forward to perform rotary tillage. Figure 2 and Figures 3 are schematic diagrams of the rotary tiller's posture under non-operational and operational driving conditions, respectively.

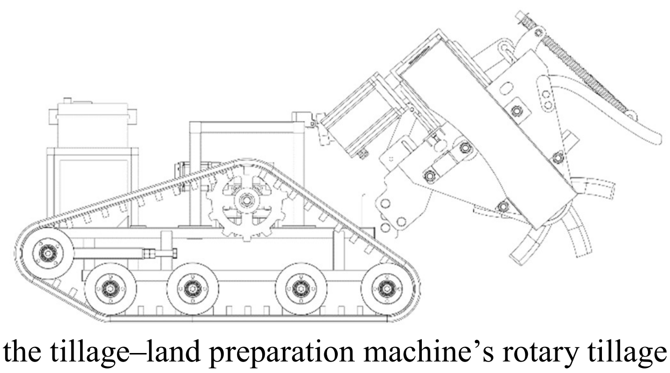


Figure 2. Posture of the tillage–land preparation machine's rotary tillage implement in normal traveling state

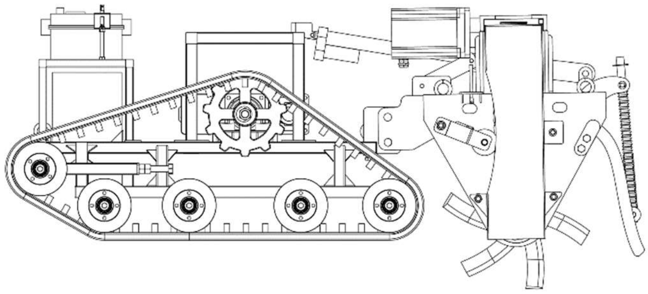


Figure 3. Posture of the tillage–land preparation machine's rotary tillage implement in operating traveling state

3. Overall Design of the Machine

3.1 Walking System

3.1.1 Selection of the Running Gear for the Powered Chassis

The power chassis of a tillage machine serves as the basic load-bearing and power platform for the entire machine, primarily providing walking power and traction for rotary tillers. Agricultural machinery chassis have three types of walking devices: wheeled, walking, and tracked. Wheeled and tracked chassis are common in hilly areas [5,6]. A comparison of the advantages and disadvantages of wheeled and tracked chassis is shown in Table 1. As can be seen from the table, small fuel-powered micro-tillers and other wheeled tillage machinery have certain advantages in cultivating plains or flat land. However, when operating on sloping farmland in hilly and mountainous areas, the contact area between the wheeled walking device and the ground is relatively small, making it prone to slippage, lateral slippage, and insufficient traction. In contrast, tracked walking devices, by increasing the contact area, can reduce ground pressure and improve ground adhesion, resulting in better stability during operation. Furthermore, when the tillage machine crosses obstacles such as field ridges and ditches during relocation, the passability of wheeled walking devices is inferior to that of tracked walking devices. To improve the driving stability and operational safety of the tillage machine, this paper proposes a tracked walking device for the chassis design of the tillage machine.

Table 1. Comparison of common walking mechanisms of tillage machines

Walking device	Wheel	Track
advantages	a. Simple structure and low cost b. High driving speed c. Easy to replace and maintain	a. Grounding specific voltage small b. High passability c. High load-bearing capacity
shortcomings	a. High ground specific voltage b. Poor passability c. Limited carrying capacity	a. Complex structure b. Slow driving speed c. Large turning radius

As shown in Figure 4, there are currently three main types of tracked walking devices: ordinary, inverted trapezoidal, and triangular [7]. Ordinary tracked chassis are more common, with strong traction, but slow travel speed and high energy consumption. They are mostly used in agricultural machinery such as harvesters and engineering machinery such as excavators. Inverted trapezoidal type has a large approach angle and departure angle, so it has strong off-road capability and high driving stability, but it is difficult to maintain and has high energy consumption. It is mostly used in the military field [8]. Triangular type has strong mobility, low ground pressure, and low risk of soil compaction. It can travel on soft soil, mud, and other soft ground [9,10]. After comparison, the triangular tracked walking device is selected for tillage machines.

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(a) Normal type

(b) Inverted trapezoid

(c) triangle

Figure 4. Common tracked running mechanisms

3.1.2 Tracked Travel Mechanism Parameter Calculation

Tracked systems typically consist of three wheels and one track: a drive sprocket, a track roller, a tensioner, and a rubber track. The drive sprocket, located on the upper frame, supports the upper track and limits vertical vibration. The track roller bears the weight of the machine and restricts the lateral movement of the track guide teeth, preventing the track from slipping off during steering or side-slipping. They are usually symmetrically arranged on both sides of the track, with the spacing related to the track pitch. Adjusting the tension bolts moves the tensioner forward, tensioning the rubber track and guiding it to move normally without slipping.

The track pitch is a key structural parameter affecting track drive engagement performance and driving stability. Its proper design is crucial for ensuring the machine's passability and operational stability. The formula for calculating the track pitch L is as follows:

$$L = \lambda \sqrt[4]{m} \tag{1}$$

In the formula, m represents the total machine weight (kg); λ is the pitch design coefficient, typically ranging from 15.0 to 17.5.After attaching the rotary tiller attachment, the total weight of the rotary tiller is approximately 230 kg, resulting in a track pitch of 60 mm.

The track ground contact length and width reflect the contact area between the track and the ground. Their values affect the track ground contact length and ground pressure. Appropriate values will improve the rotary tiller's passability and stability. Based on empirical formulas, the calculation formulas for the track ground contact length l and width b are as follows:

$$b = (0.9 \sim 1.2) \times 209 \times 1.07 \sqrt[3]{m \times 10^{-3}} \tag{2}$$

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$$\frac{b}{l} = c \tag{3}$$

In the formula, c is a proportionality coefficient, typically ranging from 0.2 to 0.3. The calculated ground contact length is 740 mm, and the track width is 150 mm.

Track ground pressure is an important parameter for measuring the risk of soil compaction. The allowable ground pressure for small agricultural machinery is 30 kPa [11]. The formula for calculating ground pressure is as follows:

$$P = \frac{mg}{2b} \tag{4}$$

The calculated grounding specific voltage is 10.15 kPa, which meets the design requirements.

3.1.3 Selection of Walking Motor and Reducer

When a tillage machine moves, it must consider both the rolling resistance of the road surface and the influence of the slope. This paper takes a slope limit of 20° and a maximum forward speed design value of 2.5 km/h. Ignoring the influence of air resistance, the formula for calculating the overall driving force is as follows:

$$F_k = f_n G + fGcos\alpha + Gsin\alpha + \delta G \tag{5}$$

In the formula, $f_n$is the internal friction coefficient, ranging from 0.04 to 0.08; f is the driving resistance coefficient, taken as 0.15; and δ is the inertial resistance coefficient, ranging from 0.01 to 0.02. The calculated driving force required on one side of the entire machine is approximately 657.5 N. Therefore, the formula for calculating the torque of the single-side drive wheel is as follows:

$$T = \frac{1}{2} F_k r \tag{6}$$

The calculated torque of the drive wheel on one side is 69.04 N·m.

The formula for calculating the maximum forward speed of a vehicle is as follows:

$$V_{max} = n_z \frac{2\pi}{60} r \tag{7}$$

In the formula, n_z is the driving wheel speed, r/min; r is the driving wheel pitch circle radius, m.

The calculated drive wheel speed is 59.9 r/min, and the motor speed is 2400 r/min. Therefore, the required single-side motor power is calculated using the following formula:

$$P_e = \frac{K_x T n_z}{9550 \eta_1 \eta_2} \tag{8}$$

In the formula, K_x is the power reserve coefficient of the walking motor, which is taken as 1.3; η_1 is the transmission efficiency of the reducer, which is taken as 0.95; and η_2 is the walking efficiency of the tracked chassis, which is taken as 0.9.

Calculations show that the single-sided motor power is approximately 658.42W, therefore a 750W DC brushless motor is selected. Specific parameters are shown in the Table 2.

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Table 2. Parameters of the walking motor of the tillage machine

Motor parameters	Value
Rated voltage	48V
Rated current	18A
Rated speed	3000r/min
Rated torque	2.38 N·m
Rated power	750 W
Weight	4.5 kg

The formula for calculating the reduction ratio of the travel motor reducer is as follows:

$$i_1 = \frac{n}{n_{out}} \tag{9}$$

After calculation, the reduction ratio is taken as 40, and a reducer with a 1:40 reduction ratio is selected. The specific parameters are shown in the Table 3.

Table 3. Parameters of Walking Motor Reducer

Reducer parameters	Value
Reduction ratio	1:40
Rated load	69.72 N·m
Maximum load	139.4 N·m

3.2 Rotary Tillage System

When a tillage machine is in operation, the rotary tiller motor drives the cutter shaft to complete the rotary tillage operation. Its power primarily depends on the power consumption during the rotary tillage process. From the perspective of stability and reliability of rotary tillage, a certain power reserve is reserved when selecting a motor; that is, the motor's rated power should be greater than the power consumed during rotary tillage. The power consumed during rotary tillage is generally calculated using the following empirical formula:

$$\begin{cases} N = 0.1K_\lambda dVB_1 \\ K_\lambda = K_g K_1 K_2 K_3 K_4 \end{cases} \tag{10}$$

In the formula, d represents the rotary tillage depth, with a design value of 8cm; V is taken as the maximum value of 0.69, and according to the design requirements, d should not be less than 8cm, so it is taken as 10cm. B_1 is designed to be 0.8m, also based on the maximum value of 0.69. The values of each coefficient are taken with reference to the agricultural machinery handbook. Based on actual operating conditions, K_g is taken as 13, $K_1$1 as 0.8, K_2 as 0.95, K_3 as 0.8, and K_4 as 0.66, resulting in $K_\lambda \approx 5.22$ N/cm^2, $N \approx 2.88$kW.

The formula for calculating the rated power P_T of a rotary tiller motor is as follows:

$$P_T \geq K_y \frac{N}{\eta_3} \tag{11}$$

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In the formula, K_y is the power reserve coefficient of the rotary tiller motor, which is taken as 1.3; η_3 is the chain drive efficiency, which is taken as 0.95. The calculated rated power of the rotary tiller motor is 3.94kW. A 4kW DC motor is selected, and its parameters are shown in Table 4.

Table 4. Rotary Tiller Motor Parameters

Motor parameters	Value
Rated power	4 kW
Rated torque	11.14 N·m
Rated speed	3000 r/min
Rated current	91 A
Rated voltage	48 V
Weight	10 kg

The rotational speed of the cutter shaft is one of the important factors of soil crushing effect and rotary tillage power consumption. When the cutter shaft speed is high, the rotary tillage soil crushing effect is better, but the rotary tillage power consumption will also increase. When the rotary tillage blade moves, its absolute motion is the combination of the horizontal motion of the whole machine and the rotational motion of the cutter shaft. If the rotation direction of the cutter shaft is the same as the horizontal motion direction of the whole machine, the blade rotates forward; otherwise, the blade rotates in reverse. Considering that reversing will increase power consumption and is suitable for fine stubble removal operations, the rotary tillage blades in this paper are operated in a forward rotation mode. When the rotary tillage cutter shaft speed is 160~300, the machine has a good working effect in actual operation [86]. The rated speed of the rotary tillage motor is 3000. The maximum speed of the cutter shaft designed in this paper is 300. Therefore, the reduction ratio of the rotary tillage motor reducer is , and the specific parameters are shown in Table 5.

Table 5. Parameters of Rotary Tiller Motor Reducer

Reducer parameters	Value
Reduction ratio	1:10
Rated load	80 N·m
Maximum load	160 N·m

3.3 Battery Parameter Calculation

The battery is the power source for the tillage machine's movement and operation. Its parameters determine the tillage machine's range. In actual operation, the tillage machine can cover 1.5 acres per trip. The battery capacity calculation formula is as follows:

$$C_r = \frac{P_a S_h}{U_e V} \times 1000 \tag{12}$$

In the formula, P_a is the rated power of the vehicle, 5.5kW; S_h is the driving range, 1.5km; U_e is the rated voltage of the battery, 48V; taking the maximum value of 0.69, the power required for a single operation is calculated to be 104Ah. Comparing the common batteries on the market, lithium batteries have advantages in terms of energy storage density, charging efficiency and service life[12]. Therefore, this paper selects a 48V 104Ah lithium battery as the power source for the vehicle.

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4. Stability Test of Tillage Depth

This experiment was conducted in accordance with the relevant provisions of the "Rotary Tiller" Agricultural Machinery Promotion and Appraisal Outline issued by the Ministry of Agriculture and Rural Affairs. Prior to the experiment, no tillage work was carried out on the experimental field. Rotary tillage was performed in farmland in Jingshi Town, Dachuan District, Dazhou City. After the operation, a region 11 meters long and one working width was designated for data collection. Within this region, the tillage depth was measured at 1-meter intervals along the direction of the tiller's movement. A total of three experiments were conducted, and the results are recorded in Table 6. The unit of experimental data is centimeters. Figure 5 shows the rotary tillage operation of the tiller.

Figure 5. Common tracked running mechanisms

Table 6. Tillage depth test data recording

Measurement points	First test	Second test	Third test
1	8.1	10	9.7
2	8.7	9.6	9.5
3	8.4	8.5	9.8
4	9.8	9.5	10.2
5	8.6	9.5	10.5
6	8.2	9	10.3
7	7.4	10	12
8	8.7	10	9.5
9	9.4	9.7	9.8
10	7.1	9.4	9.7
11	9.2	9.5	10.2

Substitute the tillage depth measurements from 11 points in each experiment into formula (13) to calculate the average tillage depth.

$$\overline{L} = \frac{\sum_{i=1}^{n} L_i}{n} \tag{13}$$

In the formula: $\overline{L}$ represents the average tillage depth in cm; L_i represents the tillage depth value at the i-th point in cm; and n represents the number of tillage depth measurement points.

The average tillage depths of the three groups of experiments were calculated and rounded to 8.51cm, 9.52cm, and 10.11cm, respectively, all meeting the design tillage depth values required above. The first experiment used data from a school experimental field, while the second and third experiments used data from farmland in Dazhou City. The tillage depth stability coefficients of the three groups of experiments were calculated according to formula (14):

$$\begin{cases} S_L = \sqrt{\frac{\sum_{i=1}^{n}(L_i - \bar{L})}{n-1}} \\ S_V = \left(1 - \frac{S_L}{L}\right) \times 100\% \end{cases} \tag{14}$$

In the formula: S_L represents the standard deviation of tillage depth, in mm; S_V represents the tillage depth stability coefficient.

The tillage depth stability coefficients of the first to third groups of experiments, after rounding, were 90.48%, 95.27%, and 92.98%, respectively, indicating that the tillage machine's performance was relatively stable.

5. Conclusion

This paper addresses the needs of agricultural machinery operations in complex hilly and mountainous terrain by designing a small, pure electric tracked tillage machine and systematically analyzing its structural parameters and system performance. The study proposes design requirements for the machine's stability, passability, and lightweight design, determining the adoption of a tracked chassis structure and optimizing key parameters. It also achieves independent drive and power system matching between the walking system and the rotary tillage system. Field test results demonstrate that the machine possesses good operational capabilities, meeting the needs of hilly and mountainous terrain operations, and has certain application value. Future research will further improve the machine's overall performance through multi-condition testing and multi-factor optimization.

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