DESIGN OF A NEW PURELY ELECTRIC AGRICULTURAL MACHINE AND ANALYSIS OF ITS OBSTACLE-CROSSING PERFORMANCE

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An electric agricultural machine equipped with a new balancing mechanism is designed to address the current operational difficulties of electric agricultural machines on complex terrain. Firstly, the principle of the mechanism is discussed, and the steering mode is analyzed. Secondly, using Unigraphics NX simulation software, the new balanced mechanism electric agricultural machine is compared with the conventional one-piece electric agricultural machine in obstacle-crossing and pit-passing simulation experiments. Finally, the sample machine was built and experimented. The results show that the new pure electric agricultural machine has good adaptability and passing ability under variable road conditions.

Keywords: electric agricultural machinery, complex terrain, new balancing mechanism, simulation

1 Introduction

Traditional oil - fired agricultural machinery, while promoting agricultural production efficiency, gradually reveals some shortcomings[1-2]. From an environmental pollution perspective, fuel - fired agricultural machinery emits many pollutants during operation. In addition, the engine structure of fuel-fired agricultural machinery is complex, which makes maintenance work cumbersome and costly. In the power performance and adaptability, in the face of complex terrain

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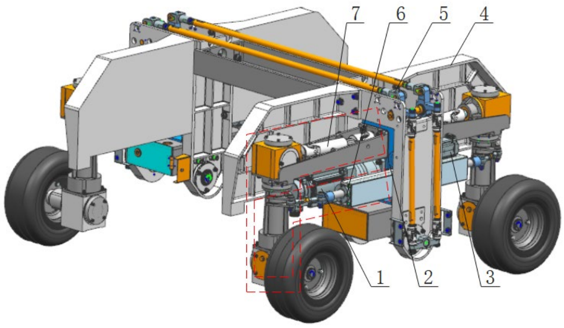
and special climatic conditions, the power output of fuel farm machinery is often difficult to meet the demand. To address these issues, agricultural mechanisation is gradually transforming to electric farm machinery. This change will not only help to reduce the environmental impact of agricultural production, but also increase the efficiency and sustainability of agricultural production [3-6].

As electric agricultural machinery increasingly gains widespread attention, domestic researchers have extensively studied electric machinery technologies. For example, Zeng Junhao's team developed a remotely controllable crawler mower with a minimum turning radius of 403.55 mm and maximum longitudinal and transverse climbing angles of 36°and 41°, respectively[7]. Jia Fang's team designed a farming vehicle traction load carrier based on an electric drive system for the problems of complicated mechanical structure and single function of traditional agricultural vehicle traction load carrier, taking the electric drive system with integrated engine-electric axle as the core unit, and using the steering traction frame to achieve the automatic following steering of the front axle platform to realize the maximum loaded traction force of 150 kN [8]. Qi Xingyuan's team developed an electric remote-controlled tea garden management machine with a pure electric design. The machine's walking track consists of small triangular tracks connected by belts and driven by motors to achieve synchronized movement. Both tracks move in sync during forward or backward motion, while steering is accomplished by the movement of a single-side track [9]. At present, the agricultural machinery developed at home and abroad is only applicable to plain areas or specific sites, however, the domestic hilly and mountainous areas account for about 43% of the total area of the country, existing machinery thus fails to meet the operational requirements of such complex terrains [10-11]. Therefore, developing agricultural machinery adaptable to complex terrains is of great significance.

In this paper, based on the existing research [12-13], the drive structure and steering mechanism of the electric farm machine are optimised for the needs of agricultural mechanisation in the hilly areas of mountains and forests, and a new type of balancing mechanism is developed to solve the problem that the farm machine is unable to turn around with a tight turning radius in a narrow field and cannot keep balance on complicated road surfaces, which is difficult to meet the mechanised operation [14-16].

2. Structural Design of the Electric Agricultural Machine

As shown in Fig.1, the new pure electric agricultural machine mainly consists of the drive motor, gear transmission box, steering motor, frame, balancing mechanism, steering mechanism, and driving mechanism. The left and right sides of the body have the same structure, composed of the drive motor, steering motor, gear transmission box, drive mechanism, and steering mechanism, and the left and right sides of the body are connected through the frame and the balancing mechanism. Based on the research literature [13], this new agricultural machine has improved the driving and steering mechanisms to solve the problem of complex operation in hilly areas.

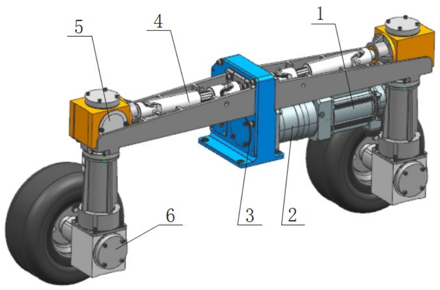


1. drive motor 2. gear transmission box 3. steering motor 4. frame 5. balancing mechanism 6. steering mechanism 7. driving mechanism

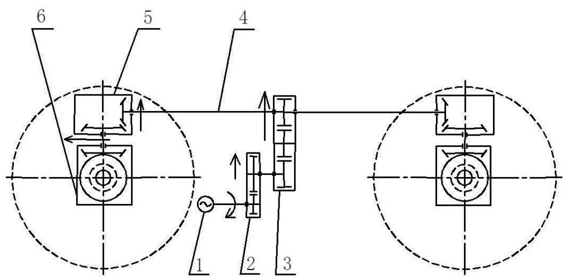
Fig. 1. Pure electric farm machinery structure

2.1 Structural Design of the Drive Mechanism

The drive mechanism of the pure electric agricultural machine primarily consists of the drive motor, motor reducer, gear transmission box, drive shaft, right-angle transmission box, and wheel-side right-angle transmission box, as shown in Fig. 2 (a).



(a) Three-dimensional diagram of the



(b) Motion diagram of the drive structure drive structure

1. drive motor 2. motor reducer 3. gear transmission box 4. drive shaft 5. right-angle transmission box 6. wheel-side right-angle transmission box

Fig. 2. Drive mechanism

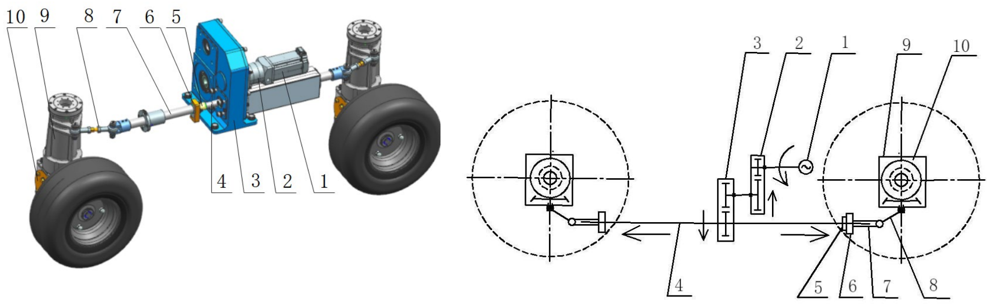
As shown in Fig. 2 (b), the power transmission path of the drive mechanism is as follows: drive motor → motor reducer → gear transmission box→ drive shaft → right-angle transmission box → wheel-side right-angle transmission box → wheels. The right-angle transmission box and the wheel-side right-angle transmission box merely change the direction of the power transmission. The motor reducer and gear transmission box are the key factors determining the wheel speed. It is known that the transmission ratio of the gear transmission box is i_1 and the reduction ratio of the motor reducer is i_2; if the output speed of the drive motor is n_1, then the rotational speed n_v of the front and rear wheels on the same side is:

$$n_v = \frac{n_1}{i_1 i_2}$$

(1)

2.2 Structural Design of Steering Mechanism

The steering mechanism of the pure electric agricultural vehicle consists of a steering motor, motor reducer, gear transmission box, lead screw, copper nut, guide block, guide rod, steering linkage, upright column, and wheel-side right-angle transmission box, as shown in Fig. 3 (a).



(a) Steering structure three-dimensional drawing (b) Motion diagram of steering structure

1. steering motor 2. motor reducer 3. gear transmission box 4. lead screw 5. copper nut 6. guide block 7. guide rod 8. steering linkage 9. upright column 10. wheel-side right-angle transmission box

Fig. 3. Steering mechanism

As shown in Fig. 3 (b), the working principle of the steering system: the steering motor generates power, which is transmitted to the lead screw through the motor reducer and gear transmission box, prompting the lead screw to rotate. As the copper nut, guide block, and guide rod are fixedly together, when the motor drives the lead screw to rotate, the copper nut will make a linear reciprocating motion along the lead screw, which will push the guide rod to make a linear reciprocating motion. The guide rod is connected to the upright column via the steering linkage, and the upright column is fixed to the wheel-side transmission box. The linear reciprocating motion of the guide rod causes the steering linkage to rotate the upright column, achieving wheel steering.

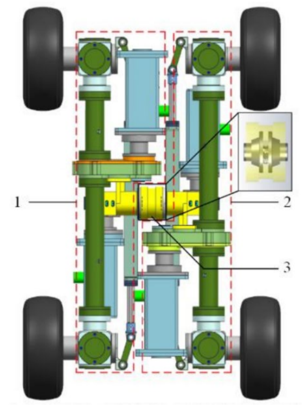
The gear transmission box contains two spur gears with the same number of teeth, resulting in a transmission ratio 1. The transmission ratio of the motor reducer is i_3, and if the output speed of the steering motor is n_2, the lead screw rotational speed n_w is:

$$n_W = \frac{n_2}{i_3} \tag{2}$$

2.3 Balancing mechanism

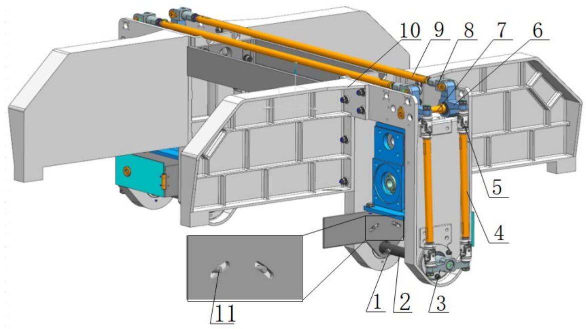
As shown in Fig. 4, based on the research experience in the literature [13], this paper develops a new type of balancing mechanism to enhance the adaptive performance of pure electric agricultural machines in complex road conditions and the ability to cross obstacles. The mechanism can be better adapted to operate in hilly areas and has a simple structure.

As shown in Fig. 5, the new balancing mechanism mainly consists of shoulder screws, swing arm axis, swing arm, vertical bar, universal joint coupling, fork rocker arm, mandrel, Y-type connector, horizontal bar, frame, limit screws, and so on. The body consists of the drive mechanism and steering mechanism, the unilateral body and the swing arm axis are fixedly connected by two shoulder screws, the swing arm axis and the swing arm are fixed by a flat key, a universal joint coupling connects the vertical bar and the swing arm, the fork-shaped rocker arm is mainly to change the direction of force transmission, and is connected with the Y-type connector at one end, and the other end is connected with the vertical bar through the universal joint coupling, and the horizontal bar is fixedly connected with the Y-type connector. The fork-shaped rocker arms at the left and right ends of the frame are connected to the frame through a mandrel, and due to the limitation of the mechanical structure, the fork-shaped rocker arms only rotate around the mandrel when they are subjected to the force of the horizontal bar or the vertical bar. The frame is not fixedly connected to the body, and when the vehicle crosses an obstacle, the frame rotates at a certain angle relative to the body, and a limited screw limits the maximum rotation angle of the frame.



1. Left vehicle body 2.Right vehicle body 3.Planetary gear differential mechanism

Fig. 4. Literature [13] Balancing mechanism



1. shoulder screws 2. swing arm axis 3. swing arm 4. vertical bar 5. universal joint coupling 6. fork rocker arm 7. mandrel 8. Y-type connector 9. horizontal bar 10. frame 11. limit screws

Fig. 5. New balancing mechanism

As shown in Fig 6, O is the rotation center of the swing arm of the left side body, A_1 and A_2 are the connection points of the swing arm and the universal joint coupling, B_1 and B_2 are the center points of the universal joint coupling between the vertical bar and the swing arm, C_1 and C_2 are the centers of the universal joint coupling between the upper end of the vertical bar and the fork-shaped rocker arm, D_1 and D_2 are the connection points of the fork-shaped rocker arm and the universal joint coupling, and O_1 and O_2 are the rotation centers of the fork-shaped rocker arm.

When a single wheel on the front side of the vehicle crosses an obstacle, that side of the vehicle's body drives the swing arm axis to rotate. Since the swing arm is fixedly connected to the swing arm axis, the swing arm rotates around the swing arm axis at point O. The vertical bar B_1C_1 moves upwardly under the action of the thrust generated by the rotation of the swing arm. At this time, the fork-shaped rocker arm rotates upwardly clockwise around O_1. A portion of the movement will be canceled out because the vertical bar is equipped with a Cardan joint coupling on both ends of the vertical bar. At the same time, under the upward thrust of the vertical bar B_1C_1, the frame rotates upward by a certain angle around the swing arm axis O point, which produces a tendency for the vertical bar B_2C_2 to move upward.

Still, at this time, the horizontal bar moves to the vertical bar B_2C_2 side under the action of the vertical bar B_1C_1 and the fork-shaped rocker arm above it. Then, the horizontal bar produces a tendency of downward movement in the vertical bar B_2C_2 through the fork-shaped rocker arm above the vertical bar B_2C_2. With the coordination of the universal joint couplings at both ends of the vertical bar B_2C_2, the upward and downward movement tendencies of the vertical bar B_2C_2 are canceled out so that the swinging arm on the obstacle-free side always remains horizontal. Therefore, the wheels on the obstacle-free side always stay in contact with the road surface.

Similarly, the motion of the rear side counterbalance mechanism is opposite that of the front side counterbalance mechanism.

3. Analysis of steering modes of purely electric agricultural machinery

3.1 Ackermann Four-Wheel Steering Mode

In Ackermann four-wheel steering mode, all four wheels can be steered, reducing the turning radius compared to conventional steering systems. As shown in Fig. 7, P is the theoretical steering center when the four wheels are steered, O point is the center of mass of the whole vehicle, O_1, O_2, O_3, O_4 are the rotational centers of the four steering wheels, α_1, α_2, α_3, α_4 are the steering angles of the four steering wheels, respectively, r is the distance between the rotational centers of the wheels to the center plane of the tires, H is the distance between the rotational centers of the wheels of left and right.Wheel rotation centers, and L is the distance between the wheel rotation center on the front and rear sides. In Ackermann steering mode, since the angle of rotation of the wheels on the same side is the same, then the following mathematical relationship is fulfilled:

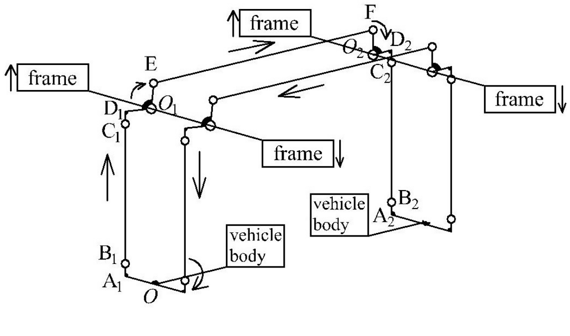


Fig. 6. Motion sketch of the balancing mechanism

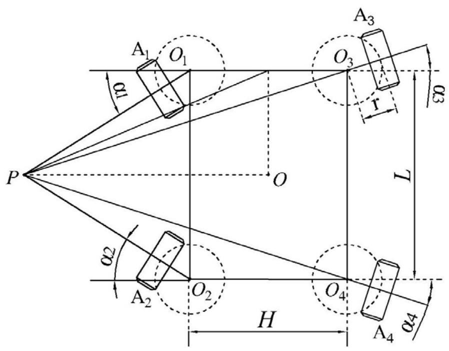


Fig. 7. Ackermann four-wheel steering mode

$$\begin{cases} R = OP = \dfrac{0.5L}{\tan\alpha} \\ \alpha_1 = \alpha_2 = \tan^{-1}\left(\dfrac{0.5L}{R-0.5H}\right) = \tan^{-1}\left(\dfrac{L\tan\alpha}{R-H\tan\alpha}\right) \\ \alpha_3 = \alpha_4 = \tan^{-1}\left(\dfrac{0.5L}{R+0.5H}\right) = \tan^{-1}\left(\dfrac{L\tan\alpha}{R+H\tan\alpha}\right) \\ R_1 = R_2 = \sqrt{(R-0.5H)^2+(0.5L)^2} - r \\ R_3 = R_4 = \sqrt{(R+0.5H)^2+(0.5L)^2} + r \end{cases} \tag{3}$$

In equation (3), α is the chassis steering angle, and H and L are the known. They can be derived from the chassis and wheel steering angles of the relationship shown in Fig. 8. As the vehicle's chassis steering angle increases, the wheels' steering angle increases inside and outside, and the inner wheel steering angle is greater than the outer wheel steering angle.

In Ackermann's steering mode, the steering angle of the inside wheel and the outside wheel is different, and the speed is different; the front and rear wheels of the same side have the same steering radius when steering, and the steering angle is equal in size and opposite in direction, the speed of the wheels is equal. So it satisfies the following mathematical relationship equation:

$$\begin{cases} V_1 = V_2 = V\dfrac{R_1}{R} \\ V_3 = V_4 = V\dfrac{R_3}{R} \end{cases} \tag{4}$$

In the equations, V is the movement velocity of the chassis center of mass (the overall velocity of the vehicle movement); assuming that V is fixed at 1.25m/s, from the above mathematical equation, it can be derived that the relationship between the wheel speed and the chassis steering angle when the vehicle is steering is shown:

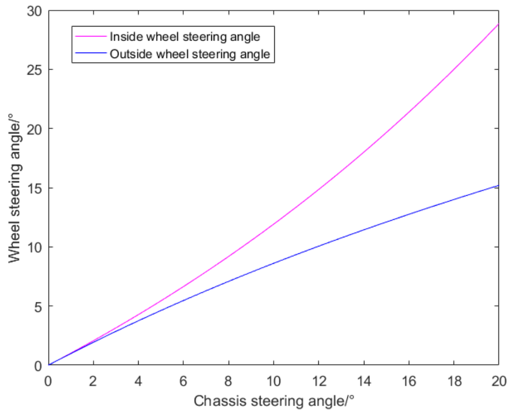


Fig. 8. Relationship between chassis turning angle and wheel steering angle of the whole vehicle

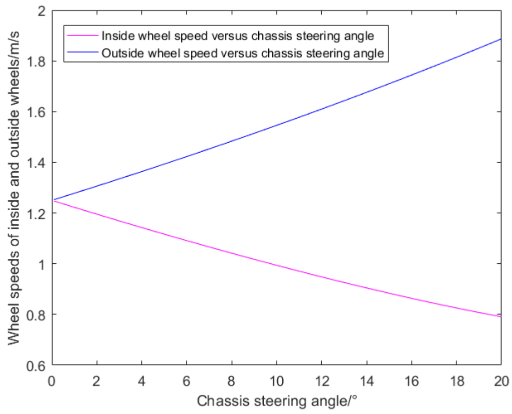


Fig. 9. Wheel speed of inner and outer wheels plotted against chassis steering angle

As can be seen from Fig. 9, when the movement speed of the chassis center of mass is fixed, the inner wheel speed decreases with the increase of the chassis steering angle, and the outer wheel speed increases with the rise of the chassis steering angle. Hence, the vehicle can better complete the steering.

3.2 Steering in situ mode

In the Steering in situ mode, as shown in Fig. 10, the four wheels have the same steering angle, the wheels on the same side are in the opposite direction, the diagonal wheels are in the same direction, and the four steering wheels are steering in situ with the position of the chassis's center of mass as the center of rotation.

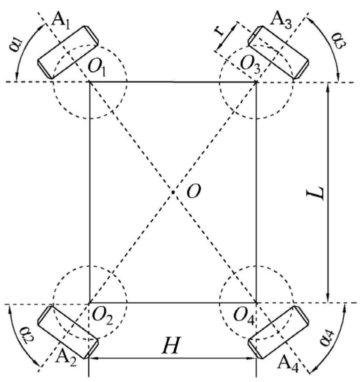


Fig. 10. Turn-in-Place Mode

In the Steering in situ mode, the steering angles of the four wheels, as well as the turning radii of the wheels and the traveling speeds of the wheels, should satisfy the following mathematical relationship equation:

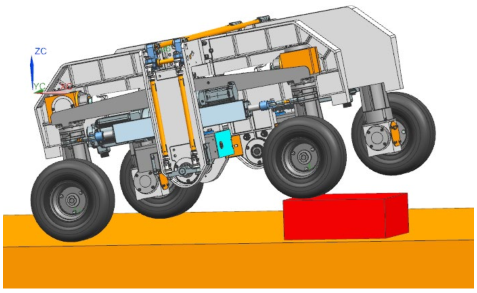
$$\begin{cases} \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \tan^{-1}\left(\dfrac{L}{H}\right) \\ R_1 = R_2 = R_3 = R_4 = \sqrt{\dfrac{H^2 + L^2}{2}} + r \\ V_1 = V_2 = V_3 = V_4 = \dfrac{\pi r_A n_A}{30} \end{cases} \tag{5}$$

4 Simulation analysis

4.1 Simulation analysis of obstacle crossing

In this paper, the motion simulation of a pure electric agricultural machine and a conventional one-piece agricultural machine was carried out using Unigraphics NX simulation software, in which the linkage mechanism and kinematic pair were added according to the actual motion of the whole vehicle. Four tires were used as the drive, 3D contact was added between the tires and the ground, and the friction parameter between the tires and the road surface was adjusted. surface.The set stiffness is 100000N/mm, the material damping is 10N • s/mm, the maximum penetration depth is 0.0254mm, and the coefficients of static and kinetic friction are 0.3 and 0.2 respectively. According to the requirements of the design task book, the length of the obstacle is set to 400mm, the width is 300mm, and the height is 150mm.

As shown in Fig. 11 (a), when the right wheel of the conventional one-piece agricultural machine climbs the obstacle, the rear wheels on both sides are in contact with the ground, and the left front wheel is in suspension. At this time, the vehicle body is in an unstable state. As shown in Fig. 11 (b), when the right wheel of the agricultural machine with the new balance mechanism climbs the obstacle, the other three wheels are in contact with the ground; at this time, the vehicle body state is relatively stable, improving the stability of the vehicle's driving.


(a) Conventional one-piece agricultural machines

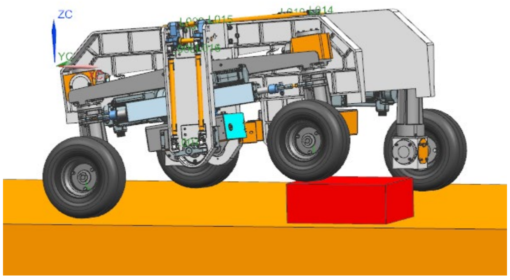

(b) New Balance Mechanism Agricultural Machines

Fig. 11. Body attitude of different chassis in obstacle-crossing simulation

As shown in Fig. 12, the chassis center of mass Z-displacement curves of different chassis when crossing obstacles, the chassis center of mass Z-displacement of conventional one-piece agricultural machines and agricultural machines with a new type of counterbalance mechanism both increase when crossing barriers, and the swings of the chassis center of mass Z-displacement of the conventional one-piece agricultural machines are more significant than those of the farming machines with a new type of counterbalance mechanism. As the left front wheel of the traditional one-piece agricultural machine is suspended when it crosses the obstacle, the process of crossing the obstacle may cause the left front wheel and the right rear wheel diagonal wheel to be suspended at the same time or the body sway. The body is unstable, reducing the vehicle's traveling stability. With the new balance mechanism of agricultural machinery over the obstacle, the four wheels are always kept in contact with the ground, the body is in a smooth state, and the friction significantly improves the vehicle in the complex road passing and driving smoothness.

Fig. 13 shows chassis tilt angle when crossing obstacles with different chassis. It can be seen from the figure that the tilt angle of the chassis of the one-piece vehicle fluctuates significantly during the process of crossing the barriers. In contrast, the tilt angle of the vehicle's chassis with the new counterbalance mechanism fluctuates more smoothly. The tilt angle of the chassis of the trolley is too large when crossing the obstacle, which leads to the shift of the center of gravity, reduces the vehicle's stability, and easily causes accidents such as rollover.

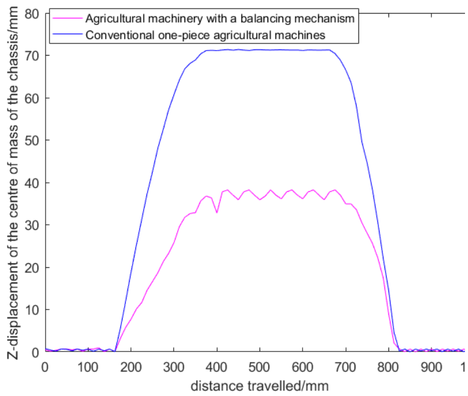


Fig. 12. Z-direction displacement of chassis center of mass during obstacle crossing for different chassis

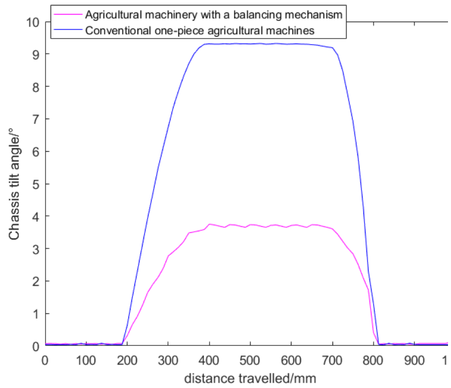
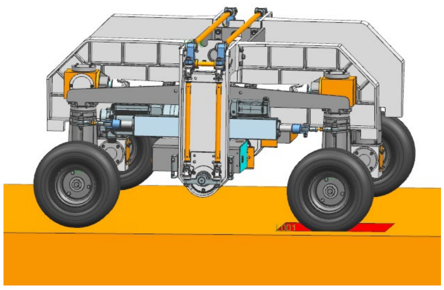


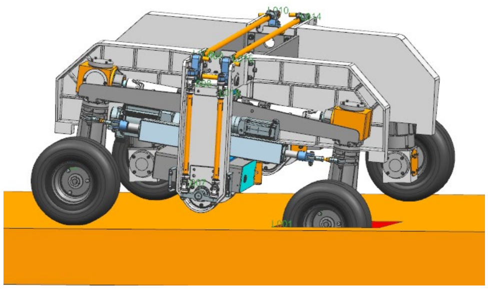
Fig. 13. chassis tilt angle when crossing obstacles with different chassis

4.2 Simulation analysis of crossing small pits

As shown in Fig. 14 (a), the right front wheel is suspended when the conventional one-piece agricultural machine passes through a small pit. The other three wheels are in contact with the ground. The wheels' suspension causes the vehicle to lose part of its traction, reducing its stability and passability. In a complex environment, it may not be able to obtain sufficient traction and be challenging to pass. In the process of passing through the tiny pits, the vehicle's body will sway. As shown in Fig. 14 (b), when the agricultural machine with the new balancing mechanism passes through a small pit, the four wheels always remain in contact with the ground, which ensures that the vehicle obtains sufficient traction under complex environments and dramatically improves the stability and passability of the vehicle.



(a) Conventional one-piece electric agricultural machine through a small pit



(b) Electric agricultural machines with balancing mechanisms through a small pit

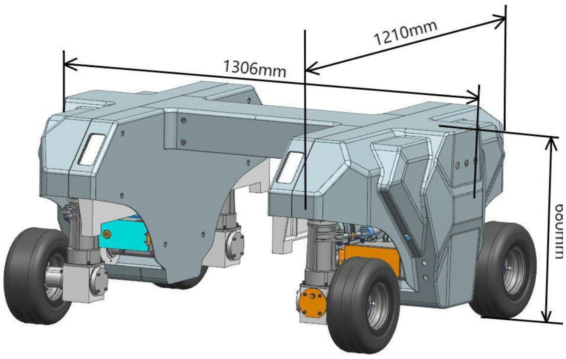
Fig. 14. Body attitude of different chassis when passing through a small pit

5 Sample Machine Testing

5.1 Sample Machine Basic Parameters

In order to verify the feasibility of the mechanical mechanism of the pure electric farm machine, according to the technical specifications and requirements of the design task book to complete the sample machine trial production, as shown in Fig. 15, the basic parameters of the pure electric farm machine is shown in Tables 1, 2 and 3. Pure electric farm machine based on STM32 microcontroller in the development platform to complete the main control code writing, as shown in Fig. 16.

(a) Sample machine



(b) Dimensions of the sample machine

Fig. 15. Purely electric agricultural machinery

Table 1

Basic parameters of pure electric agricultural machinery

Serial number	Name	Parameter
1	Vehicle mass/kg	280
2	Overall Vehicle dimensions/mm×mm×mm	1306×1210×680
3	Maximum Vehicle moving speed/(km/h）	5.4
4	Maximum Vehicle climbing gradient/(°)	15
5	wheel radius/mm	155
6	Total Battery Capacity/Ah	2×23.4
7	Battery Dimensions/ mm×mm×mm	290×177×72
8	Individual Battery mass/kg	5.6

Table 2

Basic parameters of motors and motor reducers

Serial number	Name	Parameter
1	Drive motor power/kW	1.5
2	Rated speed of the drive motor/(r/min)	3000
3	Drive motor torque/N • m	4.77
4	Steering motor power/kW	0.4
5	Rated speed of steering motor/(r/min)	3000
6	Steering motor torque/N • m	1.21
7	Maximum speed of drive motor reducer/(r/min)	93
8	Maximum speed of steering motor reducer/(r/min)	230

Table 3

agricultural machinery parts and components material table

Serial number	Name	Materials
1	frames	ZL101A-T5
2	upright column	ZL101A-T5
3	Horizontal bar, vertical bar	Q235A
4	fork rocker arm	Q235A
5	swing arm axis, swing arm	40Cr
6	lead screw	40Cr
7	drive shaft	40Cr

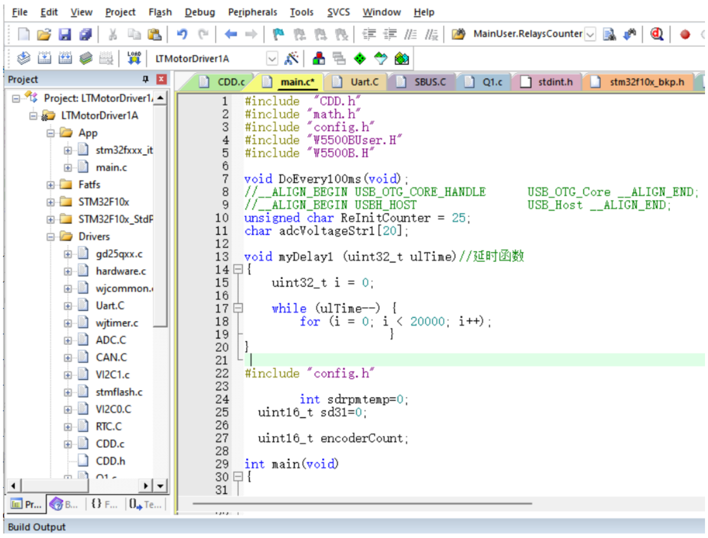
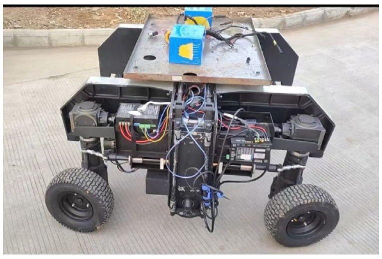


Fig. 16. Underlying main control code

5.2 Experimental Results Analysis

Fig. 17 (a) Ackermann steering test shows that the relative errors between the measured maximum steering angle of 19.2° (theoretical value 20°) for the inner wheel and 12.8° (theoretical value 12.2°) for the outer wheel are 4% and 4.9%, respectively. The errors were mainly due to mechanical clearance and tyre grounding deformation, and were within the permissible design range. Fig. 17 (b) shows the testing of the sample machine for in-situ steering, the theoretical steering radius is 791mm, the actual measured is 782mm, and the relative error is 1.1%, this error is mainly caused by the combined effect of tyre ground slip and elastic deformation of the mechanism. Fig. 17 (c) shows the sample machine performing an obstacle-crossing test. The height of the step is 150 mm, and during the obstacle crossing, all four tires consistently maintain contact with the ground and can cross the steps smoothly. Fig. 17 (d) shows the sample machine undergoing a hill-climbing test with a gradient of 13°, all performance indicators meet the design requirements. During hill climbing, the engine torque output is stable and the tyres have great grip.

The agricultural machinery designed in this paper needs to mount implements when carrying out operations, so the load test is extremely important, at present, only the sample machine production and power performance tests have been completed, and the prototype load test will be carried out at a later stage.



(a) Ackermann steering test

(b) In-situ steering test

(c) Obstacle-crossing test

(d) Hill climbing test

Fig. 17. Sample machine experiment

6. Conclusion

1. In this paper, through theoretical analysis and simulation experiments, a pure electric agricultural machine with a new type of balancing mechanism is designed, which has two steering modes of Ackermann four-wheel steering and in-situ steering. The current pure electric agricultural machinery in the steering mode switching, for the steering angle and speed of the precise control there are some limitations, the future can study the introduction of more advanced sensors and intelligent algorithms, in order to achieve more accurate steering control.

2. The simulation experiments of overcoming obstacles and passing through small pits were carried out for the agricultural machine equipped with the latest balancing mechanism and the conventional one-piece agricultural machine, respectively. The simulation results show that the new balancing mechanism can ensure that the four wheels of the purely electric agricultural machine can come into contact with the ground when it crosses the obstacles and passes through the tiny pits, can be adapted to adjust to the complex road surface. At present, the adaptive performance of this balancing mechanism under extreme complex terrain still needs to be improved, and the subsequent research can consider going deeper from the direction of structural optimisation or adding auxiliary adaptive devices.

3. The sample machine trial production was completed, and steering mode experiments, hill climbing experiments, and obstacle crossing experiments were carried out. The experimental results show that the new balanced mechanism pure electric agricultural machine can drive flexibly under different steering modes, which proves the correctness and feasibility of the mechanical mechanism design. In the sample machine's obstacle-crossing and slope-climbing experiments, the four wheels always keep in contact with the ground, and the body attitude is stable, which proves that the sample machine with the new balance mechanism has a solid adaptive ability to complex environments and a strong ability to climb slopes. Compared with the planetary gear counterbalance mechanism in the literature [13], the new one has a simple structure and can be better adapted to the operation in hilly areas. The current sample machine has certain shortcomings in terms of range and power output continuity. Future research could focus on upgrading the battery technology and optimising the power system to enhance the performance of agricultural machines in long-duration, high-intensity operations.

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