DESIGN OF A WHEELED ADAPTIVE CHASSIS LEVELING SYSTEM FOR HILLY AND MOUNTAINOUS AREAS
/
丘陵山区轮式自适应底盘调平系统设计

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ABSTRACT
The cultivated land in hilly and mountainous areas of China accounts for a high proportion. However, the complex terrain makes it extremely difficult for traditional agricultural machinery to operate. There is a high risk of rollover, and the operation effect is not satisfactory. Achieving agricultural mechanization in these areas faces huge challenges. This study is dedicated to designing a four-wheel adaptive chassis suitable for hilly and mountainous areas to solve the stability problem of agricultural machinery during operation. The research adopts the leveling strategy of tracking the lowest fixed point plane in the four-point leveling method. By constructing the chassis coordinate system and analyzing the coordinate transformation matrix, the motion relationships of each support point are determined, and precise leveling is achieved based on this. In the system design, the hydraulic system is crucial. According to the preset vehicle parameters, various parameters of the hydraulic cylinder are accurately calculated, and a suitable gear pump is selected to ensure stable operation under different working conditions. The control system calculates the height errors of each point based on the body tilt angle data collected by the biaxial sensor, and then controls the action of the hydraulic valve to achieve automatic leveling of the chassis. The MATLAB/Simulink platform is used to simulate different tilt angle conditions, verifying the effectiveness of the control system. The experimental results show that the chassis can achieve rapid leveling within the range of -12° to 12° in the transverse direction and -8° to 8° in the longitudinal direction, and the leveling time is within two seconds. The leveling process is stable, without shaking and insufficient stroke problems. This indicates that the leveling strategy and system design of the chassis are reasonable and effective, which can significantly improve the stability and safety of agricultural machinery during operation in hilly and mountainous areas, providing important technical support for promoting agricultural mechanization in hilly and mountainous areas.

摘要
中国丘陵山区耕地占比高，但地形复杂致使传统农机作业困难重重，翻车风险大且作业效果不佳，实现农业机械化面临巨大挑战。本研究致力于设计一种适用于丘陵山区的四轮自适应底盘，以解决农机作业的稳定性问题。研究采用四点调平中的最低点不动面追逐调平策略，通过构建底盘坐标系和分析坐标变换矩阵，确定各支撑点的运动关系，以此为基础实现精准调平。在系统设计上，液压系统是关键，根据预设的车辆参数，精确计算液压缸的各项参数，选用合适的齿轮泵，确保在不同作业工况下都能稳定运行。控制系统依据双轴传感器采集的车身倾斜角度数据，计算各点高度误差，进而控制液压阀动作，实现底盘自动调平。利用 MATLAB/Simulink 平台对不同倾斜角度工况进行仿真，验证了控制系统的有效性。实验结果显示，该底盘在横向 -12°至 12°、纵向 -8° 至 8° 范围内可实现快速调平，且调平时间在两秒以内，调平过程平稳，无晃动和行程不足问题。这表明底盘的调平策略和系统设计合理有效，能显著提升农机在丘陵山区作业的稳定性和安全性，为推动丘陵山区农业机械化发展提供了重要技术支持[1]。

INTRODUCTION
China has a vast territorial area and complex and diverse terrains. Among them, the cultivated land area in hilly and mountainous areas with a slope exceeding 2 degrees accounts for 38% of the country's total cultivated land area.

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The southwestern region is a typical representative of hilly and mountainous areas in China, and the area of hilly and mountainous areas in its major provinces generally exceeds 70% of the total area. Specifically, the area of hilly and mountainous areas in Sichuan Province accounts for 94.1% of the total area, 92.5% in Guizhou Province, 88.8% in Yunnan Province, 85.3% in Chongqing City, and the proportion of the area of hilly and mountainous areas in the Guangxi Zhuang Autonomous Region also reaches 76.1% *(Luo, 2019)*. Due to the undulating terrain, fragmented plots and relatively large slopes in hilly and mountainous areas, conventional agricultural machinery is faced with the predicament of "difficulty in accessing and poor stability". If this problem is not properly solved, rollover accidents are highly likely to occur during the operation of agricultural machinery, resulting in irreparable losses. In addition, as the terrain is sloping, the chassis of agricultural machinery often fails to remain level during operation. Coupled with the rugged and uneven terrain, the operation effect of agricultural machinery, especially that of harvesting operations, is significantly affected. Therefore, achieving the full mechanization in hilly and mountainous areas has always been a difficult problem that urgently needs to be solved *(Wang et al., 2024; Sun et al., 2023; Mou et al., 2024; Li et al., 2019).*

In recent years, the international and domestic academic communities have conducted extensive research on the adaptive performance of agricultural machinery chassis. For example, the Tri-star Ⅱ robot developed by the National Space Development Agency of Japan (NASDA), as a typical representative of three-wheeled all-terrain mobile robots, adopts a suspension structure design with three components arranged at equal angles *(Liu et al., 2005)*. This design significantly improves the robot's performance in obstacle crossing and adaptation to diverse terrain environments. The SHRIMP robot, developed by the Swiss Automation and Systems Laboratory (SASL), is a representative six-wheeled all-terrain mobile robot *(Hussain et al., 2005)*. This robot adopts six-wheel drive technology and has the ability to overcome obstacles with a height up to twice the diameter of its wheels. The bipedal robot Atlas, developed by Boston Dynamics, needs to be controlled by algorithms to simulate human walking movements and has the working ability in complex environments *(Kuindersma et al., 2016)*. In China, remarkable progress has also been made in relevant fields in recent years. For example, *Wu. et al., (2021),* designed an electromechanical automatic leveling system based on STM32, which achieves multi-point leveling by controlling the speed of different leg servo motors, avoiding mutual coupling caused by step-by-step adjustment of legs, and combining sensor technology to solve the problem of virtual legs. Finally, an experimental platform was built according to the design scheme to prove the feasibility of the leveling method and control system. *Jian. et al., (2023),* aimed to solve the problems of easy tipping and poor trafficability of tractors in hilly and mountainous areas. In this study, the virtual prototype technology was applied. A three-dimensional simplified model of the chassis was established by SolidWorks. The roll stability and obstacle-crossing performance were analyzed under simulated working conditions in ADAMS/View, and the finite element analysis was carried out on key components using ANSYS Workbench. The results show that the maximum roll stability angle of the tractor chassis meets the standard, the obstacle-crossing performance is good, the stress and deformation displacements of key components all meet the requirements, and the whole machine is within the safe range of use and can meet the operation requirements in hilly and mountainous areas. *Yin Xiang et al., (2021),* and the research team developed an automatic leveling system for the spray boom of high-clearance pesticide applicators. This system utilizes the incremental PID algorithm. By calculating and outputting control signals to the solenoid valve, it further controls the movement of the leveling cylinder to achieve real-time adjustment of the spray boom's posture.

This research aims to design an adaptive wheeled chassis suitable for the terrain characteristics and working environment of hilly and mountainous areas. This chassis can achieve precise stability adjustment to solve the problems of excessive adjustment amplitude and insufficient stability that occur during the adjustment process of existing adaptive chassis. Through the chassis design proposed in this study, it is expected to significantly improve the overall operational stability of agricultural machinery and the safety during its movement.

MATERIALS AND METHODS

Construction of the Motion Model for the Leveling Strategy

Under the classification of support structures, leveling systems can mainly be divided into three types: three-point leveling, four-point leveling, and six-point leveling. The advantages of three-point leveling are its simple structure, absence of virtual legs, and simple control. However, due to the small number of support points, it has poor stability and cannot bear heavy loads, and is suitable for occasions with small slopes and light loads. Four-point leveling, as the most widely used method in practical applications, can maintain balance both longitudinally and transversely compared with three-point leveling, ensuring stability during the operation process. Six-point leveling, due to the large number of support points and complex control process, is usually applied in large machinery *(Skrickij et al., 2024)*. Based on this, this research chooses to adopt the four-point leveling method.

According to the differences in leveling methods, they can mainly be classified into two major categories: position leveling and angle leveling. The position error leveling method mainly adopts the "tracking" leveling strategy, which can be further subdivided into four ways: the highest point remaining fixed, the lowest point remaining fixed, the center point remaining fixed, and the specified point remaining fixed. The core of the tracking leveling method lies in using the highest point, the lowest point, the center point or the specified point as the reference and achieving precise leveling through continuous adjustment *(Peng et al., 2018)*. This method performs well in terms of leveling speed and accuracy, but its control algorithm is relatively complex. In this design, the tracking leveling strategy with the lowest point remaining fixed was adopted. Given that harvesting machinery has a relatively large mass when fully loaded, using other leveling methods may lead to mechanical tilting or shaking. Therefore, choosing the tracking leveling strategy based on the lowest point is aimed at improving the stability of agricultural machinery during operation and ensuring the high efficiency of agricultural machinery operations. The angle leveling method detects the tilt angle through an angle sensor and adjusts the length of each support leg accordingly to reach the preset minimum angle threshold and complete the calibration process. This calibration technique is often applied in two-point calibration scenarios. Its algorithm structure is simple and avoids complex coupling calculations. However, this method has certain limitations in calibration time.

In practical application scenarios, the lowest point adjustment method within the position adjustment methods can be further subdivided into the conventional lowest point fixed leveling method, the lowest point fixed line tracking leveling method, and the lowest point fixed plane tracking leveling method. During the four-point leveling process, the conventional lowest point tracking leveling method may lead to chassis tilting or large movement amplitudes, thus having a negative impact on the operation effect. Comparatively, the lowest point edge tracking leveling method, that is, leveling by connecting two points and taking the lowest point as the target, is more suitable for the application of three-point leveling. Given that this research adopts the four-point leveling technique, this research has adopted the plane tracking leveling mode within the lowest point fixed leveling method *(Che et al., 2023)*. This mode constructs three adjustment points into a plane and conducts posture adjustment based on the lowest point to achieve the adjustment goal.

Fig.1 illustrates the schematic diagram of the rotation of the chassis coordinate system. A biaxial sensor is installed at the center of the chassis to measure the tilt angles of the chassis relative to the X - axis and Y - axis. Taking the plane ABCD as the coordinate plane of the chassis, OXYZ represents the chassis coordinate system. In this coordinate system, the center point of the chassis remains fixed, while the XY - axis will tilt at specific angles according to different terrains, forming the plane $OX_1Y_1Z_1$. Nevertheless, the position of the center point O remains unchanged. The tilt angles θ and δ of the X - axis and Y - axis can be measured by the sensor located at the center of the chassis.

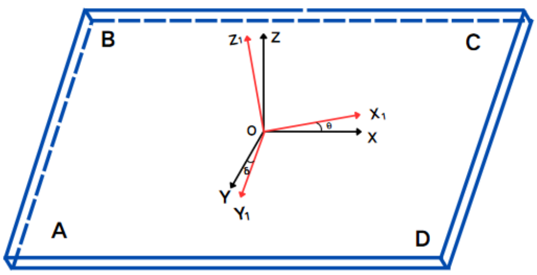


Fig. 1 – Schematic Diagram of the Rotation of the Chassis Coordinate System

Based on the rotation angles θ and δ detected by the sensor, and in combination with the transformation scenarios in different sequences, the following situations can be distinguished:

1. The moving coordinate system rotates by an angle θ around the X-axis of the reference coordinate system, and then rotates by an angle δ around the Y-axis. Since the operations in the back are performed first when multiplying, the transformation matrix is obtained as follows:

$$F_1 = Robot(Y,\delta)Robot(X,\theta) = \begin{bmatrix} \cos\delta & 0 & \sin\delta \\ 0 & 1 & 0 \\ -\sin\delta & 0 & \cos\delta \end{bmatrix} \bullet \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} = \begin{bmatrix} \cos\delta & \sin\theta\sin\delta & \sin\delta\cos\theta \\ 0 & \cos\theta & -\sin\theta \\ -\sin\delta & \sin\theta\cos\delta & \cos\theta\cos\delta \end{bmatrix} \tag{1}$$

2. The moving coordinate system rotates by an angle δ around the Y-axis of the reference coordinate system first, and then rotates by an angle θ around the X-axis, and the transformation matrix is obtained as follows:

$$F_2 = \mathrm{Robot}(X,\theta)\mathrm{Robot}(Y,\delta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\Theta & -\sin\Theta \\ 0 & \sin\Theta & \cos\Theta \end{bmatrix} \bullet \begin{bmatrix} \cos\delta & 0 & \sin\delta \\ 0 & 1 & 0 \\ -\sin\delta & 0 & \cos\delta \end{bmatrix} = \begin{bmatrix} \cos\delta & 0 & \sin\delta \\ \sin\Theta\sin\delta & \cos\Theta & -\sin\Theta\cos\delta \\ -\sin\delta & \sin\Theta & \cos\Theta\cos\delta \end{bmatrix} \tag{2}$$

Since the tilt angles during the agricultural machinery operation can basically be regarded as small angles, it can be obtained that:

$$sin\delta \approx \delta, sin\theta \approx 0, sin\theta sin\delta \approx 0, cos\theta \approx cos\delta \approx 1 \tag{3}$$

It can be derived that:

$$\mathrm{F}_1 = \mathrm{F}_2 \approx \begin{bmatrix} 1 & 0 & \delta \\ 0 & 1 & -\theta \\ -\delta & \theta & 1 \end{bmatrix} \tag{4}$$

Therefore, regardless of whether the rotation occurs first around the X - axis or the Y - axis, under the condition that the tilt angles are small, the matrices are the same. When the chassis is horizontal, the coordinate system coincides with the moving coordinate system. Suppose point N is a certain point on the chassis when it is horizontal. Fix point N where the moving coordinate system coincides with the chassis. Thus, N_{Z1}=0. When the platform rotates by an angle δ relative to the Y - axis and by an angle θ relative to the X - axis, and the coordinates of point N in the reference coordinate system are (N_X, N_Y, N_Z), can be obtained that:

$$\begin{bmatrix} N_X \\ N_Y \\ N_Z \end{bmatrix} = F \cdot \begin{bmatrix} N_{X1} \\ N_{Y1} \\ N_{Z1} \end{bmatrix} \tag{5}$$

$$Nz = -6 \cdot N_{X1} + \theta \cdot N_{Y1} + N_{Z1} \tag{6}$$

Among them, with N_{Z1} = 0, then $N_Z = -\delta \cdot N_{X1} + \theta \cdot N_{Y1}$, and the coordinate positions of each support point on the Z - axis can be calculated.

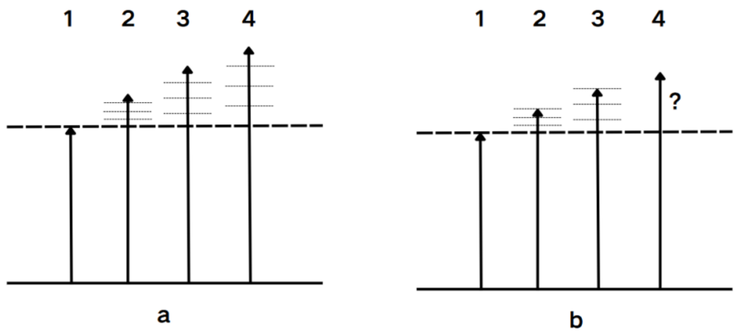


Fig. 2 -The leveling process of tracking the lowest point plane

The core of the leveling strategy in this study lies in dividing the four legs into four levels according to their height differences: the highest point, the second - highest point, the second - lowest point, and the lowest point. By subdividing the vertical height error of each leg relative to the lowest point into three intervals, during the initial adjustment stage, the displacement distances of the second - highest point and the second - lowest point relative to the lowest point are both equal to one - third of the distance of the lowest point. The lowest point, the second - lowest point, and the second - highest point form a plane. During this process, the highest point needs to track the plane formed by the lowest point, the second - lowest point, and the second - highest point.

Assume that the coordinates of the four support points in the reference coordinate system are a(X_a, Y_a, Z_a), b(X_b, Y_b, Z_b), c(X_c, Y_c, Z_c), and d(X_d, Y_d, Z_d). According to the different positions of the four points, the following three cases can be summarized (as shown in Fig.3).

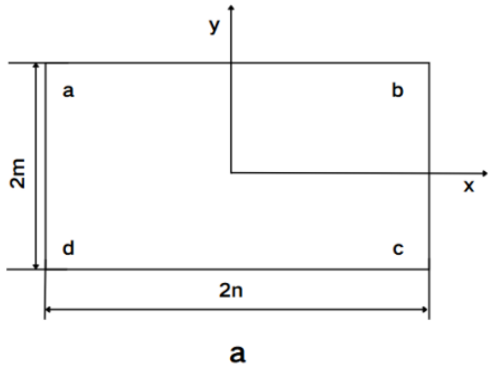


Fig. 3 - Basic Situation of the Chassis Plane

Assume that point **a** is the lowest point, point **b** is the second - lowest point, point **c** is the second - highest point, and point **d** is the highest point.

Determine the normal vector of the plane passing through points **a**, **b**, and **c**.

$$n = \begin{vmatrix} i & j & k \\ x_c - x_a & y_c - y_a & z_c - z_a \\ x_b - x_a & y_b - y_a & z_b - z_a \end{vmatrix} = [y_c - y_a)\Delta z_b - (y_b - y_a)\Delta z_c]i - [(x_c - x_a)\Delta z_b - (x_b - x_a)\Delta z_c]j + [(x_c - x_a)(y_b - y_a) - (x_b - x_a)(y_c - y_a)]k \tag{7}$$

$$\Delta z_i = z_a - z_i = \delta(x_i - x_a) + \theta(y_a - y_i)(i = a, b, c, d) \tag{8}$$

The normal vector of the plane formed by points **a**, **b**, and **c** in Figure 3 is:

$$n = -4mn\delta i + 4mn\theta j \ - 4mnk \tag{9}$$

Therefore, the equation of the plane is:

$$\delta(x - x_a) + \theta(y - y_a) - (z - z_a) = 0 \tag{10}$$

Assume that the moving speeds of points **b** and **c** are k（i=b,c） After the moving time t, the vertical position errors of points **b** and c relative to the lowest point are:

$$\Delta z_i(t) = \Delta z_i - tk\Delta z_i = (1 - tk)\Delta z_i \tag{11}$$

At this point, the plane determined by points **a**, **b**, **c** is:

$$-\delta(1 - tk)(x + x_a) + \theta(1 - tk)(y + y_a) - (z + z_c) = 0 \tag{12}$$

By substituting the x - and y - coordinates of point d into the formula of the plane formed, the z - coordinate of point **d** can be obtained.

$$z_d(t) = z_a - 2n\theta(1 - tk) \tag{13}$$

Therefore, the rising distance of **d** within time t is:

$$s_d = z_d(t) - z_d = 2n\theta tk \tag{14}$$

The rising speed of point **d**.

$$v_d = \frac{s_d}{t} = 2nek \tag{15}$$

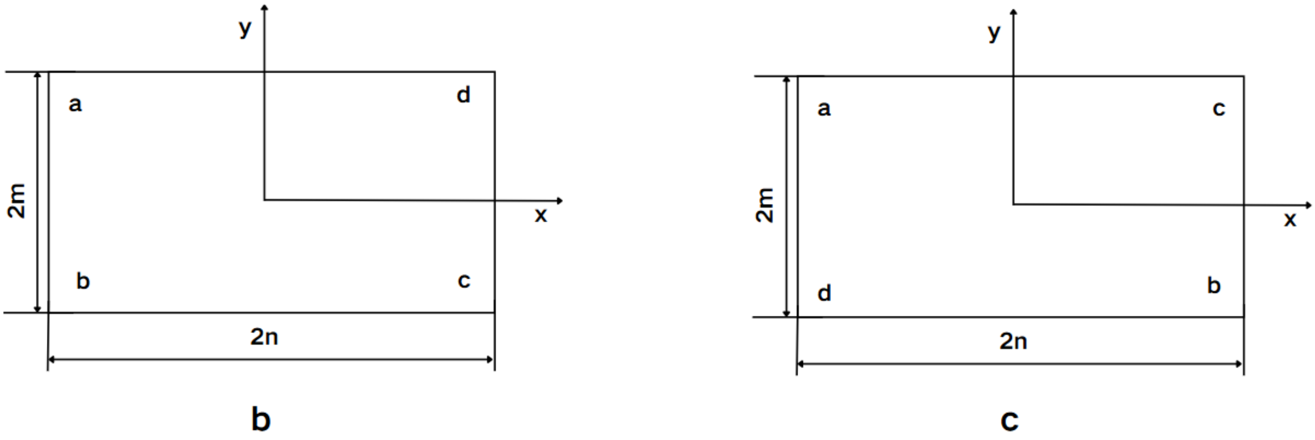


Fig. 4 - The other two basic situations

Similarly, the ascending speed of point **d** in Figure 4b $v_d = 2n\delta k$, the ascending speed of point **d** in Figure 4c $v_d =（2m\delta + 2n\theta）k$ can be known.

Through predictive calculations for a variety of different situations, it was found that:

(1) When the projected distance between points a and d on the horizontal plane is 2 m, the ascending speed of point d is the same as that in Figure 4a, that is, $v_d = 2n\theta k$。

(2) When the projected distance between points a and d on the horizontal plane is 2n, the ascending speed of point d is the same as that in Figure 4b, that is, $v_d = 2n\delta k$。

(3) When the projected distance between points **a** and **d** on the horizontal plane is equal to the diagonal distance of the plane, that is, $(2\sqrt{m^2+n^2})$, the ascending speed of point d is the same as that in Figure 4c, that is, $v_d = (2m\delta + 2n\theta)$.

Therefore, it is only necessary to detect and process to calculate the positional relationship between the highest point and the lowest point, and then the movement speed of the lowest point can be determined.

Hydraulic System

The leveling system in this study consists of a detection system, a leveling mechanism, and a control system. The detection system is a dual - axis sensor. The dual - axis sensor is installed at the center point of the chassis and is used to detect the tilt angles of the chassis in the front - rear and left - right directions. The leveling mechanism is composed of a hydraulic system, which includes suspension hydraulic cylinders and direction valves respectively equipped at the four wheels.

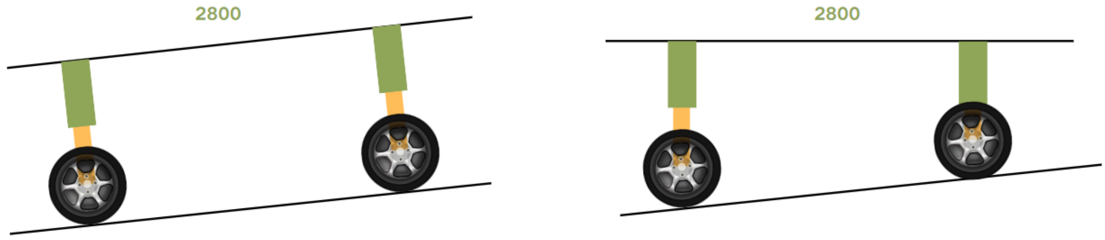
As the core power source for adjusting the chassis attitude, the hydraulic system realizes the leveling function of the vehicle body through the telescopic movement of the hydraulic cylinders. In this study, the design of the chassis is mainly based on preset parameters, according to table 1.

Table 1

Preset Parameters

Item	Parameter
Overall Vehicle Length	6000 mm
Entry 2	2400 mm
Wheelbase	2800 mm
Track Width	1400 mm
Predetermined Net Body Mass	5500 kg
Predetermined Full Load Mass of the Grain Bin	1500 kg

The hydraulic system mainly consists of key components such as the oil tank, filter, hydraulic pump, relief valve, two - position two - way solenoid valve, three - position four - way solenoid valve, one - way throttle valve, and hydraulic cylinder. The chassis designed in this research for the agricultural machinery field has a preset net vehicle body mass of 5500 kg. If it is applied to the harvesting machinery field, the additional weight when fully loaded with grains needs to be considered, and this load is estimated to be approximately 1500 kg.

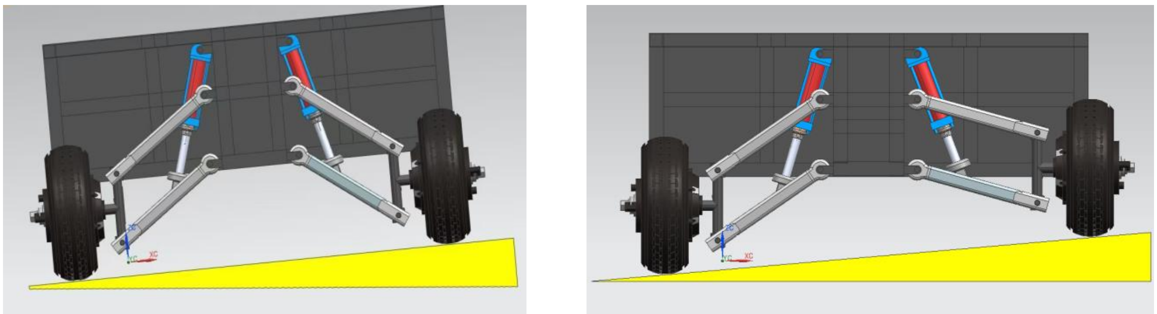


(**a**) (**b**)

Fig. 5 - Schematic diagram of the leveling process in the longitudinal direction

During the actual operation of agricultural machinery, there are mainly four single - direction tilting conditions, namely forward tilt, backward tilt, left tilt, and right tilt, as well as four compound tilting conditions, including left - rear tilt, right - rear tilt, left - front tilt, and right - front tilt. Since the leveling is carried out in a way of tracking the plane formed by the four lowest points, regardless of the tilting condition, it only needs to determine the lowest point, the second - lowest point, the second - highest point, and the highest point. Taking Figure 5 as an example, in the case of backward tilt, the rear wheels are the lowest points. Then, the two front wheels need to track the rear wheels, and the hydraulic cylinders perform a retracting motion to lower the front part of the vehicle body, thus leveling the vehicle body. The same principle can be applied to other single - direction tilting situations.

Fig. 6-



(**a**) (**b**)

Schematic diagram of the leveling process in the transverse direction

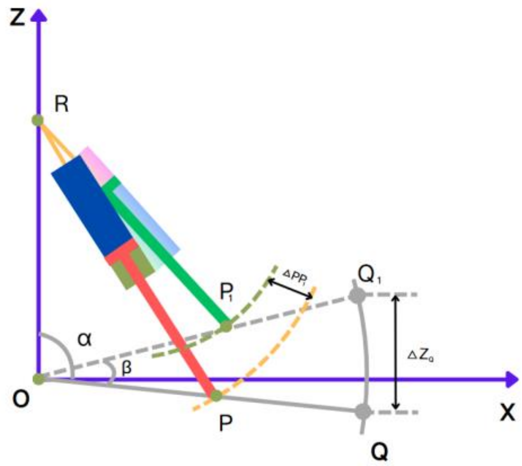


Fig. 7 - Schematic diagram of the leveling hydraulic mechanism

When there is a left - front tilt, the right - rear wheel is the lowest point and the left - front wheel is the highest point. During the leveling process, the distances between the other two wheels and the right - rear wheel are calculated. Subsequently, the hydraulic cylinders perform a retracting motion. The hydraulic cylinder of the left - front wheel retracts to track the plane formed by the other three points, reducing the distance between the vehicle body and the wheel, thus ensuring a stable leveling process. The same method can be applied to other compound - direction tilting situations.

The cosine law in triangle ORP.

$$\cos\alpha = \frac{|\overrightarrow{OR}|^2 + |\overrightarrow{OP}|^2 - |\overrightarrow{RP}|^2}{2|\overrightarrow{OR}||\overrightarrow{OP}|} \tag{16}$$

$$\alpha = \arccos\frac{|\overrightarrow{OR}|^2 + |\overrightarrow{OP}|^2 - |\overrightarrow{RP}|^2}{2|\overrightarrow{OR}||\overrightarrow{OP}|} \tag{17}$$

$OQ_1$is obtained by rotating OQ around point O. Let the coordinates of point Q be (X_Q, Z_Q), and the coordinates of point Q_1 be (X_{Q1}, Z_{Q1}), where:

$$X_Q = \cos\left(\alpha - \frac{n}{2}\right) = |\overline{OQ}|\sin\alpha \tag{18}$$

$$Z_Q = |\overrightarrow{OQ}| = \sin\left(\alpha - \frac{n}{2}\right) = |\overrightarrow{OQ}|\cos\alpha \tag{19}$$

Derived from the rotation matrix:

$$Q_1 = (X_{Q1}, Z_{Q1}) = \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} X_Q \\ Z_Q \end{bmatrix} = \begin{bmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} |\overrightarrow{OQ}|\sin\alpha \\ |\overrightarrow{OQ}|\cos\alpha \end{bmatrix} \tag{20}$$

Among them, the coordinate of point Q_1 in the Z-axis direction can be obtained by adding the required lifting amount to the coordinate of point Q in the Z-axis direction:

$$Z_{Q1} = Z_Q + \Delta Z_Q = |\overrightarrow{OQ}|\cos\alpha + \Delta Z_Q = -|\overrightarrow{OQ}|\sin\alpha\sin\beta + |\overrightarrow{OQ}|\cos\alpha\cos\beta \tag{21}$$

It can be simplified to obtain:

$$\cos\alpha + \frac{\Delta Z_Q}{|\overrightarrow{OQ}|}\cos\alpha\cos\beta - \sin\alpha\sin\beta = \cos(\alpha+\beta) \tag{22}$$

Thus, the size of the rotation angle β can be obtained as follows:

$$\beta = a - \arccos\left(\cos\alpha + \frac{\Delta Z_Q}{|\overrightarrow{OQ}|}\right) \tag{23}$$

Based on the angles α and β as well as the lengths of sides OR and OQ_1 in triangle ORQ_1, according to the cosine theorem, the length of side RQ_1, which is the length of the hydraulic cylinder after extension and contraction, is:

$$|\overrightarrow{RP_1}| = \sqrt{|\overrightarrow{OR}|^2 + |\overrightarrow{OP_1}|^2 - 2|\overrightarrow{OR}||\overrightarrow{OP_1}|\cos(\alpha-\beta)} \tag{24}$$

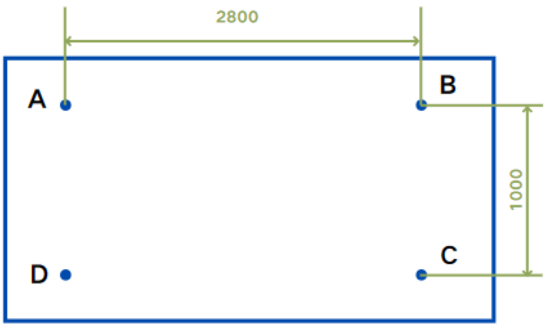
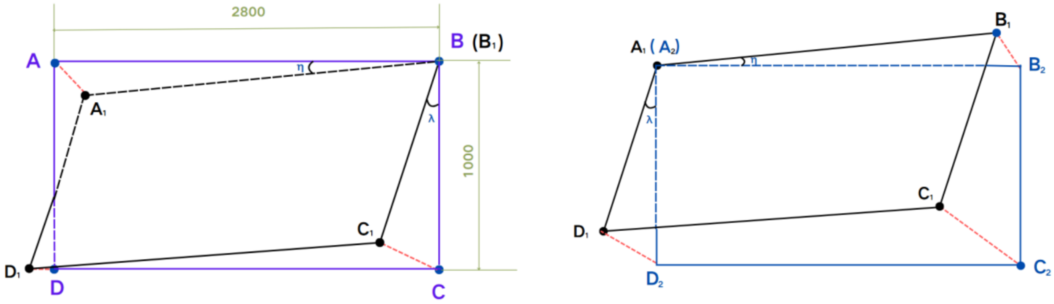


Fig. 8 - Schematic diagram of the chassis plane

As shown in the figure, the total length of the chassis in this paper is 6500 mm, and the width is 2400 mm. Among them, **A**, **B**, **C**, and **D** are hydraulic cylinders. The horizontal spacing between **A** and **D** is 1000 mm, and the longitudinal distance between **A** and **B** is 2800 mm.

This design simulates the maximum longitudinal leveling angle of ±8° and the maximum transverse leveling angle of ±12°.

1. Calculation of the Stroke of the Hydraulic Cylinder.



(a) (b)

Fig. 9 - Schematic diagram of the chassis leveling process

As shown in the figure, plane ABCD is the placement diagram of the chassis in the default state. $A_1B_1C_1D_1$ is the placement diagram of the chassis after tilting when encountering an obstacle, and $A_2B_2C_2D_2$ is the result after leveling by means of the lowest point surface tracking method.

Point C is the highest point, and point A is the lowest point:

$|\overrightarrow{C_1C_2}|$ = $|\overrightarrow{AA_1}|$ + $|\overrightarrow{CC_1}|$ ==389mm+208mm=597mm.Therefore, in order to achieve leveling with a longitudinal angle of 8° and a transverse angle of 12°, it is necessary to take mm.

Based on the schematic diagram of the motion model, with a value of $|\overrightarrow{OR}|$=500 mm, the default length of the hydraulic cylinder being $|\overrightarrow{RP}|$=534 mm, the default position being $|\overrightarrow{OP}|$=150 mm, and α being α=95°, by substituting the above data into the formula of the motion model, a value of ΔPP_1=162 mm can be obtained. In order to achieve a leveling of 8° in the longitudinal direction and a left-right leveling of the hydraulic cylinder with a stroke not less than 12° in the transverse direction, the stroke should be approximately 162 mm. Therefore, the stroke of the hydraulic cylinder is set to 200 mm.

In this design, the mass of the vehicle body is 1500 kg, the preset full load weight is 5500 kg, and the total load mass is 7000 kg. Since the chassis coordinate system is located at the position of the center of gravity of the chassis, and the distances from the four support points to the center of gravity are basically the same, the loads on the four hydraulic cylinders are also basically the same, each being one-fourth of the total load on the chassis, that is, 1750 kg.

$$\sin\lambda = \frac{|\overrightarrow{CC_1}|}{|\overrightarrow{BC}|}\frac{|\overrightarrow{CC_1}|}{1000} \tag{25}$$

$$\sin 12° \approx 0.208 = \frac{|\overrightarrow{CC_1}|}{1000} \tag{26}$$

$$|\overrightarrow{CC_1}| = 208 \tag{27}$$

$$\sin\eta = \frac{|\overrightarrow{AA_1}|}{|\overrightarrow{AB}|} = \frac{|\overrightarrow{AA_1}|}{2800} \tag{28}$$

$$\sin 8° \approx 0.139 = \frac{|\overrightarrow{AA_1}|}{2800} \tag{29}$$

$$|\overrightarrow{AA_1}|=389 \tag{30}$$

$$G=mg \tag{31}$$

Substituting the load of a single hydraulic cylinder into the above formula, G = 17.15 KN is obtained.

In addition, the preset system pressure is 10 MPa, the back pressure is 0.5 MPa, and the mechanical efficiency is 0.8. By referring to the table, the speed ratio can be obtained as 1.33. When the speed ratio is 1.33, the ratio of the inner diameter of the cylinder barrel (the diameter of the rodless cavity) of the hydraulic cylinder to the diameter of the plunger rod of the hydraulic cylinder is 0.5. Through calculation, the inner diameter of the cylinder barrel of the hydraulic cylinder is 53.38 mm, and the diameter of the piston rod is 21.35 mm. According to the reference to GB/T 2348 - 1993, the inner diameter of the cylinder barrel of the hydraulic cylinder is 63 mm, and the diameter of the piston rod is 25 mm.

Table 2

Hydraulic Cylinder Dimension Diagram

Item	Parameter
hydraulic cylinder travel	200mm
inner diameter of the hydraulic cylinder barrel	63mm
diameter of the piston rod	25mm

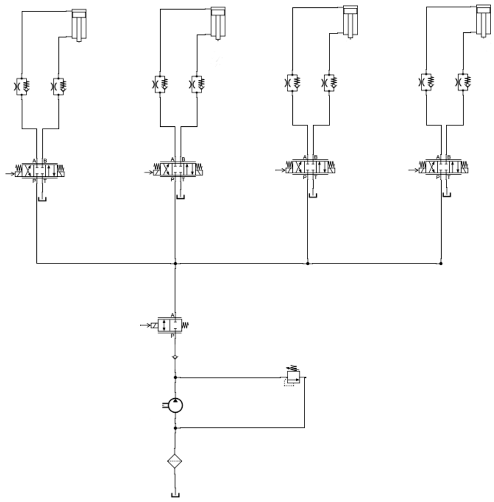


Fig. 10 - Hydraulic Schematic Diagram

1. When the vehicle body is stationary or leveling is not required, the two-position two-way solenoid valve is in the right position and in a cut-off state. Meanwhile, all four three-position four-way solenoid valves are in the middle position, the oil circuits are cut off, and none of the four hydraulic cylinders will operate.

2. When the hydraulic system enters the leveling working state: take the process where point a on the vehicle body is the highest point and point c is the lowest point as an example. At this time, after the two-position two-way solenoid valve is energized, it will be in the left position, and the main hydraulic oil circuit will be connected. Subsequently, the three-position four-way solenoid valves corresponding to **A, B**, and **D** are all energized and in the left position. Then, the hydraulic oil enters the rod chambers, and the hydraulic oil in the rodless chambers flows back to the oil tank. At this moment, the hydraulic cylinders **A, B**, and **D** perform contraction movements, and the vehicle body translates downward to achieve the leveling effect. Afterwards, if the vehicle body drives onto a flat ground and point C becomes the highest point while point A becomes the lowest point, then the three-position four-way solenoid valves corresponding to **A, B**, and **D** are all energized and in the right position. The hydraulic oil then enters the rodless chambers, and the hydraulic oil in the rod chambers flows back to the oil tank. At this time, the hydraulic cylinders **A, B**, and **D** perform extension and contraction movements, and the vehicle body translates upward to achieve the default balanced state.

Design and Simulation of the Control System

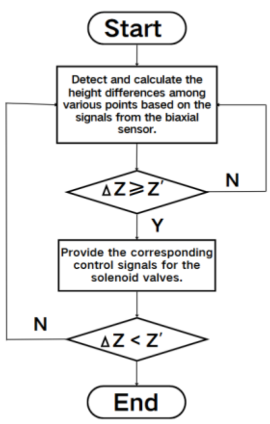


Fig. 11 - Control System Flowchart

The leveling logic of the control system is as follows:

①When the leveling starts, the dual-axis sensor collects the inclination angles of the vehicle body in the X-axis and Y-axis directions. And according to the above formula, the height of each point and the height position error in the vertical direction of the Z-axis from the lowest point are calculated.

②Judge the positional relationship between the highest point and the lowest point, and compare the relationship between ΔZ and Z'(where ΔZ represents the vertical height difference between the highest point and the lowest point, and Z' represents the threshold value for determining whether to carry out the leveling movement). If $\Delta Z \geq Z'$, the controller will send signals to each control valve to control the corresponding hydraulic cylinders to move. If $\Delta Z < Z'$, then return to the first step, and the dual-axis sensor will collect signals again to detect the position error among each point.

In order to verify the reliability and effectiveness of the adaptability of the chassis leveling parameters, this research uses the Simulink platform of MATLAB simulation software to conduct simulations and build simulation models according to the leveling strategy.

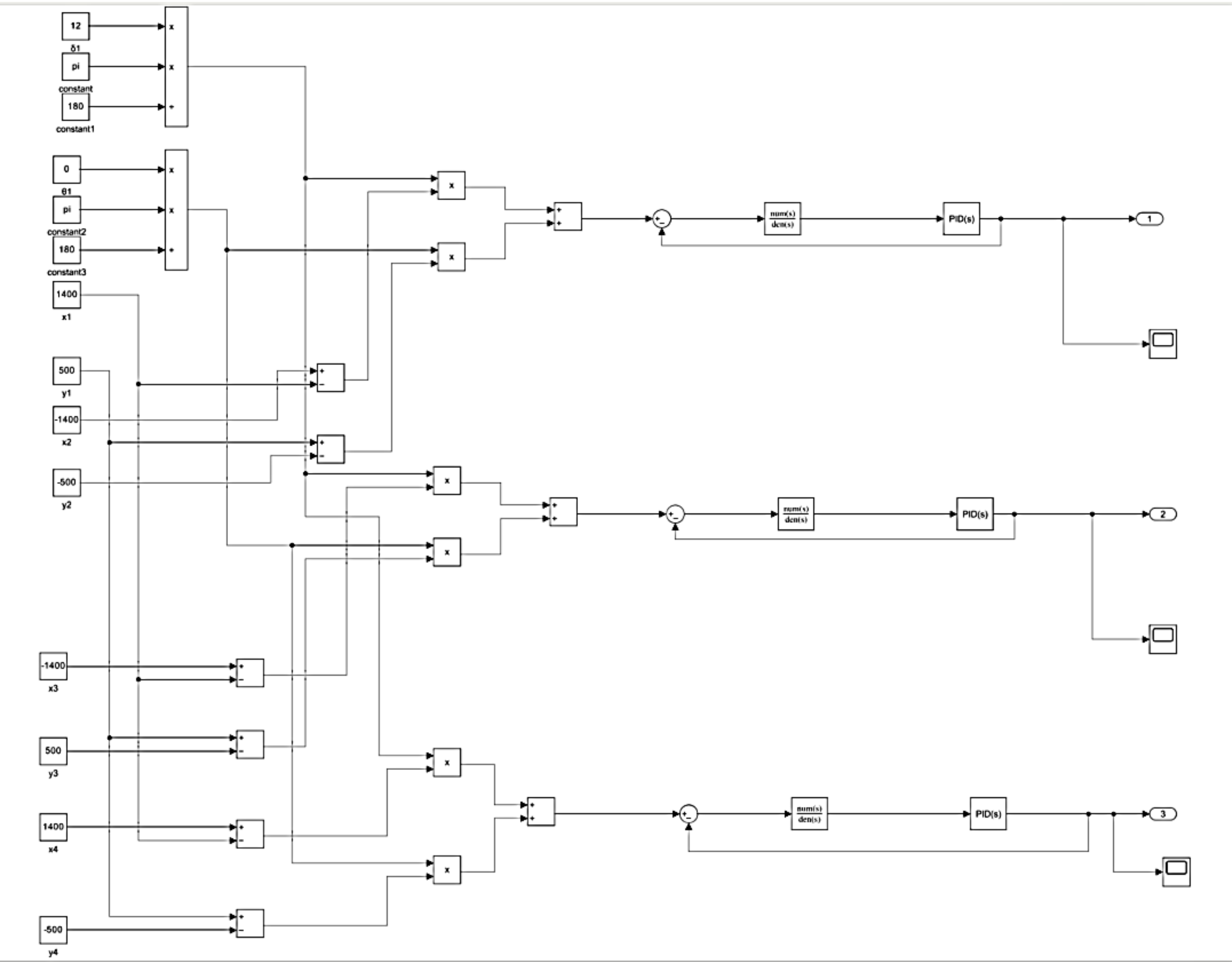
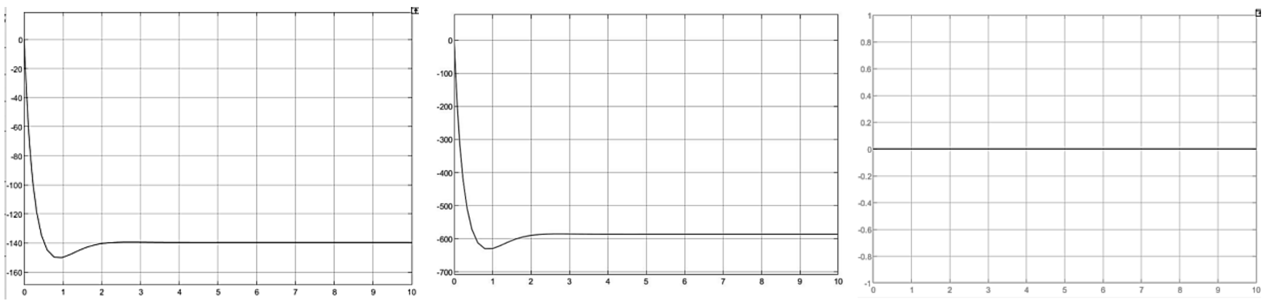


Fig. 12 - Simulation diagram on the Simulink platform

To preliminarily verify the correctness of the leveling control system, simulations will be carried out for different situations next.

1. When θ=8° and δ=0°.

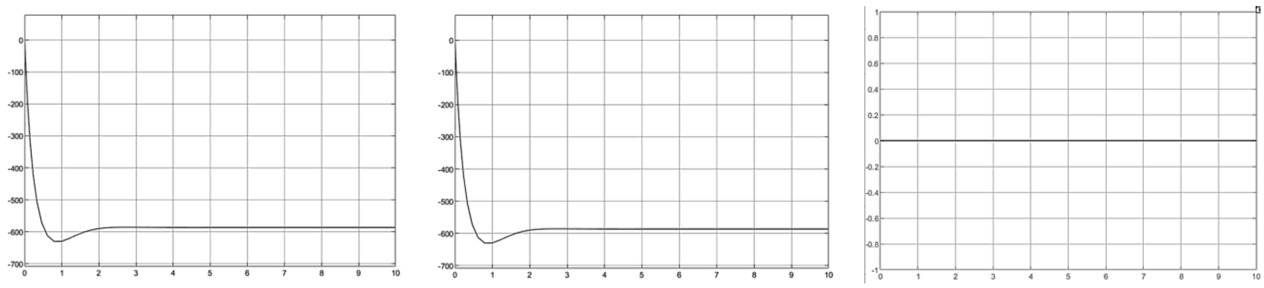


a) highest point b) second highest point c) second lowest point

Fig. 13 - Simulation diagram on the Simulink platform

When θ = 8°and δ = 0°, unilateral inclination occurs. The heights that need to be adjusted for the highest point and the second highest point are the same, and the heights of the lowest point and the second lowest point are the same. At this time, it is only necessary for the higher side to approach the lower side.

2. When θ=0° and δ=12°.

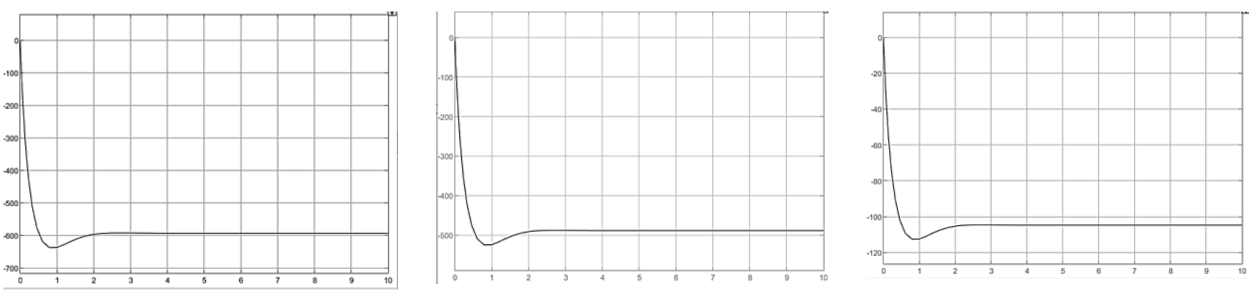


a) highest point b) second highest point c) second lowest point

Fig. 14 - Simulation diagram on the Simulink platform

When θ = 0° and δ = 12°, unilateral inclination occurs. The heights that need to be adjusted for the highest point and the second highest point are the same, and the heights of the lowest point and the second lowest point are the same. At this time, it is only necessary for the higher side to approach the lower side.

3. When θ=8° and δ=12°.



a) highest point b) second highest point c) second lowest point

Fig. 15 - Simulation diagram on the Simulink platform

When θ = 8° and δ = 12°, the highest point, the second highest point and the second lowest point appear. At this time, these three points approach the lowest point to complete the chassis leveling action.

4. When the angle is negative, the lowest point changes. Therefore, the simulation results are the same as when the angle is positive.

Simulation experiments on six angle conditions of inclination angles were carried out through MATLAB/Simulink. The experimental results show that each sub-process of the leveling control can work normally. The maximum range of the inclination angles is θ = -8° to 8°, and δ = -12° to 12°.

RESULTS

The effect of adaptive attitude adjustment will influence the performance of the whole machine during operation. Therefore, it is necessary to verify the chassis strategy and design through experiments.

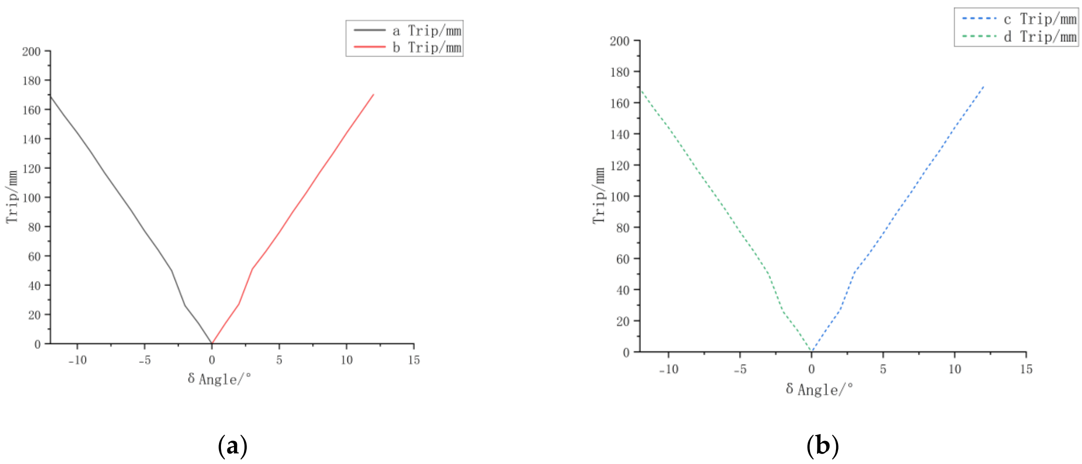
Fig. 16 - Experimental site diagram

To test the working performance of the chassis' attitude adjustment structure and attitude adjustment control system more accurately, four experiments will be carried out, and each experiment will be repeated three times. The average value will be taken and recorded.

Experiment One

Set the δ angle to incline in sequence as -12°, -10°, -8°, -6°, -4°, -2°, 0°, 2°, 4°, 6°, 8°, 10°, 12°, that is, add obstacle slopes on the left or right side according to the angles one by one to achieve the inclination of the target value of the chassis δ angle. Then immediately record the extension and contraction amounts of the attitude adjustment mechanism. Each experiment will be carried out three times to avoid contingency.

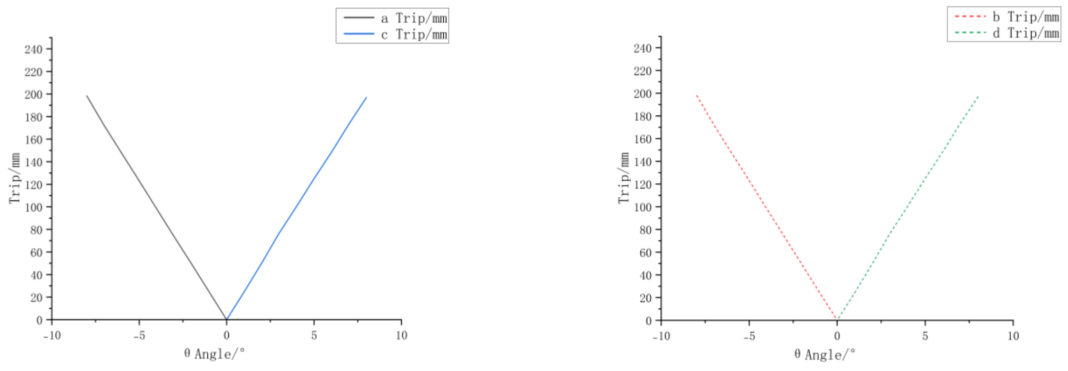
Fig. 17 -



Experiment One: transversal direction tilt the stroke of each hydraulic cylinder

Experiment Two

Set the θ angle to incline in sequence as -8°, -6°, -4°, -2°, 0°, 2°, 4°, 6°, 8°, that is, add obstacle slopes in front of or behind the chassis according to the angles one by one to achieve the inclination of the chassis θ angle. Then immediately record the extension and contraction amounts of the attitude adjustment mechanism. Each experiment will be carried out three times to avoid contingency.



(a) (b)

Fig. 18 - Experiment Two: longitudinal direction tilt the stroke of each hydraulic cylinder

Experiment Three:

Set the θ angle to incline in sequence as -8°, -6°, -4°, -2°, 0°, 2°, 4°, 6°, 8° and the δ angle to incline in sequence as -12°, -9°, -6°, -3°, 0°, 3°, 6°, 9°, 12° simultaneously, that is, add obstacle slopes according to the angles one by one to achieve the simultaneous inclination of the chassis θ and δ angles. Then immediately record the extension and contraction amounts of the attitude adjustment mechanism. Each experiment will be carried out three times to avoid contingency.

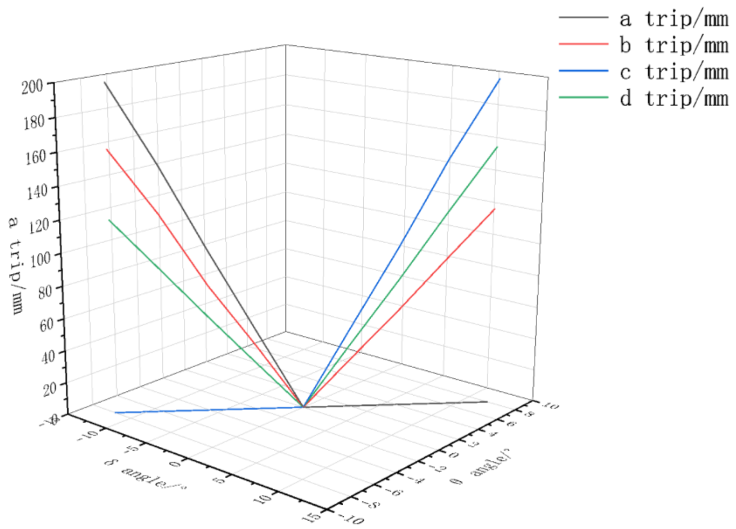


Fig. 19 - Experiment Three: The Moving Amount of Each Hydraulic Cylinder Stroke under Different Inclination Angles

Experiment Four:

Set the θ angle to incline in sequence as 8°, 6°, 4°, 2°, 0°, -2°, -4°, -6°, -8° and the δ angle to incline in sequence as -12°, -9°, -6°, -3°, 0°, 3°, 6°, 9°, 12° simultaneously, that is, add obstacle slopes according to the angles one by one to achieve the simultaneous inclination of the chassis θ and δ angles. Then immediately record the extension and contraction amounts of the attitude adjustment mechanism. Each experiment will be carried out three times to avoid contingency.

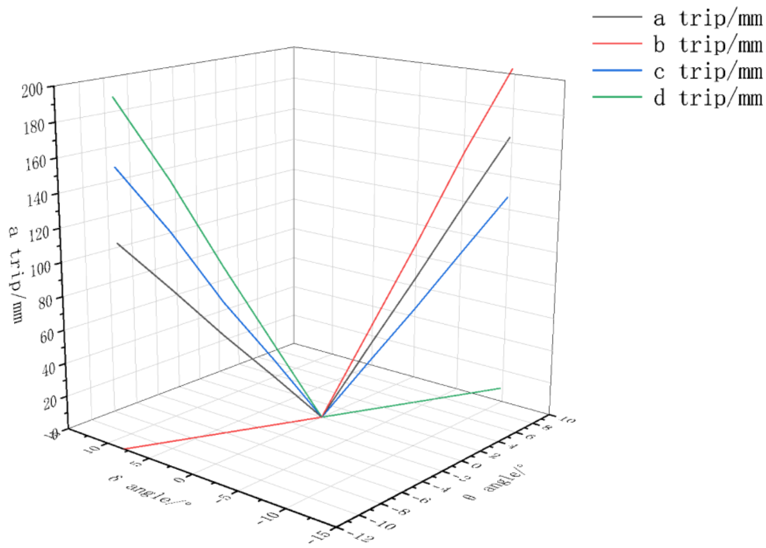


Fig. 20 - Experiment Four: The Moving Amount of Each Hydraulic Cylinder Stroke under Different Inclination Angles

CONCLUSIONS

The experimental results show that the chassis can perform leveling motion in the transverse direction within the range of [-12°, 12°] and in the longitudinal direction within [-8°, 8°]. During the experiment, there was no instance of insufficient stroke in the hydraulic cylinder. Due to the implementation of the surface track leveling strategy, the chassis exhibited good stability throughout the leveling process, with no shaking or jolting. The chassis strategy and hydraulic cylinder stroke effectively meet the design requirements.

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