Novel three-degrees-of-freedom hitch mechanism for hillside tractors

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Abstract
A hitch mechanism with three rotational degrees of freedom (DOF) is proposed, which can be used on tractor in hill region. The three DOFs hitch mechanism is composed of two telescopic upper links, one lower link and one hanging frame of farm implements. The hitch mechanism can adjust the posture of farm implements and realize the profiling operation on hillside. It can improve the uniformity of the tillage depth during tilling on sloped land. We studied the inverse kinematics solution model of this hitch mechanism, which can be used to control the position and posture of farm implements. Furthermore, we carried out the mechanical analysis of the hitch mechanism and established the mechanical model, which can be used to calculate the lifting force parameters and power parameters of the driving element. The solution method of the important parameters is given in the given workspace of the three DOFs mechanism. Taking a 25kW hillside tractor as an example, under the condition of meeting the ISO tractor's standard, we calculated the length range of the upper link, load of the upper link and the lower link. The calculation results show that this mechanism is feasible for the Hillside tractor.

Keywords: Hillside tractor, Hitch mechanism, Posture control, Profiling operation

1. Introduction
The hilly and mountainous areas of China account for more than 43% of the country’s total area. Moreover, the population of the hilly and mountainous areas account for more than 50% of the country’s population. In 2011, the grain output from China’s hilly and mountainous areas accounted for 31.5% of the country’s total grain output (Luo Xiwen, 2011). Therefore, the insufficient agricultural mechanisation of these hilly and mountainous areas has become a bottleneck for realising mechanised agriculture in all parts of China. A significant obstacle is the lack of agricultural equipment that is suitable for operation on mountain slopes (Wang Shengsheng et al., 2016). Considering the lack of stability of the traditional agricultural machinery on the slope (Iamn. A et al., 2011), some researchers proposed automatic levelling for a tractor chassis (Mashadi B. et al., 2009; Wang T. et al., 2014; Han Jiangyi, Xia Changgao, Shang Gaogao et al., 2017; Pingyi L., Fengjuan P, Haitao L I. et al., 2017 ; Yang Fuzeng, Zhu Ruixiang, Zhang Jiqing, 2011) that can adjust the gravity center of tractor chassis and increase the stability of operation on the slope land. When the chassis of a tractor is automatically adjusted on a slope, the tractor should control the position and posture of farm implements to profiling operation on terrain. However, at present, the tractor is equipped with the traditional three-point hitch mechanism that only can only adjust the height parameter of farm implements, which is suitable for the flat farm land. The tractor can not adjust the posture parameters of farm implements to realize the profiling operation on hillside. Thus, some scholars have proposed useful improvements to the traditional three-point hitch mechanism. One improved scheme is to adjust the position of the lower link by using two lifting arms to adjust the inclination angle of the farm implements (Zhu Zhongxiang, Deng Yabin, Zhang Shuo et al., 2017). However, the improved hitch mechanism cannot restrict the lateral swinging of farm implements. The farm implement will be swing under the action of gravity when tractor hangs farm implement by the improved hitch mechanism on the slope. This will change the working posture of the farm implement and make the tractor unable to work on the slope land. Therefore, the key technology is how to control the position and posture of farm implements by the hitch mechanism. In this study, a novel three-degrees-of-freedom (three DOFs) hitch mechanism was proposed, which is used to control the position and posture of farm implements.
2. Materials and methods

The traditional hitch mechanism is shown in Figure 1, which includes two lift arms, one upper link, two lift rods, two lower link and one lift cylinder. The ends of two lower links and the upper link are used to connect with farm implements by spherical joints. The other ends of two lower links and the upper link are hinged at tractor body by spherical joints. The two lift rods are used to connect the lift arms and lower links. The lift cylinder connects the lift arm and drives it. The two lower links will rotates relative to the tractor body when the lift cylinder drives the lift arms. The height position of farm implements will be adjusted as the lower links is rotating. It can be seen that the traditional mechanism can only adjust the height of farm implements and cannot limit the yaw movement of farm implements. As working on the flat land, the tractor only needs to control the height of the farm implement. As working on the slope land, the posture of some hillsides tractor need to be kept horizontal for improving the anti-rollover ability. In this case, the farm implement should be profiled on slope land for maintain the working quality. Therefore, it necessary to control the posture of implement, which is not competent by the tradition hitch mechanism. In order to make farm implement profile on slope land, a novel three-degrees-of-freedom (three DOFs) hitch mechanism was designed.

![Fig.1 Traditional hitch mechanism](image1)

The three DOFs hitch mechanism includes one left upper link (1), one right upper link (7), one lower link (2), and one hanging frame (3) that can be used to hang the farm implement, as shown in Figure 2. Each upper link includes a prismatic pair. One end of each upper link is connected to the tractor body through a spherical hinge, and the other end is connected to the hanging frame of the farm implements with another spherical hinge. Moreover, one end of the lower link is connected to the tractor body through a rotary hinge, and the other end is connected to the hanging frame (7) with a universal kinematic pair (U pair). The U pair comprises a hinge joint for the lower link, universal cross shaft, and hinge joint for the hanging frame, which has two orthogonal rotational degrees of freedom, as shown in Figure 3. One rotation direction of the U pair is parallel to the direction of the rotary hinge that is used to connect the lower link to the tractor body, and the other rotation direction is perpendicular to the hanging frame. The farm implements (8) are connected to the three joining points on the hanging frame, the design realises a three-point hanging mechanism for the farm implement. To avoid interference with the power take-off output shaft of the tractor, lift cylinders (5) are placed on both sides of the lower link. One end of the lift cylinder is hinged to the tractor body, and the other end is hinged to a lift arm (4). Moreover, one end of each lift arm is connected to the tractor body through a rotary hinge, and the other end controls the angular displacement of the lower link by using a lift rod (6).

![Fig.2 Hitch mechanism with three DOFs](image2)

In the figure, 1. left upper link, 2. lower link, 3. hanging frame, 4. lift arm, 5. lift cylinder, 6. lift rod, 7. right upper link, 8. farm implement.
3. Analysis of the freedom of the hitch mechanism

The hitch mechanism is a parallel mechanism, and the hanging frame determines the position and posture of the farm implement. The degrees of freedom of the hanging frame are limited by the two upper links and the lower link. Each upper link has two spherical hinges (S) and a prismatic pair (P), as shown in Figure 4. Moreover, the lower link has a rotary hinge (R) and a U pair, as shown in Figure 5. According to the formula of the DOFs by Kutzbach–Grübler (Huang Zhen, 2006) $f = 6 \times (n - g - 1) + \sum f_i - v$, where $n$ is the number of parts in the mechanism, $g$ is number of attachment pairs on every parts, $f_i$ is the degrees of freedom on each pair, $v$ is the number of the local passive degrees of freedom, and $i = 1, 2, 3, \ldots , n$). Thus, the upper link has six DOFs and cannot constrain the DOFs of the hanging frame. Because the lower link has three DOFs, therefore, the hanging frame has three DOFs. As shown in Figure 5, the three DOFs are the rotational DOF around the body $n_1$, the rotational DOF $n_2$ that is parallel to the $n_1$ direction, and the rotational DOF of the body $n_3$ that rotates around the normal direction of the hanging frame plane. The position and posture of farm implements are determined using the three DOFs. The DOFs $n_1$, $n_2$, and $n_3$ determine the height position, inclination angle, and pitching posture of farm implements, respectively. As shown in Figure 6, the angle $\theta$ of the rotational DOF $n_1$ can be controlled when the rotary hinge $R$ of the lower link is the active pair, and the height ($h$) of the farm implements can be adjusted. When the prismatic pair $P$ of the two upper links is the active pair, the pitching angle $\beta$ and inclination angle $\alpha$ of farm implements are controlled. During transportation, the departure angle $\gamma$ (in Fig.6) is an important parameter to evaluate vehicle trafficability. The adjusting of pitch angle can increases the trafficability of tractor with the farm implements. As shown in Figure 6, the value of $\alpha$ is adjusted to achieve profiling of farm implements to the terrain when a hillside tractor operates on a slope.
3.1 Inverse kinematic position and posture model of farm implements

The position and posture of the farm implements depended on the hanging frame because farm implements were hooked by a hanging frame. The position and posture of the hanging frame can be controlled by the prismatic pair (on left upper link and right upper link) and the rotation angle that the lower link connects the tractor body. Therefore, a mathematical model of the inverse kinematic position and posture of the hanging frame was required to control the farm implements. The mathematical model was used to calculate the parameters of the prismatic pair in different position and posture of the farm implements. Obviously, the input parameter of the inverse kinematic model are position \( (h) \) and posture \( (\alpha, \beta) \) of farm implements, and the output parameters are the length of the two upper links and the rotation angle \( (\theta) \) of the lower link. The kinematic analysis diagram of the three DOFs hitch mechanism is shown in Figure.8. A fixed coordinate system \( B-XYZ \) is set up with \( B \) as the origin. The rotary hinge at \( B \) rotates along the \( Y \) axis, and the \( Z \) axis is vertically perpendicular to the \( Y \) axis. Therefore, the direction of the \( X \) axis is determined. Moreover, a dynamic coordinate system \( E-XYZ \) is set up with \( E \) as the origin. The \( U \) pair rotates along the \( X \) and \( Y \) axes, and the \( Z \) axis is determined by the \( X \) and the \( Y \) axes. The posture of the plane \( DEF \) can be expressed by \( \alpha \) around the \( X \) axis and by \( \beta \) around the \( Y \) axis in the \( E-XYZ \) coordinate system. The orientation of the plane \( DEF \) can be expressed by the position coordinates of point \( E \) \( (x_E, y_E, z_E) \) in the \( B-XYZ \) coordinate system. Let the coordinates of point \( D \) be \( [x_D, y_D, z_D, 1] \) and those of point \( F \) be \( [x_F, y_F, z_F, 1] \) in the \( E-XYZ \) coordinate system. Let the length of \( AD \) be \( l_i \), that of \( BE \) be \( l_j \), that of \( CF \) be \( l_k \), that of \( FD \) be \( l_i \), that of \( ED \) be \( l_j \), and that of \( FE \) be \( l_k \). In the \( B-XYZ \) coordinate system, let the coordinates of the point \( A \) be \( [x_A, y_A, z_A, 1] \), those of point \( B \) be \( [x_B, y_B, z_B, 1] \), those of point \( C \) be \( [x_C, y_C, z_C, 1] \), those of point \( D \) be \( [x_D, y_D, z_D, 1] \), those of point \( E \) be \( [x_E, y_E, z_E, 1] \), and those of point \( F \) be \( [x_F, y_F, z_F, 1] \).

\[
\theta = \arcsin\left(\frac{z}{l}\right).
\]

The equation for \( \theta \) can be given as follows:

\[
\theta = \arcsin\left(\frac{z}{l}\right).
\]

The coordinate transformation matrix around the \( X \) axis of \( E-XYZ \) is written as follows:

\[
R_E^a = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \alpha & -\sin \alpha & 0 \\
0 & \sin \alpha & \cos \alpha & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}.
\]

The coordinate transformation matrix around the \( Y \) axis of \( E-XYZ \) is written as follows:
The coordinate transformation matrix of E-XYZ is transformed to that of B-XYZ.

\[
R_E^B = \begin{bmatrix}
\cos \beta & 0 & \sin \beta & 0 \\
0 & 1 & 0 & 0 \\
-\sin \beta & 0 & \cos \beta & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}.
\]

The coordinates of points D and F on the E-XYZ coordinate system are transformed to the B-XYZ coordinate system, and the coordinates are written as follows:

\[
[x_d, y_d, z_d, 1]^T = R_E^B \cdot R_E^C \cdot [x_e, y_e, z_e, 1]^T, \quad (2)
\]

\[
[x_r, y_r, z_r, 1]^T = R_E^B \cdot R_E^C \cdot [x_c, y_c, z_c, 1]^T. \quad (3)
\]

The lengths of the prismatic pair AD and CF can be obtained by Equations (4) and (5):

\[
l = \sqrt{(x_d - x_a)^2 + (y_d - y_a)^2 + (z_d - z_a)^2} \quad (4)
\]

\[
l = \sqrt{(x_r - x_c)^2 + (y_r - y_c)^2 + (z_r - z_c)^2}. \quad (5)
\]

Equations (1), (4), and (5) provide the inverse kinematic mathematical models for controlling the position and posture of the farm implements. The \(Z_e\) (the height position of farm implement), \(\alpha\) and \(\beta\) (posture of the farm implements) are the input parameters of the mathematical models; The \(\theta\), \(l_1\), and \(l_2\) are the output parameters of the mathematical models. Equation (1) indicates that the rotation angle \(\theta\) at point B is solved by the coordinates of point E \([x_e, y_e, z_e, 1]\). Equations (4) and (5) indicate the length(\(l_1\)) of the prismatic pair AD and the length(\(l_2\)) of the prismatic pair CF that are solved by the posture angles \(\alpha\) and \(\beta\), respectively.

3.2 Force analysis of the hitch mechanism

The hitch mechanism should meet lifting capacity of the tractor. Therefore, the mathematical models between the lifting force and driving load should be studied and established, which could also provide a method for selecting the parameters of the driving element. Taking the hanging frame shown in figure 7 as an example, the mechanical model analysis between lifting force and driving load is carried out below. The driving load of the hitch mechanism are drive force of two upper links (AD, CF) and drive torque of BE around point B. The object that is analysed to calculate the drive force and drive torque of the farm implement, as shown in Figure 7.

From the condition of the force vector balance, the following equation can be derived:

\[
\vec{F}_D + \vec{F}_F + \vec{F}_x + \vec{F}_z = 0 \quad (6)
\]

Where \(\vec{F}_D = (F_{Dx}, F_{Dy}, F_{Dz})\) is the force vector of point D, \(\vec{F}_F = (F_{Fx}, F_{Fy}, F_{Fz})\) is the force vector of point F, \(\vec{F}_x = (F_{EX}, F_{EY}, F_{EZ})\) is the force vector of point E; Considering that the hitch mechanism is used to lift farm implements, the load of the hitch mechanism is set as gravity, so \(\vec{F}_g = (0, 0, mg)\) is the gravity vector.

The \(\vec{F}_D\) and \(\vec{F}_F\) are drive force of the farm implement. The drive force can be written as follows:

\[
\vec{F}_D = \{F_D(x_d - x_a)/l_1, F_D(y_d - y_a)/l_1, F_D(z_d - z_a)/l_1\};
\]

\[
\vec{F}_F = \{F_F(x_r - x_c)/l_2, F_F(y_r - y_c)/l_2, F_F(z_r - z_c)/l_2\};
\]
\[ \vec{F}_t = \{ F_x(x_x - x_c)/l_x, F_y(y_y - y_c)/l_y, F_z(z_z - z_c)/l_z \}. \]

From the equilibrium condition of the moment of point E, the following equation can be derived:

\[ \vec{F}_x \times \vec{DE} + \vec{F}_y \times \vec{FE} + \vec{F}_z \times \vec{GE} + \hat{M}_e = 0 \]  \hspace{1cm} (7)

Where \( \hat{M}_e \) is the force couple of point E; The direction of \( \vec{M}_e \) should be the intersecting line of plane EDF and plane XBZ, the plane XBZ is the plane in coordinate system B-xyz in Figure7. Thus, the direction of \( \vec{M}_e \) can be obtained by the cross-product between normal line of plane XBZ and the normal line of plane EDF. The \( \vec{M}_e \) can be express by its model \( \vec{M}_e \) and direction cosine as follow:

\[ \vec{M}_e = \left[ \frac{M_{E \cdot n_1}}{\sqrt{n_1^2 + n_2^2}}, \frac{M_{E \cdot n_2}}{\sqrt{n_1^2 + n_2^2}} \right]^T \]

\[ n_1 = x_{FE} \cdot y_{ED} - x_{ED} \cdot y_{FE} \] \hspace{1cm} \[ n_2 = y_{FE} \cdot z_{ED} - y_{ED} \cdot z_{FE}. \]

Here, \( x_{FE} = x_F - x_E \). Other symbols (such as \( y_{ED}, x_{ED}, y_{FE} \)) express the same meaning.

Equations (6) and (7) can be expanded into a set of equations including six linear equations, and the unknown variables are \( F_D, F_F, F_{EX}, F_{FY}, F_{EZ}, \) and \( \vec{M}_e \). The number of unknown variables equals the number of equations, thereby, unknown variables can be solved by the set of equations. Here, the \( F_D \) and \( F_F \) are the driving forces needed in controlling the hitch mechanism.

In Fig.8, let \( M_{BY} \) is the drive torque of BE link around point B. In order to solve \( M_{BY} \), taking the BE link be as the research object, set the torque balance equation of external force to point B as follows:

\[ \vec{F}_D \times \vec{DB} + \vec{F}_E \times \vec{FB} + \vec{F}_D \times \vec{GB} + \vec{M}_e = 0 \]  \hspace{1cm} (8)

Where \( \vec{M}_e \) is the force couple vector of point B. \( \vec{M}_e = \begin{bmatrix} M_{EX} & M_{BY} & M_{EZ} \end{bmatrix}^T \). The unknown variables are \( M_{EX}, M_{BY}, M_{EZ} \) in Equation (8). Equation (8) can be expand into three equations, and the number of variables is equal to the number of the equations. Thus, the drive torque \( M_{BY} \) can be solved. Through the above analysis, the driving load \( (F_D, F_F, M_{BY}) \) of the hitch mechanism are be calculated.

3.3 The solution method of important parameters

The hitch mechanism should meet the requirements of the workspace of the farm implement, such as lifting range, lateral inclination angle range and pitching angle range of the farm implement. As shown in Figure 7, the \( a \) is the lateral inclination angle, the \( \beta \) is pitch angle. According to the international standard (ISO730,2009) requirements for rear hitch mechanism of agricultural tractors, take class I tractors (less than 48kw) as examples: the minimum distance between the lower hinge point and the ground is not more than 200 mm, the maximum distance is not less than 820mm when the farm implement is placed in a transport state. Hence, the lifting distance not less than 620 mm. According to the ISO 730-2009 standards, the departure angle of farm tools during transportation is not less than 10 degrees, so the pitch angle of farm tools is set to \(-10^\circ\sim10^\circ\).

According to the above requirements, the length \( l_2 \) of the lower link is selected according to the radius of tractor rear wheel. The coordinate parameters of the upper link hinge point \( (x_0, y_0, z_0) \) and the coordinates of upper link hinge point \( (x_a, y_a, z_a; x_c, y_c, z_c) \) are determined. Then, the length variation of the upper link is calculated according to the workspace of the farm implement.

The procedure for calculating the length variation of the upper link is shown in Figure 9:

1) Input the coordinates of the hinge point of the upper link and lower link, and the length of the lower link.

2) Determining computational variables and step size. Height of the lower hinge point from the ground: \( h(t) = 200 + dh \cdot t \), \( dh \) is the calculation step, \( i = (820 - 200)/dh \); Lateral inclination angle: \( a(t) = a_0 + da \cdot j \cdot da \) is the calculation step, \( j = (a1-a0)/da \); Pitch angle: \( \beta(t) = \beta_0 + d\beta \cdot k \), \( d\beta \) is the calculation step, \( k = (\beta_k - \beta_0)/d\beta \)

3) Calculate the length \( l_i (i, j, k) \) and \( h_i (i, j, k) \) of the upper link at each step.

4) Determine the minimum and maximum of the upper link.
4. Application example of the three DOFs hitch mechanism

The three DOFs hitch mechanism presented in this paper was applied in a hillside tractor. The hillside tractor with an automatic chassis adjusted is a wheeled tractor for mountainous and hilly regions (Power: 25kW). According to the structure diagram of the three DOFs hitch mechanism shown in Fig.7, a double acting hydraulic cylinder with a displacement sensor was used as the upper link. The diameter of the cylinder was 40 mm, and the diameter of the piston rod was 25 mm. The rotation of the lower link was realised by lifting cylinders, lifting arms, and a lifting rod. The diameter of the hydraulic cylinder was 70 mm, and the maximum pressure of the hydraulic system was 12MPa. Most of the farmland on the hillsides has been modified so that their slopes do not exceed 20 degrees in China, so the lateral inclination angle of the farm implements was set in the range from −20° to 20°. The range of pitch angle was set to -10°~10°. The coordinates of the joining points between the hitch mechanism and the tractor body are shown in Table 1, and the lengths of the hitch mechanism rods are shown in Table 2.

| Table 1 Coordinate parameters of the joining points (unit: mm). |
|---------------------------------------------------------------|
| X | 0 | 0  | 0 | 0 | 188 |
| Y | -250 | 0 | 250 | 0 | 240 |
| Z | 600 | 0 | 600 | 600 | 230 |

| Table 2 Length parameters of links (unit:mm). |
|-----------------------------------------------|
| BE  | DE  | DF  | FE  | IQ  | TV  | TI  | BQ  |
| 900  | 600 | 700 | 600 | 570 | 200 | 350 | 450 |
5. Results and discussion

The three DOF hitch mechanism of the hillside tractor must meet specific lifting stroke and the lifting force (According to the ISO730-2009, the distance of the hanging point of the farm implements must not be less than 620 mm; the lifting force must not be less than 300N/kW at a point 610 mm back from the hanging point). According to the parameters in Table 1 and Table 2, the lifting stroke of the farm implements and the length range of the upper link were calculated. The lifting distance curve of the farm implements is shown in Figure 10. In Fig.10, the horizontal axis represents the angle variable \( \theta \) of the lower link. When \( \theta \) is between -10 ° and 40 °, the lifting distance of the hitch mechanism is 735 mm, which can meet the ISO500-2009 standard (620 mm). According to the calculation method of the upper link length shown in Fig. 9, a calculation program is edited by the Matlab software. Figure. 11 shows the length variation range of the upper link when the lifting distance and the attitude angle \((\alpha, \beta)\) of the farm implements are taken as variables. In the Fig.11, the horizontal axis represents the number of calculations and the vertical axis represents the length of the left upper link. The result shows that the length range of the left upper link was in the range of 708–1073 mm, which provide a basis for the selection of the upper link cylinder. Because the left and right upper links were symmetrically located on both sides of the vertical plane of the tractor, the length range of the right upper link was the same as that of the left upper link.

The power of the tractor is 25 kW, therefore, the backward 610 mm load at the hanging point was not less than 2500 N(According to the ISO730-2009, the lifting force must not be less than 300N/kW at a point 610 mm back from the hanging point). The farm implement should be kept level in the driving direction when the farm implement are used in field work, that the \(\beta=0\). According to equations (7) and (8), the load of each cylinder can be calculated in the range of the lifting distance \( h \) and the lateral inclination angle \( \alpha \) of the farm implements. Figure.12 displays the load surface of the upper link and the load range from \(-2.7 \times 10^3\) N to \(3.1 \times 10^3\) N (Tensile force was positive, pressure was negative). Figure.13 displays the load surface of a lifting cylinder and the maximum load of the lifting cylinder was \(1.23 \times 10^4\) N. The maximum oil pressure of the hydraulic cylinder can be calculated. The maximum oil pressure of a hydraulic cylinder in an upper link was 4.1 MPa, and the maximum oil pressure of a lifting cylinder was 3.2 MPa. Thus, the requirement of maximum oil pressure of the hydraulic system was met. The load calculation results show that the three DOF hitch mechanism is feasible for design and manufacture.
This paper proposed a hitch mechanism with three DOFs to adjust the position and posture of farm implements by using three active prismatic pairs. The inverse solution model of the three DOFs hitch mechanism was established to control the position and posture of the farm implements. The calculation method of lifting stroke and lifting force is presented, which can be to select the prismatic pair parameters and structural parameters of the hitch mechanism. The mechanism is applied to a 25kW mountain tractor. The three DOFs hitch mechanism can adjust the lateral inclination angle and pitch angle of farm implements to adapt to the profile of the slope. The range of lateral inclination angle is $-20^\circ$ to $20^\circ$, and the range of pitch angle is $-10^\circ$ to $10^\circ$. And the lifting distance of farm implement can reach 735mm, and the lifting force can reach 7500N, which meet the requirements of ISO730-2009. The maximum force load of the upper link of the three DOFs hitch mechanism is $2.7 \times 10^3$ to $3.1 \times 10^3$ N, and the maximum load of the lifting cylinder is $1.23 \times 10^4$ N, which is feasible to design and manufacture for hillside tractors.

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