A Novel Cable-Driven Parallel Robot for Inner Wall Cleaning of the Large Storage Tank

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Abstract. Large vertical tanks are widely used in the storage of slag and powder in metallurgical industry. For inner wall cleaning of these large storage tanks, traditional working platforms such as hanging baskets and scaffolds have disadvantages of high labor intensity, high danger and low efficiency. Hence, this paper presents a novel cleaning robot working in the large tank based on the cable-driven parallel mechanism. A novel kinematic modeling method based on lifting point coordinates for the cable-driven parallel mechanism is proposed, which need not directly calculate the position and orientation of the center of the moving platform, but just indirectly analyzes the position and orientation of the moving platform through the positions of lifting points. In this way, the kinematic analysis becomes concise, and the workspace of the moving platform is convenient to obtain. For the cleaning robot working in a large storage tank with 50 m high and 18 m diameter, the forward and inverse kinematic solutions of the parallel mechanism with three cables are studied under the kinematic modeling method based on lifting point coordinates. Finally, the specific structure of the cable-driven parallel robot is designed.

Keywords: Cable driven · Parallel mechanism · Cleaning robot · Kinematic analysis

1 Introduction

Solid wastes such as dust and mud are inevitably produced in iron and steel production process. These by-products can be used for building materials. Iron and steel mills store all the dust in the large storage tank, which will harden and stick to the tank wall during the long storage process, so it needs to be cleaned regularly. The tank studied in this

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paper is 50 m high and 18 m in diameter. The clearance work in this suspended environment is dangerous. At present, the cleaning of the tank wall is mainly carried out by artificial hanging baskets. The labor intensity, high risk and low efficiency of the workers are urgently needed. Therefore, it is urgent to research a new type of clearance device to meet the large load and sufficient space for activities.

The cable-driven parallel mechanism has the advantages of high rigidity and high precision of the rigid parallel mechanism, and also has the advantages of small mass, inertia and large length range of the cable. By controlling the length change of the cable, the cable-driven parallel mechanism has a great working space advantage; Through the synchronous control of multiple ropes, the dynamic platform orientation of the cable parallel mechanism can be flexibly adjusted. And this kind of mechanism mainly uses light weight, high strength and low inertia polymer rope [1], in order to meet the need for high sensitivity occasions. These advantages make the cable-driven parallel mechanism an ideal substitute for rigid link manipulators in many industries or combined with connecting rods to produce light components [2]. Therefore, it is a good application potential and prospect to realize the cleaning operation of large vertical storage tanks by using cable-driven parallel mechanism.

The force and motion of the driving unit of a cable-driven parallel robot are transmitted to the moving platform through the cable [3–5], Compared with the rigid link parallel robot, the position and direction of the moving platform are determined by the cable length. However, due to the special characteristics of the cable, it can only bear tension but not pressure, that is to say, the tensile force of each driving cable must be greater than zero [6–8]. Such unilaterality means that the existing analysis and design methods of rigid linkage mechanisms cannot be directly applied to cable-driven parallel robot. This is also a difficult point in the application of cable-driven parallel robots. At present, Diao et al. [9] discussed the singularity analysis of a fully constrained planar cable robot with four or more cables. And based on the rank analysis of Jacobian matrix, a set of Jacobian singularities were proved mathematically. Yang et al. [10] carried out kinematics and singularity analysis of 4-cable 3-DOF cable-driven parallel robot in the plane, and calculated the singularity of robot motion. Carricato and Merlet [11] analyzed the dynamic and static characteristics of under-constrained 3-cable parallel robot under crane conditions. Soon afterwards Abbasne and Carricato [12] extended the research to underconstrained n-cable-driven robots and looked for cable tensile force distribution under equilibrium conditions. While Xu et al. [13] analyzed the dynamics and control of a cable-driven hyper-redundant manipulators Barrette et al. [14] introduced a new concept of dynamic workspace to analyze workspace. Merlet [15] establishes a new model and gives a general solution to the inverse solution of 6-cable-driven robot. To perform the static and kinematic analysis, the screw theory with wrenches and twists can be adopted [16–18].

In above papers, the rigid parallel mechanism kinematical modeling method is usually used to establish the kinematics model of the flexible parallel mechanism. The process of modeling and solving is complex and complicated, and the structural characteristics of the flexible mechanism are not utilized. Therefore this paper presents a lifting point coordinate modeling method for kinematics analysis of cable-driven parallel mechanism. This method does not directly calculate the position and orientation of the center of the moving platform, but indirectly analyzes the position and orientation of the moving platform through the position of each lifting point of the moving platform. And it has a simple and intuitive kinematics modeling process, which is convenient for analyzing the advantages of the moving platform workspace.

2 Statics of the Cable-Driven Mechanism

According to the working conditions in practical application, the stereogram and structure of the 3-cable-driven parallel robot are given at first in Fig. 1.

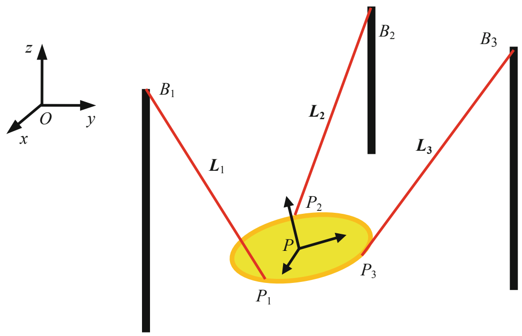

Fig. 1. Structure of the 3-cable-driven parallel robot

Assuming that the mass of the cable is neglected, that is, the weight of the cable is not taken into account and the cable is considered to be straight at rest. As shown in the figure, the global fixed coordinate system (X_O, Y_O, Z_O) is established on the stationary platform and the local coordinate system (X_P, Y_P, Z_P) is established on the moving platform. B_1, B_2, and B_3 denote the anchor points on the stationary platform; P_1, P_2, and P_3 denote the lifting points on the moving platform. According to the static equilibrium relationship of the moving platform, the following equations can be obtained.

$$\begin{cases} \sum_{i=1}^{3} \boldsymbol{u}_i T_i + \boldsymbol{f} = \boldsymbol{0} \\ \sum_{i=1}^{3} (\boldsymbol{R} \cdot \boldsymbol{r}_i) \times \boldsymbol{u}_i \cdot T_i + \boldsymbol{M} = \boldsymbol{0} \end{cases} \tag{1}$$

where $\boldsymbol{u_i}$ denotes the unit vector of the ith cable; T_i denotes the tensile force of the ith cable; $\boldsymbol{r_i}$ denotes the vector from the center of moving platform to the anchor point described in the coordinate system P; $\boldsymbol{f}$ and $\boldsymbol{M}$ denote the external force and moment on the moving platform; and $\boldsymbol{R}$ denotes the rotation matrix of the coordinate system P relative to coordinate system O, and

$$R = \begin{bmatrix} \cos\beta\cos\gamma & -\cos\beta\sin\gamma & \sin\gamma \\ \cos\gamma\sin\alpha\sin\beta + \cos\alpha\sin\gamma & \cos\alpha\cos\gamma - \sin\gamma\sin\alpha\sin\beta & -\cos\beta\sin\alpha \\ \sin\alpha\sin\gamma - \cos\alpha\cos\gamma\sin\beta & \cos\alpha\sin\gamma + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta \end{bmatrix}$$

where α, β, and γ are three Euler angles.

Equation (1) can be rewritten in the matrix form:

$$\boldsymbol{JT} = \boldsymbol{W}$$

where

$$J = \begin{bmatrix} \boldsymbol{u_1} & \boldsymbol{u}_2 & \boldsymbol{u}_3 \\ (\boldsymbol{R} \cdot r_1) \times \boldsymbol{u_1} & (\boldsymbol{R} \cdot r_2) \times \boldsymbol{u}_2 & (\boldsymbol{R} \cdot r_3) \times \boldsymbol{u}_3 \end{bmatrix}$$

$$\boldsymbol{T} = \begin{pmatrix} T_1 & T_2 & T_3 \end{pmatrix}^{\mathrm{T}}$$

$$\boldsymbol{W} = -(\boldsymbol{f} \;\; \boldsymbol{M})^{\mathrm{T}}$$

In the global coordinate system, the unit vector of the cable is as follows.

$$\boldsymbol{u}_i = \frac{\boldsymbol{OB_i} - \boldsymbol{OP_i}}{||\boldsymbol{OB_i} - \boldsymbol{OP_i}||}$$

3 Kinematical Analysis

3.1 Inverse Kinematic Solution

Inverse kinematic solution refers to the solution of each cable length with the position of the moving platform known. In this paper, a lifting point coordinate modeling method is proposed. This method does not directly calculate the position and orientation of the center of the moving platform, but indirectly analyses the position and orientation of the moving platform through the position of each hanging point of the moving platform. In this way, instead of calculating the transformation between the dynamic and static coordinate systems, only a global coordinate system is needed on the static platform, which reduces the amount of calculation and improves the accuracy of calculation.

We know the coordinates of the anchor points B_i of the cable on the stationary platform, and the distribution of the lifting points P_i on the moving platform. In order to calculate the cable length through the center of moving platform P (P_x, P_y, P_z), the formula of cable length is as follows.

$$\boldsymbol{L_i} = \boldsymbol{OB_i} - \boldsymbol{OP}_i \tag{2}$$

where $\boldsymbol{L_i}$ denotes the vector of cable i.

Equation (2) shows that $l_{\mathrm{i}} = \|\boldsymbol{OB_i} - \boldsymbol{OP_i}\|$. Then we requires coordinates of P_1, P_2 and P_3. Because the three-cable parallel mechanism studied in this paper is only affected by gravity of the moving platform, if the gravity is G, then the following equations hold.

$$\boldsymbol{f} = (0 \quad 0 \quad G)^T$$

$$\boldsymbol{M} = \boldsymbol{f} \times \boldsymbol{OP}$$

The static equilibrium equations can be obtained by Eq. (1). In order to avoid the influence of direction vectors on the calculation, we express the tensile force of each cable as follows.

$$T_i = t_i \|\boldsymbol{OB}_i - \boldsymbol{OP}_i\| \tag{3}$$

$$\boldsymbol{S}_i = \boldsymbol{OP}_i \times \boldsymbol{L}_i \tag{4}$$

Where T_i represents the tensile force, l_i represents the length. Substituting $\boldsymbol{L}_i$ and $\boldsymbol{S}_i$ into Eq. (1), the following equation is obtained.

$$\begin{cases} \boldsymbol{L} \cdot \boldsymbol{T} = \boldsymbol{f} \\ \boldsymbol{S} \cdot \boldsymbol{T} = \boldsymbol{M} \end{cases} \tag{5}$$

where

$$\begin{matrix} \boldsymbol{L} = [\boldsymbol{L}_1 \quad \boldsymbol{L}_2 \quad \boldsymbol{L}_3] \\ \boldsymbol{S} = [\boldsymbol{S}_1 \quad \boldsymbol{S}_2 \quad \boldsymbol{S}_3] \end{matrix}$$

represent the vector matrix of cable. From Eq. (3), we know $t_i = \frac{T_i}{\|\boldsymbol{OB}_i - \boldsymbol{OP}_i\|}$, and $\boldsymbol{T} = [T_1 \quad T_2 \quad T_3]^T$. In this way, we avoid the calculation of unit vectors and treat as an unknown number. Since the length of the cable is inversely decomposed by the center coordinate of the platform, and the position of three anchor points of the moving platform is uniformly fixed on the moving platform and the size of the moving platform is known. Hence, the position relation of three points can be mathematically described as follows.

$$\begin{cases} (P_{1x} + P_{2x} + P_{3x})/3 = P_x \\ (P_{1y} + P_{2y} + P_{3y})/3 = P_y \\ (P_{1z} + P_{2z} + P_{3z})/3 = P_z \end{cases} \tag{6}$$

and

$$\begin{cases} \|\boldsymbol{OP}_1 - \boldsymbol{OP}_2\|^2 = p_{12}^2 \\ \|\boldsymbol{OP}_1 - \boldsymbol{OP}_3\|^2 = p_{13}^2 \\ \|\boldsymbol{OP}_2 - \boldsymbol{OP}_3\|^2 = p_{23}^2 \end{cases} \tag{7}$$

where P_{ix}, P_{iy}, P_{iz} denote the x, y, z coordinates of the P_i point, and p_{ij} denotes the distance between P_i and P_j.

From the previous illustration, it can be seen that there are 9 unknowns from three lifting points, and 3 unknowns t_i. Hence, there are totally 12 unknows. By combining Eqs. (5), (6), and (7), a total of 12 scalar equations can be conveniently solved through mathematics software.

3.2 Forward Kinematic Solution

Forward kinematic solution refers to solving the position and orientation parameters of the moving platform with the given length of each cable. For the analysis of the positive kinematics solution of the parallel mechanism, it is often necessary to solve a set of nonlinear equations coupled with position and orientation, which is rather difficult. The Newton-Raphson method may be adopted, where the length of the cable obtained by the inverse solution approximates the target length of the cable and finally obtains the forward kinematic solution. Although this method is effective, the error will always accumulate to a large extent. In this paper, the lifting point coordinate modeling method is established to avoid these problems and simplify the calculation steps.

Solving the position and orientation parameters of the moving platform by the cable length, the coordinates of the center point of the platform and the corresponding *X-Y-Z* Euler angles need to be obtained. The relationship of cable length has been expressed in Eq. (2). Thus, substituting $l_1, l_2, l_3, p_{12}, p_{13}, p_{23}$ into Eqs. (2), (5), and (7), results in the forward position solution. After solving the coordinates of P_1, P_2, P_3, the center point can be mathematically expressed from Eq. (6). And the orientation of the moving platform can be obtained through three lifting points. Then the corresponding *X-Y-Z* Euler angles of the moving platform can be calculated.

4 Orientation Analysis of the Moving Platform

The motion of moving platform is limited by cables. Only when the path of moving platform is planned in the workspace can the required motion be realized. The workspace is to measure the translational and rotational performance of the cable-driven parallel robot, which is defined as the set of all position and posture points of the moving platform satisfying the cable tensile force constraints in space. In traditional research, workspace is usually computed by traversing all required points in a range. But these methods are computationally expensive and inaccurate. In this paper, based on the singular condition that the cable tensile force is zero, assuming one of the three cables has a cable tensile force of 0, that is $T_1 = 0$, the following equations hold.

$$\begin{cases} \begin{bmatrix} B_{2x} - P_{2x} & B_{3x} - P_{3x} \\ B_{2y} - P_{2y} & B_{3y} - P_{3y} \\ B_{2z} - P_{2z} & B_{3z} - P_{3z} \end{bmatrix} \begin{bmatrix} t_2 \\ t_3 \end{bmatrix} = \boldsymbol{f} \\ \begin{bmatrix} \boldsymbol{S}_2 & \boldsymbol{S}_3 \end{bmatrix} \begin{bmatrix} t_2 \\ t_3 \end{bmatrix} = \boldsymbol{M} \\ \|\boldsymbol{OP}_1 - \boldsymbol{OP}_2\|^2 = p_{12}^2 \\ \|\boldsymbol{OP}_1 - \boldsymbol{OP}_3\|^2 = p_{13}^2 \\ \|\boldsymbol{OP}_2 - \boldsymbol{OP}_3\|^2 = p_{23}^2 \end{cases} \tag{8}$$

We take the coordinates of x, y and z of P_i as output, take t_1 and t_2 as input, and the functional relationship between them is expressed by f. The polynomial expression can be obtained.

$$\left(P_{ix}, P_{iy}, P_{iz}\right) = f_i(t_2, t_3)$$

So that

$$\left(P_x, P_y, P_z\right) = \frac{1}{3}\sum f_i(t_2, t_3)$$

According to the working conditions of the cable, the tensile force of each cable is positive when the moving platform is subjected to external force $(\boldsymbol{f}\ \boldsymbol{M})^T$ at any point in the working space. And a minimum positive force is needed to ensure that the cable is not relaxed during the movement. In addition, the maximum tensile force of the cable cannot be infinite, it should be more practical, and the maximum value should be less than the ultimate tensile force of the cable. By combining Eqs. (3) and (4), the range of t_i can be obtained.

$$T_{\min} < t\|\boldsymbol{OB}_i - \boldsymbol{OP}_i\| < T_{\max}$$

According to the range of a singular surface with tensile force of 0 for each cable, the three-sided closed part is the workspace of the three-cable-driven mechanism. On the basis of workspace, there are various paths that can be planned. For the purpose of research, we choose the path as shown in the Fig. 2.

This path can be described as

$$r(\alpha) = (9\ \sin\alpha \quad 4.5\sin\alpha \quad \alpha),\ \alpha \in [0, 2\pi]$$

Set the starting point of motion on point $P_0(9, 9, 25)$, the position and orientation of the moving platform can be obtained as shown in Fig. 3.

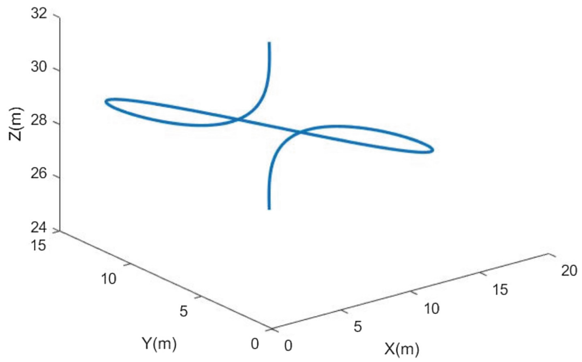

Fig. 2. The path of moving platform

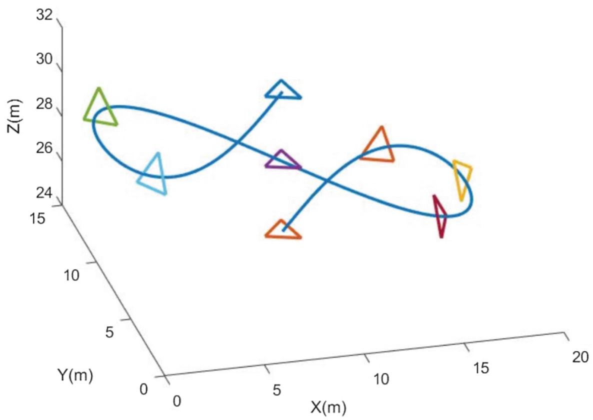

Fig. 3. The position and orientation of the moving platform

5 Structural Design

The main function of the cable-driven parallel robot designed in this paper is to clear the tank. Considering the influence of the workspace of the mechanism, the top view of the cleaning robot is shown in the Fig. 4.

The moving platform is driven by three cables. One end of the cable is connected to a guide rail driven by a motor at the top of the tank, and the other end is connected to three fixed joints connected by hooks and rings on the moving platform as shown in the Fig. 5. Four saw blades for cleaning work are installed under the moving platform. The four saw blades are interlaced to ensure that no matter which side of the moving platform moves to the tank wall, they can work normally. In the working state, the dust adhering to the tank wall is cut by high-speed rotating gear. The electric saw is controlled to rotate in the way that the direction of the cutting force acting on the tank wall is upward. Therefore, the direction of the reaction force acting on the moving platform is downward, which is consistent with the gravity direction. Hence, the tensile

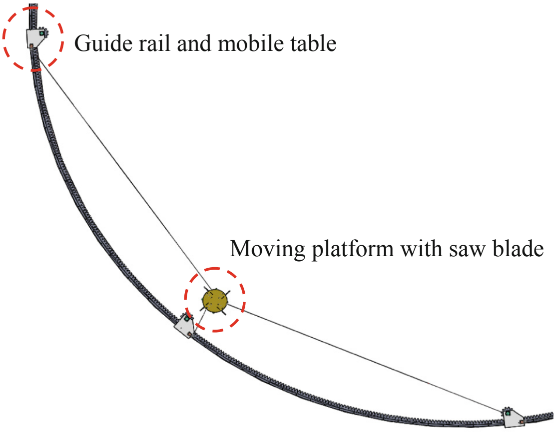

Fig. 4. The top view of the cleaning robot

forces of three cables, the gravity and the reaction force produced by cutting can ensure the force closure of the moving platform when the electric saw rotates. At this time, fasteners will be subject to greater vertical tensile force, so the bolts between the motor and the installation plate, and the bolts between the installation plate and the moving platform should be fastened.

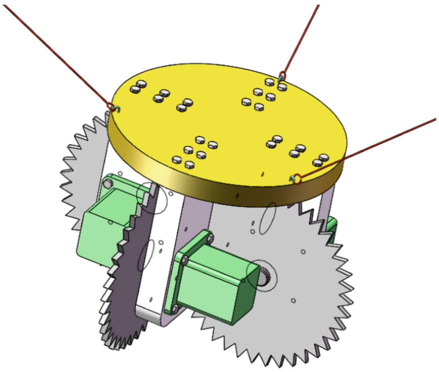

Fig. 5. The structure of the moving platform

In view of the actual working conditions, this paper proposes a method of installing guide rail along the wall of the tank, which can move the fixed hanging point at the upper end, and make the mechanism clean the wall completely in a limited number of times of movement. Motors are installed on the mobile table and gears are installed under the mobile table. In order to prevent undercutting, the modified gears should be used here. Rollers are installed on the worktable to control the collection and release of cables. The motor drives the gear to rotate. With the movement of the gear, the position of the lifting points on the wall can be changed (Fig. 6).

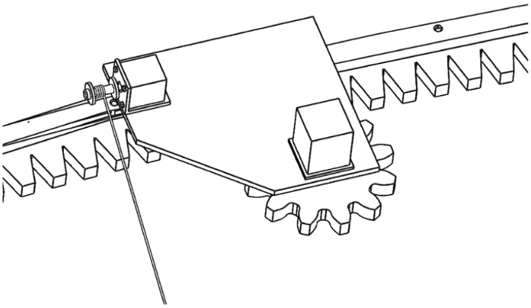

Fig. 6. The structure of the guide rail and the mobile table

Considering the actual situation, three lifting points of the tank are evenly distributed in a quarter of the circle area, and the center of the moving platform is located in the center of the gravity center vertical line of the isosceles triangle formed by the three lifting points. Overhead view of the overall structure is shown in the Fig. 7.

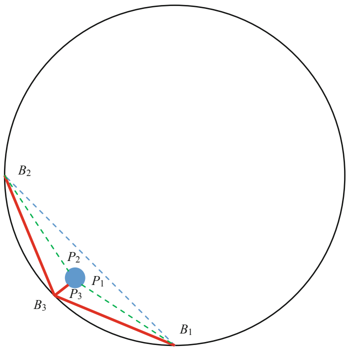

Fig. 7. The top view sketch

The minimum distance between moving platform and tank wall is as follows.

$$D_P = D/2 - ||OP_3|| \tag{9}$$

Where D denotes the diameter of the tank, The center of the moving platform is the center of gravity of $\Delta B_1B_2B_3$. By substituting coordinates of three lifting points B_1, B_2 and B_3 of static coordinate into Eq. (6), coordinates P_1, P_2 *and* P_3 can be obtained, then substituting coordinates B_1, B_2 *and* B_3 into Eq. (8), we can obtain that D_P = 1.21 m. Figure 8 shows the change of the triangle orientation of lifting points on the moving platform. The solid line graph shows the initial distribution position of three lifting points on the moving platform, and the dotted line graph shows the distribution of lifting points under the working condition. From calculation we can see that the z-Euler angle of the moving platform is 15°, that is to say, the moving platform rotates 15° around the z-axis. At this time, the center of the moving platform is 1.21 m away from the tank wall and the radius of the moving platform is 1 m. Therefore, in order to ensure that the moving platform keeps close to the horizontal posture, the radius of the saw blade can be designed to be about 0.25 m.

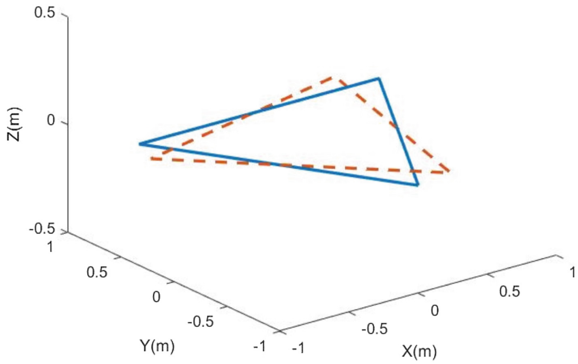

Fig. 8. The position of lifting points on the moving platform

In order to ensure that the orientation angle of the working process is not too large, and the dust can be cleaned smoothly. In practice, we change the cleaning position by moving the mobile station on the guide rail. Starting from the upper boundary of the initial position, the moving platform moves vertically along the tank wall through the extension and shortening of the cable. When the moving platform moves to the lower boundary, a cleaning step is completed. Then the motor drives the moving platform to move a certain distance along the circumferential direction of the tank wall, and the moving platform continues to move vertically. In this way, the whole tank is cleaned up after the moving platform circles the tank.

6 Conclusions

In this paper, a cable-driven parallel robot for cleaning large vertical storage tank is proposed. A kinematic model based on lifting point coordinates is established, and the forward and inverse kinematic solutions of the three-cable parallel mechanism are analyzed. Finally, the mathmatica software can be used to quickly calculate the platform posture and cable length corresponding to the position of each moving platform. On the basis of calculation, the workspace constraints of the cable structure are obtained, and the traveling path of the moving platform is planned in the space under the condition of equal lifting points, and shows the changing trend of the position and posture of the moving platform. For storage tanks with a diameter of 18 m and a height of 50 m, a control device using track control motion is designed. Saw blades can be used to achieve the action of clearing dust up and down. Saw blade diameter is designed to keep the moving platform close to the horizontal posture, so that the effective working space can cover the whole tank wall that needs to be cleaned by sliding smoothly through the lifting point position.

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