Design and Analysis of Full Rolling Cable-suspended Parallel Mechanism of Moving Platform

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Abstract. A cable-suspended parallel mechanism for full rolling motion of moving platform is designed, a kinematic mathematical model and a statics model of the mechanism are established, the variation of cable length during full rolling motion at two deflection angles of 0° and 10° are analyzed, by creating a virtual prototype, the distribution of cable tension and the change of centroid displacement of the moving platform are analyzed. The research results will provide a new technical scheme for full rolling of moving platform.

Introduction

Cable-suspended parallel mechanisms have attracted extensive attention due to their excellent performance, many researchers at home and abroad have done a lot of research work on the design, kinematics and dynamics analysis, workspace analysis, stiffness analysis of the mechanism, and achieved good results. Such as R.L. Williams II, etc. designed a flexible cable robot based on automatic machining, construction, sculpture [1]; J.P. Merlet, etc. designed a parallel mechanism driven by seven cables, based on limb rehabilitation machinery, recreational machinery, rescue machinery and industrial machinery [2]; R. Yao, etc. designed and analyzed a large cable-suspended parallel mechanism based on the large radio telescope whose feedback cabins controlled by four cables have 3T degrees of freedom [3]; L.W. Tang, etc. proposed a docking parallel mechanism driven by seven cables which are consisted of six pull down cables and a crane cable [4]; Y.W. Xiao, etc. studied and analyzed a cable-suspended parallel mechanism with eight cables based on low-speed wind tunnel test [5-10].

The technical characteristics of common cable-suspended parallel mechanism include: the hinge point on the fixed frame is immovable, by changing lengths of cables that the position of the hinge point on the moving platform can be changed, thus six degrees of freedom motion can be brought about under the cable-suspended parallel mechanism. However, due to the configuration constraint, the moving platform has a limited motion space of six degrees of freedom, and it is difficult to achieve an attitude change of large angle, especially the full rolling motion from 0° to 360°. In this paper, a new kind of cable-suspended parallel mechanism is proposed, the turntable will be used as a part of the mechanism, by which the full rolling motion of the moving platform can be brought about.

Mechanism Design Scheme

A kind of cable-suspended parallel mechanism can be carried out the full rolling motion of the moving platform is designed in this paper. As shown in Fig.1, the cable-suspended parallel mechanism with eight cables is used in the design scheme, and then the eight cables are respectively fixed on two turntables, which are coaxial and synchronous rotating. For the sake of simplicity and generality, the moving platform in Fig.1 is designed to be a long cylindrical shape of a square. The initial state of the mechanism is that the long axis of the moving platform overlaps the rotation axis of the two turntables.
The two turntables rotate from 0° to 360° will make the moving platform achieve the full rolling motion when there is no relative motion in between in the process of movement. When changing the lengths of cables, the position of the moving platform can be adjusted (reference to its center of mass), the angle between the axis of the moving platform and the common axis of the two turntable can be adjusted too (here, this angle is called angle of deflection, and represented by symbol \( \alpha \)), which will make the moving platform six degrees of freedom.

![Schematic diagram of full rolling of cable-suspended parallel mechanism.](image)

In Fig.1, one end of the traction cable is fixed on the hinge point \( P_i \) (i=1,2,..8) of the moving platform, and the other end is fixed on the hinge point \( B_i \) (i=1,2,..8) of the turntable. The two turntables are composed of two groups of identical mechanisms and symmetrically arranged relative to the moving platform. When both sides of the turntable rotate synchronously, the point \( B_i \) rotates corresponding angle, the lengths and the tensions of cables change as well. In order to investigate whether the moving platform can do steady rolling motion under the combined action of turntables and cable-suspended parallel mechanism, the kinematics and dynamics of the design scheme need to be analyzed.

**Kinematic Model**

Kinematics schematic of full roll of cable-suspended parallel mechanism is shown in Fig.2, remember \( P_i = O\bar{P}_i, Q_i = O\bar{Q}_i, B_i = O\bar{B}_i, L_i = \bar{P}_i\bar{B}_i \) and \( O\bar{B}_i = O\bar{P}_i + P_i\bar{B}_i \), that is \( Q_i + B_i = P_i + L_i \), in the static coordinate system \( OXYZ \), the cable vector \( L_i \) satisfies:

\[
L_i = X_Q + \alpha Rx_Q - (X_P + \beta Rx_P)
\]  

(1)

![Kinematics schematic of full rolling of cable-suspended parallel mechanism.](image)
In Eq (1), point \( P \) is the origin of the moving coordinate system \( PxPyPz \), whose coordinate in the static coordinate \( OXYZ \) is \( x_P=(x_P, y_P, z_P)^T \), and the coordinate of point \( P_i \) in the moving coordinate system \( PxPyPz \) is \( x_P=(x_P, y_P, z_P)^T \); point \( Q \) is the origin of the moving coordinate system \( QxQyQz \), whose coordinate in the static coordinate \( OXYZ \) is \( x_Q=(x_Q, y_Q, z_Q)^T \), and the coordinate of point \( Q_i \) in the moving coordinate system \( QxQyQz \) is \( x_Q=(x_Q, y_Q, z_Q)^T \), where \( i=1,2,...,8 \). The attitude of the model is \( (\theta, \psi, \phi)^T \); \( \theta \), \( \psi \) and \( \phi \) are respectively regarded as the angle of deflection around \( OX \) axis, \( OY \) axis and \( OZ \) axis, and \( \gamma \) is regarded as the angle of rotation of the turntable around \( OX \) axis in the static coordinate \( OXYZ \); \( \frac{\partial R}{\partial \theta} \) and \( \frac{\partial R}{\partial \psi} \) are coordinate transformation matrix of the moving coordinate system \( PxPyPz \), \( QxQyQz \) to the static coordinate system \( OXYZ \), which can be expressed as follow:

\[
\frac{\partial R}{\partial \theta} = \begin{bmatrix}
\cos\phi\cos\psi & \cos\psi\sin\phi\sin\theta - \sin\psi\cos\phi & \cos\psi\sin\phi\cos\theta + \sin\psi\sin\phi \\
\sin\phi\cos\psi & \sin\phi\sin\psi\sin\theta + \cos\phi\cos\phi & \sin\phi\sin\psi\cos\theta - \cos\phi\sin\phi \\
-\sin\theta & \cos\theta & \cos\theta
\end{bmatrix}
\]

(2)

\[
\frac{\partial R}{\partial \psi} = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos\gamma & -\sin\gamma \\
0 & \sin\gamma & \cos\gamma
\end{bmatrix}
\]

(3)

Let \( L_i (i=1,2,...,8) \) represents the length of the \( i \)th cable:

\[
L_i = \sqrt{(X_Q - X_P + \frac{\partial R}{\partial \theta} X_{Q0} - \frac{\partial R}{\partial \psi} X_{Q0})^T (X_Q - X_P + \frac{\partial R}{\partial \theta} X_{Q0} - \frac{\partial R}{\partial \psi} X_{Q0})}
\]

(4)

**Static Model**

According to the principle of static balance, the force analysis of the mechanism is carried out, and the static model is obtained as follow:

\[
\sum_{i=1}^{8} T_i + F_G = 0
\]

\[
\sum_{i=1}^{8} r_i \times T_i + \tau_p = 0
\]

(5)

The combination of Eq (5) can be obtained:

\[
\begin{bmatrix}
T_1 \\
T_2 \\
\vdots \\
T_8
\end{bmatrix} + \begin{bmatrix}
F_G \\
\tau_p
\end{bmatrix} = 0
\]

(6)

That is:

\[
J_f^T T_i + w = 0
\]

(7)

In Eq (6), \( F_G \) is the gravity of the moving platform, \( \tau_p \) is the external torque acting on the moving platform, \( T_i = (T_1, T_2, \ldots, T_8)^T \) is the matrix of cable tension, and \( w = (F_G, \tau_p)^T \).

The cable can only be pulled along the direction of cable, but can’t be pressed, that is to say, the cable should always be tensioned. In this case, the minimum force acted upon the cable should be greater than the preload \( T_{\min} \) and the maximum force should be less than the safe limit tension \( T_{\max} \), that is:

\[
0 \leq T_{\min} \leq T \leq T_{\max}
\]

(8)
According to the above static model, a distribution of the cable tension can be obtained by optimization solution [11].

**Simulation Analysis**

**Virtual Prototyping of Full Rolling Cable-Suspended Parallel Mechanism**

Create virtual prototyping of full rolling cable-suspended parallel mechanism using software ADAMS, as shown in Fig.3. Of which, the moving platform is set as a cuboid rigid structure, the size is 4m×0.6m×0.6m (X direction, Y direction, Z direction), and the mass is 15.12kg. Two turntables are placed symmetrically and driven by rotary motions separately, the rotary angular velocity is 1°/s. The cable diameter is set to 1mm, and the elastic modulus is set to $1.31 \times 10^{11}$Pa. The cable which is going through pulley is pulled by slider block, the pulley and the slider block are placed on and rotating with two turntables at the same angular speed.

![Figure 3. ADAMS model of full rolling of cable-suspended parallel mechanism.](image)

**Analysis of Variations of the Cables’ Lengths in Full Rolling Motion Process of the Moving Platform**

Above-mentioned coordinates of point $B_i$ and point $P_i$ are as shown in Table 1, and $X_p=(0,0,-3)^T$, $X_Q=(3,0,-3)^T$, $\theta(\gamma)=0$~360, $\psi=0$, $\phi=0$.

<table>
<thead>
<tr>
<th>Cable $i$</th>
<th>The coordinates of $B_i$ points In coordinate system $Qx_Qy_Qz_Q$</th>
<th>The coordinates of $P_i$ points In coordinate system $x_p y_p z_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0, 2, 2</td>
<td>2, 0.3, 0.3</td>
</tr>
<tr>
<td>2</td>
<td>0, -2, 2</td>
<td>-2, -0.3, 0.3</td>
</tr>
<tr>
<td>3</td>
<td>-6, -2, 2</td>
<td>-2, -0.3, 0.3</td>
</tr>
<tr>
<td>4</td>
<td>-6, 2, 2</td>
<td>-2, 0.3, 0.3</td>
</tr>
<tr>
<td>5</td>
<td>0, 2, -2</td>
<td>2, 0.3, -0.3</td>
</tr>
<tr>
<td>6</td>
<td>0, -2, -2</td>
<td>2, -0.3, -0.3</td>
</tr>
<tr>
<td>7</td>
<td>-6, -2, -2</td>
<td>-2, -0.3, -0.3</td>
</tr>
<tr>
<td>8</td>
<td>-6, 2, -2</td>
<td>-2, 0.3, -0.3</td>
</tr>
</tbody>
</table>
In this paper, the kinematics calculations of two kinds of full rolling motions are carried out, one of the deflection angles is 0°, and the other is 10°. The variations of cables’ lengths are got as shown in Fig 4. When the angle of roll is 0°: in Fig 4(1) the initial lengths of eight cables are identical, in Fig 4(2) the initial lengths of cable1, cable2, cable7 and cable8 are identical, and the rest of four cables have the same initial lengths, which is related to the layout of the two points \(B_i\) and \(P_i\). In the rolling process of 360°, the moving platform keeps 10° of deflection angle and rolls synchronously with the two turntables around its own axis: in Fig 4(1) the lengths of eight cables remain constant, in Fig 4(2) the lengths variations of cable1 and cable7 are consistent, which are the same with cable2 and cable3, cable5 and cable8, cable6 and cable7, but the tension between each pair of cables is slightly different.

Analysis of Distributions of Cables’ Tensions in Full Rolling Motion Process of the Moving Platform

According to the static model, the tensions of the initial state calculated by Eq.(7) and Eq.(8) are set as preloads of eight cables. At the same time, the variations of cables’ lengths calculated by the kinematic model are set as displacements of slide blocks in full rolling motion, and the roll direction is determined by the right-hand rule. Through simulation, the distribution curves of cables’ tensions in full rolling motion process of the moving platform are discovered as shown in Fig.5.

Fig.5(1) shows the tension distribution curve of each cable at deflection angle 0°, the variation tendencies of tensions of cable1 and cable4 are consistent, which is the same with cable2 and cable3, cable5 and cable8, cable6 and cable7, but the tension between each pair of cables is slightly different. Fig.5(2) shows the tension distribution curve of each cable at deflection angle 10°: tensions of cable5 and cable6 are smaller than other six cables’ in the initial equilibrium state. When rolling to a certain angle the cable5 and cable6 show the maximum tensions successively, the amplitudes of two cables above are close, and are greater than the other six cables’. In the process of full rolling motion, the tension amplitude of each cable is different, and there is a certain phase difference, all of which are related to the mechanism configuration and the full rolling motion process.
Analysis of Displacement of the Moving Platform

Displacement of the moving platform mass center is shown in Fig. 6. Under two kinds of deflection angles, the displacement along $P_z$ axis is the largest, and the value of displacement at 10° is larger than that at 0°. However, the order of magnitude of displacement is small and far less than the structural dimensions of the moving platform.

Conclusions

In this paper, a cable-suspended parallel mechanism for full rolling of moving platform has been proposed. Firstly, a kinematics model and a static model are established. Secondly, the variation of cable length and the distribution of cable tension are analyzed during full rolling motion at two deflection angles of 0° and 10°. Finally, by analyzing the center of mass displacement, the design scheme is verified to have a good effect on maintaining the position of moving platform. The research results show that the design scheme can be used as a support mechanism to meet the requirements for full rolling motion of the moving platform.

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Reference