Design of 6-DOF Multi-Ring Coupled Parallel Robot Based on Helix Theory

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Abstract. Based on the helix theory and kinematic pair type analysis, the unconstrained branch chain configuration of 6-DOF parallel mechanism is synthesized. According to the principle of installation rationality and transmission lightweight design, the driving device of multi-ring coupling branch chain is transferred to the frame through parallelogram link equivalent transmission, and the mechanism transformation with branch chain type of 6-RSS is completed. A multi-ring coupling 6-DOF parallel robot with the branch chain type of 3-RSS-PRSS is designed. Based on the helix theory, the multi-ring coupling branch chain mechanism is split and the degree of freedom of the mechanism is calculated. The modified G-K formula is used to verify that the optimization model is equivalent to the theoretical model. The optimized mechanism reduces the inertia of the robot, improves the speed of the robot, and makes it have the high-speed characteristics of delta robot and the flexibility of 6-DOF serial robot.

1. Introduction

In today's manufacturing industry and service industry, the role of industrial robots is indispensable, especially in the field of automated logistics production line [1]. Multi-ring coupling parallel mechanism has the characteristics of high rigidity and compact structure, and has a good application prospect. The research of spatial multi-ring coupling mechanism is still in the initial stage. Q Zeng et al. [2-4] added the artificial logic idea to the synthesis method of displacement group, and synthesized some spatial coupling mechanisms; Zoppi et al. [5] proposed two spatial mechanisms including coupling branches; Wei et al. [6] synthesis Several folding polyhedral mechanisms are combined; Z Huang et al. [7] calculated the degrees of freedom of the cube mechanism and the chameleon ball mechanism by using the method of constraint helix; F Gao [8] synthesized the six degree of freedom forging machine, H P Shen [9] researched the hybrid high-speed spraying robot, etc.

Based on the analysis of the type and rigidity of the 6-DOF parallel mechanism, a theoretical configuration of the multi-ring coupling 6-DOF parallel robot is proposed, and the structural modification of the robot is designed according to the requirements of the actual robot assembly design. The analysis and verification of the DOF are carried out by using the helix theory and the modified G-K formula. Finally, the robot 3D model is designed.
2. Configuration design

2.1. Theoretical analysis

Line vector is that a vector in space is limited to a line in space. In the line vector, the vector is \( S \), the line distance is \( S_0 \), and \( S \cdot S_0 = 0 \). The Plucker coordinates of the line vector as shown in Figure 1 are \( (S; S_0) \). The line vector becomes a spinor at \( S \cdot S_0 \neq 0 \). The sum of the superposition of a line vector and an even quantity can form a spinor, which is expressed as \( S = (S; S_0) = (S; S_0 - hs) + (0; hs) \). All force spirals on rigid bodies can be represented by Plucker coordinates. According to the reciprocal calculation method of the helix, when \( S' \circ S = 0(i = 1,2,3...n) \), \( S' \) is the opposite helix of the helix, the total helix is composed of the moving helix and the constrained helix, and the rank of the total helix is 6.

![Figure 1. Geometric representation of line vector](image)

According to the theory of helix, if the moving helix of the branch chain of a mechanism is \( S_i = (L_i, M_i, N_i; P_i, Q_i, R_i)(i \geq 6) \), the opposite moving helix of the moving helix system is \( S'_i = (L, M, N; P, Q, R) \). According to the theory of reciprocal helix, when the branch anti helix \( S_i = (1,0,0,0,0,0) = (0,0,0,0,0,0) \), it shows that the rank of the moving helix system of the branch is 6. At this time, there is no anti helix in the branch of the mechanism, that is, there is no constraint helix on the moving end of the branch. Only in this case can the parallel mechanism have 6 degrees of freedom.

Based on the above analysis, if a 6-DOF parallel robot mechanism is constructed, each branch chain of the mechanism has 6 degrees of freedom, so the base of the single branch chain’s moving spiral system can be expressed as

\[
S_1 = (1,0,0,0,0,0), S_2 = (0,1,0,0,0,0), S_3 = (0,0,1,0,0,0), S_4 = (0,0,0,1,0,0), S_5 = (0,0,0,0,1,0), S_6 = (0,0,0,0,0,1)
\]

In the above formula, the baseline combination of six moving spirals can form a branch of the moving spiral system in the parallel robot mechanism, but in order to form a 6-DOF parallel robot, it is necessary to ensure that six moving spirals are linearly independent in the combination, that is, the rank of the moving spiral system is 6. The branch chain configuration is generally composed of several kinematic pairs in series or in parallel, and multiple branches are connected in parallel to the dynamic platform and the static platform of the robot, thus forming the parallel closed loop of the robot. The common types of kinematic pairs are shown in Table 1.
Table 1. Common types of motion pairs

| Motion pair | Symbol | Motion helix | Instructions | Degrees of freedom |
|-------------|--------|--------------|--------------|--------------------|
| R           | (1,0,0,0,0) | Rotating pair, relative rotation between two members. | 1             |
| P           | (0,0,1,0,0) | Move the pair, relative to each other. | 1             |
| H           | (1,0,0,P,Q,R) | A helical pair in which two members can move relative to each other while rotating around an axis. | 1             |
| C           | (1,0,0,0,0,0) | Cylindrical pair, two parts for the axis as the center of the rotation and along the axis direction of the translation. | 2             |
| U           | (1,0,0,0,0,0) | The universal hinge (Hooke hinge) has two degrees of freedom of relative rotation between the two members. | 2             |
| S           | (1,0,0,0,0,0) | Spherical pair having three independent relative rotations between two members. | 3             |

Based on the helix theory of unconstrained 6-DOF motion branches, we can see that there are many combinations of unconstrained branches. The possible branch types are RUS, RSU, PUS, PSU, SPU, UPS, SPU, SUR, URS, USR, SUP and USP. The branch forms that can be combined by using spherical hinge instead of Hooke hinge are RSS, PSS, SPS, SRS, SSR and SSP, but it will cause redundant local degrees of freedom in the branch chain. The cylindrical joint is used as the drive of the mechanism, and UCS, SCU, CSS, CRS, CPS, UCU, CUU, CUS, CSU, SCS, RCS, SCR, PCS, SCH, CSR and CSP forms also meet the requirements.

2.2. Branch chain design
Considering the principle of unconstrained branch chain selection and the symmetry and rationality of the robot structure, 6-RSS mechanism is adopted as the branch chain structure of the robot. The rotating pair is used as the driving pair, and the spherical pair is used as the moving pair connecting the moving platform at the end of the execution. It is convenient to install the driving device of the robot and effectively increase the attitude angle of the moving platform at the end of the execution of the robot. Its structure is shown in Figure 2. In order to further improve the rigidity of the six chain parallel robot, the driving device of the driving arm 1 is installed on the frame, the driving device of the driving arm 2 is installed on the driving arm 1, the six moving branches are coupled to form three groups of branch chains, and the three groups of branch chains are symmetrically arranged around the frame, as shown in Figure 3. Due to the mass of servo motor and planetary reducer, the inertia of robot drive arm 1 is too large, so it is necessary to transfer and install the drive device of drive arm 2 on the frame. In order not to damage the coupling structure, a space four-bar mechanism is added to the driving arm 2 by using the parallelogram equivalent transmission effect, so that the driving arm 2 is transferred to the coaxial position with the driving arm 1. The modified branch chain group is shown in Figure 4.
2.3. Degree of freedom analysis

In order to study whether the equivalent parallelogram structure designed in the transmission scheme design is reasonably equivalent to the transmission scheme in the theoretical model, the helix theory is used to analyze the mechanism motion and degree of freedom. The method of mechanism splitting is used to calculate the degree of freedom of multi-ring coupling parallel mechanism. After splitting the coupling mechanism to be analyzed, the coupling mechanism is still equivalent to a single branch chain by using the knowledge of helix theory, so that the multi-ring coupling parallel mechanism is equivalent to a common parallel mechanism [10].

As shown in Figure 4, the two members connected with the moving platform are respectively recorded as 5 and 6, and the independent direct motion connection to the rack is set as C1 and C2. C2 only drive arm 4, movement is not affected by other parts. The member 3 in C1 has three motion pairs, which are coupling nodes. Therefore, C1 must contain an effective structure to realize the motion transmission of the rack to coupling node 3, and the coupling node needs to continue to split it. The member 3 has three motion pairs, two of which point to the frame. The connecting part of the member 3 with respect to the frame is divided into two independent motion chains, the first and the second, as shown in Figure 5.
Take the midpoint of the axis line of the two driving arms as the origin, along the axis line direction of the two arms as the X axis, and vertically upward as the Z axis to establish the coordinate system. Component 3 is connected by two branch chains, $R_a1-R_a2$ and $R_b1-R_b2-R_b3$. As the output, the motion mode of the output component relative to the static platform is studied.

The spiral system of $R_b1-R_b2-R_b3$ is as follows

$$S_1 = \begin{pmatrix}
1 & 0 & 0;0 & 0 & 0 \\
1 & 0 & 0; a & b \\
1 & 0 & 0; c & d
\end{pmatrix}$$  \hspace{1cm} (1)

The anti spiral system is

$$S_1^r = \begin{pmatrix}
1 & 0 & 0;0 & 0 & 0 \\
0 & 0 & 0;0 & 0 & 1 \\
0 & 0 & 0;0 & 1 & 0
\end{pmatrix}$$  \hspace{1cm} (2)

The spiral system of single branched $R_a1-R_a2$ is

$$S_2 = \begin{pmatrix}
1 & 0 & 0;0 & 0 & 0 \\
1 & 0 & 0; e & f
\end{pmatrix}$$  \hspace{1cm} (3)

The anti spiral system is

$$S_2^r = \begin{pmatrix}
1 & 0 & 0;0 & 0 & 0 \\
0 & 0 & 0;0 & 0 & 1 \\
0 & 0 & 0;0 & 1 & 0 \\
0 & -f & e ;0 & 0 & 0
\end{pmatrix}$$  \hspace{1cm} (4)

To find the second anti spiral of

$$S_3^r = \begin{pmatrix}
1 & 0 & 0;0 & 0 & 0 \\
0 & 0 & 0;0 & e & f
\end{pmatrix}$$  \hspace{1cm} (5)

The results show that the coupling node 3 is equivalent to a rotating pair and a moving pair, and the motion relative to the frame is a rotation around X and a movement in the YOZ plane. Therefore, the
branch chain group is equivalent to RSS branch chain and PRSS branch chain. Among them, the rank of RSS branched chain motion spiral system is 6, and one of the seven pairs is local degree of freedom, which does not affect the motion characteristics, that is, RSS branched chain is 6 degree of freedom unrestricted branched chain. The rank of the kinematic helix of PRSS branch chain is 6. Two of the eight kinematic helixes are linearly related to other kinematic helixes, so two of them are local degrees of freedom, that is, PRSS mechanism is also a 6-degree of freedom unrestrained branch chain. Since each branch of the mechanism is a 6-DOF unconstrained branch, there is no common constraint and parallel redundant constraint, that is to say, there is no constraint for the moving platform, so it can be seen that the moving platform of the multi-ring coupling parallel robot mechanism has 6 degrees of freedom.

The modified G-K formula is used to verify the number of degrees of freedom of the mechanism

\[
M = d(n - g - 1) + \sum_{i=1}^{g} f_i + v + \xi
\]  

(6)

Where, \( M \) represents the degree of freedom of the mechanism, \( n \) is the number of components including the rack, \( g \) is the number of kinematic pairs, \( f_i \) Represents the number of ground degrees of freedom of the \( i \)th kinematic pair, \( v \) is the number of parallel redundant constraints, and \( \xi \) is the number of local degrees of freedom of the mechanism

PRSS mechanism has 3 components and RSS mechanism has 2 components, so the total number of components \( n \) of the mechanism is

\[
n = (3 + 2) \times 3 + 2 = 17
\]  

(7)

The number of kinematic pairs \( g \) is 21, the total number of degrees of freedom \( f_i \) is 45, and the number of local degrees of freedom \( \xi \) is 9. Therefore, the number of degrees of freedom of the mechanism is calculated according to equation 6

\[
M = 6 \times (17 - 21 - 1) + 45 - 9 = 6
\]  

(8)

Through the analysis of the helix theory and the verification of the degree of freedom formula, it can be seen that the degree of freedom of the coupling mechanism is 6, which meets the design requirements.

![Image](a) Branch chain group model. (b) Multi-ring coupled parallel robot model.

**Figure 6.** Mechanism model.
3. Simulation modeling
According to the analysis, the corresponding branch chain groups are designed, as shown in Figure 6.(a); the branch chain groups are combined into a 6-DOF robot structure in parallel, as shown in Figure 6.(b).

4. Conclusion
Based on the theory of 6-DOF unconstrained branch chain, this paper analyzes the type of 6-DOF multi-ring coupling parallel robot, and designs a multi-ring coupling 6-DOF parallel robot with branch chain type of 3-RSS-PRSS by changing the mechanism of branch chain type of 6-RSS. The transmission scheme and mechanism arrangement are more reasonable. The degree of freedom of the mechanism is calculated by the helix theory, and verified by the modified G-K formula. Finally, the three-dimensional model is established according to the mechanism.

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