Design and Analysis of a Series-Parallel Compliant Manipulator

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Abstract. Because of friction and assembly clearance, the accuracy of traditional rigid parallel mechanism cannot be maintained for a long time. Compliant mechanism has the advantages of light weight, high precision and low wear. Combining the characteristics of the two mechanisms, this paper designs a series-parallel compliant manipulator structure, and studies its forward and backward kinematics. Finally, it uses MATLAB software to study its workspace. Motion analysis was carried out.

1. Introduction
Due to the traditional rigid parallel mechanism, there is a friction such as friction, the traditional parallel mechanism can only be applied to non-precision situations, and the requirements for precision instruments cannot be reached for precision instruments that require long-term high precision. The compliant parallel mechanism is a combination of a flexible mechanism and a parallel mechanism. Its advantage is that the conventional hinge in the traditional parallel mechanism is replaced with a flexible hinge, so that there are no influencing factors such as friction, wear, and assembly clearance in the mechanism. And the mechanism has a plurality of freedom motion mechanisms to complete the designated motion like the traditional mechanism [1]. In view of the characteristics of the two, this paper introduces a flexible branches in 3-RRS rigid parallel agencies to design a 3-RRS type flexible skewers. The in-line institution has a small working space, and the series mechanism is low, and the combination of the two is increased, which increases the work space of the institution, and improves the accuracy of the institution. At the same time, it uses a soft mechanism to reduce the quality of the institution, increase the stiffness of the institution, and the accuracy remains unchanged for a long time. This structure belongs to a small degree of parallelized mechanisms that have strong adaptability, and easy to control, etc., currently in the current research. Finally, this paper performs a spatial simulation analysis of its model.

2. Research status
The parallel mechanism has the advantages of high stiffness, strong load capacity, small inertia and no cumulative position error, has been widely used in precision positioning devices. It is now designed to
design a precision positioner based on the international popularity. For problems such as traditional parallel positioning mechanisms, there is a problem such as friction and assembly gap, some scholars use flexible hinges to replace traditional moving departments, design all flexible parallel positioning mechanisms that achieve movement or energy transfer through their own elastic deformation. In order to study the new buffer technology, Defense Science and Technology University proposed a new type of soft buffer remote. In order to make the robot arm with better position and the safety of human-machine interaction, Beijing Jiaotong has designed a 3DOF lightweight mechanical arm, which is lightweight using carbon fiber material, and is designed with a series elastic drive (SEA) implementation. Surprises in the structure of the robot. Later, in order to address the dynamic changes of the working environment and the uncertainty of human-computer interaction, Beijing's interaction is designed. Succusive robotic arm [2]. Hebei Agricultural University In order to achieve automated production of scallop high-efficiency and low loss, Hebei is aimed at the method of absorbing the scallop coils, and a gas suction separation drive structure based on large deformation distributed compliance mechanism is proposed. Dun Ya and others: Aiming at the problem of spatial robot avoiding rigid collision and lacking visual feedback, there is no visual flexion assembly method [3].

3. Brief Introduction

![Figure.1 string and soft robotic arm](image)

The mechanical arm designed in this paper is a compliant series-parallel mechanism, as shown in Figure 1. The mechanism is composed of two parts, the middle joint part is a compliant parallel mechanism composed of three branch chains. The above end-effector is composed of a series mechanism with only two joints, which is a simple series mechanism. The two parts are combined to form a new combination, thereby improving the accuracy of the robotic arm, increasing the working space and reducing the overall quality. The comparative parallel mechanism and simple series mechanism are analyzed below.

4. Soft co-contained agency pseudo-rigidity model

As shown in Fig.2, the parallel mechanism employs a 3-RRS structure, consisting of three branches and two platforms, each branch consisting of a rotation sub-(b) and two universal hingers (P, M), and rotate. For the active joint, the rest is the passive joint.
As shown in Fig.3, Fig.3 is a simplified map of Fig.2, establishing a Cartesian coordinate system in the plane of three rotation pairs, the origin is located in the center O \{xyz\} of the static platform, the z-axis perpendicular to the bottom surface, the x-axis parallel at the bottom surface, the Y-axis determined according to the right hand of the right hand, and the Cartesian coordinate system \(O_p\{X_pY_pZ_p\}, O\{XYZ\}\) as the static platform coordinate system, \(O_p\{X_pY_pZ_p\}\) is the moving platform coordinate system [4]. \(\theta\) is the angle between the lower rod and the stationary platform, as shown in Fig. 11 is the angle of the BC rod and the stationary platform; \(\alpha\) is the projection of the lower rod in the static platform and the angle of the X-axis.

### 5. Parallel mechanism

5.1. Co-connected mechanism position is reversed

The position of the parallel mechanism is based on the position of the output end point, to solve the position of the input joints [5], which means the coordinate of the center point of the platform is known to the center point of the platform. \([X_p\ Y_p\ Z_p]\). The position of each joint is solved by establishing a closed-loop vector equation for a hinge, i.e., the joint angle \([\theta_1\ \theta_2\ \theta_3]\).

The closed loop vector equation is established by Figure 3:

\[
OB_1 + B_1C_1 + C_1P_1 + P_1P_Z = OP_Z
\]

Substitutes worth

\[
\begin{align*}
(X_p + r\cos\alpha_i - R\cos\alpha_i + l\cos\theta_i\cos\alpha_i)^2 \\
(Y_p + r\sin\alpha_i - R\sin\alpha_i + l\cos\theta_i\cos\alpha_i)^2 \\
(Z_p - l\sin\theta_i)^2 = L^2
\end{align*}
\]

Where R is the radius of the outer surface of the upper and bottom movable platform, \(R\) is the radius of the lower surface of the lower surface, and \(L\) is the length of each branched lower lever (Bici), and \(L\) is the length of each branched rod (CiPi). i is a branched branched branch.

Solutions have to:

\[
\theta_i = 2\arctan\left(\frac{-Z_p\sqrt{r^2 - m_i^2 + n_i^2}}{m_i + n_i}\right)
\]
among them:

\[ X_i = x_p + r \cos \alpha_i - R \cos \alpha_i \]  
\[ Y_i = y_p + r \sin \alpha_i - R \sin \alpha_i \]  
\[ m_i = \frac{2l_i^2 - x_i^2 - y_i^2 - z_i^2}{2l_i} \]  
\[ n_i = X_i \cos \alpha_i + Y_i \sin \alpha_i \]  

5.2. Parallel institution position

The position of the parallel mechanism is based on the position of the input joint, and the position and posture of the endpoint is determined in this paper, it is known that the various rotational joints are known \([\theta_1 \quad \theta_2 \quad \theta_3]\), by establishing a closed-loop vector equation for a hinge. The location of the moving platform center point, that is, the coordinate point \([X_p \quad Y_p \quad Z_p]\).

The closed loop vector equation is established by Figure 3:

\[
OB_1 + B_1C_1 + C_1P_1 + P_1P_Z = OP_Z \\
(X_p - X_1)^2 + (Y_p - Y_1)^2 + (Z_p - Z_1)^2 = L^2 \\
(X_p - X_2)^2 + (Y_p - Y_2)^2 + (Z_p - Z_2)^2 = L^2 \\
(X_p - X_3)^2 + (Y_p - Y_3)^2 + (Z_p - Z_3)^2 = L^2
\]

Substitutes worth

\[
\begin{align*}
    &a_1 = x_1 - x_2, a_2 = x_1 - x_3, \\
    &b_1 = y_1 - y_2, b_2 = y_1 - y_3, \\
    &c_1 = z_1 - z_2, c_2 = z_1 - z_3, \\
    &d_1 = (x_1^2 - x_1^2 + y_1^2 - y_1^2 + z_1^2 - z_1^2)/2, \\
    &d_2 = (x_1^2 - x_2^2 + y_2^2 - y_2^2 + z_2^2 - z_2^2)/2
\end{align*}
\]

The above intermediate variable expression is substantially in the closed loop vector equation:

\[
\begin{align*}
    X_p &= \frac{b_2d_1 - b_1d_2 + (c_2b_1 - c_1b_2)Z_p}{b_2a_1 - b_1a_2} \\
    Y_p &= \frac{a_2d_1 - a_1d_2 + (c_2a_1 - c_1a_2)Z_p}{a_2b_1 - a_1b_2} \\
    Z_p &= \left( -N + \sqrt{N^2 - 4MG} \right)/2M
\end{align*}
\]

among them

\[
\begin{align*}
    &M = \left( \frac{c_2b_1 - c_1b_2}{b_2a_1 - b_1a_2} \right)^2 + \left( \frac{c_2a_1 - c_1a_2}{a_2b_1 - a_1b_2} \right)^2 + l \\
    &N = 2 \left( a_2d_1 - a_1d_2 \right. \\
    &\left. \frac{c_2b_1 - c_1b_2}{b_2a_1 - b_1a_2} - \frac{c_2b_1 - c_1b_2}{b_2a_1 - b_1a_2} \right. \\
    &\left. \frac{c_2a_1 - c_1a_2}{a_2b_1 - a_1b_2} - \frac{c_2a_1 - c_1a_2}{a_2b_1 - a_1b_2} \right) \times X_1 + \\
    &\left( \frac{a_2d_1 - a_1d_2}{a_2b_1 - a_1b_2} - \frac{a_2d_1 - a_1d_2}{a_2b_1 - a_1b_2} \right) \times Y_1 - Z_1 \\
    &G = \frac{b_2d_1 - b_1d_2}{b_2a_1 - b_1a_2} \times X_1^2 + \left( \frac{a_2d_1 - a_1d_2}{a_2b_1 - a_1b_2} - \frac{a_2d_1 - a_1d_2}{a_2b_1 - a_1b_2} \right) \times Y_1^2 + Z_1^2 - L^2
\end{align*}
\]

In summary: The analysis of the designs \([X_p \quad Y_p \quad Z_p]\) is the coordinates of the center point center point of the upper movable platform.

5.3. Parallel mechanism sports simulation

Using MATLAB, the corresponding angle of motion analysis can be verified by comparing the positive retroreflectances by the results of the corresponding angle of rotation by the two sets of coordinate values. By solving the two sets of data, the first set of data shown in Table 1 is compared:
Table 1 First set Positive solution data table

| angle  | coordinate | Theta1 | Theta2 | Theta3 | $X_p$  | $Y_p$  | $Z_p$  |
|--------|------------|--------|--------|--------|--------|--------|--------|
| 100    | 120        | 150    | 15.8654| -24.5302| 87.0161|

Drawing according to the data of Table 1, the lower platform represents the static platform, the upper platform represents the moving platform, and each branch is composed of the upper link and the lower rod, and the mechanical platform is made by MATLAB, as shown in Fig4.

Comparison of the second set of data shown in Table 2:

Table 2 Second set of positive solution data table

| angle  | coordinate | Theta1 | Theta2 | Theta3 | $X_p$  | $Y_p$  | $Z_p$  |
|--------|------------|--------|--------|--------|--------|--------|--------|
| 130    | 150        | 160    | 4.8692 | -15.4818| 73.5176|

Drawing according to the data of Table 2, the drawing of the mechanical platform is shown by MATLAB as shown in Figure 5.

5.4. Series agency location solve

The series mechanism of the end of the end of the parallel mechanism is described below, which is a series mechanism on the parallel mechanism, which performs translation and rotation of the center point of the upper plane platform. The basic translational rotation matrix is as follows:

$$
\text{Trans}(x,a) = \begin{pmatrix}
1 & 0 & 0 & a \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\text{Trans}(y,a) = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & a \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix},
\text{Trans}(z,a) = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & a \\
0 & 0 & 0 & 1
\end{pmatrix},
\text{Rot}(x,\theta) = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos\theta & -\sin\theta & 0 \\
0 & \sin\theta & \cos\theta & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}.
$$

(14)
Rot(y,θ)=
\begin{pmatrix}
cosθ & 0 & sinθ & 0 \\
0 & 1 & 0 & 0 \\
-sinθ & 0 & cosθ & 0 \\
0 & 0 & 0 & 1 
\end{pmatrix}, \quad \text{Rot(z,θ)=}
\begin{pmatrix}
cosθ & -sinθ & 0 & 0 \\
sinθ & cosθ & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 
\end{pmatrix}.

As shown in FIG. 6, the structure is a series mechanism of the end of the parallel mechanism, which has three joint points, and the joint point 0 is connected to the center point of the parallel mechanism platform, the joint point 1 is the rotating joint, the joint point 2 is the end joint. The following is based on three joint points, and the joint coordinate system is established according to the D-H method of the robot. The parameters are shown in Table 3:

| #   | θ    | d    | a  | α |
|-----|------|------|----|---|
| 0-1 | 0    | 0    | H  | 0 |
| 1-2 | θ    | 0    | L  | 0 |

The meaning of each parameter in Table 3: h is the link length of the joint point 0 to the joint point 1, θ is the X-axis of the joint point 1 joint coordinate system to the clip of the joint 2 joint coordinate system X-axis, L is the joint point 1 to the distance of the joint point 2.

From the D-H table, the end point of the parallel mechanism, that is, the gate node 0 to the conversion matrix T of the end of joint point 2 of the series mechanism endode:

\[ T = \text{Trans}(Z, H) \ast \text{Rot}(Z, \theta) \ast \text{Trans}(X, L), \]

\[ [X_2 \ Y_2 \ Z_2]^T = T \ast [X_0 \ Y_0 \ Z_0]^T. \]

In summary, this article first is positively inverse kinematics by parallel agencies, and then establish DH table in series, analyzing the positive motion of series mechanisms, combining the two, can result in a string-parallel mechanism solution.

6. Working space analysis based on MATLAB

Since the string-stranded robot arm is a simple series mechanism and a compliance inlay mechanism, the series mechanism does not affect the final result. Therefore, the working space of the robot arm is analyzed by the parallel part of the robot arm, so MATLAB programming and simulation is performed on the positive motion of the parallel arm. The position of the end point is calculated by the joint angle. The form of a robot arm is drawn. As shown in Figure 6, three working spaces from XZ, YZ, XY are separately drawn.

Figure 6 MATLAB workspace map
7. Conclusion
This paper proposes a series-parallel compliant manipulator. Compared with the traditional rigid parallel manipulator, the mechanism not only has the working space of the traditional manipulator, but also improves the accuracy of the mechanism. At the same time, the series-parallel compliant manipulator reduces the mass of the mechanism and increases the rigidity of the mechanism.

1) Positive inverse kinetics is performed by establishing a vector equation.
2) On the basis of the parallel mechanism, establish a DH counter in the series part of the positive motion, and then obtain the positive motion of the entire body.
3) Simulation analysis using MATLAB on the working space of the robot.

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