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Research Article

Workspace Analysis of a Novel Parallel Robot Named 3-R2H2S with Three Freedoms

Xin-Jie Wang, Chao-Hui Zhang, Cai-Dong Wang and Hui Zheng
Mechanical and Electrical Engineering Institute,
Zhengzhou University of Light Industry, Zhengzhou, Henan, 450002, China

Abstract: In order to meet the sorting and packing needs of the drug and food industries, a novel parallel robot mechanism named 3-R2H2S is proposed in this study, the kinematics equation of the robot was deduced and the inverse kinematics was calculated. The workspace model of the robot is analyzed by the boundary search method through the MATLAB and ADAMS kinematics software. The analysis results show that the robot has a large effective workspace with smooth boundary and can be widely applied in the field of industrial robots, the kinematics of micro robots and 3D coordinate measurements and the workspace of the robot can meet the needs of drug and food automation production line.

Keywords: Parallel robot, position inverse solutions, workspace

INTRODUCTION

Parallel robot is a new kind of robot; it has a series of advantages: higher stiffness, strong bearing capacity, small error, high precision, small ratio of weight load, good dynamic performance, easy to control and so on (Kemal and Korkmaz, 2009; Nicola and Vincenzo, 2011). Parallel robot is widely used in areas such as flight simulator, parallel machines and parallel manipulators (Huang *et al*., 2009; Yun *et al*., 2008). The workspace of parallel robot is an important index to evaluate its working performance, so it has an important practical significance to analysis and research the workspace of the parallel robot (Chen *et al*., 2010). In recent years, many scholars at home or abroad have done a lot of research work on parallel robot's workspace, like Duan *et al*. (2011) who have researched the kinematics and workspace of the 6-PUS/UPU parallel robot and concluded the workspace of the mechanism at different flexible poses; Lee *et al*. (2006) made a detailed analysis for the 3-UPS parallel mechanism, later they draw out the workspace and concluded that the workspace is symmetrical in space. At present, most of the workspace research is based on the robot's structure size and constraint conditions to seek the workspace, which is called the positive problem, but the research of the reverse problem which is based on the workspace of the robot to seek the structure size and constraint conditions is less.

Recently, a large number of people are working among the food and drug industries for the sorting tasks and it has lots of disadvantages such as unsanitary, unsafely and high cost. In order to improve the automation degree of these enterprises and guarantee the products' quality, a novel parallel robot mechanism named 3-R2H2S is proposed according to the food and drug sorting operation requirements. This study researches the workspace of the parallel robot end-effect or based on the inverse solution.

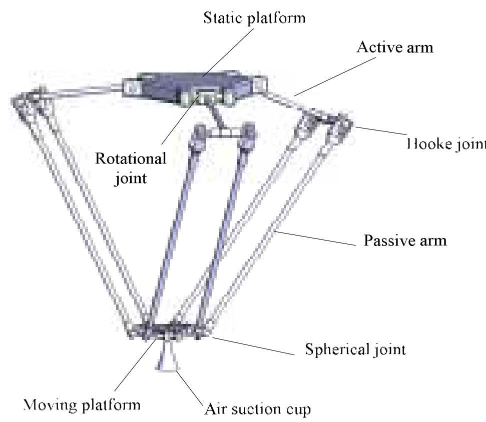

Fig. 1: 3-D model of 3-R2H2S parallel robot

STRUCTURE DESIGN

According to the new parallel robot mechanism in this study, two spherical joints have been replaced by Hooke joints based on the delta robot; the structure is shown in Fig. 1.

The static platform and moving platform are connected through three same branches and the angle of every two adjacent branches is 120°, each branch is

Corresponding Author: Cai-Dong Wang, Mechanical and Electrical Engineering Institute, Zhengzhou University of Light Industry, Zhengzhou, Henan, 450002, China

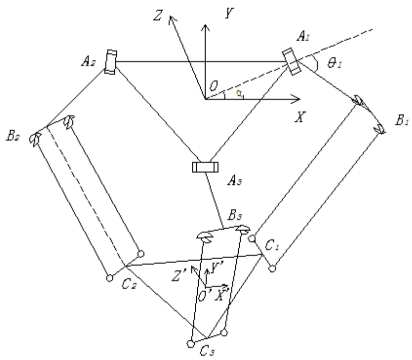

Fig. 2: Structure diagram of 3-R2H2S mechanism

consist of one Rotational joint (R joint), two Hooke joints (H joint) and two Spherical joints (S joint) that connecting in turn. The simulation result shows that the new structure not only overcomes the traditional structure's problem that the connecting bar which connect two spherical joints rotate around its own shaft (Zhu *et al*., 2003), but also moves smoothly and has bigger workspace and good kinematics performance.

An air suction cup is fixed at the moving platform's center, the suction cup can grabs drugs or foods by the negative air pressure and then the robot moves the drugs or foods into the corresponding packaging box in a very fast speed. The suction cup can be exchanged according to different products to meet the sorting requirements.

Freedom analysis and calculation: The structure diagram of 3-R2H2S mechanism is shown in Fig. 2. According to the Kutzbach-Grubler formula of spatial mechanism freedom, we can calculate:

$$F = 6(n - g - 1) + \sum_{i}^{g} f_i \tag{1}$$

where,

n : The number of parts

g : The number of kinematic pairs

$\sum_i^g f_i = 33$: The sum freedoms of all pairs

In this mechanism, the influence of the local freedom was eliminated due to the replacement of two spherical joints with two Hooke joints in each branch, which was completely equivalent with the traditional delta mechanism in kinematics. According to the calculation formula, number of parts n = 11, number of kinematic pairs g = 15, the sum freedoms of all pairs $\sum_i^g f_i = 33$, so the freedom of the mechanism is 3.

Inverse solution of position: The inverse solution of robot position is based on the reference point's coordinate of moving platform in the coordinate system, to calculate the three control motors' rotation angle on the static platform; it is also to calculate the three active arms' pendulum angle relative to the static platform. The inverse solution of robot position is the basis of trajectory planning for parallel robot; only obtain the correct solution can we make the end manipulator to reach the required pose. This study uses geometry method to solve the mechanism position.

As is shown in Fig. 2, setting the static platform's circumscribed circle's radius is R, the static platform's circumscribed circle's radius is r, $AB_i = l_\alpha$, $B_iC_i = l_b$, building static coordinate system O-XYZ in the center of the static platform and dynamic coordinate system O'-X'Y'Z' in center of the moving platform.

According to the geometrical relationship, the position vector of the rotational joint's center A_i in static coordinate system O-XYZ is:

$$a_{io} = R(\cos\alpha_i, \sin\alpha_i, 0)^T \quad (i = 1,2,3) \tag{2}$$

where, α_i represents the included angle between OA_i and the positive direction of X axis:

$$\alpha_i = \frac{4i-3}{6}\pi \quad (i = 1,2,3)$$

Similarly, we can obtain the position vector of the equivalent center C_i on the moving platform in dynamic coordinate system is:

$$c_{io'} = r(\cos\alpha_i, \sin\alpha_i, 0)^T \quad (i = 1,2,3) \tag{3}$$

where, α_i represents the included angle between O'C' and the positive direction of X' axis:

$$\alpha_i = \frac{4i-3}{6}\pi \quad (i = 1,2,3)$$

Setting the rotate angle form OA_i to A_iB is θ_i, from the geometrical relationship, we can obtain the position vector of B_i in static coordinate system is:

$$b_{io} = \begin{bmatrix} (R + l_a\cos\theta_i)\cos\alpha_i \\ (R + l_a\cos\theta_i)\sin\alpha_i \\ -l_a\sin\theta_i \end{bmatrix} \tag{4}$$

Setting the coordinate of the center O' of moving platform in the dynamic coordinate system O-XYZ is (x, y, z), the rotate angle of the moving platform relative to static platform in the direction of Z axis is zero, so the vector OC_i in the dynamic coordinate system O-XYZ can be expressed as:

$$c_{io} = \begin{bmatrix} r\cos\alpha_i + x \\ r\sin\alpha_i + y \\ z \end{bmatrix} \tag{5}$$

For $|B_i\ C_i| = l_b$, from the definition of the vector module, we can get the equation:

$$\begin{aligned}&[(R + l_a \cos\theta_i - r)\cos\alpha_i - x]^2 + \\ &[(R + l_a \cos\theta_i - r)\sin\alpha_i - y]^2 + \\ &(-l_a \sin\theta_i - z)^2 = l_b{}^2\end{aligned} \quad (6)$$

The above formula is the inverse solution equation of kinematics. After reduction we can obtain:

$$M_i t_i{}^2 + N_i t_i + P_i = 0 \;\; (i = 1,2,3) \quad (7)$$

where,

$$t_i = \tan\left(\frac{1}{2}\theta_i\right) \;\; (i = 1,2,3)$$

$$\begin{aligned}M_i = &(R-r)^2 + l_a{}^2 + x^2 + y^2 + z^2 - l_b{}^2 \\ &- 2(R-r)(x\cos\alpha_i + y\sin\alpha_i) \\ &- 2l_a(R - r - x\cos\alpha_i - y\sin\alpha_i)\end{aligned}$$

$$N_i = 4zl_a$$

$$\begin{aligned}P_i = &(R-r)^2 + l_a{}^2 + x^2 + y^2 + z^2 - l_b{}^2 \\ &- 2(R-r)(x\cos\alpha_i + y\sin\alpha_i) \\ &+ 2l_a(R - r - x\cos\alpha_i - y\sin\alpha_i)\end{aligned}$$

According to Eq. (7), we can get:

$$t_i = \frac{-N_i \pm \sqrt{N_i^2 - 4M_iP_i}}{2M_i} \;\; (i = 1,2,3)$$

The angle θ_i can be obtained by:

$$\theta_i = 2\arctan(t_i) \quad (8)$$

From the solution we can find that there are 8 groups of joint positions of the mechanism when the pose of moving platform is given.

In order to validate the correctness of the inverse position solution, we calculate inverse position solution through an example to observe the corresponding relation between input and output. First we set the mechanism's basic parameters R = 105 mm, r = 50 mm, l_α = 220 mm, l_b = 495 mm, the center's coordinate of moving platform is $(x, y, z)^T = (35, 60, -321)^T$, then we can calculate the three active arms' pendulum angle θ_i relative to the static platform. According to the inverse solution equation we can get:

$$\theta_1 = (-0.7784\pi, -0.2321\pi)$$

$$\theta_2 = (-0.7417\pi, -0.1497\pi)$$

$$\theta_2 = (-0.7136\pi, -0.0673\pi)$$

and the 8 groups of inverse solution respectively are:

- $(\theta_1, \theta_2, \theta_3) = (-7784\pi, -0.7417\pi, -0.7136\pi)$
- $(\theta_1, \theta_2, \theta_3) = (-7784\pi, -0.7417\pi, -0.0673\pi)$
- $(\theta_1, \theta_2, \theta_3) = (-7784\pi, -0.1497\pi, -0.7136\pi)$
- $(\theta_1, \theta_2, \theta_3) = (-7784\pi, -0.1497\pi, -0.0673\pi)$
- $(\theta_1, \theta_2, \theta_3) = (-2321\pi, -0.7417\pi, -0.7136\pi)$
- $(\theta_1, \theta_2, \theta_3) = (-0.2321\pi, -0.7417\pi, -0.0673\pi)$
- $(\theta_1, \theta_2, \theta_3) = (-0.2321\pi, -0.1497\pi, -0.7136\pi)$
- $(\theta_1, \theta_2, \theta_3) = (-0.2321\pi, -0.1497\pi, -0.0673\pi)$

Some groups will cause interference when the mechanism in actual motion in the above 8 groups inverse solution. Therefore, to calculate the parallel robot's inverse position solution is to find the optimal solution of the 8 groups, so that the system can realize the best and fastest control and has the best kinematic performance.

WORKSPACE ANALYSIS

The workspace of parallel robot is the set of points where the end-effector can reach, it is an important index to evaluate the robot's working performance, its size and shape determine the motion range of the end-effector and it is also the direct reflection of the working ability of parallel robot. Generally speaking, the workspace's small and irregular shape has restricted the application of parallel robot in a certain degree; therefore, to analysis the workspace is particularly important.

According to this structure, the workspace's size and shape is mainly determined by the arms' length, the circumscribed circle radius of static and moving platforms, the pendulum angle range of active arm and the turning angle range of spherical joint and Hooke joint in each branch. Considering the interference among parts when the mechanism is moving, the pendulum angle of the three active arms and the movement limit of spherical joint and Hooke joint, we set the pendulum angle range of the three active arms as:

$$\theta_{i\min} \le \theta_i \le \theta_{i\max} \;\; (i = 1,2,3) \quad (9)$$

The turning angle range of spherical joint as:

$$\theta_{bi} = \arccos\frac{L_i \cdot (Rn_{bi})}{|L_i|} \le \theta_{b\max} \;\; (i = 1,2,3) \quad (10)$$

where,

L_i : The bar's length vector
n_{bi} : The pose of spherical joint in dynamic coordinate system
$\theta_{b\max}$: The biggest turning angle of spherical joint

The turning angle range of spherical joint as:

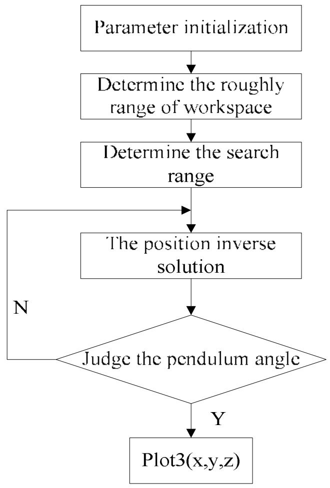

Fig. 3: The flow chart of search process

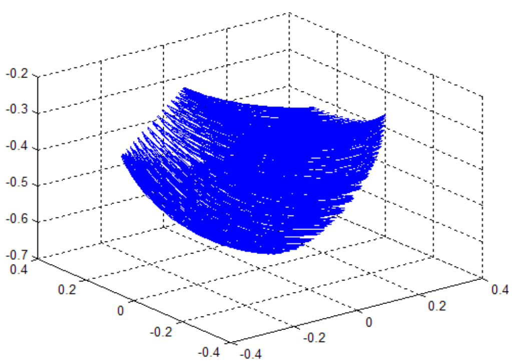

Fig. 4: Workspace of 3-R2H2S robot

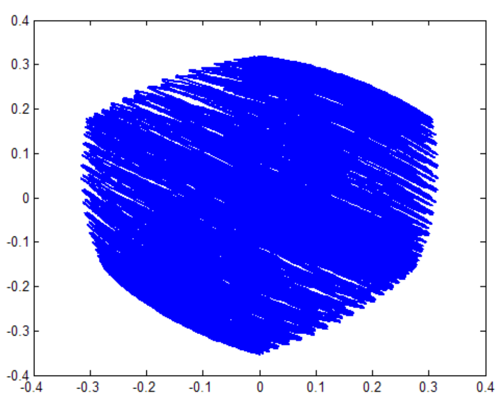

Fig. 5: Projection of XY plane

$$\theta_{Bi} = \arccos \frac{L_i \cdot (Rn_{Bi})}{|L_i|} \leq \theta_{B\max} \quad (i = 1,2,3) \qquad (11)$$

where,

L_i : The bar's length vector

n_{Bi} : The pose of hooke joint in static coordinate system

$\theta_{B\max}$: The biggest turning angle of hooke joint

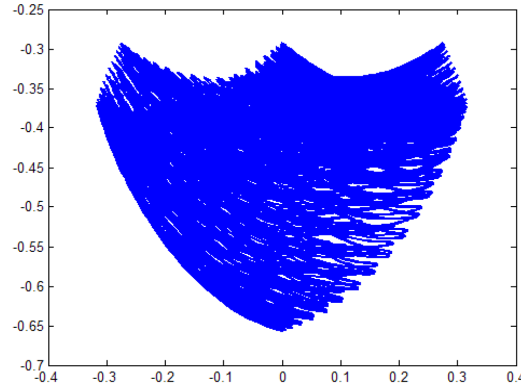

Fig. 6: Projection of XZ plane

Generally, the workspace of parallel mechanism is obtained through the kinematics inverse solution. One group of arms' pendulum angle can be obtained from the corresponding pose matrix of a point and if the arms' pendulum angle meets the Eq. (9), we can judge the position point belong the workspace, otherwise it doesn't. If we can seek out all the boundary points, then the parallel mechanism workspace consists of the points within or on the boundary, this is the boundary search method principle of the workspace.

Through the Eq. (10) and (11), we can find the roughly range of parallel mechanism's workspace and then specify the corresponding search range. Later a group of pendulum angle of a corresponding point can be obtained through the position inverse solution; if the angles meet Eq. (9) and then the point is inside of the work space. The flow chart of search process is shown in Fig. 3.

The structural parameters of the robot are: R = 105 mm, r = 50 mm, l_α = 220 mm, l_b = 495 mm, $-45^o \leq \theta_i 70^o$, $\theta_{bi} \leq 55^o$, $\theta_{Bi} \leq 60^o$. Based on robot kinematics inverse solution, the workspace model of the robot is analyzed by the boundary search method through the MATLAB and ADAMS kinematics software. The workspace of the moving platform's center O' is obtained, as is shown in Fig. 4. The workspace's projections in XZ plane and YZ plane are shown in Fig. 5 and 6, respectively. The workspace's boundary is smooth and the effective workspace is large and without holes in the space.

CONCLUSION

- A novel parallel robot mechanism named 3-R2H2S with three freedoms was proposed and the mathematical model of the kinematics inverse solution was also established.
- The workspace is symmetrical about XZ plane and YZ plane, the movement space is increasing along with the increasing of constraint turning angle when there no singular occurs. And the workspace of the robot can meet the needs of drug automation production line.

- The workspace of parallel robot named 3-R2H2S with three freedoms was studied in this study, which has provides reliable basis for the application research, design and its full advantage study of this kind robots.

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