Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 2, No. 3, 2022

Workspace Analysis for Humanoid Wrist Mechanism

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Abstract: Based on the analysis of human wrist, a humanoid wrist joint with 5R parallel mechanism as prototype is proposed. It is an orthogonal spherical two-degree-of-freedom parallel mechanism, which has the advantage of easy to process and manufacture. The inverse position solution of the mechanism is obtained by analytic method, and the velocity Jacobian matrix is established, and the working space of the mechanism is analyzed considering the working constraints of the mechanism. It provides a theoretical basis for its practicality.

Keywords: Wrist joint, PARallel mechanism, Workspace, Performance analysis.

1. Introduction

Manipulator is a kind of mechanical device created by imitating human arm, which can achieve the purpose of moving the claw to the desired position and bearing the weight of the workpiece and the arm itself [1]. Since the first robotic arm came into being, academia and engineering circles in various countries have invested a lot of manpower and material resources in the research of robotic arm，many breakthroughs have been made，various types of prototypes have been developed successively[2-3]. Because of the advantages of simple structure, simple control and large workspace, the humanoid manipulators on industrial manipulators and humanoid robots mostly adopt the serial mechanism [4-8]. However, the inherent error accumulation effect and poor dynamic characteristics of the serial mechanism limit its application in the case of increasing performance requirements of the manipulator. It is of great practical significance to develop new humanoid joints.

Parallel mechanism has many advantages, such as high stiffness, strong bearing capacity, low inertia, no error accumulation, compact structure, low dead load ratio and so on[9]. A humanoid wrist joint based on orthogonal spherical two-degree-of-freedom parallel mechanism is presented in this paper，which is a kind of parallel mechanism with less degrees of freedom. It inherits the advantages of parallel mechanism and has the characteristics of easy manufacture.

2. Mechanism Design Based on Analysis of Wrist Motion

2.1. Motion Analysis of Wrist

Fig. 1 shows the motion of the human wrist[10], which is performed by the driving muscles distributed in the upper arm rather than in the wrist itself. From the perspective of mechanism, the wrist is a two-degree-of-freedom mechanism.

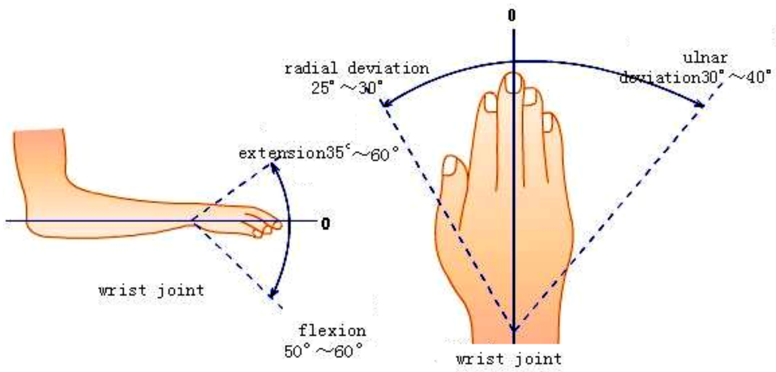
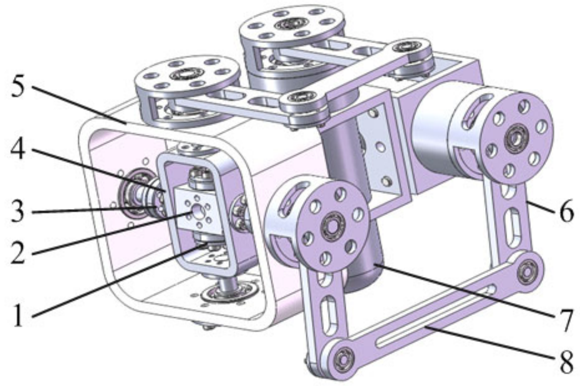


Figure 1. Movement form of wrist

2.2. Mechanism Design

The 5R parallel mechanism has two rotational degrees of freedom, which can achieve motion similar to wrist，and its driving device can be installed on the fixed base, so that the superior motor does not become the lower rotation load，and the inertia of the moving parts can be reduced. This arrangement makes the wrist joint have the advantages of compact structure, strong bearing capacity and good dynamic characteristics. Therefore, the 5R parallel mechanism is suitable as a mechanism prototype of the wrist joint of the anthropomorphic arm.

The wrist joint designed with 5R parallel mechanism as prototype is shown in Figure 2. It is an orthogonal two-degree-of-freedom parallel mechanism, which consists of connecting rod, moving platform, ring connecting rod, frame, driving rod and driving connecting rod. Two rods are connected with the revolute pairs, and the axes of all the revolute pairs intersect at one point. The mechanism can simulate the flexion and extension, internal rotation and external rotation of human wrist.

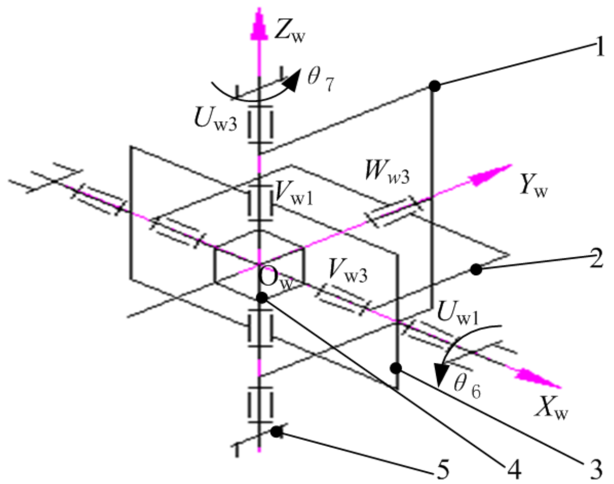


1connecting rod 2moving platform 3 connecting frame rod 4ring connecting rod5 frame 6driving rod 7 driver 8driving connecting rod

Figure 2. Prototype of the wrist joint

3. 2 Kinematic Analysis

The sketch of wrist mechanism designed with 5R parallel mechanism as prototype is shown in Fig. 3. Two rods are connected with the revolute pair, and the axes of all the revolute pairs intersect the point Ow. The axes of U_{w1} and V_{w1}, V_{w3} and W_{w3}, W_{w3} and U_{w3} are perpendicular to each other, and V_{w1} and V_{w3} are perpendicular to each other on the moving platform. In this way, a five-bar mechanism with orthogonal structure is formed. The input of the mechanism is the rotation angle θ_6 around the Xw axis and the rotation angle θ_7 around the Zw axis.



1 U driving rod Ⅰ 2 U connecting rod 3 ring driving rod 4 Moving platform 5 Frame

Figure 3. Mechanism of the wrist joint

With O_w as the origin of the coordinate system, the coordinate system is established, as shown in Figure 3. In the fixed coordinate system O_w-$X_wY_wZ_w$, the axes of X_w and Z_w coincide with the axes of revolute pairs U_{w1} and U_{w3} respectively, the direction of Y_w axis is determined by the right-handed screw rule. In the moving coordinate system O_w-$x_wy_wz_w$, the axes of x_w and z_w coincide with the axes of the revolute pairs V_{w3} and V_{w1} respectively, the direction of y_w axis is determined by the right-handed screw rule. The directions of coordinate axes are shown in Figure 3. In the initial attitude, the fixed coordinate system coincides with the moving coordinate system. The size parameters of the mechanism are defined as

$$\overline{\boldsymbol{O}_w\boldsymbol{V}}_{w1} = l_{w1},\ \overline{\boldsymbol{O}_w\boldsymbol{V}}_{\boldsymbol{w}3} = l_{w5},\ \overline{\boldsymbol{O}_w\boldsymbol{W}}_{\boldsymbol{w}3} = l_{w3},$$

$$\overline{\boldsymbol{O}_w\boldsymbol{U}}_{\boldsymbol{w}1} = l_{w2},\ \overline{\boldsymbol{O}_w\boldsymbol{U}}_{\boldsymbol{w}3} = l_{w4},\ l_{w2} = l_{w4}$$

The method of Euler angle is used to describe the transformation matrix between the moving coordinate system and the fixed coordinate system[11]. The transformation matrix is given as

$$\boldsymbol{R}_w = \boldsymbol{R}(x_w, \gamma_w)\boldsymbol{R}(z_w, \alpha_w) = \begin{bmatrix} \cos\alpha_w & -\sin\alpha_w & 0 \\ \cos\gamma_w \sin\alpha_w & \cos\gamma_w \cos\alpha_w & -\sin\gamma_w \\ \sin\gamma_w \sin\alpha_w & \sin\gamma_w \cos\alpha_w & \cos\gamma_w \end{bmatrix} \quad (1)$$

where α_w and γ_w are the attitude angles of the moving platform.

3.1. Inverse Position Solution

Using eq. (1), the direction cosine of each axis V_{wi} relative to the fixed coordinate system on the moving platform can be given as

$$\boldsymbol{V}_{wi} = \boldsymbol{R}_w \boldsymbol{v}_{wi} \tag{2}$$

where $\boldsymbol{v}_{wi}$ is the coordinate of the revolute pair connected to the moving platform in the moving coordinate system.

According to the orthogonal characteristic and rotation relationship of the mechanism, the vectors of the axes of the rotating pairs connected to the input axes relative to the fixed coordinate system $O_w - X_w Y_w Z_w$ are given as

$$\boldsymbol{V}_{w1} = (0 \ \ -\sin\theta_6 \ \ \cos\theta_6)^{\mathrm{T}} \tag{3}$$

$$\boldsymbol{W}_{w3} = (-\sin\theta_7 \ \ \cos\theta_7 \ \ 0)^{\mathrm{T}} \tag{4}$$

According to the geometric relationship of the mechanism, the kinematics constraint equation by using staggered angle theorem[12] for the mechanism can be written as

$$\boldsymbol{W}_{w3} \cdot \boldsymbol{V}_{w3} = 0 \tag{5}$$

From eqs. (2)-(5), the inverse solution of position is given as eq. (6), the forward solution of the position is given as the eq. (7).

$$\left.\begin{aligned} \theta_6 &= \gamma_w \\ \theta_7 &= \arctan(\tan\alpha_w \cos\gamma_w) \end{aligned}\right\} \tag{6}$$

$$\left.\begin{aligned} \alpha_w &= \arctan(\tan\theta_7 / \cos\theta_6) \\ \gamma_w &= \theta_6 \end{aligned}\right\} \tag{7}$$

3.2. Structural Constraint

(1) $\theta_{6\max}$ and $\theta_{6\min}$ are defined as the maximum and minimum rotation angles of the actuator U_{w1} respectively, $\theta_{7\max}$ and $\theta_{7\min}$ are the maximum and minimum rotation angles of the actuator U_{w3} respectively, and the constraint conditions of no interference between the fixed platform and the connecting rod can be expressed as

$$\left.\begin{aligned} \theta_{6\min} < \theta_6 < \theta_{6\max} \\ \theta_{7\min} < \theta_7 < \theta_{7\max} \end{aligned}\right\} \tag{8}$$

(2) The constraint conditions for the mechanism to avoid singular posture can be expressed as

$$\left.\begin{aligned} -90^\circ < \theta_6 < 90^\circ \\ -90^\circ < \theta_7 < 90^\circ \end{aligned}\right\} \tag{9}$$

(3) It is assumed that section of the rods is round, and its diameter is d, the shortest distance between the same side of the connecting rod and the rod connected to the frame is set D_i, the constraint conditions that there are not interference between two rods can be expressed as

$$D_i < d \tag{10}$$

4. Workspace Analysis

The structural parameters of the mechanism are shown in Table 1. The point $\boldsymbol{p}_w = [0 \ \ \text{-}20 \ \ 0]^T$ on the moving platform of the mechanism is selected as reference point for the workspace. Given the constraints of eqs. (10)-(12), $-60^\circ \le \alpha_w \le 60^\circ$, $-45^\circ \le \gamma_w \le 45^\circ$, and the step length is $\Delta\alpha_w = \Delta\gamma_w = 5^\circ$, then, the three-dimensional search method is used to simulate and analyze the workspace of the mechanism with MATLAB. The results are shown in Fig. 4-5. Compared with the range of human wrist motion, the mechanism can basically meet the motion requirements of the human wrist joint.

Table 1. Structural parameters and inertial parameters

Structural Parameters	Value
$a_w b_w$ length l_{w1} / mm	20
$b_w c_w$ length l_{w2} / mm	35
$d_w e_w$ length l_{w3} / mm	30
$g_w h_w$ length l_{w3} / mm	30
$e_w f_w$ length l_{w4} / mm	35
$f_w g_w$ length l_{w5} / mm	20
D_i (mm)	10
$\theta_{7\max}$ (d) / $\theta_{7\min}$ (d)	60/-60
$\theta_{6\max}$ (d) / $\theta_{6\min}$ (d)	60/-60

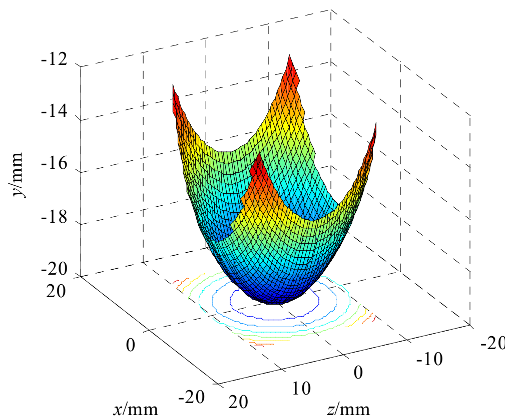


Figure 4. Three-dimension graph of the workspace

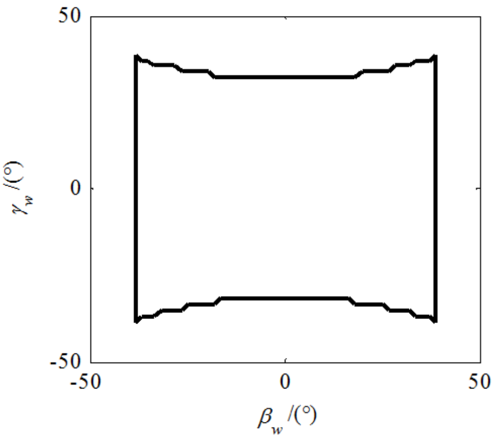


Figure 5. Boundary map of the workspace

5. Conclusion

Based on the analysis of the motion form of human wrist joint, a humanoid wrist joint based on orthogonal spherical two-degree-of-freedom parallel mechanism is proposed. Based on the inverse kinematics solution of the mechanism, the result of workspace analysis shows that the mechanism can basically meet the motion requirements of human wrist joint.

Acknowledgment

This work is supported by Teaching case project in Hebei Normal University of science and technology, Project number: 2021AL02，and Teaching Reform Project of Hebei Normal University of Science and Technology, Project number: JYYB202153, and Hebei Professional Degree teaching case base project, Project number: KCJSZ2021074，Project of Hebei Industrial Manipulator Control and Reliability Technology Innovation Center (Hebei University of Water Resources and Electric Engineering), Project number: JXKF2108 and JXKF2107.

References

[1] Tianmiao Wang, Yong Tao. Research Status and Industrialization Development Strategy of Chinese Industrial Robot [J]. Journal of mechanical engineering[J], 2014, 50(9): 1-13. (in Chinese)

[2] SAHA S K. Introduction to robotics [M]. Beijing: China Machine Press, 2010.

[3] Östring M, Gunnarsson S, Norrlöf M. Closed-loop Identification of An Industrial Robot Containing Flexibilities[J]. Control Engineering Practice, 2003, 11(3): 291-300.

[4] Dongchao Yang, Guoming Zhao, Ken Chen, et al. Analysis of degrees of Freedom of humanoid Robot [J].China Mechanical Engineering, 2003, 14(6): 453-456. (in Chinese)

[5] Xiuli Yu, Shimin Wei, Qizheng Liao. Development and Technology Research of Humanoid Robot[J]. Journal of mechanical engineering[J]. 2009, 45(3): 71-75. (in Chinese)

[6] Artermiadis P K， Katsiaris P T, Kyriakopoulos K J. A biomimetic approach to inverse kinematics for a redundant robot arm[J]. Autonomous Robots, 2010, 29(3-4): 293-308.

[7] Bauml B, Schmidt F, Wimbock T, et al. Catching Flying Balls and Preparing Coffee: Humanoid Rollin' Justin Performs Dynamic and Sensitive Tasks[C]. 2011 IEEE International Conference on Robotics and Automation, Shanghai, China, 2011：3443-3444.

[8] Jing Zhao, Chunyu Song, Bin Du. Configuration of Humanoid Robotic Arm Based on Human Engineering [J]. Journal of mechanical engineering, 2013, 49(11): 16-21. (in Chinese)

[9] Merlet J P. Parallel robots [M]. Springer Netherlands, 2014.

[10] Kai Zhang. Joint motion recording method- Neutral Zero Method [EB/OL]. http://guzhe.baike.com/article-49292.html.

[11] Zhen Huang, Yongsheng Zhao, Tieshi Zhao. Advanced Spatial Mechanism[M]. China Higher Education Press, 2006. (in Chinese)

[12] Youlun Xiong, Han Ding, Encang Liu, et al. Robotics[M]. Beijing: China Machine Press, 1992.