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Research on kinematics of 3-dof connecting rod manipulator based on 5R kinematic chain -Take the bionic pelican fishing device as an example

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Abstract
Based on the flexibility of the neck manipulator of the bionic pelican fishing device, the demand for carrying capacity and the consideration of economic benefits, a 3-DOF connecting rod manipulator based on the 5Rkinematic chain was designed, and the kinematic characteristics of the 5R five-bar mechanism in two-dimensional space and the mobility of the mechanism under the constraint of the bar length were studied. Through the application of matlab simulation, the movable range of the mechanism is obtained and the data analysis of the predetermined track is realized within the movable range, and the angle change curve chart required for the motor to achieve the predetermined track is obtained. The predetermined movement track is simulated by using the corresponding data and motion characteristics of the curve chart, which verifies the feasibility of achieving the target track setting within the movable range of the track.

Key words: 5R kinematic chain; Three degrees of freedom; connecting rod manipulator; Kinematics; trajectory control

Introduction

The traditional manipulator is divided into elbow joint manipulator and connecting rod manipulator. The elbow joint manipulator has the advantage of small size, but large working range. The flexibility of the connecting rod manipulator is slightly less than that of the elbow joint manipulator . However, the large weight parts can be concentrated together through the connecting rod configuration, so as to reduce the torque demand of the motor while ensuring that the mechanical arm can meet the working requirements of the remote end and save costs, Therefore, the connecting rod manipulator has also been widely used in various industries [1-4]. The connecting rod manipulator is a kind of manipulator based on the kinematic characteristics of the multi-bar mechanism. The research of the connecting rod manipulator is mainly to study the motion of the multi-bar mechanism. Many domestic scholars have carried out research on the multi-bar mechanism in different degrees and directions. Taking the commonly used five-bar mechanism as an example, J. Li et al. [5] have made corresponding research on the change and selection of the planar five-bar mechanism, and H.M.Tian et al. [6] have studied the existence conditions of the double-crank of the five-bar mechanism, Y.X.Wang et al. [7] studied the configuration bifurcation and configuration retention of the five-bar mechanism, and J.G.Wang et al. [8] extended the five-bar mechanism in two-dimensional space to the spherical five-bar mechanism in three-dimensional space, and carried out the kinematics research and performance analysis on it. In this study, a bionic pelican fishing device of three-DOF connecting rod manipulator based on 5R kinematic chain was proposed based on the previous research foundation and the application scenario of manipulator. The head and neck of the device are used for fishing, and the flexibility of the manipulator is not high. At the same time, the head is used for picking up garbage on the water, and the weight of the neck and head is large. In order to balance the body and reduce the material consumption, The traditional three-degree-of-freedom connecting rod manipulator is used to simulate and realize the neck fishing function.

1 Working principle of bionic pelican neck manipulator

The bionic pelican fishing device is composed of head, neck and main body as shown in Figure 1. The working principle is that after the fishing device finds the water floating garbage, the head picks up the water floating garbage, and carries the garbage picked up by the head to the container at the back of the main body through the neck manipulator. The neck manipulator is the key part of the whole device, as shown in Figures 2 and 3.

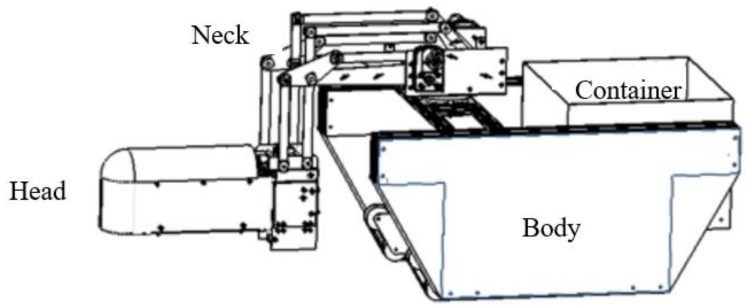

Figure 1： Bionic pelican fishing device

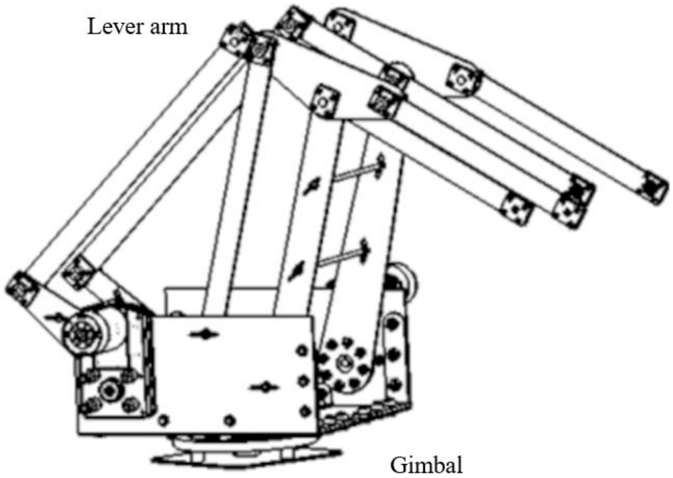

Figure 2： Bionic pelican neck manipulator

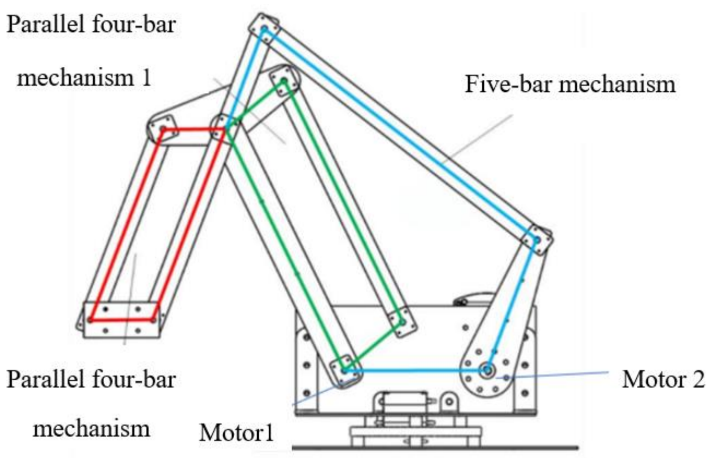

Figure3： Simplified image of bionic Pelican neck manipulaator

The neck manipulator is a three-degree-of-freedom connecting rod manipulator. The movable and kinematic characteristics of the lever arm are realized by using 5R kinematic chain. At the same time, two parallel four-bar mechanisms is installed to ensure the stability and strength of the manipulator. The base of the mechanical arm is a single rotation degree of freedom. When the mechanical arm works, the base gimbal rotates to the target angle, and the lever arm can move within the range of motion of the mechanical arm driven by the motor mounted on the hinge of the two driving rod bases above the gimbal.

In the whole mechanical arm, the most important part is the 5R motion chain of the arm. The two parallel four-bar mechanisms in the arm are redundant degrees of freedom, which will not affect the motion form and state of the five-bar mechanism itself, and play a role in strengthening the arm and maintaining the level of the working part of the end of the mechanical arm.

2 Kinematic Analysis of Bionic Pelican Neck Manipulator

In the whole movement process of the manipulator, the rotation control of the gimbal is relatively simple, just control the output angle of the gimbal steering gear. Therefore, this study focuses on the analysis of the lever arm. Unlike the elbow joint arm, the link arm's range of motion is limited by its motion characteristics and the length of the link, and its flexibility and mobility are relatively poor compared with the elbow joint arm. Therefore, it is necessary to focus on the analysis of the kinematic characteristics and range of motion of the arm. The arm is based on the 5R kinematic chain, supplemented by two groups of parallel four-bar mechanisms. As shown in Figure 4, its kinematic characteristics are determined by the 5R kinematic chain. When the arm is kinematic analyzed, the influence of the parallel four-bar mechanism on the analysis results can be ignored. Therefore, in the following analysis, the arm is simplified to a five-bar mechanism for separate analysis.

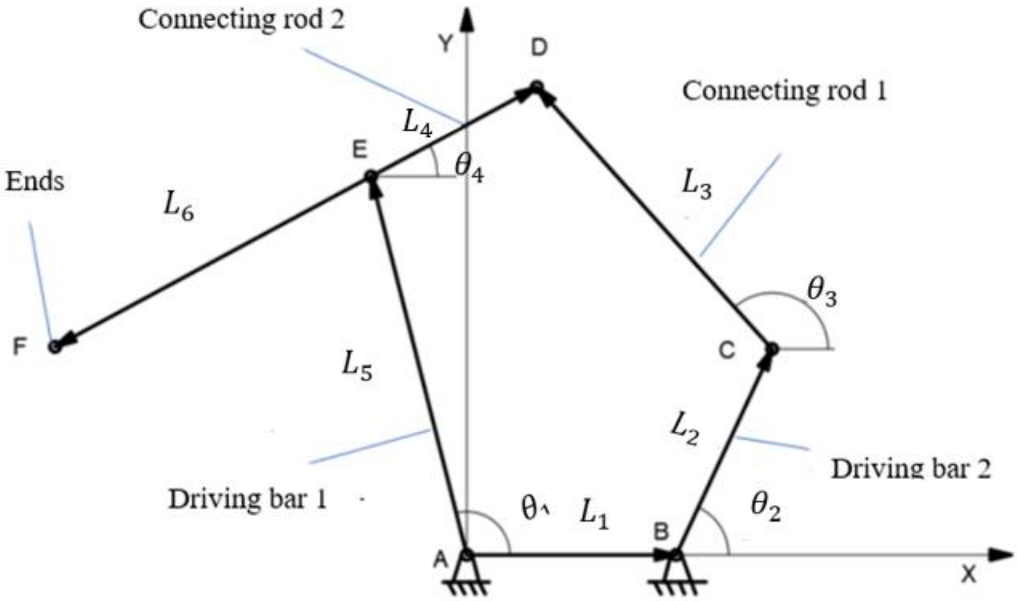

Figure 4： Bionic Pelican neck mechanical arm five-bar mechanism

In this study, the traditional analytical method is adopted, and the hinge of the driving bar L_5 is taken as the coordinate origin, and the coordinate system as shown in Figure 4 is established. The structural parameters of each part of the manipulator are: the length of the two driving bars L_5 and L_2. The hinge spacing between the two driving bars (L_5 and L_2) is the frame length L_1. Length of connecting rod 1 L_3. Length of connecting rod 2 L_4. Length of actuating rod L_6. Motor 1 corner θ_1. Motor 2 corner θ_2, and connecting rod included angle θ_3 and θ_4。

2.1 Position analysis of connecting rod and end

It can be obtained from vector method：

$$\boldsymbol{L_1} + \boldsymbol{L_2} + \boldsymbol{L_3} = \boldsymbol{L_5} + \boldsymbol{L_4} \tag{1}$$

Project in the x and y directions as：

$$\begin{cases} L_1 + L_2 \cos\theta_2 + L_3 \cos\theta_3 = L_5 \cos\theta_1 + L_4 \cos\theta_4 \\ L_2 \sin\theta_2 + L_3 \sin\theta_3 = L_5 \sin\theta_1 + L_4 \sin\theta_4 \end{cases} \tag{2}$$

$\theta_1$and$\theta_2$given by the active motor, solve this equation to obtain:

$$\theta_4 = 2\tan^{-1}\frac{(A \pm \sqrt{A^2+B^2-C^2})}{B-C} \tag{3}$$

Additionally
$$\begin{cases} A = 2yL_4 \\ B = 2xL_4 \\ C = {L_4}^2 + x^2 + y^2 - {L_3}^2 \end{cases}$$

Substitute (3) into (2) to obtain θ_3

Then the analytical coordinates of the F point of the execution end coordinate of the manipulator are：

$$\begin{cases} X_F = L_5\cos\theta_1 + L_6\cos(\theta_4+\pi) \\ Y_F = L_5\sin\theta_1 + L_6\sin(\theta_4+\pi) \end{cases} \tag{4}$$

2.2 Speed analysis of connecting rod and end

The angular velocity of connecting rod 1 and connecting rod 2 can be obtained by derivative of （4）

$$\begin{bmatrix}\omega_3\\ \omega_4\end{bmatrix} = \begin{bmatrix}-L_3\sin\theta_3 & L_4\sin\theta_4\\ L_3\cos\theta_3 & -L_4\cos\theta_4\end{bmatrix}^{-1}\begin{bmatrix}-L_5\sin\theta_1 & L_2\sin\theta_2\\ L_5\cos\theta_1 & -L_2\cos\theta_2\end{bmatrix}\begin{bmatrix}\omega_1\\ \omega_2\end{bmatrix} \tag{5}$$

And the speed of executing ends F:

$$\begin{bmatrix}V_{Fx}\\ V_{Fy}\end{bmatrix} = \begin{bmatrix}-L_5\sin\theta_1 & -L_6\sin(\theta_4+\pi)\\ L_5\cos\theta_1 & L_6\cos(\theta_4+\pi)\end{bmatrix}\begin{bmatrix}\omega_1\\ \omega_4\end{bmatrix} \tag{6}$$

2.3 Acceleration analysis of connecting rod and end

The derivative of the angular velocity of formula **(5)** and the terminal velocity of formula **(6)** can be Obtained：

$$\begin{bmatrix}\alpha_3\\ \alpha_4\end{bmatrix} = \begin{bmatrix}-L_3\sin\theta_3 & L_4\sin\theta_4\\ L_3\cos\theta_3 & -L_4\cos\theta_4\end{bmatrix}^{-1}\begin{bmatrix}L_3\cos\theta_3\,\omega_3{}^2 - L_4\cos\theta_4\,\omega_4{}^2 - L_5\cos\theta_1\,\omega_1{}^2 + L_2\cos\theta_2\,\omega_2{}^2\\ L_3\sin\theta_3\,\omega_3{}^2 - L_4\sin\theta_4\,\omega_4{}^2 - L_5\sin\theta_1\,\omega_1{}^2 + L_2\sin\theta_2\,\omega_2{}^2\end{bmatrix} \tag{7}$$

$$\begin{bmatrix}a_{Fx}\\ a_{Fy}\end{bmatrix} = m_3\begin{bmatrix}\omega_1\\ \omega_4\end{bmatrix} + m_4\begin{bmatrix}\alpha_1\\ \alpha_4\end{bmatrix} \tag{8}$$

Additionally：

$$\begin{cases} m_3 = \begin{bmatrix}-L_5\cos\theta_1\,\omega_1 & -L_6\cos(\theta_4+\pi)\,\omega_4\\ -L_5\sin\theta_1\,\omega_1 & -L_6\sin(\theta_4+\pi)\omega_4\end{bmatrix} \\ m_4 = \begin{bmatrix}-L_5\sin\theta_1 & -L_6\sin(\theta_4+\pi)\\ L_5\cos\theta_1 & L_6\cos(\theta_4+\pi)\end{bmatrix} \end{cases}$$

To sum up, the motion state of the 5R five-bar mechanism can be obtained one by one by the formula given above, and all the motion parameters can be obtained by substituting each parameter.

3 Kinematics simulation analysis of bionic Pelican neck manipulator

3.1 Parameter setting

All motion parameters of the mechanism have been analyzed above, but in practical application, it is necessary to compile motion algorithm for the manipulator and design its motion path, and the setting of motion path must be established within the movable range of the mechanism. The movability of the mechanism needs to consider the condition of rod length. The following takes a rod length given according to the empirical formula as an example for analysis. The parameters of each rod length are shown in Table 1.

Table 1:Length parameters of 5R moving chain rod (unit: mm)

bar	L_1	L_2	L_3	L_4	L_5
length	132	130	298	100	250

As shown in Figure 5, without loss of generality, for any given θ_1, the value range of θ_2 can be determined by the bar length condition. For a given θ_1, rod L_5 and L_1 can be equivalent to rod L, so the five-bar mechanism can be equivalent to the four-bar mechanism BCDE shown in the figure.

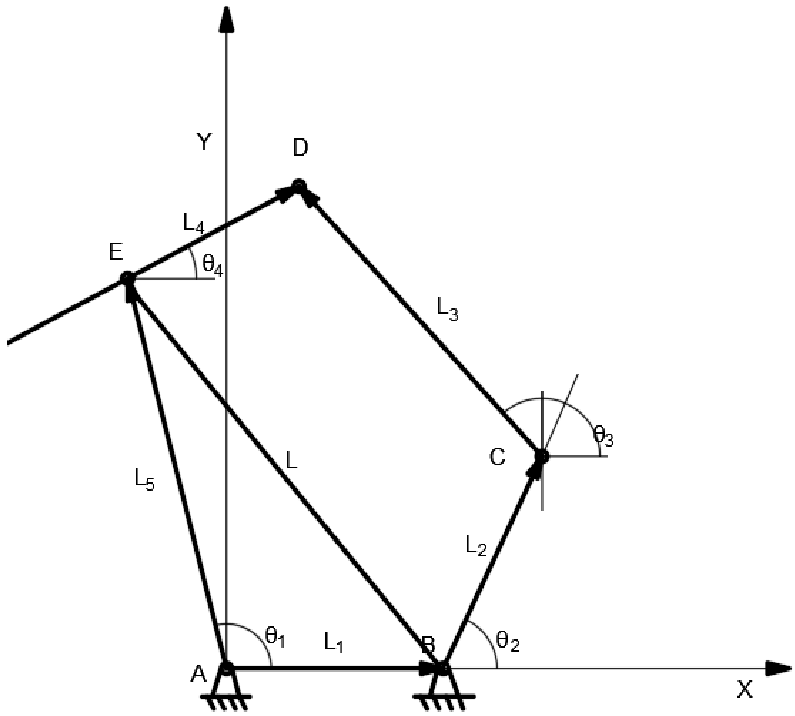

Figure 5: Simplification of five-bar mechanism

And: $L = \sqrt{{L_1}^2 + {L_5}^2 - 2L_1L_5\cos\theta_1}$

Additionally $L \in (118,382)$

3.2 Kinematic trajectory analysis

When $L \in (298,382)$, L is the longest rod,

$$\begin{cases} \text{when } L > 328, \text{the condition of rod length is not satisfied,} \\ \text{mechanism is a double}-\text{rocker mechanism, B is swing pair} \\ \text{when } L \leq 328, \text{the condition of rod length is satisfied,} \\ \text{mechanism is a crank rocker mechanism, B is a swing pair} \end{cases}$$

When $L \in (118,298)$, L_3 is the longest bar,

$$\begin{cases} \text{when } L \geq 268, \text{the condition of rod length is satisfied,} \\ \text{mechanism is a crank rocker mechanism, B is swing pair} \\ \text{when } L < 268, \text{the condition of rod length is not satisfied,} \\ \text{mechanism is a double}-\text{rocker mechanism, B is a swing pair} \end{cases}$$

It follows that no matter what θ_1 value is, B is always a swing pair.
When $L\in(328,382)$, the Swing Angle model is shown in Figure 6.
Swing Angle φ :

$$\varphi = 2\cos^{-1}\frac{L^2+{L_2}^2-(L_4+L_3)^2}{2LL_2} \quad (9)$$

$$\theta_{01} = \cos^{-1}\frac{{L_1}^2+L^2-{L_5}^2}{2LL_1} \quad (10)$$

And $$\theta_2 \in \left(\pi-\theta_{01}-\frac{\varphi}{2}, \pi-\theta_{01}+\frac{\varphi}{2}\right) \quad (11)$$

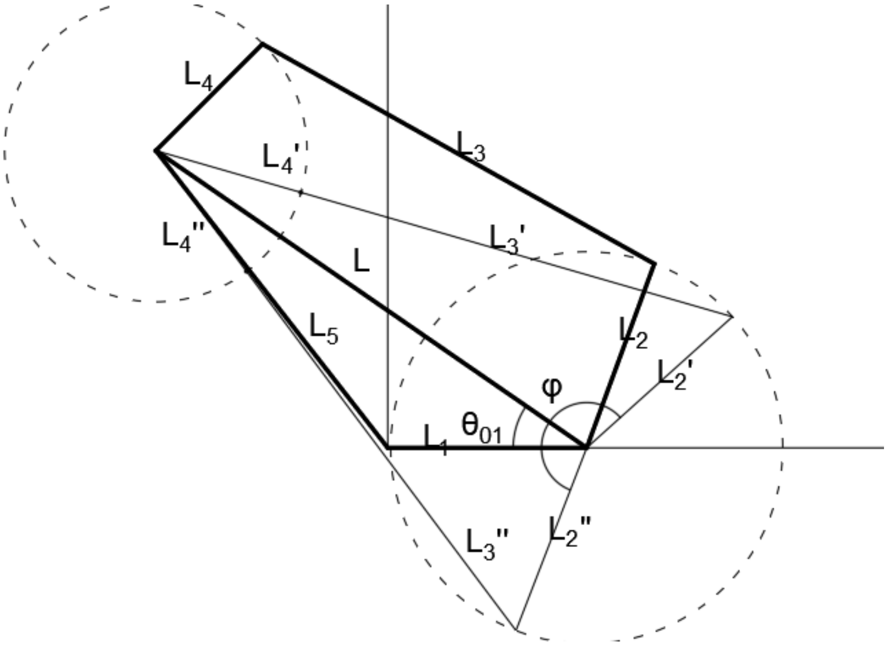

Figure 6: Bar length state 1

When L∈(268,328), the Swing Angle model is shown in Figure 7.

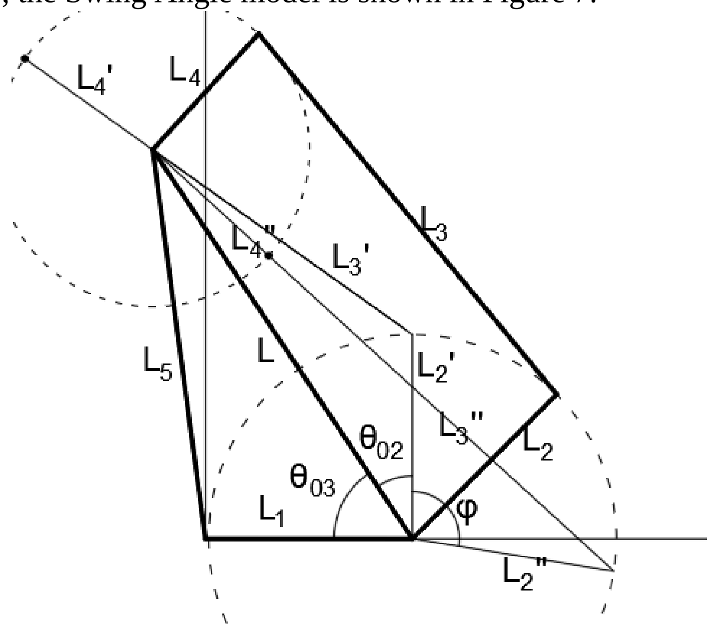

Figure 7: Bar length state 2

$$\theta_{02} = \cos^{-1}\frac{{L_2}^2+L^2-(L_3-L_4)^2}{2LL_2} \quad (12)$$

$$\theta_{03} = \cos^{-1}\frac{{L_1}^2+L^2-{L_5}^2}{2LL_1} \quad (13)$$

$$\theta_{02}+\varphi = \cos^{-1}\frac{L^2+{L_2}^2-(L_4+L_3)^2}{2LL_2} \quad (14)$$

And

$$\theta_2 \in (\pi-\theta_{03}-\theta_{02}-\varphi, \pi-\theta_{03}-\theta_{02}) \quad (15)$$

When L∈(118,268), the Swing Angle model is shown in Figure 8.

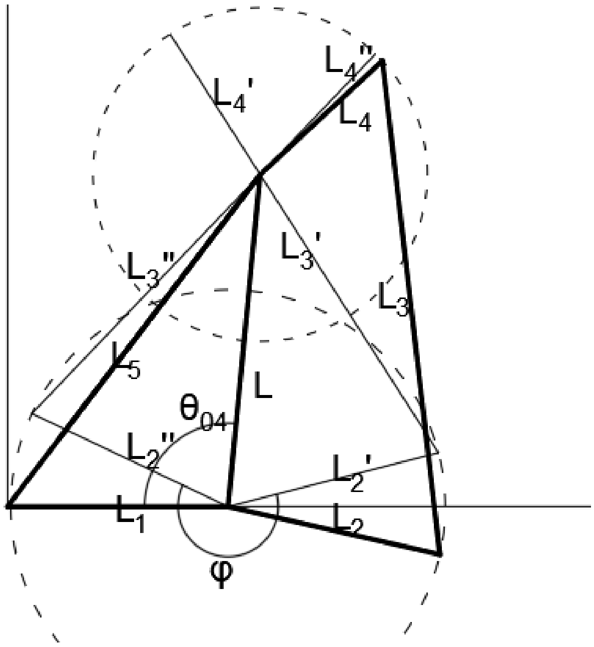

Figure 8: Bar length state 3

$$\pi - \frac{\varphi}{2} = cos^{-1}\frac{{L_2}^2 + L^2 - (L_3 - L_4)^2}{2LL_2} \quad (16)$$

$$\theta_{04} = cos^{-1}\frac{{L_1}^2 + L^2 - {L_5}^2}{2LL_1} \quad (17)$$

And $$\theta_2 \in \left(2\pi - \theta_{04} - \frac{\varphi}{2}, 2\pi - \theta_{04} + \frac{\varphi}{2}\right) \quad (18)$$

In combination with (11) (15) (18), it is obtained that

$$\begin{cases} when\ \ \theta_1 \in (114.7772,180) \\ \theta_2 \in \left(\pi - \theta_{01} - \dfrac{\varphi}{2}, \pi - \theta_{01} + \dfrac{\varphi}{2}\right) \\ when\ \ \theta_1 \in (82.9505,114.7772) \\ \theta_2 \in (\pi - \theta_{03} - \theta_{02} - \varphi, \pi - \theta_{03} - \theta_{02}) \\ when\ \ \theta_1 \in (0,82.9505) \\ \theta_2 \in \left(2\pi - \theta_{04} - \dfrac{\varphi}{2}, 2\pi - \theta_{04} + \dfrac{\varphi}{2}\right) \end{cases} \quad \begin{cases} wehn\ \ \theta_1 \in (-180, -114.7772) \\ \theta_2 \in \left(-\left(\pi - \theta_{01} + \dfrac{\varphi}{2}\right), -\left(\pi - \theta_{01} - \dfrac{\varphi}{2}\right)\right) \\ when\ \ \theta_1 \in (-114.7772, -82.9505) \\ \theta_2 \in \left(-(\pi - \theta_{03} - \theta_{02}), -(\pi - \theta_{03} - \theta_{02} - \varphi)\right) \\ wehn\ \ \theta_1 \in (-82.9505,0) \\ \theta_2 \in \left(-\left(2\pi - \theta_{04} + \dfrac{\varphi}{2}\right), -\left(2\pi - \theta_{04} - \dfrac{\varphi}{2}\right)\right) \end{cases}$$

Based on the angle relationship obtained from the above analysis and the angle range under the constraint of rod length, using matlab to program and process data, the movable range of the manipulator end execution point F can be obtained, as shown in Figure 9. The overall movable range of the manipulator is an irregular band with a blue color that tends to be circular, and the center of the movable range is an irregular hollow. The outer edge is a combination of irregular curves and arcs, due to the limited movement of each rod due to its own or other rod stiffness and length conditions at the limit position。

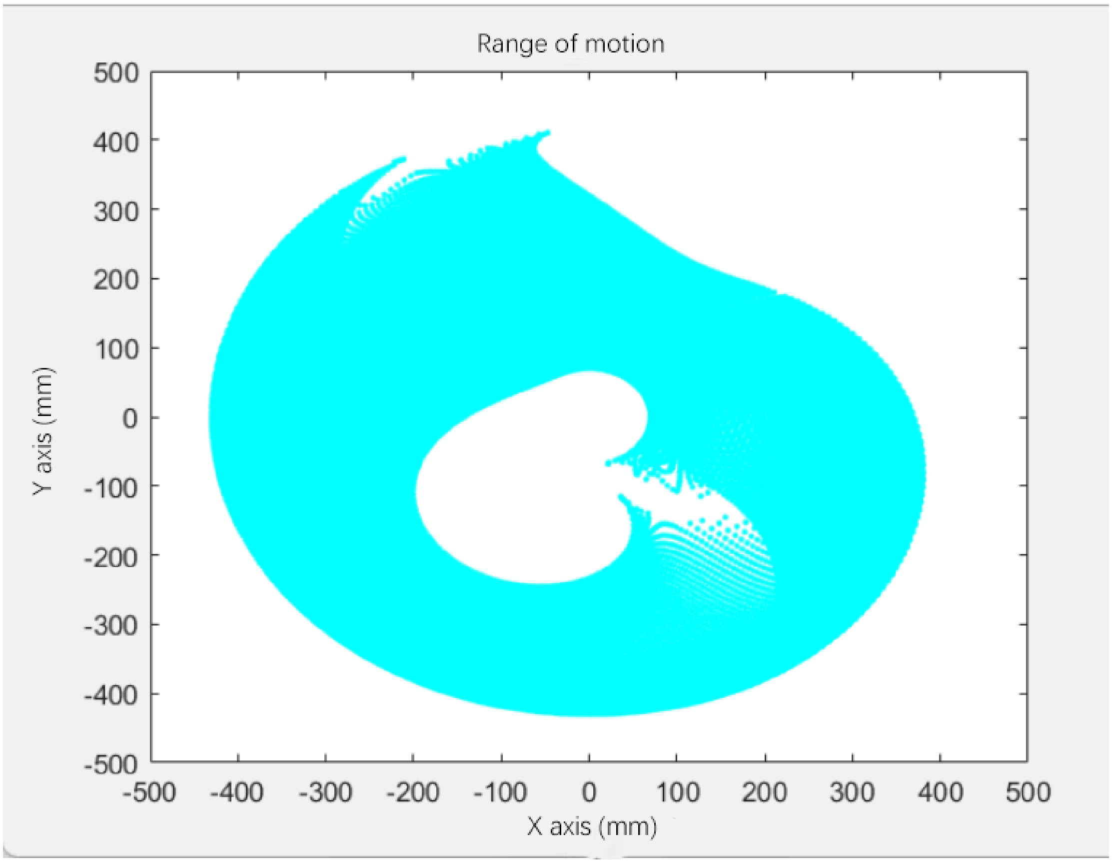

Figure 9 : Motion range of the end of the manipulator

By solving equation (2), (3), and (4) simultaneously, for any trajectory that satisfies the equation $Y_F = f(X_F)$,the required angles for the driving rods 1 and 2 can be obtained

$$\theta_1 = 2\tan^{-1}\frac{\left(A_1 \pm \sqrt{{A_1}^2 + {B_1}^2 - {C_1}^2}\right)}{B_1 - C_1} \quad (19)$$

$$\theta_2 = 2\tan^{-1}\frac{\left(A_3 \pm \sqrt{{A_3}^2 + {B_3}^2 - {C_3}^2}\right)}{B_3 - C_3} \quad (20)$$

Additionally

$$\begin{cases} A_1 = 2Y_F L_5 \\ B_1 = 2X_F L_5 \\ C_1 = -{X_F}^2 - {Y_F}^2 - {L_5}^2 + {L_6}^2 \end{cases} \quad \begin{cases} A_3 = 2nL_2 \\ B_3 = 2mL_2 \\ C_3 = {L_3}^2 - m^2 - n^2 - {L_2}^2 \end{cases} \quad \begin{cases} m = L_5\cos\theta_1 + L_4\cos\theta_4 - L_1 \\ n = L_5\sin\theta_1 + L_4\sin\theta_4 \end{cases}$$

3.3 Example analysis of motion trajectory

Within the movable range of the manipulator, the angular output required by the two driving motors corresponding to the two driving rods at any point of any trajectory can be obtained according to Equation **(19) (20)**, thereby obtaining the desired target working trajectory. Taking a linear trajectory ($Y_F = 0.5X_F + 200 \quad X_F \in (-400,0)$) as an example, a matlab program is written to solve the angle required for the motor output at any point of the trajectory, and the results are shown in Figure 10. When the manipulator end point F moves along this linear trajectory, the output angle of the driving motor 1 gradually changes from 161.89 ° along the blue curve in Figure 10 to 44.50 °, and the output angle of the driving motor 2 changes from 81.82 ° along the orange curve in Figure 10 to -67.91 °

Using the data of the motor output angle curve shown in Figure 10, write a program in matlab to analyze the motion characteristics of the manipulator, and perform image rendering of the end trajectory. Figure 11 is obtained, which shows a strict linear trajectory, with the corresponding data coordinates of the curve matching the curve ($Y_F = 0.5X_F + 200 \quad X_F \in (-400,0)$), This can prove the feasibility of setting the target working trajectory through software simulation and parametric solution within the movable range of the connecting rod manipulator.

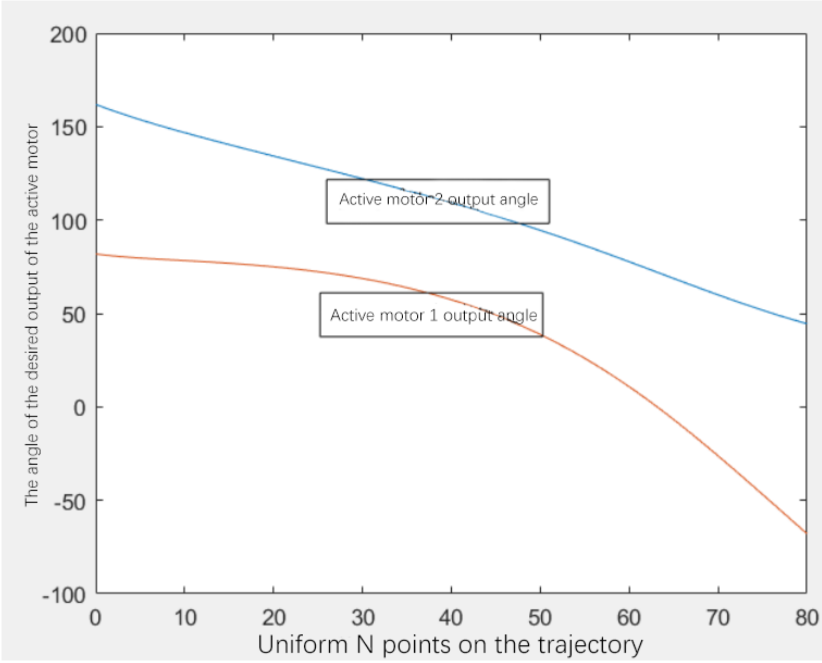

Figure 10: Motor output angle curve

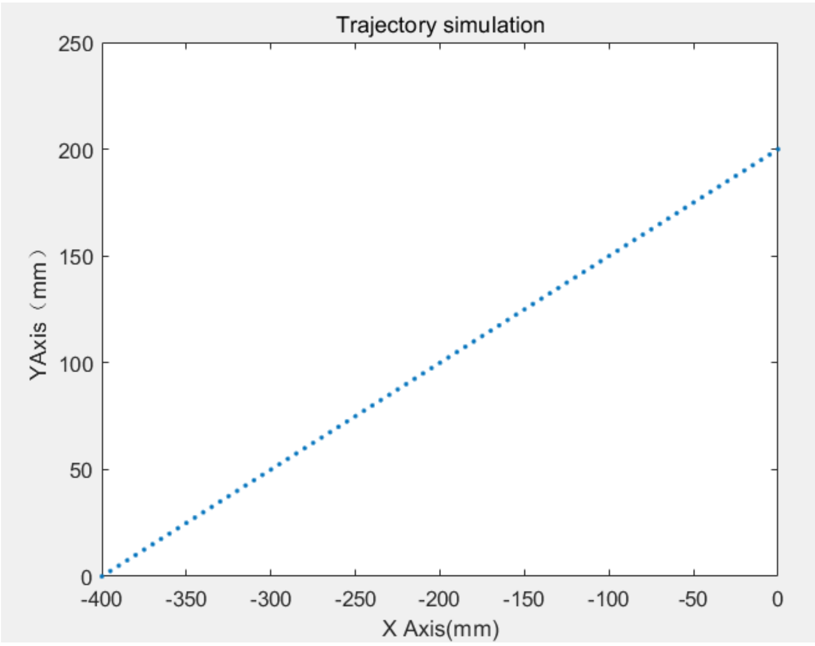

Figure 11 : End trajectory simulation

4Conclusions

This paper analyzes a scheme based on 5R kinematic chain of three-degree of freedom connecting rod manipulator to simulate the bionic pelican neck motion trajectory. The scheme can reduce the weight of the arm and improve the carrying capacity of the executive part of the arm by concentrating the driving motor and other components on the upper head of the arm base. At the same time, the kinematic analysis is carried out on the five-bar mechanism of the arm part, which plays the core role. Under the restriction of the self-interference and mutual interference between the lengths of each bar and the restriction of the length of the bar on the flexibility of the mechanism, the four-bar mechanism of the five-bar mechanism is adopted to establish the mechanism model under the condition of different lengths of the bar L, and the motion range equation of the mechanism is obtained by the analytical method. And through matlab simulation to get the mechanism activity range of two-dimensional graphics. Within the movable range of the mechanism, the target trajectory is set, and the corresponding output Angle curve of the motor is simulated by matlab. The preset target trajectory is obtained by simulating the output of the motor according to the Angle change curve.

In this study, the logic self-consistency between trajectory setting and trajectory realization of connecting rod manipulator is realized, which can provide reference for subsequent trajectory setting of connecting rod manipulator.

Ethics approval and consent to participate

Not applicable

Data Availability

The authors confirm that the data supporting the findings of this study are available within the article [and/or its supplementary materials].

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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Authors' contributions

Everyone involved in the structural design, L.H,Li did the derivation of the mechanism kinematics theory formula, and writing the entire article contents, is the main contributor of writing this manuscript. H.Zhang supervised the entire research work and the writing of the thesis, L.X.Hou provided technical support and directed the structural design,J.Yuan wrote the matlab numerical analysis program to complete the numerical simulation of the mechanism kinematics,M.Y.Liu provided the strength check of the structure and analyzed the motion data, X.Liu involved in modeling, and Y.B.Jiang and H.Y.Yan were involved in processing the images. All the other authors have read and approved the final manuscript.

References

1. Q.Z,Liao., X.L,Xu., Planar 5-Bar Pantograph Mechanism [J]. Journal of Mechanical Engineering,2015,51(13):116-124.
2. N.D,Qin., S,Lin., X.B,Dai., Transmission design and trajectory control of 3D
1. printer extruder based on five-bar mechanism [J]. Manufacturing Automation,2018,40(06):136-140.
2. Z.M,Chen., Y.F,Feng., D.T,Liang., D,Jin., Mechanism design and simulation analysis of the 6-DOF lower-limb rehabilitation mechanical leg [J]. Journal of Machine Design,2021,38(11):
3. 34-42.DOI:10.13841/j.cnki.jxsj.2021.11.040.
4. D.B,Guo., T,Mei., M.Z,Luo.,et al.,Dynamics Analysis and LigHTHeight Design of Manipulator of Elderly Serve Robot [J]. China Mechanical Engineering,2012,23(10):1146-1150.
5. J,Li., H.Y,Liao., J.Y,Kong., B,Tang., Synthesis of Type for Planar 5 -bar Mechanismwith 2 -degree of Freedom [J]. China Mechanical Engineering,2007(01):20-22.
6. H.M,Tian., C,Zhang.,X.H,Zhang., Existence conditions for double crank of planar five-bar linkage with two free degrees [J]. Journal of Machine Design,2001(03):23-25+0.DOI:10.13841/j.cnki.jxsj.2001.03.009.
7. Y.X,Wang., X.S,Liu.,Study on Multi-Bifurcation and Persistence of Configuratipon to Five -Bar Mechanism[J]. Journal of Mechanical Engineering,2004(11):17-20+25.
8. J.G,Wang.,J.F,Zhang.,Q,Wang., L.J.Xu.,Kinematics and Performance Analysis of Spherical Five-bar Mechanisms [J]. Journal of Mechanical Engineering,2008(08):33-39.