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Simulation analysis of shoulder joint for biomimetic robotic arm

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Abstract: A five degree of freedom biomimetic robotic arm was designed using the anthropomorphic method. The arm mainly uses a combination of worm and gear mechanisms to achieve the motion of the robotic arm, which has the advantages of simple structure and reliable motion. adopt D—H A mathematical model of the mechanism was established and kinematic analysis was conducted on the bionic robotic arm.

Keywords: biomimetic robotic arm; Shoulder joint; Kinematics; simulation.

1. Introduction

Robots were originally an electromechanical device developed by humans to free themselves from dangerous, cumbersome, and tedious labor, mainly used in industrial sites. With the rapid development of robotics technologies such as artificial intelligence, communication technology, computer science, and machine vision, their scope of application continues to expand, and they have great application prospects in autonomous operation fields such as aviation, military, security services, hazardous environments, medical care, space exploration, and disaster relief. Therefore, it has received increasing research and attention from technical staff.

The robotic arm, as the most important executing mechanism among various robot mechanisms, is one of the hotspots of research in robotics enterprises. At present, the research and development of robotic arms is mainly focused on light robotic arms, with typical foreign companies including YuMi from ABB in Sweden and LBRiiwa from Kuka in Germany. ABB launched the dual arm 14 axis robotic arm YuMi in 2014, which can complete high-precision assembly of small components such as mobile phones and tablets. The seven axis robotic arm LBRiiwa from German company Kuka has the advantages of fast speed and high accuracy, and is suitable for industries such as electronics, medicine, and precision that require high flexibility, flexibility, and accuracy. In China, Xinsong light manipulator is mainly developed by Shenyang Institute of Automation, Chinese Academy of Sciences, which has high load dead weight ratio, high accuracy and flexibility.

This article takes the human arm as the biomimetic object and designs a five degree of freedom biomimetic robotic arm with self-locking protection function. It mainly uses a combination of worm and gear mechanisms to achieve its movement, providing a reasonable solution for the design of biomimetic robotic arms.

2. Structural design of biomimetic robotic arms

2.1. Biomimetic objects

Robots mainly carry out bionic design from aspects such as structural bionics, material bionics, and control bionics. Under existing conditions, in order to better achieve the function of the robotic arm, this article analyzes the structure and function of the human upper limb mechanism, and adopts a combination of structural bionics and functional bionics to achieve the design of a biomimetic robotic arm.

The upper limb bones of the human body are composed of shoulder girdle bones and free upper limb bones. The clavicle and scapula form the shoulder girdle bone, while the hand bone includes the carpus, metacarpus, and phalanges. The free upper limb bone is composed of the upper arm's adipose bone, forearm flexor bone, hand bone, and ulna. The physiological and anatomical composition is shown in Figure 1.

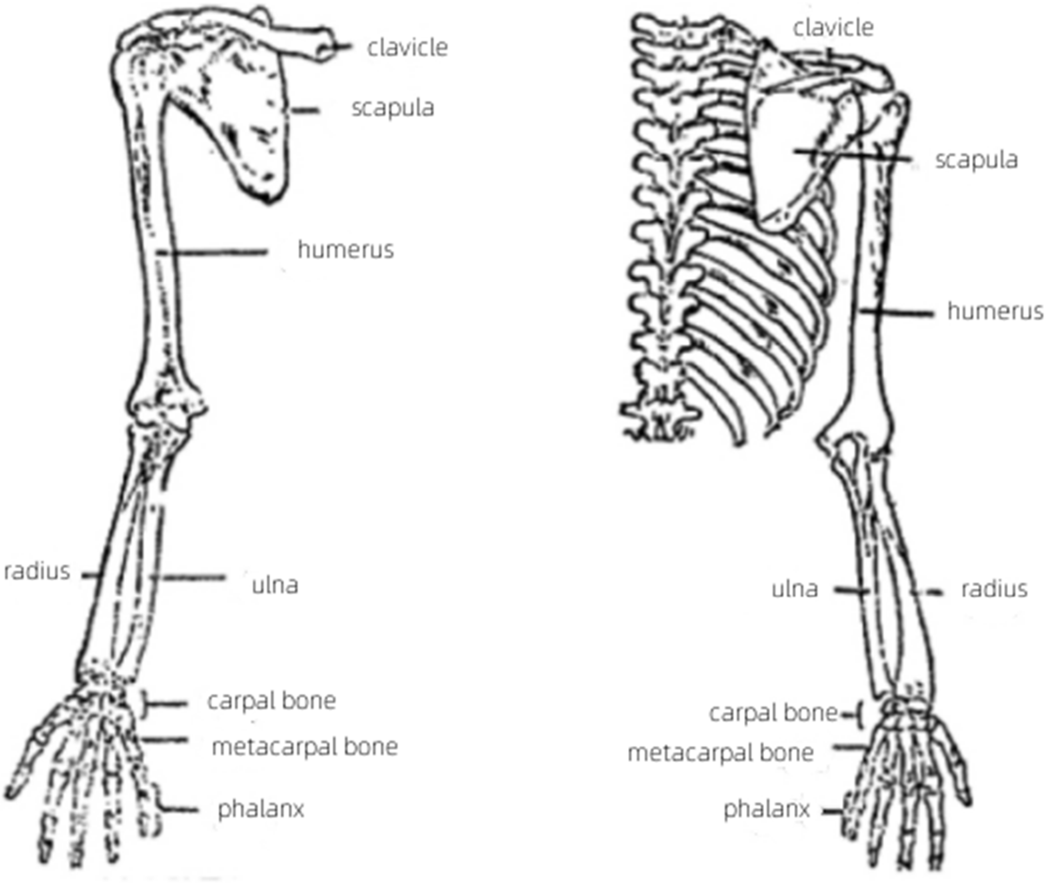

Figure 1 Structure of human upper limb bones

2.2. Biomimetic robotic arm motion model

The free movement of the arm is composed of a combination of three movements: the shoulder joint, elbow joint, and wrist joint, with a total of seven degrees of freedom, namely the three flexion/extension movements of the shoulder joint, elbow joint, and palm, the two inner and outer rotation movements of the upper arm and forearm, and the two inner/outer abduction movements of the upper arm and palm. The specific motion forms of each joint are shown in Figure 2.

(a) Upper arm flexion/extension (b) Forearm flexion/extension (c) Palm flexion/extension

(d) Upper arm outer/inner rotation (e) Forearm outer/inner rotation

(f) Upper arm abduction/adduction (e) Palm abduction/adduction

Figure 2 Arm Movement Form

2.3. Mechanical arm mechanism design

The range of motion of each joint in the human body is shown in Table 1.

Table 1 Range of Motion of Each Joint

project	Rotation angle	direction
Shoulder joint flexion/extension	-90°~45°	Upper arm forward swing is straight
Shoulder joint abduction/adduction	0°~90°	The natural droop of the upper arm is 0
Shoulder joint internal/external rotation	-40°~45°	Upper arm external rotation external alignment
Elbow joint flexion/extension	0°~125°	The natural droop of the forearm is 0
Internal/external rotation of wrist joint	0°~180°	Arm rotation to increase

Based on the analysis of various functions, structures, degrees of freedom, and range of motion of the human upper limbs, the biomimetic robotic arm is divided into three parts: arm mechanism, upper arm mechanism, and forearm mechanism. The shoulder mechanism, upper arm structure, and forearm structure are designed separately. The overall structure is shown in Figure 3.

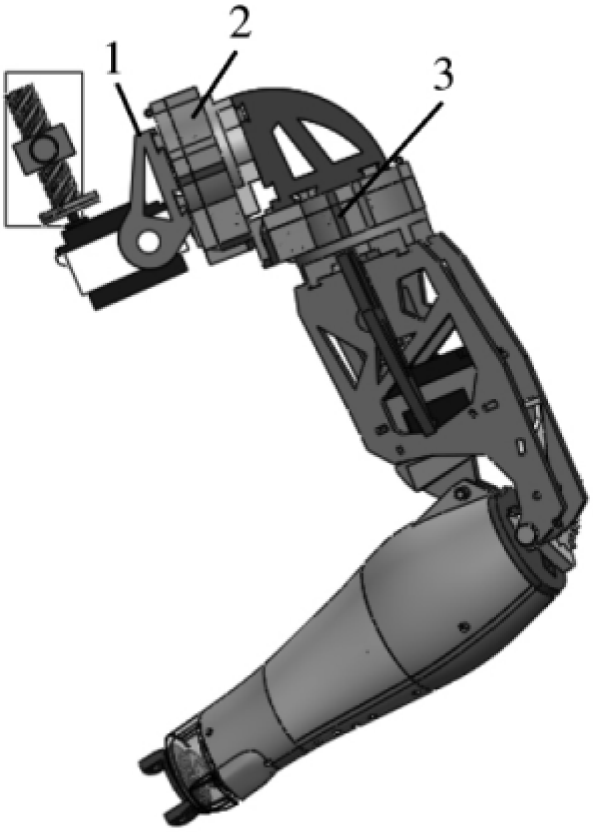

Figure 3 Arm Structure

1) Shoulder mechanism

The design of the shoulder mechanism mainly considers the rationality of the structure. Due to the fact that each joint at the shoulder must bear the weight and working force of the entire robotic arm, the required driving torque is large. To avoid the structural size not being too large, three servo motors are used to control the transmission mechanism at the three joints of the arm. By using the transmission mechanism, the transmission torque can be increased, reducing the requirement for driving torque. A servo motor with smaller power can be selected.

The shoulder joint 1 is composed of a trapezoidal screw rod coaxially connected to the output shaft of the steering gear, which forms a spiral fit with the nut fixed on the robot's upper body. When the steering gear rotates, it drives the entire mechanical arm to rotate around joint 1 for bending/extending motion; Shoulder joint 2 is a single line worm driven by the servo and paired with a helical gear, allowing the robotic arm to perform shoulder joint adduction/abduction motion around the axis of the shoulder joint 2 gear; The structure of shoulder joint 3 is similar to that of shoulder joint 2, which is also driven by the steering gear to cooperate with a single screw and a helical gear. Shoulder joint 2 is perpendicular to shoulder joint 3, driving the entire upper arm and forearm to move together. It can rotate up to 180 ° around the axis of the matched helical gear, mainly for internal and external rotation of the shoulder joint. The combination of worm and helical gears not only has a compact structure, high transmission ratio, and good self-lubricating effect, but also is simpler than the production method of a turbine and has self-locking function.

2) Upper arm structure

The design of the upper arm structure mainly focuses on the elbow joint. In order to meet the requirements of compact structure, easy rotation, and flexible movement at the elbow joint, this article divides the elbow joint into two parts for design. Firstly, the driving force is provided by the steering gear, and the torque can be increased through a screw device connected to the steering gear disc. The nut block fixed on the upper arm rotates to drive the small gear connected to the upper arm to rotate, causing the gear fixed on the forearm to rotate together with the forearm, completing the elbow joint flexion/extension movement.

3) Forearm structure

The design of the forearm structure includes the design of the wrist joint and the steering machine part of the robotic arm driving the steering gear. The small gear driven by the steering gear meshes with the large gear connected to the wrist, achieving internal/external rotation motion of the wrist joint; And considering the similarity between the structure and the human arm, a curved shell was designed for the forearm structure. In order to save space and facilitate installation, the shell was divided into six parts. The part near the elbow joint was relatively thick, and the inner part was equipped with a steering gear and a steering machine tool. The shell was divided into four parts, which can be removed at any time for steering gear debugging. The part near the wrist was designed to install a wrist driven steering gear, which is complex in structure and small in size, To avoid gear meshing accuracy issues caused by improper installation, overall installation is adopted, and bolt connections are used during installation.

3. Kinematics

The kinematics of a robotic arm mainly studies the kinematic characteristics of the robotic arm without considering the driving force. The analytical representation of the spatial displacement of the mechanism as a function of time is the kinematic analysis of the robotic arm. The specific research content includes the relationship between the end position of the robotic arm and the space and attitude of the robotic arm joint variables. Kinematic analysis is the foundation of the structural design of the robotic arm, which can determine the relationship between the rod size, workspace, and trajectory planning, It is also the foundation for subsequent dynamic analysis and control

To describe the translation and rotation relationship between adjacent members of the shoulder joint, the $D-H$ Parameter method. The coordinate origin of the shoulder joint coordinate system is selected as a relatively fixed position for theoretical calculation. The subscript 1 in the coordinate system represents the yaw joint, 2 represents the rotation joint, and 3 represents the pitch joint. The coordinate systems of each joint (degree of freedom) are shown in Figure 4. The shoulder joint $D-H$ The coordinate system parameters are shown in Table 2.

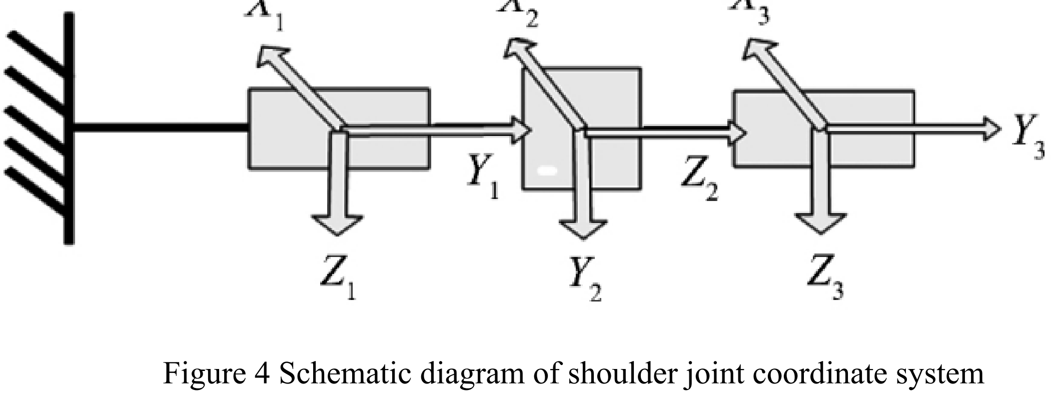

Figure 4 Schematic diagram of shoulder joint coordinate system

Table 2 Shoulder joint $D-H$ Coordinate System Parameters

	α_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	$\theta_1(p_i/2)$
2	0	$p_i/2$	41.6	$\theta_2(-p_i/2)$
3	0	$-p_i/2$	41.6	$\theta_3(0)$

In the above table α_{i-1} Represent from z_{i-1} arrive z_i along x_{i-1} Distance from; α_{i-1} Represent from z_{i-1} arrive z_i wind x_{i-1} Rotation angle of; d_i Represent from x_{i-1} arrive x_i along z_i Distance from; θ_i Represent from x_{i-1} arrive x_i wind z_i Rotation angle of.

3.1. Forward kinematic analysis

Positive kinematics refers to the solution of the pose at the end point of the rod relative to the reference frame, given the geometric parameters of the rod. It is known that the structural parameters of the shoulder joint are known, and the pose at the end of the shoulder joint is obtained. The forward kinematics analysis of the shoulder joint is the foundation of the entire shoulder joint design, providing the foundation for subsequent dynamic analysis and control of the relationship between the shutdown and the end.

$$ {}^0_1T = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

$$ {}^1_2T = \begin{bmatrix} c_2 & -s_2 & 0 & 0 \\ 0 & 0 & -1 & -41.6 \\ s_2 & c_2 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2} $$

$$ {}^2_3T = \begin{bmatrix} c_3 & -s_3 & 0 & 0 \\ 0 & 0 & 1 & -41.6 \\ s_3 & c_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

Among them, ${}^{i+1}_{i}T$ Represents a connecting rod i To connecting rod $i+1$ The transformation matrix of, $c_i = \cos\theta_i, s_i = \sin\theta_i$.

Multiply the transformation matrices of each connecting rod to obtain the shoulder joint end matrix ${}^0_3T$

$$ {}^0_3T={}^0_1T(\theta_1){}^1_2T(\theta_2){}^2_3T(\theta_3) \tag{4} $$

If used $[p_x p_y p_z]^T$ Represents the position of the last degree of freedom of the shoulder joint of the robotic arm in the base coordinate system, $[r_{11} r_{21} r_{31}]^T$ Representing the coordinate system of the last degree of freedom of the shoulder x_3 The direction vector of the axis in the base coordinate system, $[r_{12} r_{22} r_{32}]^T$ Representing the coordinate system of the last degree of freedom of the shoulder y_3 The direction vector of the axis in the base coordinate system, $[r_{12} r_{23} r_{33}]^T$ Representing the coordinate system of the last degree of freedom of the shoulder z_3 The direction vector of the axis in the base coordinate system. The matrix at the end of the shoulder joint can also be expressed as equation.

$$ {}_3^0T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

3.2. Inverse kinematics

If a given end position requires the shoulder joint to reach this position, how many angles each joint needs to rotate is a problem that inverse kinematics needs to solve, and it is also an important foundation for robotic arm control. There is no universal solution, and the main analysis methods include geometric methods, numerical analysis methods, etc. The following is solved using algebraic methods:

The end position matrix is

$$ {}_3^0T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}_1^0T(\theta_1){}_2^1T(\theta_2){}_3^2T(\theta_3) \tag{6} $$

First, solve θ_1， Available inverse transformation ${}_1^0T^{-1}(\theta_1)$By multiplying both ends of equation (6), it is obtained that

$$ {}_1^0T^{-1}(\theta_1){}_3^0T = {}_2^1T(\theta_2){}_3^2T(\theta_3) \tag{7} $$

By equating the elements (2, 3) at both ends of the matrix equation, we obtain $r_{23}c_1 - r_{13}s_1 = 0$

$$ \theta_1 = \arctan\frac{r_{23}}{r_{13}} \tag{8} $$

By equating the elements (3, 3) at both ends of the matrix equation, we obtain $c_2 = r_{33}$

$$ \theta_2 = \arccos r_{33} \tag{9} $$

By equating the elements (3, 2) at both ends of the matrix equation, we obtain $-s_2s_3 = r_{32}$

$$ \theta_3 = -\arcsin\frac{r_{32}}{\sin(\arccos r_{33})} \tag{10} $$

3.3. Joint velocity and acceleration calculation

In order to complete the design task, the end effector of a robotic arm not only needs to have a certain pose trajectory, but also has a certain speed. The linear mapping relationship between the operating space velocity and the joint space velocity - Jacobian matrix - is studied. Jacobian is not only used to represent the linear mapping relationship between the operating space and the joint space velocity, It is also used to represent the transfer relationship of force between two spaces, equivalent to instantaneous kinematics at a specific time

The Jacobian matrix of the shoulder joint of a robotic arm is defined as the linear transformation between its operating speed and joint speed, which can be seen as the transmission ratio of the motion speed from joint space to operating space. The motion equation

$$ x = x(q) \tag{11} $$

Represents the operating space x Joint space q The displacement relationship between the two sides of the equation. Velocity is the derivative of position and time, that is, the two sides of the equation are relative to time t Taking the derivative yields q and x Differential relationship between.

$$\dot{x} = J(q)\dot{q} \tag{12}$$

In the equation, $\dot{x}$ The generalized velocity of the end of the shoulder joint in the operating space, abbreviated as the operating velocity, $\dot{q}$ Is the joint velocity; $J(q)$ is $6\times n$ The partial derivative matrix of the robotic arm is called the Jacobian matrix of the shoulder joint i Row number j Column elements (whose i go j The physical meaning of a column is when j When a joint is in motion, the first i How will the rotation/translation directions move

$$J_{ij}(q) = \frac{\partial x_i(q)}{\partial q_j} \tag{13}$$

In the equation, $i = 1,2,...,6; j = 1,2,...,n$.

$$J = \begin{bmatrix} \frac{dx_1}{dq_1} & \cdots & \frac{dx_1}{dq_n} \\ \vdots & \ddots & \vdots \\ \frac{dx_m}{dq_1} & \cdots & \frac{dx_m}{dq_n} \end{bmatrix} \tag{14}$$

In equation (14), the first row and first column indicate that when the first joint rotates at a certain angle, the corresponding position of the actuator is x_1 Rotate a certain angle in the direction.

The robot toolbox can quickly calculate the Jacobian matrix at any position, with the command $J = r \cdot jacob_0([\theta_1 \quad \theta_2 \quad \theta_3])$

3.4. Workspaces

The workspace of a robotic arm is an important kinematic indicator for evaluating its ability to complete tasks. There are three main research methods: numerical method, graphical method, and analytical method. The comprehensive action of the shoulder, elbow, and wrist joints determines the position and motion energy that the end effector can reach. The shoulder joint is the foundation of the structure of the robotic arm, and if it can be achieved that its workspace is a closed approximate sphere, It is helpful to determine that the final workspace of the robotic arm is also a closed approximate sphere, which indicates that the robotic arm has the basic ability to complete tasks from a structural perspective. Using the Monte Carlo method for calculation, when each degree of freedom is randomly selected within the specified range of activity, the workspace of the robotic arm is obtained by determining all the random value sets of the end effector mechanism. The basic steps are as follows:

(1) Solve the forward kinematics solution of the shoulder joint of the robotic arm, and obtain the end pose matrix based on the forward solution;

(2) Random Function Rand Generation Based on Matlab n Random values between [0,1];

(3) Generate Random Close Step Size $(\theta i_{\max} - \theta i_{\min})*rand(n,1)$;

(4) Will N Substitute the random values of joint variables into the kinematic equation to obtain the end point N A pose matrix, the set of matrices is the workspace.

4. Kinematic simulation

The Robotictoolbox toolbox provides important functions related to robot research, such as kinematics, dynamics, and trajectory planning. This toolbox can perform graphical simulations of robots, reproduce system motion laws or processes, and analyze experimental data during actual control

Firstly, it is necessary to construct a three-dimensional model of the robotic arm in the MATLAB environment, and to perform various degrees of freedom D - H Based on the parameters, use the Link function to construct the model, and use the 'modified' password to indicate that this is an improved D-H parameter method. Enter the dirvebot (r) password to generate the model and automatically generate the kinematic model interface. The rotation angles of the three joints of the shoulder joint can be adjusted arbitrarily on this interface, and the corresponding shoulder joint model will also change accordingly, as shown in Figure 5.

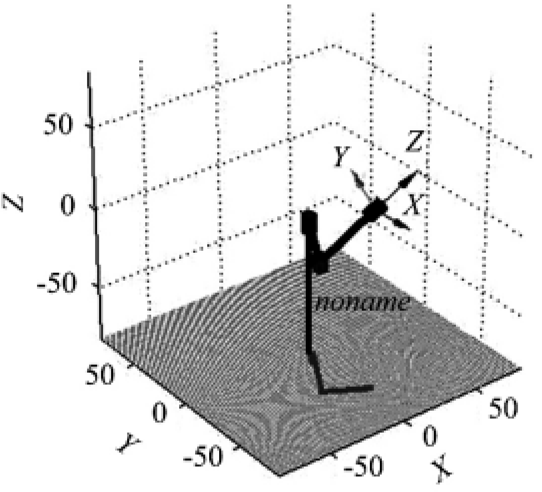

Figure 5 Toolbox interface

4.1. Verification of forward kinematics

Using the fkine function in RoboticsToolbox for a given set of joint values $q=\left[-p_i/6 \quad -p_i/4 \quad -p_i/6\right]$, Solve and obtain the shoulder joint end matrix as follows:

$$ans = \begin{matrix} 0.7571 & 0.2276 & 0.6124 & 4.6747 \\ 0.0048 & 0.9354 & -0.3536 & -50.7345 \\ -0.6533 & 0.2706 & 0.7071 & 29.4156 \\ 0 & 0 & 0 & 1.0000 \end{matrix}$$

Substitute the same joint values into the adoption D - H The end matrix obtained from the parameters is calculated, and the results are as follows.

$$T = \begin{matrix} 0.7571 & 0.2276 & 0.6124 & 4.6747 \\ 0.0048 & 0.9354 & -0.3536 & -50.7345 \\ -0.6533 & 0.2706 & 0.7071 & 29.4156 \\ 0 & 0 & 0 & 1.0000 \end{matrix}$$

The consistency of the shoulder joint end matrix obtained by two different methods proves the correctness of both the theoretical algorithm and the results verified by MATLAB simulation

4.2. Inverse kinematic verification

Use the end matrix from the previous section T, Substitute it into the ikine function, and the result of the operation in matalb is $q_i=\left[-0.5236 \quad -0.7854 \quad 0.3927\right]$

Convert the matrix T By substituting the numerical values in the previous chapter's inverse kinematics solution, the same set of solutions can be obtained, proving that the inverse kinematics equation of the robotic arm is solved correctly.

4.3. Workplace

Based on Monte Carlo simulation, the random value is taken as 50000, and the angle range of each joint is shown in Table 1. The shoulder joint workspace is generated as shown in Figure 6.

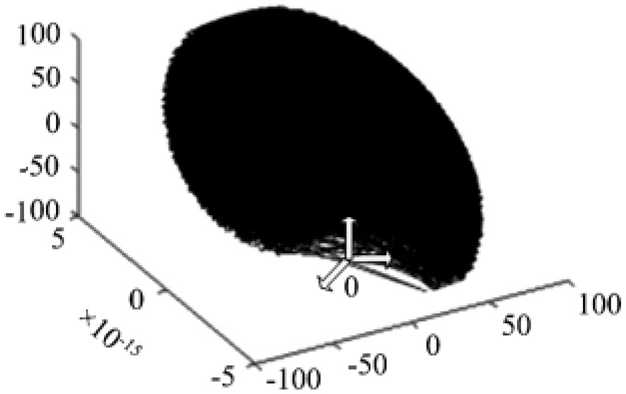

Figure 6 Shoulder joint workspace

As shown in Figure 6, the coordinate origin O represents the position of the starting end of the shoulder joint. The reachable space of the shoulder joint is a closed approximate sphere that can reach any position within this range. From a structural perspective, it has the basic ability to complete tasks

4.4. Speed and Acceleration Simulation

Plan the motion trajectories of each joint in the shoulder joint space using the jtraj function, and obtain the changes in the position, angular displacement, angular velocity, and angular acceleration of the shoulder end of each joint over time, as shown in Figures 7 to 9, respectively

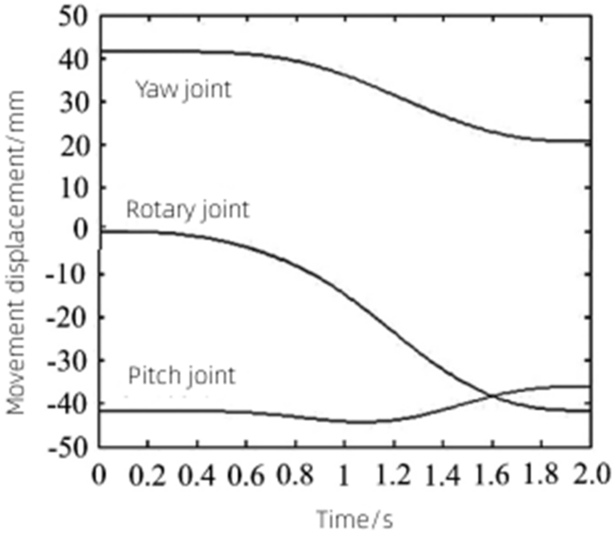

Figure 7 Changes in the position of the end of the shoulder over time

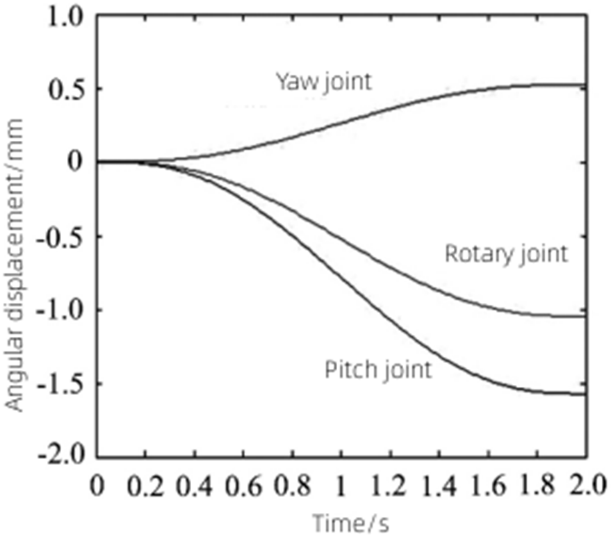

Figure 8 Changes in angular velocity of each joint over time

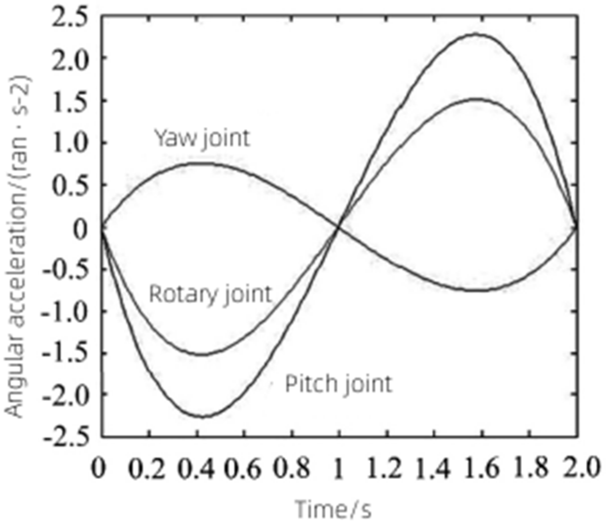

Figure 9 Changes in angular acceleration of each joint over time

From the above four figures, it can be seen that the position change curve of the shoulder joint end is smooth, without inflection points. The yaw joint speed and other changes are the most stable. However, in real life, the frequency of horizontal abduction/adduction movements completed by the human upper limb is lower than the other two movements. The designed shoulder joint is more energy-efficient and can assist the upper limb in completing similar activities

5. Summary

Taking the human upper limb as a biomimetic object, the human arm is decomposed into arm mechanism, upper arm mechanism, and forearm mechanism. The worm mechanism and gear mechanism are combined to achieve its five degrees of freedom motion. A mathematical model of the mechanism is established, and kinematic analysis of the biomimetic robotic arm is conducted. The next focus of work is to establish a constrained nonlinear optimization model for the driving mechanism of the robotic arm and carry out structural optimization design.

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