Kinematic modeling and Simulation of humanoid dual-arm robot

Jiwu Wang
School of Mechanical and Electronic Engineering, Beijing jiaotong University
Beijing, Haidian District, China

Junxiang Xu
School of Mechanical and Electronic Engineering, Beijing Jiaotong University
Beijing, Haidian District, China
E-mail: jwwang@bjtu.edu.cn, 19121251@bjtu.edu.cn
www.bjtu.edu.cn

Abstract

In recent years, dual-arm robots have attracted more and more attention due to their advantages such as strong cooperation ability and high flexibility. With the improvement of real-time requirement of dual-arm cooperation, the inverse kinematics solution of robot becomes a key problem to be solved urgently. In order to solve the time-consuming problem of inverse kinematics of robot arm, a closed inverse kinematics solution algorithm for humanoid dual-arm robot was proposed. The effectiveness of the algorithm was verified by simulation.

Keywords: dual-arm robots ; real-time ; inverse kinematics; simulation.

1. Introduction

Humanoid dual-arm robot is a kind of bionic robot designed by imitating the shape, structure and function of human body. It can work with both hands cooperatively just like human. The inverse kinematics of manipulator mainly includes geometric method, analytical method and numerical method. The geometric method is a special case of analytic method in some cases, and its applicability is weak[1,2]. Analytical inverse kinematics of the manipulator can efficiently obtain all the inverse solutions of the manipulator in the desired position, but the manipulator must satisfy the Piper criterion[3]. The numerical method has no special requirements for the joint number and structure of the manipulator, but it needs to be solved through continuous iteration, which not only takes a long time, but the average calculation error is also 10 times that of the analytical method[4,5].

Because it takes a long time to meet the accuracy requirement and solve the problem of manipulator inverse kinematics solution, the analytical solution is adopted. A closed inverse kinematics algorithm is proposed for the humanoid robot arms. The algorithm is used for simulation analysis. Simulation results show that the algorithm is effective.

2. Kinematic modeling of dual-arm robot

2.1. *Forward kinematics*

The robot model in this paper is shown in Figure 1. Each arm of the robot has six degrees of freedom. The three axes of the shoulder joint intersect at one point. Because this case conforms to the Piper criterion, there are analytic solutions. Taking the shoulder joint as the basic coordinate frame[6], figure 1 also shows the link coordinate frames of the right arm and its D-H parameters. The left arm and the right arm are identical.

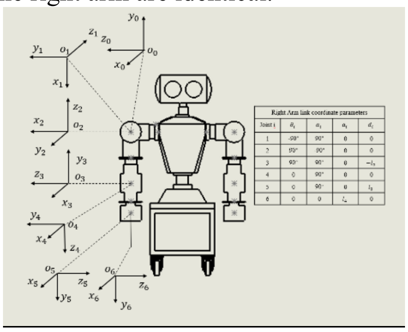


Fig. 1. Link coordinate frames of the right arm and its D-H parameters.

The position and orientation of the end-effector can be obtained by chain-multiplying the 6 link-transformation matrices together to obtain the spatial displacement of the 6th coordinate frame with respect to the base coordinate frame:

$$ {}^0T_6=\prod_{i=1}^{6} {}^{i-1}A_i={}^0A_1\,{}^1A_2\,{}^2A_3\,{}^3A_4\,{}^4A_5\,{}^5A_6 $$
$$ =\begin{bmatrix} x_6 & y_6 & z_6 & p_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}=\begin{bmatrix} n & s & a & p \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

where x_i, y_i and z_i represent the unit vectors along the principal axes of the coordinate frame i, ${}^{i-1}A_i$ is a general link transformation matrix, relating the ith coordinate frame to the (i−1)th coordinate frame, and [n, s, a, p] represents the normal vector, the sliding vector, the approach vector and the position vector of the hand respectively.

2.2. *Inverse kinematics*

We take the inverse of both sides of Eq. (1). The new matrix T' is

$$ T' = \begin{bmatrix} n & s & a & p \\ 0 & 0 & 0 & 1 \end{bmatrix}^{-1} = \begin{bmatrix} n' & s' & a' & p' \\ 0 & 0 & 0 & 1 \end{bmatrix} $$
$$ ={}^6A_5\,{}^5A_4\,{}^4A_3\,{}^3A_2\,{}^2A_1\,{}^1A_0={}^6A_0 \tag{2} $$

We can obtain an equation that we label as G_2 equation by moving the link transformation matrix ${}^5A_6$ to the left-hand side of Eq.(2).

$$ {}^5A_6T' = {}^5A_4\,{}^4A_3\,{}^3A_2\,{}^2A_1\,{}^1A_0 \tag{3} $$

The left-hand side of E_2 is

$$ E_{L2}=\begin{bmatrix} \cdots & \cdots & \cdots & C_6\left(p'_x+l_{L4}\right)-S_6p'_y \\ \cdots & \cdots & \cdots & S_6\left(p'_x+l_{L4}\right)+C_6p'_y \\ \cdots & \cdots & \cdots & p'_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4} $$

And the right-hand side of E_2 is

$$ E_{R2}=\begin{bmatrix} \cdots & \cdots & \cdots & S_4C_5l_{L2} \\ \cdots & \cdots & \cdots & -C_4l_{L2}-l_{L3} \\ \cdots & \cdots & \cdots & S_4S_5l_{L2} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

where $S_i \equiv \sin\theta_i, C_i \equiv \cos\theta_i, S_{ij} \equiv \sin\left(\theta_i+\theta_j\right), C_i \equiv \cos\left(\theta_i+\theta_j\right)$, and l_{Li} are geometric link parameters in Fig. 1. By comparing the elements (1,4), (2,4) and (3,4) of the E_{L2} and E_{R2}, we can obtain C_4 and then S_4 from C_4, and from which we can find the joint solution for θ_4. we can solve θ_5 when we have solved θ_4 .Similarly, we can solve θ_6 when we have solved θ_4 and θ_5.

$$ \begin{aligned} & C_4=\frac{\left(p'_x+l_{L4}\right)^2+p'^2_y+p'^2_z-l^2_{L2}-l^2_{L3}}{2l_{A2}l_{A3}} \\ & \theta_4=a\tan 2\left(\pm\sqrt{1-C_4^2},C_4\right) \\ & S_5=p'_z/\left(S_4l_{L2}\right) \\ & \theta_5=a\tan 2\left(S_5,\pm\sqrt{1-S_5^2}\right) \\ & \theta_6=a\tan 2\left(-\left(C_4l_{L2}+l_{L3}\right),S_4C_5l_{L2}\right)-a\tan 2\left(p'_y,p'_x+l_{L4}\right) \end{aligned} \tag{6} $$

To solve for the remaining joint angles, we can move the link transformation matrix ${}^3A_4\,{}^4A_5$ to the left-hand side of Eq.(3). And we can obtain an equation that we label as E_4 equation.

$$ {}^3A_4\,{}^4A_5\,{}^5A_6T' = {}^3A_2\,{}^2A_1\,{}^1A_0 \tag{7} $$

The left-hand side of E_4 is

$$ E_{L4}=\begin{bmatrix} a11 & a12 & a13 & a14 \\ a21 & a22 & a23 & a24 \\ a31 & a32 & a33 & a34 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8} $$

And the right-hand side of E_4 is

$$E_{R4}=\begin{bmatrix} C_1C_2C_3-S_1S_3 & C_1S_3+S_1C_2S_3 & S_2C_3 & 0 \\ -C_1S_2 & -S_1S_2 & C_2 & l_{L2} \\ S_1C_3+C_1C_2S_3 & S_1C_2S_3-C_1C_3 & S_2S_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

By comparing the element (2,3) of E_{L4} and E_{R4} ,we get C_2 and then S_2 , and the joint solution θ_2 from them,

$$\begin{aligned} &C_2=a23=a_z^{'}S_4S_5-a_y^{'}\left(C_4C_6+S_4C_5S_6\right)-a_x^{'}\left(C_4S_6+S_4C_5C_6\right) \\ &\theta_2=a\tan 2\left(\pm\sqrt{1-C_2^2},C_2\right) \end{aligned} \quad (10)$$

By comparing the elements [(1,3) (3,3)] and [(2,1) (2,2)], we can find the joint solution θ_3 and θ_1 ,

$$\begin{aligned} &a13=a_x^{'}\left(C_4C_5C_6+S_4S_6\right)+C_4S_5a_z^{'}+\left(S_4C_6-C_4C_5S_6\right)a_y^{'} \\ &a33=S_5C_6a_x^{'}-C_5a_z^{'}-S_5S_6a_y^{'} \\ &\theta_3=a\tan 2\left(a33,a13\right) \\ &a21=\left(S_4C_5C_6-C_4S_6\right)n_x^{'}+S_4S_5n_z^{'}-\left(S_4C_5S_6+C_4C_6\right)n_y^{'} \\ &a22=\left(S_4C_5C_6-C_4S_6\right)s_x^{'}+S_4S_5s_z^{'}-\left(S_4C_5S_6+C_4C_6\right)s_y^{'} \\ &\theta_1=a\tan 2\left(-a22,-a21\right) \end{aligned} \quad (11)$$

The solution of the six joints is obtained by the above procedure. The left arm is exactly the same as the right arm for the solution.

3. Dual-arm robot modeling based on Simscape

3.1. *Model building*

In this paper, the dual-arm robot simulation model mainly includes three parts, namely the trajectory planning joint Angle input module, the robot body module and the output measurement module. Its Simscape Multibody model is shown in Figure 2.

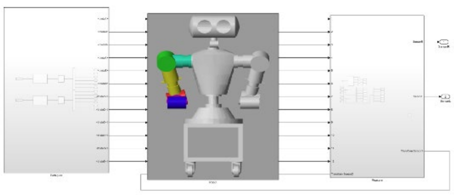


Fig. 2. Dual-arm robot simulation model

3.2. *Establishment of joint Angle input module for trajectory planning*

We plan the trajectory of space in Cartesian coordinates. After solving the inverse kinematics function, we can obtain the angles of each joint. Then we output these angles to the various joints of the arm. The joint angle input model for trajectory planning is shown in Figure 3.

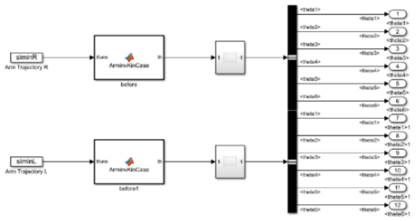


Fig. 3. The joint angle input model for trajectory.

3.3. *Establishment of robot ontology module*

Figure 4 shows the robot ontology module. It includes world coordinate frame and robot ontology. Each arm has six degrees of freedom, including three degrees of freedom for shoulder joint, one degree of freedom for elbow joint and two degrees of freedom for wrist joint.

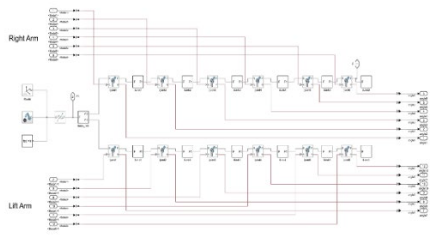


Fig. 4. The robot ontology module.

3.4. *Establishment of output measurement module*

The output measurement module shown in Figure 5 can measure the rotation Angle of each degree of freedom. Through this module, we can also obtain the displacement of the terminal coordinate frame of the manipulator relative to the base coordinate frame.

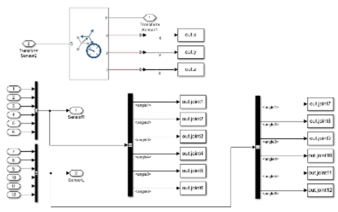
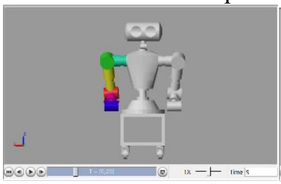


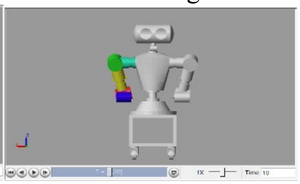
Fig. 5. The output measurement module.

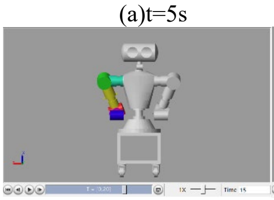
4. Simulation verification and analysis

4.1. *Simulation process*

The robot first raised their arms and then approached each other. The entire process is shown in Figure 6.


(a)t=5s


(b)t=10s


(c)t=15s

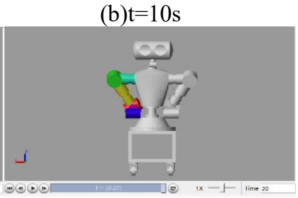
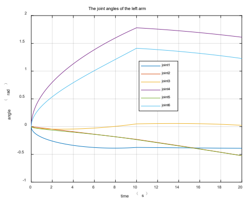

(d)t=20s

Fig. 6. Simulation diagram of each moment.

4.2. *The motion angles of each joint*

Figure 7 shows the motion angles of each joint of the manipulator. At the initial moment, the Angle of each joint is 0 radian, and at about 10 seconds, the robotic arms begin to approach each other. The Angle of each joint is continuous in the whole process, which proves that the inverse kinematics solution algorithm in this paper can solve the analytic solution effectively.


(a) Left arm's angles

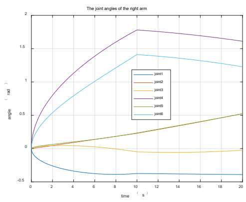

(b) Right arm's angles

Fig. 7. The motion angles of each joint of the left and right arms.

5. Conclusion

In this paper, the kinematics modeling of dual-arm robot is carried out. We present an analytical solution method for 6 DOF dual-arm robot for each arm. Simulation results show that the proposed method is effective. In the future, it will be applied to the arm trajectory planning of the robot.

Acknowledgements

This work was supported by the Key Research and Development Program (No.M18GY300021).

References

1. Ian S. Fischer. A geometric method for determining joint rotations in the inverse kinematics of robotic manipulators. 2000, 17(2):107-117.
2. Samer Tahya, M. Moghavvemi, Haider A.F.Mohamed. Geometrical approach of planar hyper-redundant manipulators: Inverse kinematics, path planning and workspace. Simulation Modelling Practice and Theory. 2010(1).
3. Buss S R. Introduction to inverse kinematics with Jacobian transpose, pseudoinverse and damped least squares methods, *J.* IEEE Transactions on Robotics and Automation, 2004.
4. Momani S,Abo-Hammour Z S,Alsmadi O M K. Solution of inverse kinematics problem using genetic algorithms. Applied Mathematics&Informaion Scienced . 2016
5. Mostafa Bayati. Using cuckoo optimization algorithm and imperialist competitive algorithm to solve inverse kinematics problem for numerical control of robotic manipulators. 2015, 229(5):375-387.
6. Ali MA, Park HA, Lee CSG. Closed-form inverse kinematic joint solution for humanoid robots. In: IEEE/RSJ 2010 international conference intelligent robotics system IROS 2010-coference proceeding.;2010. pp. 704-9

Authors Introduction

Dr. Jiwu Wang

He is an associate professor, Beijing Jiaotong University. His research interests are Intelligent Robot, Machine Vision, and Image Processing.

Mr. Junxiang xu

He is a postgraduate in Beijing Jiaotong University. His research interest is robot modeling and simulation.