Optimal Design of Industrial Robot Kinematics Algorithm

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Abstract. According to the singularity problem in the working space of industrial robot, the reachability of robot is judged from the view of equation solution. Based on this, the optimal selection algorithm of multiple solutions of inverse solution has been given. PUMA560 industrial robot is the study object, the parameters of its mechanism and linkage are analyzed, and the forward kinematics and inverse kinematics of the robot are studied by D-H method. In the MATLAB environment, the robotics toolbox for modeling and simulation has been used, the simulation results show that the forward and inverse kinematics model is reasonable and correct. It lays a solid foundation for the follow-up research and development of robot.

1. Introduction
Robot is the embodiment of the highest achievement of mechatronics and is at the forefront of science and technology development. Robot technology includes the latest research results of many disciplines and fields, including mechanical engineering, computer technology, electronic technology, artificial intelligence and automatic control theory. After years of development, the robot industry has made a lot of substantial progress and results. With the enormous progress of science and technology in industrial automation, industrial robots have been widely used in life and work, mainly for painting, welding and stacking[1]. Kinematic equation analysis is the foundation of robot control, the position and attitude of the end device analyzed each link and mechanism parameters of the robot has been determined by the kinematic analysis. Forward kinematics analysis and inverse kinematics analysis are included in the Robot kinematics. According to various work requirements, the robot end device can be moved to the specified position and attitude, and according to the previous position and attitude of robot has been reproduced, the analysis of robot motion is the basis of robot motion control and trajectory planning[2]. The major approaches of robot forward kinematics are D-H coordinate transformation and quaternion. The solution methods of robot inverse kinematics mainly include analytic method, geometric method and intelligent algorithm[3]. This paper takes puma560 industrial robot as the research object, uses D-H coordinate transformation method to obtain the positive kinematics equation expressed by position vector and Euler angle, solves the inverse kinematics of the robot through the separation method of position and attitude, and selects the most suitable group of solutions according to the shortest path principle. Finally, based on MATLAB robot toolbox, the correctness of kinematics solution is verified[4].

2. Establishment of Robot Kinematics Mode
The commonly used method of robot kinematics analysis is the D-H parameter matrix method, raised by Denavit and Hartenberg to establish an additional coordinate system for each member in the joint chain in 1955[5]. The D-H method of robot kinematics uses the homogeneous coordinates to describe
the spatial geometric relationship of each link of robot relative to the reference coordinate system, uses the $4 \times 4$ homogeneous transformation matrix to describe the spatial geometric relationship of the adjacent two links $I$ and $I-1$, and then deduces the spatial relationship between the end of robot system and the reference system[6].

The 6-DOF industrial robot analyzed in this paper consists of a base, a waist rotating part, a big arm, a small arm and a wrist, with six degrees of freedom[7], the D-H arguments of the robot is listed by Table 1.

### Table 1. DH arguments of PUMA560 robot.

| Joint i | $a_{i-1} / (\text{mm})$ | $\vartheta_{i-1} / (^\circ)$ | $d_i / (\text{mm})$ | $\vartheta_i / (^\circ)$ |
|---------|-------------------------|-----------------------------|---------------------|------------------------|
| 1       | 0                       | 90                          | 0                   | $\vartheta_1$          |
| 2       | 0                       | 0                           | 149.09              | $\vartheta_2$          |
| 3       | 438.1                   | -90                         | 0                   | $\vartheta_3$          |
| 4       | 20.3                    | 0                           | 433.07              | $\vartheta_4$          |
| 5       | 0                       | 0                           | 0                   | $\vartheta_5$          |
| 6       | 0                       | 0                           | 0                   | $\vartheta_6$          |

In Table 1, $a_{i-1}$ represents the length of the linkage $i$, $\vartheta_{i-1}$ is the angle of the linkage, $d_i$ is the distance between two perpendicular lines along the joint $i$ axis, $\vartheta_i$ is the angle between two perpendicular lines to the joint $i$ axis, and the homogeneous transformation matrix between each linkage of the robot is $^i\mathcal{T}^{-1}$ [8].

$$
^i\mathcal{T}^{-1} = \begin{bmatrix}
C_i & -S_i & 0 & a_{i-1} \\
S_i C\vartheta_{i-1} & C_i C\vartheta_{i-1} & -S\vartheta_{i-1} & -d_i S\vartheta_{i-1} \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(1)

Where, $C_i = \cos \vartheta_i$, $S_i = \sin \vartheta_i$, $C\vartheta_{i-1} = \cos \vartheta_{i-1}$, $S\vartheta_{i-1} = \sin \vartheta_{i-1}$, $i = 1, 2, \cdots, 6$.

$$
^nT = T(\vartheta_1)^\text{T} T(\vartheta_2)^\text{T} \cdots T(\vartheta_5)^\text{T} T(\vartheta_6)^\text{T} = 
\begin{bmatrix}
n_x & o_x & a_x & p_x \\
n_y & o_y & a_y & p_y \\
n_z & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(2)

Where,

- $n_x = c_1 \left[ c_{23} \left( c_{34} c_{56} + s_4 s_6 \right) - s_{23} s_5 c_6 \right] - s_1 \left( s_{34} c_5 c_6 - c_{34} c_6 \right)$
- $n_y = s_1 \left[ c_{23} \left( c_{45} c_6 + s_4 s_6 \right) - s_{23} s_5 c_6 \right] + c_1 \left( s_{34} c_5 c_6 - c_{34} c_6 \right)$
- $n_z = -s_{23} \left( c_{34} c_6 + s_4 s_6 \right) - c_{23} s_5 c_6$
- $o_x = c_1 \left[ c_{23} \left( s_4 c_6 - c_{45} c_6 \right) + s_{23} s_5 s_6 \right] + s_1 \left( s_{34} s_5 c_6 + c_{34} c_6 \right)$
- $o_y = s_1 \left[ c_{23} \left( s_4 c_6 - c_{45} c_6 \right) + s_{23} s_5 s_6 \right] - c_1 \left( s_{34} s_5 c_6 + c_{34} c_6 \right)$
- $o_z = s_{23} \left( c_{34} s_5 c_6 - s_{45} c_6 \right) + c_{23} s_5 s_6$
- $a_x = -c_1 \left( c_{23} c_4 s_5 + s_{23} c_5 \right) + s_1 s_5 s_5$
- $a_y = -s_1 \left( c_{23} c_4 s_5 + s_{23} c_5 \right) - c_1 s_4 s_5$
\[ a_z = s_2c_4s_5 - c_2c_5 \]
\[ p_x = c_1 \left( a_2c_{23} + d_4s_{23} + a_4c_2 + a_7 \right) - s_1 \left( d_2 + d_3 \right) \]
\[ p_y = s_1 \left( a_2c_{23} + d_4s_{23} + a_4c_2 + a_7 \right) - c_1 \left( d_2 + d_3 \right) \]
\[ p_z = -a_3s_{23} + d_4c_{23} - a_2s_2 \]

Where, \( c_i = \cos \theta_i \), \( s_i = \sin \theta_i \), \( c_{ij} = \cos \left( \theta_i + \theta_j \right) \), \( s_{ij} = \sin \left( \theta_i + \theta_j \right) \).

3. Optimization of Robot Kinematics Model Solution

The working space of robot refers to all positions that could be solved by the end effector of robot, its scope has a great influence on the spatial layout and operation mode of the whole robot production line[9]. In this paper, the solution of robot workspace is mainly used to judge the reachability of robot[10]. The inverse kinematics equation can be directly used to solve the problem. If there is a feasible solution, the position and attitude of the robot can be determined. From the results, there are eight groups of inverse solutions, it should be pointed out that there is root sign in the process of solving \( \theta_2 \) and \( \theta_1 \), which may lead to non real solution[11]. When non real solution occurs, it means that the task point is not within the scope of robot workspace, and the robot cannot reach in three-dimensional space, so it needs to be abandoned.

Secondly, the robot link joints have rotation range. If the rotation range is beyond, the group solution also needs to be discarded.

In addition to the above two cases, due to the singularity of the robot linkage mechanism itself, there are some singular positions and postures in the workspace, which will lead to problems in the inverse solution calculation and make some joint degrees of freedom degenerate[12]. Therefore, it is necessary to analyze the singular positions and postures of the robot specifically. The singular points of workspace refer to that in the workspace of robot, there are some special positions and postures, which can be reached by using numerous different joint configurations. These positions and postures are called singular points.

Through the above analysis, the following methods are used for the selection of multi group solutions of robot inverse solution: first, discard the non real number solutions that are not in the scope of robot workspace; secondly, the robot link joints have rotation range, if they are beyond the rotation range, the group solutions also need to be discarded; then, we judge the singularity of the residual solution and discard the solution near the singular pose to ensure the reliability of the robot motion. Finally, we establish the kinematic equation of the residual solution and choose the optimal solution.

4. Robot Kinematics Model Simulation

In order to test the normality of the kinematics equation of industrial robot, the matrix of the robot's end position and attitude is given first, then the matrix is substituted into the improved inverse kinematics equation to solve the joint angle, and then the angle matrix is calculated by using the robot toolbox of Matlab toolbox, and finally whether the two groups of solutions are consistent is judged. If they are consistent, the improved inverse kinematics algorithm is normal. The solution results are shown in Table 2:

| Joint angle | \( \theta_1 \) | \( \theta_2 \) | \( \theta_3 \) | \( \theta_4 \) | \( \theta_5 \) | \( \theta_6 \) |
|-------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Calculation results | -1.5362 | -1.0325 | 0.6853 | 0.4698 | -1.038 | -0.7856 |
| Simulation results | -1.536256 | -1.032489 | 0.56529 | 0.469802 | -1.02789 | -0.785569 |

5. Conclusion

In this paper, the kinematics equation of 6-DOF Industrial robot is analyzed, and its inverse kinematics algorithm is studied and improved. According to the actual situation and geometric analysis of the
cotton picking robot, a group of unique inverse solutions can be determined. The program of inverse solution is designed with MATLAB software and the algorithm in this paper. The correctness of the algorithm in this paper is verified by MATLAB simulation.

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