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Kinematics Modelling and Co-simulation Research of a Novel Electrical Optical Cable Pruning Robot Using V-REP and MATLAB

Chao Li1, b, Y F Yang2 and S Y Dian1, a
1. Department of Automation, College of Electrical and Information, Sichuan University, Chengdu 610065, China
2. Quzhou Electric Power Bureau of ZheJiang Province, Quzhou 324002, China
3. Corresponding Author: ascudiansy@scu.edu.cn; blcqwe147@163.com

Abstract. In this paper, a new type of serial pruning robot with five degree of freedom is developed to solve the issues of power cable inspection and maintenance. First, the kinematic model of the manipulator is established by Denavit-Hartenbreg (D-H) method, and its kinematic forward and inverse solution is obtained. Then, the kinematic co-simulation is executed by MATLAB and V-REP, the Monte Carlo method is used to analyze the working space of the pruning robot, and the workspace of the manipulator is obtained; To ensure the pruning process runs smoothly, trajectory planning simulation in the workspace is taken; Finally, the co-simulation results show that the kinematic model is valid, each joint and end effector control effect is good, and the pruning robot can achieve flexibly pruning branches and other obstacles in the range of 1 to 1.5 meters, which provides theoretical and experimental basis for follow-up research of pruning robot control problem.

1. Introduction

The inspection work of power optical fiber lines [1] is an important guarantee for the safety of electrical transmission. Traditional line inspection approaches include aerial surveys and ground-based visual inspections, etc. These approaches require the maintenance personnel of the grid to have a high accumulation of operating experience. Due to high intensity labor, low work efficiency, low detection accuracy of inspection personnel, traditional methods have obvious shortcomings. With the continuous development of robot technology, robot inspection and troubleshooting methods have gradually become a research hotspot [2-3]. The literature [4-5] introduced the transmission line inspection robot developed by Hibot in 2008 called Expliner, this robot can achieve the functions that automatic balance adjustment, lift arm to avoid obstacle, etc; The literature [6] introduces power transmission line inspection robot designed by Mexico Institute of Technology and Industrial Development, in which, the kinematics and dynamics models of the robot are established, then the robot model and the joint control algorithm of PD+G are verified by simulation. The literature [7] has designed a double boom patrol inspection robot that can step over obstacles such as shock hammers, linear clamps, and pressure cube through climbing mechanisms; Above research results are of positive significance, but they are all aimed at the inspection of high-voltage transmission lines, and there are few studies on inspection of electric optical cable.
The co-simulation of robot kinematics control system is one of the hot areas in the study of kinematics and dynamics of robot complex control model [8-9]. The current co-simulation system is mainly based on ADAMS/MATLAB virtual prototype technology [10-11]. V-REP is a kinematics and dynamics simulation platform widely used in robot virtual simulation [12]. It can be combined with MATLAB to build an independent simulation environment, and the results of simulation are more realistic and closer to the actual system.

In this paper, we are inspired by the work of traditional transmission lines mentioned above, for the inspection and pruning problem of electrical optical cable, the kinematics simulation experiment of the robot is carried out using the method of V-REP and MATLAB co-simulation. In our design, a 5-DOF serial pruning robot is mounted on the bottom of a 3-boom wheel-type patrol robot to maximally prune the branches near the cable. The kinematics model of the pruning robot is used to obtain the forward and inverse solutions of the robot. The joint simulation results verify the correctness of the kinematic model, and the Monte Carlo method combined with the MATLAB/V-REP co-simulation system is used to verify the reachable workspace of each joint of the robot.

2. Pruning robot

As shown in Figure 1, the top of the robot is a three-boom wheeled patrol robot. The design of the upper-lower wheels allows the robot to walk on the single-fiber cable not to fall off. And through opening and closing movement of the upper-lower wheels, robot can step across the cable line. the middle of the robot is an electric control box for controlling the rotation of the walking wheel and each joint motor, while the left half is equipped with a high-definition wide-angle camera for monitoring the entire walking and pruning process.

The developed 5-DOF serial pruning manipulator was mounted under the robot, and manipulator’s end effector is a fly saw, and the branches near the optical cable are cut along the line by the pruning manipulator, at the same time with the autonomous obstacle-free operation[8].

3. Positive and negative kinematics analysis of pruning robot

3.1. Positive kinematic analysis

First we established a link-pole coordinate system for pruning robots as [9]. The following D-H parameters are derived from the coordinate system diagram Figure 2.

| Link number | Joint angle $\theta_i$ | Twist angle $\alpha_i$ | Length of link $a_i$ | Link offset $d_i$ |
|-------------|------------------------|------------------------|---------------------|------------------|

Figure 1. Robot body structure design.  
Figure 2. D-H coordinate system of robot.
From the D-H parameter table 1, we can obtain the link transformation matrix $T_{i-1}^i$ of the coordinate system \{i\} relative to the coordinate system \{i-1\}, among them:

$$
T_{i-1}^i = \begin{bmatrix}
\cos \theta_i & -\sin \theta_i \cos \alpha_i & \sin \theta_i \sin \alpha_i & a_i \cos \theta_i \\
\sin \theta_i \cos \alpha_i & \cos \theta_i \cos \alpha_i & -\sin \alpha_i & a_i \sin \theta_i \\
\sin \alpha_i & \cos \alpha_i & 0 & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(1)

substituting data from table 1, and in following formula $s_i = \sin \theta_i, c_i = \cos \theta_i$:

$$
T_{s_i}^1 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(2)

From the above link coordinate system transformation matrix, a homogeneous transformation matrix of the reference coordinate system of the robot end-effector relative to the base coordinate system can be obtained:

$$
{T_e} = T_{s_5}^1 T_{s_4}^2 T_{s_3}^3 T_{s_2}^4 T_{s_1}^5
$$

(3)

where n, o, a denote the vector coordinates of the x, y, and z axes of the coordinate system where the actuator is located relative to the reference coordinate system; p denotes the coordinates of the origin of the coordinate system where the actuator is located relative to the coordinates of the reference coordinate system. And the posture equation of the end effector is as follows:

$$
\begin{bmatrix}
p_x \\
p_y \\
p_z
\end{bmatrix} = \begin{bmatrix}
n_x & n_y & n_z & p_x \\
o_x & o_y & o_z & p_y \\
a_x & a_y & a_z & p_z
\end{bmatrix}
$$

(4)
3.2. Inverse kinematic analysis

The inverse kinematics solution is based on the end position and pose given by (2). The joint angles of each joint of the robot are obtained. There are many methods for obtaining inverse solutions, including analytical method, projection method, and Pieper method. We use analytical methods to solve the inverse kinematics of the robot here. The left side of the equation (2) is multiplied by $\mathbf{T}^{-1}$,

$$\mathbf{T}^{-1} = \begin{bmatrix} c_i & s_i & 0 & -750 \\ 0 & 0 & 1 & 0 \\ s_i & -c_i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

and

$$\begin{bmatrix} n_{c3} + n_{s4} & a_{c1} & a_{s1} & a_{c5} & a_{s5} & p_{c1} & p_{s1} & p_{c5} & p_{s5} & -750 \\ n_{c1} & 0 & a_{i1} & a_{i2} & a_{i3} & a_{i4} & a_{i5} & a_{i6} & a_{i7} & a_{i8} \\ n_{s1} - n_{c1} & -a_{c1} & a_{s1} & -a_{c5} & a_{s5} & p_{c1} & p_{s1} & p_{c5} & p_{s5} & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

from the above $A_4(3,4)$:

$$p_{c1} s_{1} - p_{s1} c_{1} = 0$$

This gives the solution: $\theta_{1} = \arctan(\frac{p_{s1}}{p_{c1}})$

In the same way, we get (7) from $A_4(2,4)$:

$$-750 \sin \theta_{2} = p_{z}$$

This gives the solution: $\theta_{2} = -\arcsin(\frac{p_{z}}{750})$

Similarly, we get solutions $\theta_{3} \sim \theta_{5}$ from $A_4(3,3)$, $A_4(3,1)$, $A_4(1,1)$ and $A_4(2,1)$:

$$\theta_{3} = \arcsin(a_{y} c_{1} - a_{x} s_{1}) \quad \theta_{5} = \arccos \frac{n_{x} s_{1} - n_{y} c_{1}}{c_{4}}.$$  

4. Co-simulation using V-REP and MATLAB

4.1. Kinematics simulation and workspace analysis under MATLAB

The positive and inverse kinematics of the kinematics are calculated and verified in MATLAB. The values of the positive solutions for each joint are shown in Table 2:

| $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $\theta_1'$ | $\theta_2'$ | $\theta_3'$ | $\theta_4'$ | $\theta_5'$ |
|---|---|---|---|---|---|---|---|---|---|
| $\pi/6$ | $\pi/6$ | $0^\circ$ | $\pi/6$ | $0^\circ$ | 30.00° | 30.00° | 0° | 30.00° | 0.218° |

Solves the position matrix of the robot’s end effector $^5\mathbf{T}$:

$$^5\mathbf{T} = \begin{bmatrix} 0.2165 & -0.75 & -0.625 & 87.02 \\ -0.875 & 0.433 & 0.2165 & 50.24 \\ 0.433 & 0.5 & 0.75 & -375 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For the inverse solution, select the end positions as above to obtain the joint angles as shown in Table 2 $\theta_1' \sim \theta_5'$. It can be seen from the range of changes in the joint angles in Table 2, Table 3,
Figure 3 and Figure 4 that the angle changes in the positive and negative solutions are basically the same; the MATLAB simulation results show that the forward kinematics and inverse kinematics sought in this paper are correct.

\[ \theta_1, \theta_2, \theta_3, \theta_4, \theta_5 \]

\[ x \text{ lateral distance, } y \text{ vertical distance, } z \text{ working height} \]

The Monte-Carlo Method [13], also called statistical simulation method, is a numerical method that solves mathematical problems by means of random sampling (pseudo-random number). It is written in MATLAB as a computer program, and the output 5000 points simulate 3D space, and the workspace of the end effector of the pruning robot is as follows, where x: lateral distance, y: vertical distance, z: working height:

As shown in Figure 5, the simulated workspace conforms to the actual space of each joint. The envelope of the workspace expresses the actual position that can be reached by the manipulator intuitively. The simulation results are in accordance with the actual expectations; the manipulator can reach \( \pm 1.5 \) meters work point in the axes of \( x, y \), completely achieved the function of flexibly handling obstacles such as branches in the range of 1 to 1.5 meters near the optical cable.

4.2. Establishment of V-REP Model

In order to validate the kinematics model and reachable workspace of the pruning robot, the three-dimensional motion simulation was performed with the example of patrolling-pruning motion performed by the robot in the V-REP platform.

Firstly, the 3D model of the pruning robot was created in SolidWorks and imported into V-REP. Based on the shape construction and joint definition method [14], a three-dimensional V-REP model with dynamic characteristics was established to build a robot simulation experiment scenario. See Figure 6, where: (a) Dynamic model of the pruning robotic; (b) Visible model of the pruning robotic; (c) Dynamic model of the three-boom-armed wheeled robot and the pruning robot; (d) Visible model of the three-boom-armed robot and pruning robot.
4.3. Co-simulation of kinematics with MATLAB/V-REP

V-REP uses the Remote API to communicate with MATLAB [15] so that simulations can be run directly on MATLAB and data can be transferred simultaneously between the two programs. Using the D-H parameter table of the pruning robot proposed above, the PD controller [16] was used to control the V-REP servo motor (i.e. the above defined rotation joint) in MATLAB to complete the robot motion planning in the 3D simulating environment. Table 3 shows the initial pose and the target pose of the robot:

|    | x     | y     | z     | (α, β, γ)          |
|----|-------|-------|-------|-------------------|
| initial | 1.3   | 1.69  | 0.8   | (10.38°-19.54°54.86°) |
| target  | 1.32  | 1.73  | 0.81  | (0°0°0°)          |

Where x, y, z, α, β, γ represent the abscissa, ordinate, and vertical coordinates of the centroid of the end effector in the world coordinate system, and the corresponding attitude angles respectively.

![Figure 7. Robot body structure design.](image)

The joint angles acquired on the V-REP platform during the movement of the robot were compared with the inverse solutions obtained by the analytical method in MATLAB. See Figure 8.

Figure 7 shows the two-way communication connection between V-REP and MATLAB via SOCKET. Among them, the PD controller output control quantity designed in MATLAB, the pruning robot joint motor in V-REP rotates under control action, and then current pose of end fly saw is sent back to MATLAB so that it loops until the end fly saw reaches the target point.
Figure 8. (a), (b), (c) show comparison of every joint angle output between MATLAB and VREP

Figure 9. Trajectory planning of end effector

5. Result analysis

Figure 8 shows the rotation angles of the joints of the pruning robot in the motion planning process. It can be seen from the figure that the inverse joint angle calculated based on the kinematics model established above meets the actual motion simulation results of V-REP, indicating that the kinematics model is effective and reliable. Practically speaking, from Figure 9 we can see that the actual target position of the terminal trajectory is (1.324, 1.703, 0.805, 0°, 0°, 0°). The robot trajectory planning in 3D space based on PD controller and D-H parameter method can achieve smoothly movement from a predetermined starting point to a target point. Define the trajectory planning error as $e$:

$$e = \frac{\|P_o - P_d\|}{P_d} \quad (9)$$

Where $P_o$ represents the actual target pose vector of the robot and $P_d$ represents the set target pose vector. By calculating the actual target pose and set value error $e$ less than or equal to 1.6%, the trajectory planning results show that the kinematics co-simulation system established by MATLAB and V-REP is stable and reliable, the motion control effect is good, and it has high control accuracy.

6. Conclusion

In this paper, a new type of 5-DOF serial pruning robot kinematic model and co-simulation system is established. Its main innovations are:

1) The kinematics model of a 5-DOF serial pruning robot was established. In order to verify the accuracy of model, dynamics and kinematics simulation software V-REP was introduced and MATLAB combined with kinematics simulation and trajectory planning simulation experiments. The results show that the established kinematics model is accurate, the constraints are reasonable, and the scope of work accords with the actual situation;

2) Different from the MATLAB-based kinematics simulation method used in [13], etc. this paper uses the co-simulation of V-REP and MATLAB to establish the kinematics and dynamics model in V-REP, and the control algorithm is solved by MATLAB, by their respective advantages, established a new method of power optical cable pruning robot co-simulation based on multi-software, dynamics, kinematics and control algorithms decoupled, the final simulation results show that the method can be used for complex robot system, with good reliability and accuracy;

3) The new robot kinematics co-simulation method proposed in this paper can predict various performance indicators of the system before the physical prototype is manufactured, thus well overcoming the drawbacks of the traditional mechanical design process, improving the research and development efficiency. Therefore, it has certain guiding significance for the prototype design and
manufacture of power cable pruning robot, and can also provide theoretical basis and experimental platform for the research of follow-up control problems.

4) Compared with the ADAMS/MATLAB co-simulation system used in [9], [10], and [11], V-REP relies on good interface characteristics, accurate and high-quality physics simulation engine, which combined with MATLAB for establishing robot co-simulation system, taking into account the actual mechanical design and control algorithms need to be continuously and collaboratively iterative with product updates, can increase the speed of product updates, has better stability and high efficiency.

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