Modeling, Kinematics, and Trajectory Planning Analysis of a Three-Axis Robotic Arm

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Abstract. Robotic arms are widely used in industrial automation due to their simple structure, high flexibility, and moderate cost, especially in standardized scenarios such as conveyor belt operations. This study focuses on a three-axis robotic arm, addressing the demands of conveyor belt operations through modeling and performance analysis. First, precise structural modeling of the robotic arm was completed using SolidWorks, and its kinematic model was established using the D-H parameter method. Second, trajectory planning of the end-effector was studied based on task-specific requirements, and the variations in joint angles, velocities, and accelerations were analyzed through simulations. Finally, the smoothness of paths and workspace coverage were evaluated via simulations. Results indicate that the three-axis robotic arm can meet the demands of conveyor belt operations with good applicability. However, further improvements in control precision and dynamic stability are needed for more complex, non-standardized scenarios. This study provides theoretical support for the design optimization and broader application of three-axis robotic arms.

Keywords: Three-axis robotic arm; kinematics analysis; D-H parameter method; trajectory planning; industrial automation.

1. Introduction

With the continuous advancement of industrial automation, robotic arms are increasingly utilized in manufacturing, assembly, and material handling. The three-axis robotic arm, known for its simple structure, high flexibility, and moderate cost, has become a critical tool in various industrial scenarios. Existing studies demonstrate the significant performance advantages of three-axis robotic arms in conveyor belt operations and material handling tasks.

The kinematic modeling method based on D-H parameters is widely adopted in robotic arm design. Zhang Libin et al. analyzed the kinematic model of robotic arms using the D-H parameter method, confirming its effectiveness in workspace modeling and trajectory planning [1]. Wang Fei et al. further validated the modeling accuracy of the D-H parameter method in industrial robotic arms through MATLAB simulations, demonstrating its applicability to robotic arms with various joint designs [2]. Liu Yong et al. investigated the smoothness of end-effector paths through inverse kinematics, providing support for enhancing the precision of robotic arms in handling tasks [3]. Xiao Fei proposed an optimized trajectory generation algorithm for complex path-tracking scenarios, significantly improving the adaptability and efficiency of three-axis robotic arms [4].

In international research, Craig systematically analyzed the motion characteristics of robotic arms using the D-H parameter method and inverse kinematics, offering theoretical support for trajectory planning and joint control optimization [5]. Siciliano et al. explored the kinematics and trajectory planning of multi-degree-of-freedom robotic arms [6]. Chiaverini proposed improved damping control methods to address the stability issues of robotic arms in singular postures [7]. Yoshikawa analyzed the redundancy problem in the robotic arm's workspace, emphasizing that optimized trajectory planning is key to improving efficiency [8]. Gasparetto et al. reviewed time- and energy-optimized trajectory planning algorithms, guiding path optimization for dynamic tasks [9]. Khatib introduced a real-time obstacle avoidance strategy based on the potential field method, enabling robotic arms and mobile robots to avoid obstacles dynamically through virtual fields [10].

Despite significant progress in kinematic modeling and trajectory planning for three-axis robotic arms, several challenges remain. Existing studies often focus on performance analysis under single working conditions, lacking comprehensive evaluations of robotic arms in complex dynamic environments. The adaptability and flexibility of trajectory planning methods for non-standardized conditions require further improvement, particularly regarding the response speed and precision of robotic arms in complex scenarios.

Based on the above background, this study aims to conduct a comprehensive modeling and kinematic analysis of a three-axis robotic arm under complex conveyor belt handling conditions. The research explores trajectory planning and execution performance under various working conditions. By developing optimized models and control algorithms, this study seeks to enhance the efficiency and precision of robotic arms in dynamic and complex scenarios, providing theoretical and technical foundations for efficient operations in real industrial applications.

2. Methods

The robotic arm was designed to perform material handling tasks in a conveyor belt scenario. Its structure comprises three joints: one for the gripper angle, one for arm length adjustment, and one for end-effector posture, ensuring flexibility along the X and Y axes. The Z-axis employs a five-bar support system with sliding adjustments to control the height of the gripper during operations. During the SolidWorks modeling process, precise geometric parameters were set to ensure sufficient flexibility and load capacity, adapting to complex tasks in industrial scenarios.

This study utilized combined simulations with SolidWorks and MATLAB, employing the D-H parameter method to analyze the kinematics and trajectory planning of the three-axis robotic arm.

2.1. Definition of Joints and End Effector

The structure of the robotic arm was defined using a `rigidBodyTree`, including three joints (two rotational joints and one prismatic joint) and an end effector:

First joint (prismatic joint): Enables linear motion along the Z-axis.

Second and third joints (revolute joints): Allow rotational motion around the Z-axis.

End effector: Defined using a fixed extension length (`trvec2tform`) to represent the robotic arm's final working point, achieving precise structural modeling of the robotic arm.

2.2. Kinematic Analysis: Implementation of the D-H Parameter Method

The position of each joint was defined using fixed transformations (`setFixedTransform`) based on the D-H table, which specifies the geometric relationships between adjacent links.

Using the D-H parameter method, the overall kinematic model of the robotic arm was constructed by sequentially calculating the pose matrices from the base to the end effector.

Inverse kinematics: The `inverseKinematics` function, combined with weight parameters (`weights`), was employed to solve for the joint configurations required to achieve the target poses, ensuring the end effector reaches the designated positions.

2.3. Trajectory Planning and Simulation

The smooth trajectory planning and simulation were achieved through the following steps:

Linear Interpolation: For joint angles and displacements between the initial and target points, the `linspace` function was used to generate linearly spaced interpolation vectors. Smooth interpolation of joint angles generated continuous motion curves, avoiding abrupt changes.

Inverse Kinematics Calculation: Joint configurations for each target point were calculated using the `inverseKinematics` module. A `for` loop iteratively updated joint states and recorded the end effector's pose at each time step, forming the motion trajectory.

Path Visualization: The `show` function dynamically visualized the robotic arm's posture, while the `plot3` function depicted the 3D trajectory of the end effector.

2.4. Velocity and Acceleration Analysis

Velocity Calculation: Instantaneous velocities of joint angles over time were calculated using the `diff` function.

Acceleration Calculation: Accelerations were obtained by differentiating the velocity data, and interpolation was used to smooth the acceleration curves.

Through the above analysis, detailed kinematic modeling and analysis of the three-axis robotic arm were completed, along with trajectory planning and dynamic characteristics analysis of velocity and acceleration. Results demonstrated high motion stability and trajectory tracking accuracy during task execution, providing important references for the implementation of material handling tasks in conveyor belt scenarios.

3. Results

Fig. 1 illustrates the complete SolidWorks model of the robotic arm, showcasing its structural framework.

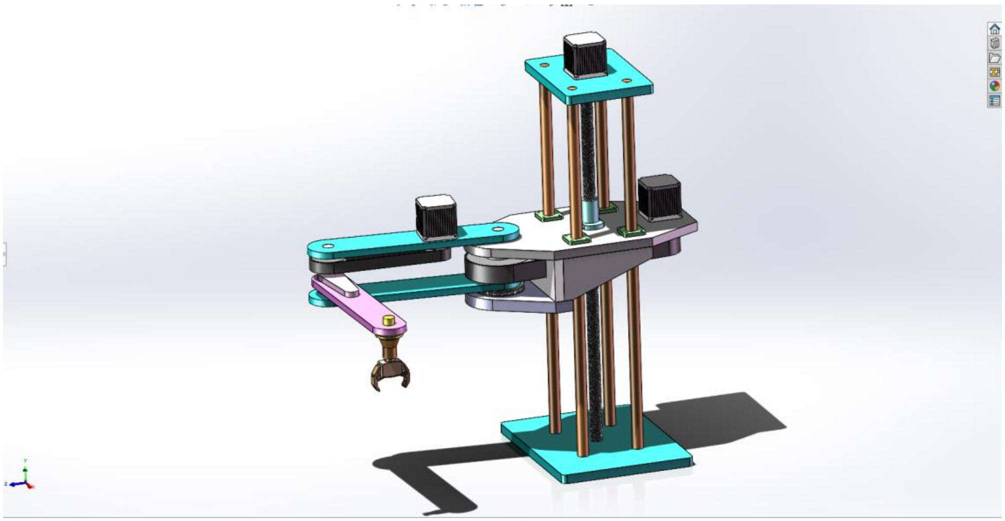

Fig. 1 SolidWorks Model

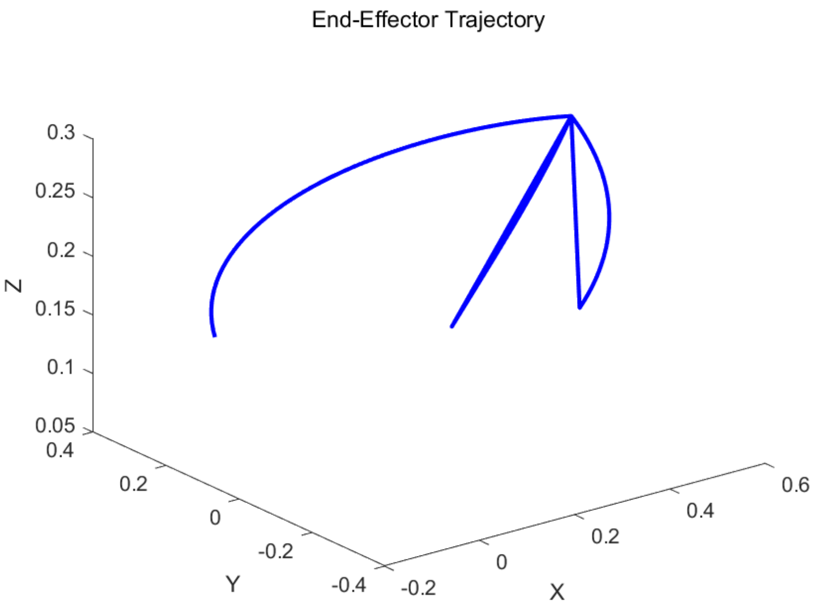

Fig. 2 End-Effector Trajectory

Fig. 2 shows the motion trajectory of the robotic arm's end-effector within its workspace. The blue curve represents the path from the initial to the target position. The trajectory demonstrates a certain degree of continuity and stability, indicating that the motion planning algorithm effectively avoids abrupt path jumps. This validates the accuracy of the inverse kinematics calculations.

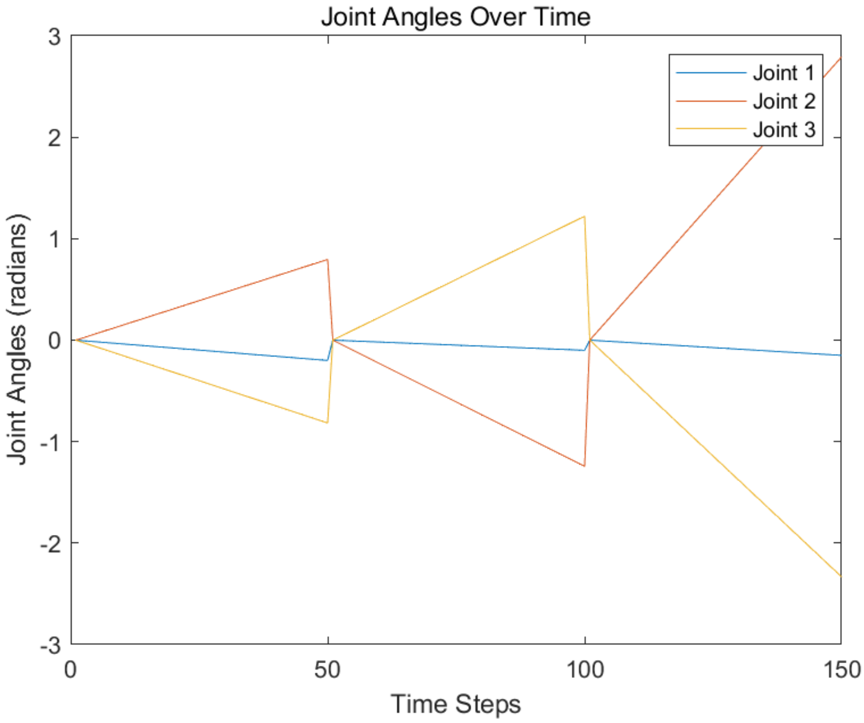

Fig. 3 Joint Angles Over Time

Fig. 3 presents the variation trends of joint angles during task execution. Joint 1 primarily exhibits vertical motion with a smooth curve, indicating uniform or gradually accelerated movement, minimizing structural wear. Joints 2 and 3 show periodic variations, reflecting rotational actions during target switching to adjust the end-effector's position.

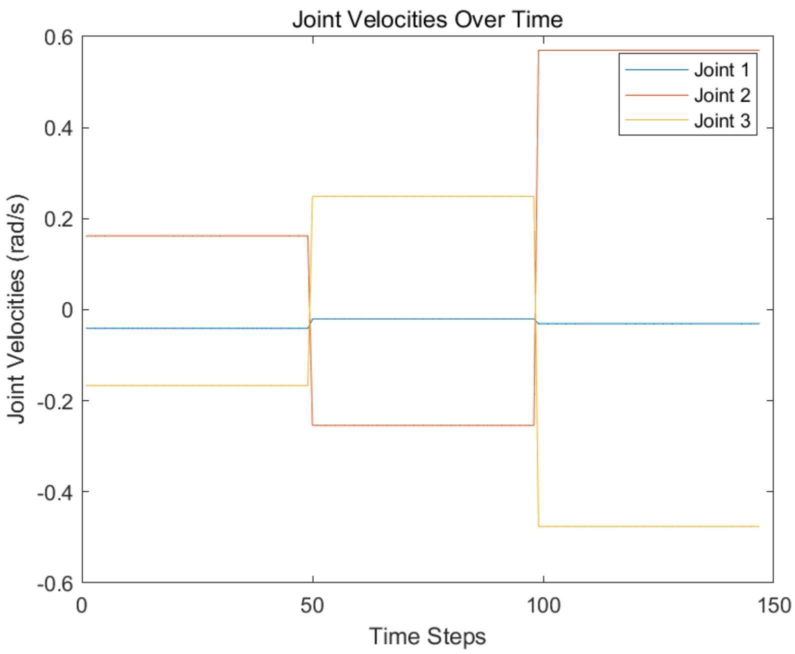

Fig. 4 Joint Velocities Over Time

Fig. 4 illustrates the velocity characteristics of each joint during task execution. The velocity curves exhibit smooth start and stop features, indicating the incorporation of acceleration limits in the velocity planning. This avoids sudden changes that could impact the robotic arm.

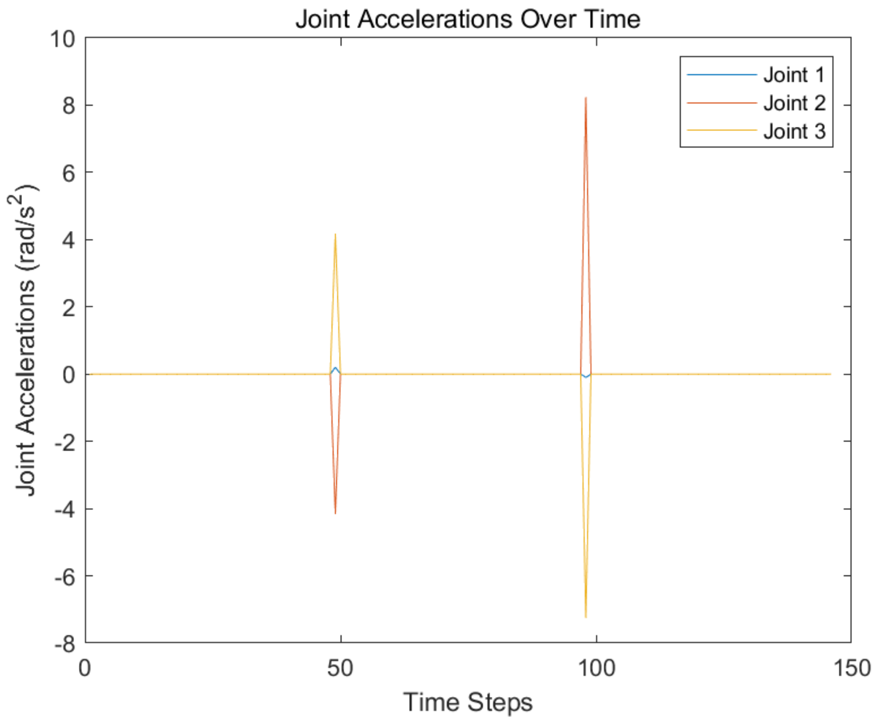

Fig. 5 Joint Accelerations Over Time

Fig. 5 shows the acceleration trends of each joint, analyzing the dynamic characteristics of the robotic arm's motion. Peaks are observed during the start and stop phases, indicating significant torque requirements to overcome inertia. Further optimization could enhance the smoothness of motion planning, reducing stress and fatigue on the mechanical structure.

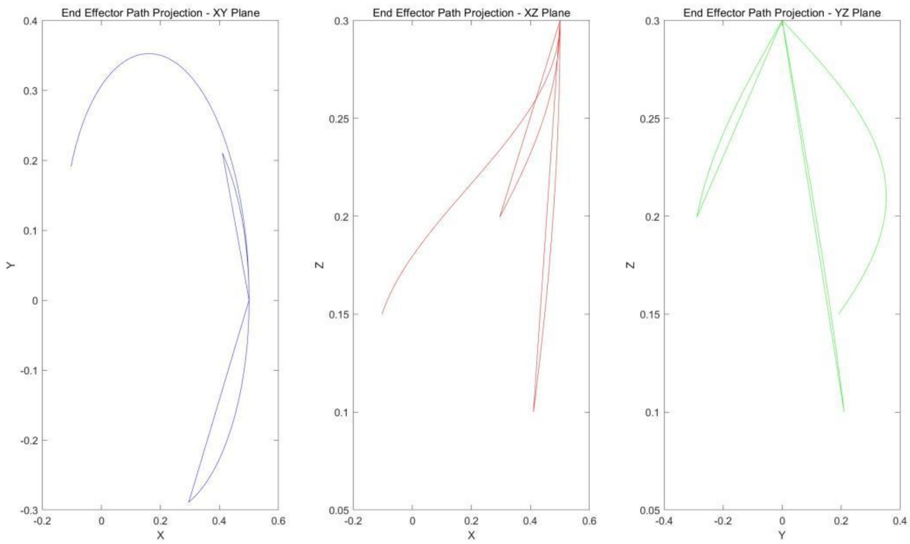

Fig. 6 End-Effector Path Projections

Fig. 6 displays the end-effector's path projections on different planes (XY, XZ, and YZ). These projections reflect the planar characteristics of the trajectory, verifying the robotic arm's motion capability to meet task requirements and providing references for trajectory optimization.

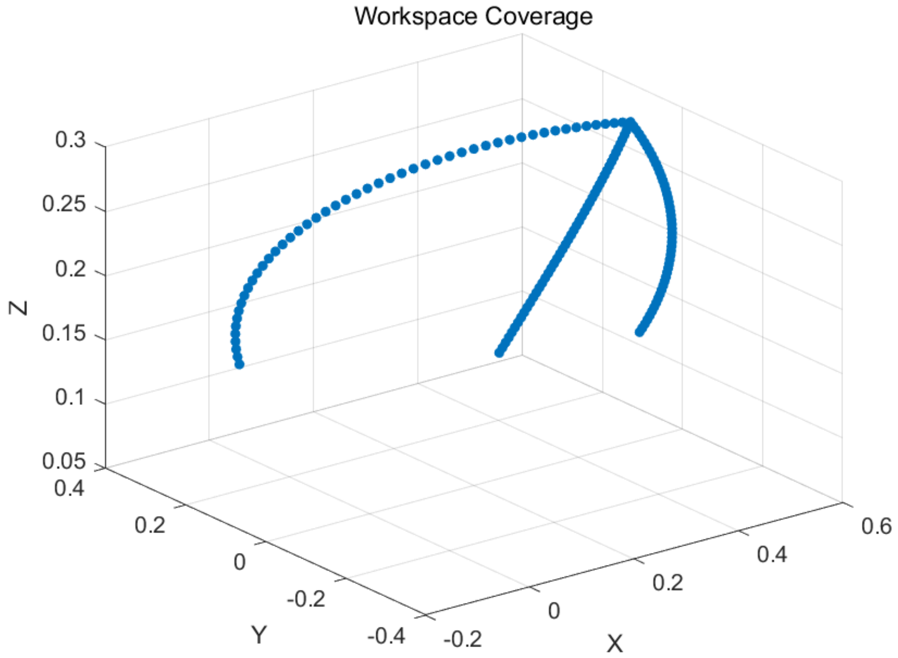

Fig. 7 Workspace Coverage of the End-Effector

Fig. 7 illustrates the workspace coverage of the robotic arm's end-effector. The scatter plot clearly depicts all reachable positions, demonstrating the range of the end-effector within the workspace.

4. Discussion

The experimental and simulation results of this study fully demonstrate the applicability and efficiency of the three-axis robotic arm in conveyor belt material handling scenarios. The SolidWorks modeling and kinematic analysis using the D-H parameter method validated the workspace coverage and the trajectory smoothness of the end-effector between various target points. The experimental results revealed the dynamic changes in joint angles, velocities, and accelerations, confirming the effectiveness of the trajectory planning algorithm in achieving smooth motion and dynamic constraint control. The spatial trajectory of the end-effector exhibited continuity and enabled rapid switching between multiple target points. Projection analyses of the trajectories showed that the end-effector could accurately reach the designated target positions, meeting the precision requirements of conveyor belt operations.

5. Conclusion

This study verified the applicability and operational efficiency of the three-axis robotic arm in conveyor belt material handling through modeling, kinematic analysis, and trajectory planning. The results demonstrated that the kinematic model established using the D-H parameter method and the trajectory planning approach effectively achieved precise positioning and smooth motion of the end-effector within the workspace. Furthermore, the dynamic analysis of joint angles, velocities, and accelerations validated the robustness and efficiency of the planning algorithm.

However, this study also identified limitations when the robotic arm encounters more complex, non-standardized target points or high-precision dynamic scenarios. These limitations are primarily reflected in motion precision and response speed. Future research will focus on the following two aspects:

1.Optimizing joint control algorithms: Introducing adaptive control strategies based on real-time feedback to enhance the response speed and precision of the robotic arm in dynamic scenarios.

2.Incorporating deep learning-based path optimization algorithms: Improving the efficiency of trajectory planning for complex tasks.

This study provides theoretical support and practical references for the application of three-axis robotic arms in conveyor belt material handling scenarios, while also offering directions for further performance optimization.

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