Structural and Functional Analysis of a 4-DOF SCARA Robot: Design, Kinematics, and Applications

Anuvind M P
AM.EN.U4AIE22010
AIE-A

Harishankar Binu Nair
AM.EN.U4AIE22023
AIE-A

Naveed E Nissam
AM.EN.U4AIE22038
AIE-A

Amrita School of Computing, Amritapuri

Abstract

The case study explores the structural description and functioning of a 4-DOF SCARA robot. The purpose of this research is to analyze the design, components, and kinematic modeling of the robot to enhance its application in industrial automation. Methodology includes comprehensive literature review, design specifications, component analysis, kinematic modeling, and simulation. Key findings reveal the robot's efficiency in high-speed and precision tasks, suggesting enhancements in control systems and integration of advanced technologies for even greater performance.

1 Introduction

In modern industrial settings, tasks requiring high precision and repetitive actions, such as assembly and material handling, are increasingly performed by robots to reduce human error and fatigue. SCARA (Selective Compliance Assembly Robot Arm) robots have become prominent for their ability to deliver high-speed, high-precision automation. Developed in the early 1980s, SCARA robots feature a unique design that provides selective compliance in certain directions, making them ideal for assembly and material handling tasks. The 4-DOF (Degrees of Freedom) SCARA robots, with three rotational movements (3R) and one prismatic (linear) movement (1P), are particularly noted for their efficiency, flexibility, and accuracy in executing complex tasks

Figure 1: EPSON SCARA Manipulator

SCARA robots offer several advantages, including speed, precision, and a compact design. They can perform repetitive tasks at high speeds, significantly boosting productivity in manufacturing environments. Their precision ensures exceptional accuracy in positioning and handling, crucial for tasks like component fitting and assembly. The selective compliance of SCARA robots reduces the risk of damaging delicate components, while their compact design allows for easy integration into limited spaces. Additionally, SCARA robots are cost-effective and versatile, suitable for various industrial tasks such as pick and place, material handling, and packaging.

Advanced technologies enhance SCARA robots significantly. They feature advanced sensors for accuracy and obstacle detection, vision systems for precise visual recognition, and AI and machine learning for adaptive task optimization. IoT connectivity enables real-time monitoring and seamless integration with other systems, enhancing operational efficiency. These advancements expand SCARA robots' capabilities for diverse industrial applications.

This case study analyzes a 4-DOF SCARA robot, emphasizing its design, components, and kinematic modeling to highlight advantages in speed, accuracy, and suitability for repetitive tasks. Future research directions include advanced control systems and vision-based technologies to further enhance performance.

2 Literature Review

The literature review presents an analysis of three primary research papers focusing on the development and implementation of 4-DOF SCARA robots. The aim of this review is to synthesize the key findings and identify the relevant design specifications, components, and theoretical foundations for the case study.

2.1 Development of a 4-DOF SCARA Robot with 3R1P for Pick-and-Place Tasks - Wen-Bo Li et.al

This paper discusses the design and technology behind a 4-DOF SCARA robot intended for industrial use, particularly in pick-and-place tasks. The robot employs three revolute joints (3R) and one prismatic joint (1P), allowing precise horizontal and vertical movements. The study highlights advancements such as hybrid mechanisms and advanced control algorithms. It also evaluates the robot's performance in material handling and assembly lines. Future research directions include enhancing precision and integrating vision systems for improved functionality

2.2 Design and development of a new 4 DOF hybrid robot with Scara motion for high-speed operations in large workspace - Wen-ao Cao et.al

This paper delves into the design and development of a 4-DOF hybrid robot that combines SCARA motion with other mechanisms to achieve high-speed operations in large workspaces. The research emphasizes optimizing the mechanical structure and kinematic modeling to enhance performance. The study suggests that future advancements could include the integration of artificial intelligence and human-robot collaboration to further industrial applications

2.3 Design and Fabrication of an Affordable SCARA 4-DOF Robotic Manipulator for Pick and Place Objects - Noshahi et.al

The focus of this paper is on the mechanical design, kinematic modeling, and control strategies of a 4-DOF SCARA robot. The robot's configuration includes three revolute joints and one prismatic joint, optimized for efficient movement and high-speed operations. The implementation of advanced control strategies like Active Disturbance Rejection Control (ADRC) and vision-based object detection enhances stability and autonomy. This makes the robot suitable for high-speed industrial applications, such as assembly lines. Future research aims to further improve control systems and integrate more advanced vision-based technologies

3 Methodology

The methodology for this case study involves a systematic approach to the design, analysis, and simulation of a 4-DOF SCARA robot. This section outlines the detailed steps and processes undertaken to achieve the study's objectives, including design specifications, component analysis, kinematic modeling, and simulation validation.

3.1 Design Specifications

The first step in the methodology involves establishing design specifications for the 4-DOF SCARA robot. This includes defining its workspace to ensure it can reach all required positions, determining its payload capacity based on the strength of its actuators, and balancing speed with accuracy for efficient industrial operations. Repeatability is crucial for maintaining precision over multiple cycles. Following this, a detailed component analysis considers the structural integrity of links and joints, the selection of appropriate actuators like servo motors for precise control, and designing an adaptable end-effector for specific tasks.

3.2 Kinematic Modeling

Kinematic modeling involves the mathematical representation of the robot's movements. The Denavit-Hartenberg (DH) parameter convention is used to describe the spatial relationships between the robot's joints

3.2.1 DH Parameters

Table 1: DH Parameters

I	$\alpha i-1$	a i-1	di	θi
1	90	0	0	$\theta 1$
2	0	L1	0	$\theta 2$
3	0	L2	0	$\theta 3$
4	0	0	0	$\theta 4$
5	90	L5	0	$\theta 5$

The DH parameters include link lengths, link twists, link offsets, and joint angles. These parameters are used to define the position and orientation of each link relative to the previous one.

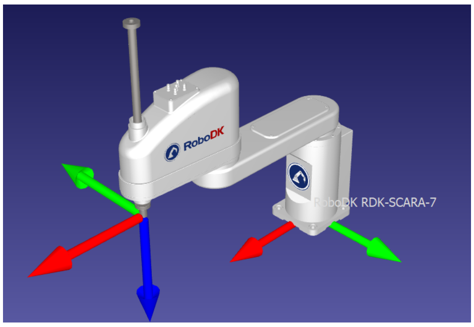

Figure 2: Simulation using RoboDK

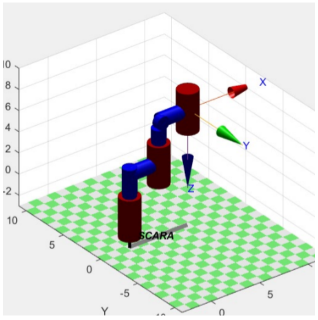

Figure 3: Simulation using MATLAB

3.3 Simulation

Simulation plays a vital role in validating the design and kinematic models. The simulation environment provides a virtual platform to test the robot's performance under various conditions without the need for physical prototypes.

Tools such as MATLAB and RoboDK are used to create a digital twin of the SCARA robot. These platforms allow for the simulation of the robot's movements and interactions with the environment.

4 Results and Discussion

The results and discussion section presents the findings from the design, analysis, and simulation of the 4-DOF SCARA robot. This section is divided into several subsections to provide a detailed analysis of the robot's structural and functional performance.

4.1 Structural Analysis

The structural analysis focuses on the design and physical characteristics of the SCARA robot, including its dimensions and materials.

The robot's workspace is mapped using forward kinematic equations. The analysis shows that the SCARA robot can cover a wide area with its 3R1P configuration, providing extensive reach in the horizontal plane and adequate vertical movement for pick-and-place tasks.

The reachable volume is the three-dimensional space within which the robot can position its end-effector. The results indicate that the robot can access all necessary points within its designated operational area, making it suitable for various industrial applications.

4.2 Functional Analysis

The functional analysis evaluates the robot's performance in terms of its workspace,kinematic performance and potential applications.

The robot's workspace is mapped using forward kinematic equations. The analysis shows that the SCARA robot can cover a wide area with its 3R1P configuration, providing extensive reach in the horizontal plane and adequate vertical movement for pick-and-place tasks.

The reachable volume is the three-dimensional space within which the robot can position its end-effector. The results indicate that the robot can access all necessary points within its designated operational area, making it suitable for various industrial applications.

The kinematic analysis reveals that the SCARA robot can achieve high velocities and accelerations, essential for high-speed industrial tasks. The joints' smooth and rapid movements ensure efficient task execution without compromising precision.

5 Conclusion

The study of the 4-DOF SCARA robot highlighted its compact design, structural robustness, and high-speed performance, affirming its suitability for assembly and material handling tasks in industrial applications. While achieving its objectives, the study acknowledged limitations such as focusing solely on the 4-DOF configuration and using simulations. Future research directions include exploring advanced control strategies, integrating AI, and enhancing human-robot collaboration to extend the robot's capabilities in complex industrial environments. This study serves as a foundational step toward advancing SCARA robot technology for improved efficiency and reliability in automation.

6 References

[1] *S. F. Noshahi, A. Farooq, M. Irfan, T. Ansar and N. Chumuang, "Design and Fabrication of an Affordable SCARA 4-DOF Robotic Manipulator for Pick and Place Objects," 2019 14th International Joint Symposium on Artificial Intelligence and Natural Language Processing (iSAI-NLP), Chiang Mai, Thailand, 2019, pp. 1-5, doi: 10.1109/iSAI-NLP48611.2019.9045203.*

[2] *Cao, Wen-ao, et al. "Design and development of a new 4 DOF hybrid robot with Scara motion for high-speed operations in large workspace." Mechanism and Machine Theory 198 (2024): 105656.*

[3] *Li, Wen-Bo, et al. "Development of a 4-DOF SCARA robot with 3R1P for pick-and-place tasks." 2015 6th International Conference on Power Electronics Systems and Applications (PESA). IEEE, 2015.*