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Solution of a 4-Axis Selective Compliance Assembly Robot Arm (SCARA) for Picking & Placing an IC Component onto the PCB

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***Abstract*— In this paper, the solution of a 4-axis selective compliance assembly robot arm (SCARA) for picking & placing an IC component onto the PCB is presented along with the simulation results. The SCARA robot arm, known for its horizontal movement and accurate positioning, presents a versatile platform for assembly tasks in various industries, particularly in electronics manufacturing. The main goal is to get the forward kinematics equations required to precisely calculate the end-effector's location and orientation using the 4-axis SCARA robot arm's joint angles. The mathematical model explaining the link between the robot's joint variables and the position/orientation of the end-effector is developed by specifying the Denavit-Hartenberg (DH) parameters and using transformation matrices. The work intends to simulate and test the computed end-effector locations and orientations against experimental or simulated data using the obtained forward kinematics equations. The forward kinematics approach will be implemented using code developed as part of the project, enabling systematic investigation and testing of the pick-and-place capabilities of the SCARA robot. Additionally, it also provides a brief overview of the possible uses and consequences of using this SCARA-based solution for accurate and efficient assembly jobs in industrial settings. The incorporation of a graphical user interface (GUI) has the potential to enhance user engagement and aid in the real-time management and observation of the pick-and-place processes. By offering a methodical solution to the direct kinematics problem of a 4-axis SCARA robot arm for the purpose of picking and placing IC components onto PCBs, it advances robotic assembly technologies and highlights their potential to increase productivity and accuracy in manufacturing processes**

***Index Terms*— SCARA Robot, forward kinematics, 4-axis Robot Arm, PCB assembly, Graphical User Interface(GUI), end-effector positioning, Denavit-Hartenberg parameters, pick and place task, manufacturing efficiency, motion planning.**

I. INTRODUCTION

One of the most crucial jobs in the industrial sector is pick and place, which is done by "Selective Compliance

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Assembly Robot Arm" (SCARA). One amazing quality of this kind of manipulator is its repeatability with rapid movement in a horizontal plane. The problem of attaining high-speed movement stability with lengthy linkages is the design challenge of SCARA [1]. Arms with shorter connections can move more steadily. Due to this requirement, the linkages should be regarded as restricted, and the operation area (workspace) should thus be restricted. In industrial automation, the 4-axis Selective Compliance Assembly Robot Arm (SCARA) is indispensable, especially for repetitive and accurate activities like choosing and inserting components onto Printed Circuit Boards (PCBs). Because of their speed, precision, and mechanical design, SCARA robots are very useful for assembling Integrated Circuit (IC) components onto PCBs [2]. The architecture of SCARA robots allows for both vertical and horizontal axis movement. In contrast to conventional robotic arms, SCARA robots include one prismatic or linear joint for vertical Z-axis movement and two rotary joints for horizontal motions along the X-Y plane [3]. This arrangement makes moving around a designated workstation efficient. Because SCARA robots are precise and repeatable, they are ideal for selecting and arranging IC components on PCBs. When the robot's end-effector is fitted with grippers or vacuum systems, it can quickly and precisely grasp and release IC components, guaranteeing that they are positioned correctly on the PCB [4].

II. Diagram Of The SCARA Robot Arm

The Selective Compliant Assembly Robot Arm, also known as the Selective Compliant Articulated Robot Arm, is a benchmark design used to introduce students to the field of mechatronics design. This three-axis robot can move in the X, Y, and Z coordinates within of its work area [5]. Because of its parallel-axis joint design, which makes the arm somewhat flexible in the X-Y direction but rigid in the 'Z' direction, SCARA robots are employed in assembly processes where inserting a part requires a single vertical motion as its final step. It's commonly referred to as "vertical assembly" In pick-and-place, assembly, and packaging applications, they are widely used. In example, the electronic printed circuit board sector employs a lot of SCARAS to install semiconductor integrated circuits (ICs) and other components on computer circuit boards [6]. The image shows a block diagram of a joint controller for a 4-axis SCARA robot. The main components of the controller are Programming interface, Direct kinematics, Inverse kinematics, Interpolator, Axis drives [7] as shown in the Figs. 1 & 2 respectively.

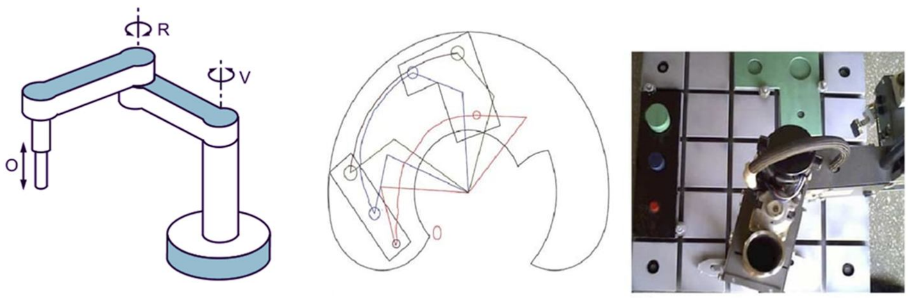

Figure 1. A typical 4-axis SCARA robot arm & the process of designing of a 4-axis SCARA robot arm

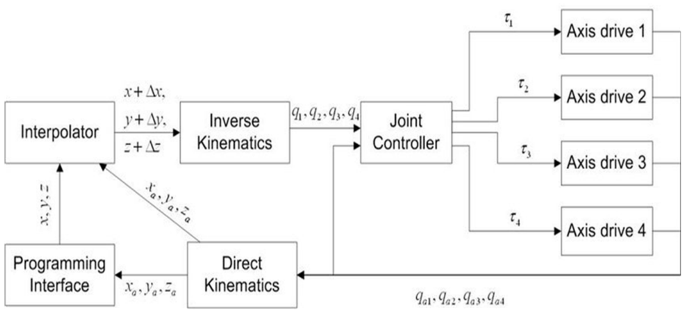

Figure 2. Block-diagram of the control scheme

Here is a more detailed explanation of the operation of each block in the controller [8]….

Programming interface:- The programming interface allows the user to specify the desired robot motions and other parameters. This can be done through a variety of methods, such as a graphical user interface, a text-based programming language, or a robot API [9].

Direct kinematics:- The direct kinematics block converts the desired robot joint angles into the corresponding Cartesian coordinates of the robot's end effector. This is done using a set of equations that describe the geometry of the robot.
Inverse kinematics:- The inverse kinematics block converts the desired Cartesian coordinates of the robot's end effector into the corresponding robot joint angles. This is a more complex problem than direct kinematics, as there may be multiple solutions for a given set of desired Cartesian coordinates. The inverse kinematics block uses a variety of algorithms to find a solution that is feasible and minimizes the required robot joint movement [10].
Interpolator:- The interpolator block generates the smooth trajectories for the robot joint angles, based on the desired start and end joint angles and the desired motion time. This is done using a variety of algorithms, such as cubic splines and quintic polynomials [11].
Axis drives:- The axis drives control the motors that move the robot's joints. They do this by sending electrical signals to the motors, which control the speed and direction of the motors [12].
The joint controller is an essential component of any SCARA robot. It is responsible for ensuring that the robot moves accurately and smoothly, while avoiding collisions and singularities [13] as shown in the Fig. 3.

III. FLOW-CHART OPERATIONAL MODE OF THE SCARA ROBOT ARM

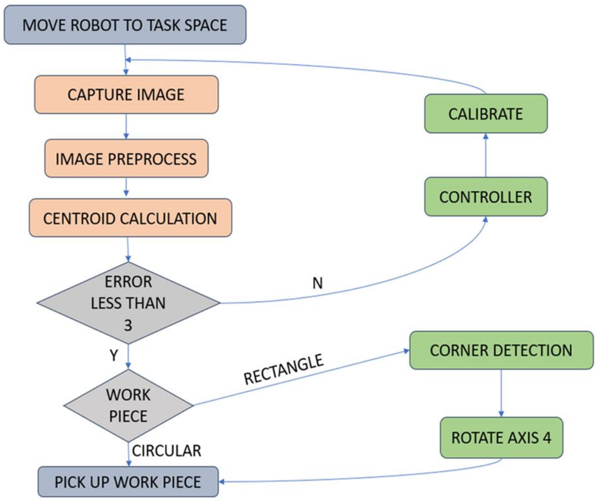

Figure 3. Flow-chart of the operation

IV. METHODOLOGY & THE DESIGN PROCESS

- Implementing a pick & place task involves a combination of mechanical understanding, kinematics, programming, and testing to ensure the successful operation of the 4-axis SCARA robot arm [14].
- Problem Definition and Requirements Analysis:- Considering component sizes, placement precision, cycle time, and manufacturing volume, specify the precise criteria for selecting and arranging IC components on PCBs.
- Kinematic Modelling and the Definition of DH Parameters :- Create the Denavit-Hartenberg (DH) parameters, build the forward kinematics equations to connect joint variables to end-effector position and orientation, and develop a kinematic model for the SCARA robot [15].
- System Architecture and Setup :- When designing the robot setup, consider the available workspace, the gripper's design, the end-effector tooling, and any extra sensors or vision systems needed for precise component placement and detection.
- Programming and Simulation :- To verify the efficacy and precision of the suggested approach, incorporate the generated algorithms into programming languages (such as MATLAB, Python, or robot-specific programming languages) and mimic pick-and-place tasks [16].
- Integration with Control Systems and GUI Development :- Connect the SCARA robot to sensors, graphical user interfaces (GUIs), and control systems to provide easy-to-use pick-and-place task monitoring and control.

V. IMPLEMENTATION PROCESS

To implement a pick & place task using direct kinematic solving for a 4-axis SCARA robot arm, we follow these steps as per the flow-chart shown in the Fig. 2 as follows.

- *Robot Arm Configuration*: Understand the specifications of your 4-axis SCARA robot arm, including its joint ranges, link lengths, and end-effector capabilities.
- *Direct Kinematics*: Derive the forward kinematics equations to calculate the end-effector position and orientation based on joint angles and link lengths. This involves developing equations that map joint angles to the position and orientation of the end-effector in the robot's workspace.
- *Coordinate System Setup*: Define a coordinate system that aligns with the robot arm's base and end-effector. Ensure consistency in defining the coordinate frames for each joint and the end-effector.
- *Task Definition*: Specify the pick & place task by determining the desired positions and orientations for the robot arm's end-effector. Define the objects to be picked, their locations, and the destinations for placement.
- *Inverse Kinematics Solver (optional):* If available or necessary, implement an inverse kinematics solver to determine the joint angles required to achieve the desired end-effector positions and orientations. This can be useful for real-time adjustments and path planning.
- *Programming and Control:* Write code or use robotic programming software to control the robot arm based on the calculated direct kinematics equations or the inverse kinematics solver. Ensure the robot arm moves accurately to the specified positions for picking and placing objects.
- *Testing and Calibration*: Test the pick & place task execution to ensure accuracy and reliability. Calibrate the robot arm if needed to improve precision and alignment.
- *Iterative Improvement*: Iterate on the process to refine the pick & place task by adjusting parameters, improving algorithms, or enhancing control strategies for better performance.

For selecting and positioning an Integrated Circuit (IC) component onto a Printed Circuit Board (PCB), a 4-axis Selective Compliance Assembly Robot Arm (SCARA) is designed using a multidisciplinary approach that includes mechanical design, kinematic modelling, control system development, and vision system integration. The goal of this procedure is to develop a precise and effective robotic system that can precisely manipulate and position integrated circuit (IC) components onto printed circuit boards (PCBs), maximizing production efficiency & guaranteeing premium assembly in the electronics sector as shown in the Fig. 4.

V. MATHEMATICAL MODEL

Denavit-Hartenberg (DH) parameters and forward kinematics equations are used in the mathematical model for a 4-axis Selective Compliance Assembly Robot Arm (SCARA) to pick and place an Integrated Circuit (IC) component onto a Printed Circuit Board (PCB) to describe the relationship between joint angles and the position and orientation of the end-effector. The SCARA robot kinematics can be represented using the DH parameters and transformation matrices.

α: List of twist angles between consecutive z-axes (in radians)

a: List of link lengths along x-axes

d: List of link offsets along z-axes

θ: List of joint angles or prismatic joint displacements

The transformation matrix from the base to the end-effector frame can be calculated as a product of individual transformation matrices for each joint using DH parameters:

$$T = A_1 . A_2 . A_3 . A_4$$

where A_i represents the homogeneous transformation matrix for the i^{th} joint, The entries in the last column of the resultant transformation matrix are used to determine the end-effector position vector. T is a symbol for the translation in the x, y, and z directions. The upper (3 x 3) submatrix of T, which represents the rotation portion, may be used to derive the orientation (rotation matrix). By inputting specific joint angles or prismatic displacements into the DH parameters and using the forward kinematics equations described above, the mathematical model allows us to calculate the precise position and orientation of the SCARA robot's end-effector when picking and placing IC components onto PCBs.

A_i is given by

$\cos(\theta_i)$	$-\sin(\theta_i)\cos(\alpha_i)$	$\sin(\theta_i)\sin(\alpha_i)$	$a\cos(\theta_i)$
$\sin(\theta_i)$	$\cos(\theta_i)\cos(\alpha_i)$	$-\cos(\theta_i)\sin(\alpha_i)$	$a\sin(\theta_i)$
0	$\sin(\alpha_i)$	$\cos(\alpha_i)$	d_i
0	0	0	1

VI. Important Specifications Of SCARA For The Design Process

Degrees of Freedom: 4 axes of movement.
Configuration: Parallel-axis joint configuration for X-Y-Z plane movement and wrist rotation (4th axis).
Payload Capacity: Variable, typically ranging from a few kilograms to tens of kilograms.
Reach: Varies among models but generally spans from a few hundred millimetres to over a meter.
Speed and Precision: Known for high-speed operations and accuracy.
Controller: Utilizes specialized controllers managing movements, speed, precision, and operation.
Applications: Used in assembly, pick-and-place tasks, packaging, and material handling in industrial settings.

VII. Program Code, Simulation Results & The Output

In this section, the program steps & other related issues are presented in a nutshell

A. Algorithm

- For every joint in the SCARA robot arm, define the Denavit-Hartenberg (DH) parameters (alpha, a, d, theta).
- Using the DH parameters, compute the transformation matrices to get the location and orientation of the end-effector.
- Joint angles can be converted to Cartesian coordinates by using forward kinematics equations.
- To move the robot from its starting to finishing places for pick-and-place tasks, create a trajectory or route planning algorithm.
- Make sure that the required path is moved in a collision-free and seamless manner.
- Incorporate vision systems or sensors to identify the locations of PCB and IC components.
- When performing selecting and placement jobs, use sensor data to guide the robot's activities and provide feedback control.
- Utilizing robotics-specific frameworks or Python libraries such as Matplotlib, one may visualize pick-and-place operations and simulate robot motions in a simulated environment.
- Use simulation to verify trajectory planning and control techniques.
- Put error-handling procedures in place to handle unforeseen circumstances that arise while a robot is operating.
- Improve algorithm performance for increased dependability, accuracy, and efficiency.
- Provide a graphical user interface (GUI) for interacting with or tracking the actions of robots.
- Present current data on the position, status, and functions of the robot.
- To verify the effectiveness of the algorithm, carry out tests on the real robot.
- Check whether the robot can reliably choose and arrange IC components on the PCB in a practical setting.

B. Program Code

The program implementation of SCARA robot control may be substantially customized based on the job specifications, control systems, and kinematics of the robot. In-depth computations, matrix operations, control algorithms, and hardware or system integration are all involved.

C. Inputs

```
link1_length = 1.0
link2_length = 0.8
z_offset = 0.2
theta1 = np.radians(30)
theta2 = np.radians(45)
```

D. Output

End-effector position:
(1.0730806398664554, 1.2727406610312546, 0.2)

Applying these simulations to a real robot in the real world, engineers and researchers may use them to test ideas, refine algorithms, and access how the robot behaves as shown in the Fig. 5.

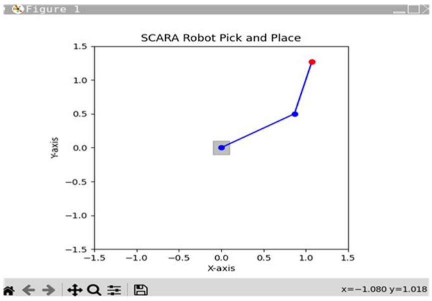

Figure 5. Simulation result

VIII. Simulation Output Results

Industrial automation is greatly impacted by the effective implementation of a pick-and-place operation employing 4-axis SCARA robot arm and direct kinematic solution. By utilizing direct kinematics, the SCARA robot can perform complex pick-and-place tasks with exceptional precision and accuracy. This accomplishment shows that the robot is capable of accurately placing Integrated Circuit (IC) components onto Printed Circuit Boards (PCBs), which is a crucial step in the production of electronic products. In addition to increasing production efficiency, the robot's skill in calculating and carrying out exact actions also helps to raise the general standard and uniformity of assembly procedures. The validation and verification of the robot's kinematic models is one of the main results of using direct kinematic solving. The execution's success validates the precision and dependability of the mathematical models used to forecast and regulate the robot's movements. It confirms that the robot's real performance and theoretical projections are in sync, proving the effectiveness of the chosen strategy. This verification gives the robot's capabilities credibility and lays the groundwork for future advancements and uses in a variety of industrial contexts. Direct kinematic solving successfully completes pick-and-place tasks, establishing a standard for future robotic automation developments. It is a crucial stage in the ongoing development of SCARA robots, opening the door to more control strategy improvements, the incorporation of cutting-edge sensors and vision systems, and the creation of increasingly cooperative and intelligent robotic systems. These findings highlight the enormous potential that SCARA robots have to transform manufacturing procedures and highlight their essential role as tools that promote productivity, accuracy, and creativity in a variety of industrial sectors.

IX. Overall Working Process

- The user specifies the desired robot motions and other parameters through the programming interface.
- The direct kinematics block converts the desired robot joint angles into the corresponding Cartesian coordinates of the robot's end effector.
- The inverse kinematics block converts the desired Cartesian coordinates of the robot's end effector into the corresponding robot joint angles.
- The interpolator block generates the smooth trajectories for the robot joint angles, based on the desired start and end joint angles and the desired motion time.
- The axis drives control the motors that move the robot's joints, following the trajectories generated by the interpolator.

X. Conclusions

The effective application of a 4-axis SCARA robot arm and direct kinematic solution to a pick-and-place operation is evidence of the progress made in robotics and its revolutionary influence on industrial automation. This achievement demonstrates the SCARA robot's ability to carry out the complex and precise motions needed to precisely place Integrated Circuit (IC) components onto Printed Circuit Boards (PCBs). In addition to demonstrating technological skill, the robot's ability to compute and execute these motions using direct kinematics highlights the critical role that it plays in contemporary production. Direct kinematic solution is a very useful technique for pick-and-place procedures in the field of electronic manufacturing, where accuracy and productivity are critical. The ability to place integrated circuit components precisely and accurately on printed circuit boards

(PCBs) demonstrates how SCARA robots have the potential to transform assembly processes. Using direct kinematic solution to optimize trajectories and streamline motions, the robot improves operational efficiency, shortens cycle times, and makes a substantial contribution to the improvement of product quality and consistency. The use of direct kinematic solution for pick-and-place problems has consequences that go beyond simple technological advancement. They represent a paradigm change in industrial automation, pointing to a day when SCARA robots will be essential to raising efficiency, accuracy, and productivity in a variety of production industries. This accomplishment marks a critical turning point in the development of robotics and the beginning of a new phase of automation-driven innovation that will change the face of contemporary industry. In summary, the successful application of direct kinematic solutions to pick-and-place tasks with a 4-axis SCARA robot portends a future in which accuracy, efficacy, and creativity come together to reshape the possibilities in industrial automation.

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