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Design and Construction of a SCARA Robot for Automated Assembly Applications

24 ***Abstract*—This paper presents the design and construction of a SCARA (Selective Compliance Assembly Robot Arm) robot aimed at automated assembly tasks. The work addresses mechanical design, actuator selection, control architecture, and experimental validation of the system. The developed prototype enables precise and repetitive operations, making it viable for low-cost production lines. The final result demonstrates that, through the use of accessible technologies such as 3D printing and open-source platforms, it is possible to develop functional prototypes with a high degree of customization and applicability in real manufacturing environments.**

***Keywords*—SCARA robot, automated assembly, mechanical design, motion control, industrial robotics**

18

I. Introduction

Currently, the accelerated advancement of industrial automation has generated a growing need for efficient, cost-effective, and adaptable technological solutions for various production processes. One of the key elements in this context is the use of specialized robots that increase precision, speed, and repeatability in tasks previously performed manually. In this scenario, the SCARA robot (Selective Compliance Assembly Robot Arm) has become a fundamental tool in production lines, especially for assembly operations.

6 This paper describes the complete development of a SCARA robot for educational and experimental purposes, as part of the Robotics module in the Systems and Computer Engineering program at Universidad Doctor Andrés Bello, Sonsonate campus. The project was designed and built by seventh-semester students, aiming to apply theoretical knowledge in a practical and innovative solution that reflects real industry challenges

26 and opportunities.

Thus, the document presents a comprehensive approach covering the robot's functional description, mechanical design in CAD environments, virtual simulation using CoppeliaSim, and physical manufacturing of components via 3D printing. Additionally, the integration of a control platform based on Arduino is detailed, enabling the execution of programmed sequences and validation of simulated movement accuracy.

This work not only represents a concrete application of robotics and automation principles but also an opportunity to

4 strengthen interdisciplinary skills in areas such as mechanical design, electronics, programming, and systems control.

II. SCARA Robot Description

6 The SCARA robot (Selective Compliance Articulated Robot Arm) is an industrial robot type used in various applications requiring high speed and precision, excelling in assembly and object manipulation [1].

The SCARA concept originated in Japan by Professor Hiroshi Makino at the University of Yamanashi, who later formed the SCARA Robot Consortium in the late 1970s. As a result of these efforts, the first SCARA prototype was developed in 1978. After multiple industrial tests and design optimizations, a second version was released two years later. Finally, in 1982, the first commercial SCARA robot was launched, marking a significant milestone in industrial automation [2].

SCARA robots resemble a human arm, featuring ”shoulder” and ”elbow” joints, a ”wrist” axis, and vertical movement capability. These machines are excellent for a wide range of tasks requiring fast, repeatable, and precise point-to-point movements, such as machine loading/unloading and assembly [3]. Their ”elbow” movement also makes them valuable for applications needing constant acceleration along circular paths, such as material dispensing [4].

Due to their workspace, these robots are considered cylindrical robots. SCARA robots have two parallel rotary joints that ensure precision in a specific plane. According to Peter Cavallo from Denso Robotics [4], SCARA robots are often the first choice for manufacturers due to their speed, robustness, and durability.

Morphologically, a SCARA robot can be found in 4-axis or 3-axis configurations (as in this project). The first two axes are rotational joints enabling horizontal plane movement. The third axis provides vertical movement. The fourth axis (if present) is a rotary joint allowing wrist rotation around the z-axis [5].

SCARA robots are used in a wide range of industries for tasks such as pick and place, assembly, material dispensing, machine tending, and material handling. They are especially popular in the electronics, automotive, pharmaceutical, and food processing industries.

Key advantages of this robot type for production processes are detailed in Table I.

III. SCARA Robot Design

A. Model Selection and Design

The selected model is a SCARA robot with three degrees of freedom: two in the horizontal axis (the arm with two joints) and one in the vertical axis. The SCARA robot design was carried out using 3D CAD modeling software to develop a functional, modular structure compatible with both virtual simulation and physical manufacturing. All robot parts

TABLE I: Advantages of SCARA Robots

Feature	Description
Compact design	Occupy little space, with an efficient cylindrical workspace, and are easy to relocate.
High speed	Fast due to fewer axes and joints compared to other robots, resulting in very short work cycles.
Easy synchronization	Integrate seamlessly with other production processes, facilitating coordinated workflows.
Versatility	While their main use is pick and place, they are adaptable to multiple applications by using different end effectors.

were modeled considering system kinematics and mechanical requirements for subsequent 3D printing and assembly.

Each component (base, arm 1, arm 2, Z column, end-effector support) was designed individually to facilitate modifications, maintenance, and assembly.

B. Mechanical Structure

The structure focuses on two articulated links, similar to a human arm, with rotary joints driven by Nema17 motors. The base provides a stable platform and houses the linear movement mechanism for the Z axis. The end effector is a gripper mechanism controlled by a servomotor, designed for specific manipulation tasks.

Vertical movement is achieved using an 8 mm diameter lead screw, driven by a Nema17 motor via a 5x8 mm flex ible coupling. Three smooth rods (8 mm diameter, 30 cm length) act as linear guides for vertical movement, ensuring stability and preventing rotation around the Z axis. LM8UU linear bearings (8x15x24 mm) are used for smooth movement along the rods.

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The arm links are coupled at one end of the central base using bearings, connected to the motors via timing belts and 20-tooth pulleys. The design process involves the creation of individual components, each fulfilling the specific functions described above. Fig.1 shows the Full CAD model.

C. Virtual Simulation and Manufacturing

Parts were exported in .STL format and optimized for fabrication with an Ender 3 v3 3D printer using PLA+ filament. Special attention was given to tolerances, print orientation, and structural strength.

IV. Electronic Circuit Design

For the robot's electronic circuit, an Arduino UNO board was selected along with A4988 drivers and a breadboard for connections, which also provides power to the Nema 17 motors.

The Arduino UNO serves as the main component, being a versatile development platform consisting of an open-source hardware electronic board. It includes a programmable microcontroller and features female pin headers that greatly facilitate connection with various sensors and actuators [6].

To control the stepper motors, controllers or drivers are needed, which in this case are the A4988 drivers. These are controllers specifically designed for operating bipolar stepper motors. One of their most notable features is their integrated translator, which greatly simplifies their use. Thanks to this, only two pins from our microcontroller are needed to manage it: one for rotation direction and another for motor steps [7].

Fig. 1: SCARA CAD Model

This driver offers five different step resolutions (full step, half step, quarter step, eighth step, and sixteenth step), allowing for more precise and smooth motion control. Although, in this case, full step mode is used. Additionally, the A4988 includes a potentiometer to adjust the output current to the motor, along with protection features such as thermal shutdown for overheating and cross-current protection [7].

Stepper motors are responsible for moving the robot's extremities, making them vital to the project. In this case, Nema17 motors are used. Nema17 stepper motors are fundamental when high-precision position control is required. Their design is distinguished by a step angle of 1.8°, meaning the motor shaft rotates with great precision at each advance and requires 200 steps to complete one full revolution (360°). This characteristic significantly improves positioning precision, making them ideal for robotic systems [8].

These motors typically operate with a 12V voltage and can handle up to 1.2 A per phase, which is essential for achieving their maximum holding torque of 3.2 kg-cm. This capacity makes them a robust option for supporting the load demands present in automation equipment [9].

V. Robot Assembly

A. Materials List

Table II shows the materials used in creating the robot, including electronic components and parts required for robot operation.

TABLE II: List of components

Component	Description	Qty.
Arduino UNO	It is the brain of the robot, it will contain the code for its movement.	1
A4988 Drivers	Drivers for stepper motor control.	3
Nema17 Motors	Stepper motors, responsible for moving the robot.	3
Power supply min. 12V 4A	Power supply to feed the motors.	1
Female plug for power supply	To adapt to the power supply and connect it to the male plug.	1
Male plug for power supply	Connected to the female plug to connect and disconnect the power supply.	1
3x25 mm screws with nut	To join parts of link 1.	2
3x30 mm screws with nut	To join the motor with the coupling on the Z axis.	2
3x10 mm screws with nut	For the support of motors 1 and 2 and other components.	14
8x45 mm screw with nut and hex head	To join link 1 with link 2.	1
3x15 mm screws with nut	For mounting the tool (gripper).	2
Arduino UNO	It is the brain of the robot, it will contain the code for its movement.	1
A4988 Drivers	Drivers for stepper motor control.	3
Nema17 Motors	Stepper motors, responsible for moving the robot.	3
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3x10 mm screws with nut	For the support of motors 1 and 2 and other components.	14
8x45 mm screw with nut and hex head	To join link 1 with link 2.	1
3x15 mm screws with nut	For mounting the tool (gripper).	2

B. Assembly Process

With everything prepared for robot assembly, each printed part is joined with others and with required components. Each piece is placed with precision and care to avoid damage. The assembly follows a systematic approach, ensuring proper alignment and functionality. The exploded view for assembly and the real prototype are depicted in Fig. 2 and 3 respectively.

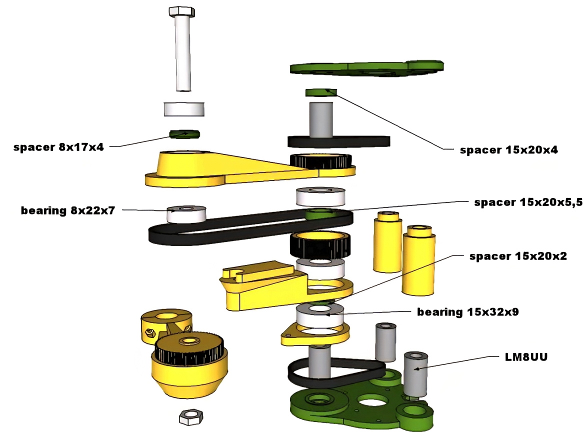

Fig. 2: Exploded View of the SCARA Robot [10]

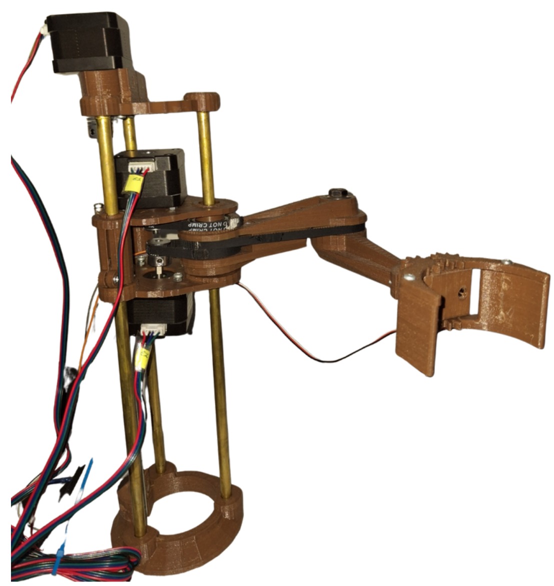

Fig. 3: Real SCARA Prototype

VI. Robot Programming

A. General Software Architecture

The software architecture of our system is divided into two main components. The embedded firmware in the Arduino microcontroller is responsible for direct hardware control, managing motors and kinematics. Complementarily, a dynamic web user interface, developed with Python and the Django framework, allows operator interaction and real-time visualization of the robot's status and movements.

B. Microcontroller Firmware (Arduino)

The low-level control brain of the robot resides in an Arduino UNO board, selected for its number of input/output pins and processing capacity, suitable for managing multiple axes simultaneously. The firmware was developed in C++ using the Arduino IDE. It directly interacts with A4988 microstepping drivers, which are crucial for precise control of NEMA 17 bipolar stepper motors for each rotary axis and the Z-axis motor.

To ensure smooth and precise movements, the firmware incorporates trajectory generation algorithms. The AccelStepper library was fundamental for managing stepper motor movement, allowing independent control of velocity, acceleration, and deceleration for each axis, which is vital for avoiding vibrations and step loss.

C. Web User Interface (Python/Django)

User interaction is managed through a robust web interface developed with Python 3 and the Django framework. Django was selected for its ability to build dynamic and secure web applications, allowing the interface to be accessible from any device with a compatible browser.

The interface provides a manual control panel that allows users to move each axis of the robot incrementally. This functionality includes validations on both the client side (JavaScript) and the server side (Django), ensuring that all manual movements comply with the operational limits defined for each motor. A "Reset" button sends a specific command to the Arduino, returning the robot to its initial position and thereby facilitating calibration and the restarting of operations.

A key feature for debugging and monitoring is the integrated communication terminal, which displays in real time all commands sent from the interface to the Arduino, as well as the received telemetry responses (Fig. 4).

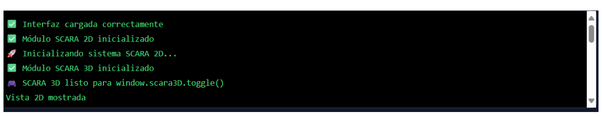

Fig. 4: Terminal in the Interface

To enhance the user experience and enable movement previewing, the interface incorporates visual simulations. A real-time 2D view (Fig. 5) was developed to reflect the planned movements of the end effector in the XY plane, allowing the user to verify the trajectory before or during the robot's actual execution. Additionally, a 3D view (Fig. 6) was included, offering a more comprehensive three-dimensional representation of the robot's kinematics and providing a deeper spatial understanding of its behavior.

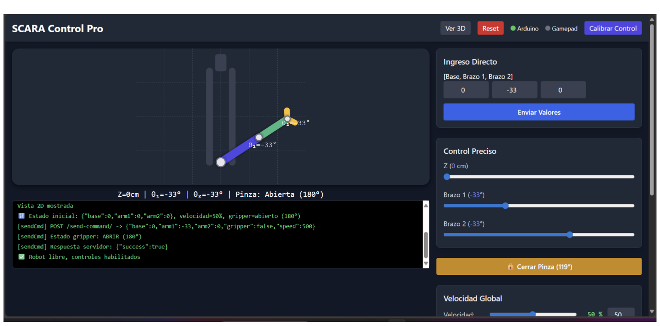

Fig. 5: 2D Interface

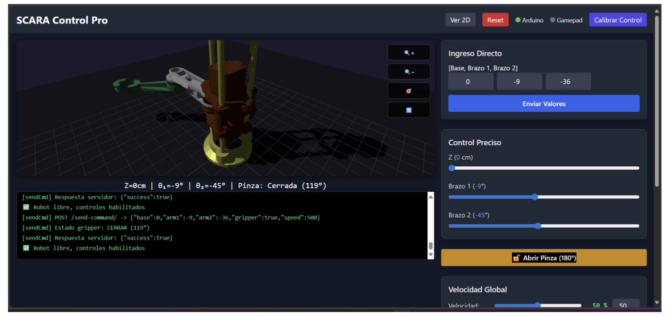

Fig. 6: 3D Interface

Furthermore, a wireless connection was implemented through a controller, enabling remote operation of the robot and thereby increasing interactivity.

VII. Kinematics Analysis

Kinematic analysis of a robot arm studies its movement relative to a fixed reference frame, without considering the forces that cause the movement [11], [12]. Essentially, it focuses on understanding the relationship between the robot's joint positions and the end-effector's location. Kinematic analysis can be divided into forward and inverse kinematics [13], [14]: the goal of forward kinematics is to determine the end-effector's position given the joint positions, whereas inverse kinematics consists of finding the joint positions needed to reach a desired end-effector location.

A. Forward Kinematics

Let:

- θ_1: Angle of the first (base) joint
- θ_2: Angle of the second (elbow) joint
- d_3: Displacement of the prismatic (vertical) joint
- L_1: Length of the first arm
- L_2: Length of the second arm

The position of the end-effector (x, y, z) is given by:

$$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)$$
$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$$
$$z = d_3$$

B. Inverse Kinematics

Given a desired position (x, y, z), the joint variables are calculated as follows [11]:

$$d_3 = z$$
$$r^2 = x^2 + y^2$$
$$\cos\theta_2 = \frac{r^2 - L_1^2 - L_2^2}{2L_1L_2}$$
$$\theta_2 = \arccos\left(\frac{r^2 - L_1^2 - L_2^2}{2L_1L_2}\right)$$
$$\theta_1 = \arctan 2(y, x) - \arctan 2\left(L_2 \sin\theta_2, L_1 + L_2 \cos\theta_2\right)$$

where r is the straight-line distance from the robot's base to the desired end-effector position, ignoring the vertical (Z) component.

C. Differential Modeling (Jacobian Matrix)

Jacobian Analysis explores the connection between the end effector's velocity and the rates at which joints move. The Jacobian is a matrix that converts the velocity in the end effector's space into values in the actuator (joint rates) space. Furthermore, the Jacobian matrix plays a crucial role in analyzing singularities and performance, as well as in creating trajectories within the end-effector space [13], [15].

Let the joint variables be θ_1, θ_2, and d_3. The end-effector position is:

$$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)$$
$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$$
$$z = d_3$$

The Jacobian matrix $\mathbf{J}$ relates the joint velocities to the end-effector linear velocities [16]:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \mathbf{J} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{d}_3 \end{bmatrix}$$

where the Jacobian $\mathbf{J}$ is:

$$\mathbf{J} = \begin{bmatrix} -L_1 \sin\theta_1 - L_2 \sin(\theta_1 + \theta_2) & -L_2 \sin(\theta_1 + \theta_2) & 0 \\ L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) & L_2 \cos(\theta_1 + \theta_2) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

VIII. Testing and Validation

During the project validation phase, various tests were conducted to verify the mechanical, electronic, and control functionality of the SCARA robot. These tests allowed parameter adjustment, error identification, and system performance optimization before use in actual tasks.

A. Basic Movement Tests per Axis

Goal: Verify correct displacement of each joint (arm 1, arm 2, and Z axis) independently. Results: Smooth movement without vibrations or blockages, within the allowed mechanical range.

B. Automated Sequence Test

Goal: Execute a programmed sequence of movements representing a typical assembly task. Results: The sequence was executed with acceptable precision. Speeds and accelerations were adjusted to avoid overloads.

C. Physical vs. Simulation Movement Comparison

Goal: Validate that simulated kinematics match the physical implementation. Results: Very similar behavior was obtained between both environments. Minor differences were due to mechanical tolerances and motor resolution.

D. Repeatability Test

Goal: Evaluate the robot's ability to repeat the same task multiple times with precision. Results: Minimal variation (less than 2 mm) in final position was observed, within acceptable margins for basic applications.

IX. Discussion

The development and validation of the SCARA robot prototype demonstrate the feasibility of constructing a functional, low-cost robotic system using accessible technologies such as 3D printing, open-source electronics, and modular software architectures. The integration of NEMA 17 stepper motors, A4988 drivers, and an Arduino UNO microcontroller provided a reliable platform for precise motion control, as evidenced by the successful execution of both manual and automated movement sequences.

The experimental results indicate that the robot achieves smooth and repeatable movements within the designed mechanical limits. The basic movement tests for each axis confirmed the absence of significant vibrations or blockages, while the automated sequence tests validated the system's ability to perform typical assembly tasks with acceptable accuracy. The comparison between simulated and physical movements revealed a high degree of correspondence, with only minor discrepancies attributable to mechanical tolerances and stepper motor resolution. Repeatability tests further demonstrated that the robot can consistently return to the same position with minimal deviation (less than 2 mm), which is sufficient for basic automation applications.

A notable strength of the system is the dynamic web-based user interface, developed with Python and Django, which enables intuitive manual control, real-time monitoring, and visual simulation of planned trajectories. The inclusion of both 2D and 3D visualizations enhances user understanding and facilitates pre-execution verification of robot movements. The wireless control option adds further flexibility and interactivity, making the platform suitable for educational and experimental environments.

Future work should focus on workspace and dynamic analysis in order to develop control techniques.

X. Conclusions

In summary, this project has culminated in the construction of a functional and cost-effective SCARA robot, suitable for light automation tasks. The successful integration of mechanical hardware (NEMA 17 motors, A4988 drivers) and software (Arduino firmware and advanced Python/Django interface with simulation) underscores the capability to develop complex robotic systems with optimized resources. This SCARA not only meets the objective of positioning precision and modest load handling but also ensures adaptability and longevity through its modular design.

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