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Original Article

A Comparative Study of Various Control Strategies for a 4-DOF Scara Robot

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Abstract - *The SCARA robot, abbreviated for Selective Compliance Articulated Robot Arm, is a type of industrial robot distinguished by its ability to move quickly and agilely within a two-dimensional workspace. A key feature of the SCARA robot is its 4 degrees of freedom, allowing it to perform remarkably flexible movements within a plane and rotate around the vertical axis. This article focuses on the mathematical modeling of a 4-degree-of-freedom SCARA robot. Subsequently, the paper investigates three typical control algorithms applied to this robot: the PD-G law, the Li-Slotine law, and fuzzy logic control. The results of numerical simulations conducted using MATLAB/Simulink demonstrate that all three control algorithms achieve good control performances when the load parameters remain constant. However, when the load parameters change, the PD-G control law exhibits a dependence on gravity that results in inferior performance compared to the other two algorithms. The promising simulation results of the Li-Slotine and fuzzy logic control algorithms suggest potential applications for 4-degree-of-freedom SCARA robots in industry.*

Keywords *- 4-DOF-Scara robot, PD-G law, Li-Slotine law, Fuzzy logic law, Load.*

1. Introduction

Robots were developed to substitute for humans in numerous challenging and intricate problem-solving tasks, particularly within industrial settings. Leveraging an array of sensors, actuators, and programming, robots exhibit the capacity to traverse environments, manipulate objects, and engage with humans. Consequently, the field of robotics control has emerged as a highly stimulating area of academic inquiry for researchers [1, 2].

The control of robots has long been a captivating field for researchers, driven by the constant pursuit of improved control quality to meet the diverse demands of industrial production. However, this aspect does not adhere to a one-size-fits-all scenario. Some industrial processes necessitate robots with lightning-fast movements and the fortitude to handle hefty payloads.

For instance, assembly lines benefit from robots capable of swiftly manoeuvring parts at high speeds. Conversely, other tasks prioritize pinpoint precision over raw power. Consider a robot delicately etching a circuit board or flawlessly applying a coat of paint – these applications require robots that meticulously follow pre-defined trajectories, often handling delicate objects. Consequently, the ideal control method for a robot is highly dependent on the specific task at hand. Each method boasts its own strengths and weaknesses, rendering them more or less suitable for various applications within the vast realm of industrial robotics. By carefully considering the task requirements, control system engineers can select the most appropriate method to ensure the robot operates with optimal efficiency and effectiveness [3-8].

In [9], the authors proposed an optimal model-based adaptive controller, a modified version of MBACs to regulate effectively a two-link robot applied for an upper limb rehabilitation robot. Similarly, for rehabilitation purposes, in [10], the authors presented a control system for the 3-DOF robot based on a series of switching laws. In [11], a low–cost 3-DOF arm robot with a counterbalance mechanism was successfully designed.

In [12], a type of Scara robot was controlled using a fractional-order passivity–based adaptive controller. The authors in [13] selected a nonlinear optimal control approach for a 4-DOF Scara robot applying a stabilizing optimal (H-infinity) feedback controller. A review of control strategies for Scara robots was provided in [14]. Furthermore, there are many other studies, both domestic and international, implementing and applying various control methods, including intelligent strategies for robots [15-19]. Despite the emergence of more sophisticated control algorithms, the classic PID controller remains a mainstay in many industrial applications due to its enduring popularity stemming from its simplicity, robustness, and ease of implementation. However, even this well-established workhorse can benefit from advancements in control theory.

The integration of PID controllers with intelligent algorithms, such as adaptive, fuzzy, or neural networks, unlocks a new level of control performance. These intelligent algorithms can mitigate the limitations of the PID controller, such as its inability to handle highly non-linear systems or cope with significant parameter variations. By incorporating features like online learning and self-tuning, adaptive control algorithms can dynamically adjust the PID parameters to optimize performance under changing conditions. Fuzzy logic control, on the other hand, excels at processing imprecise or subjective data, enabling the PID controller to make control decisions based on human-like reasoning.

Similarly, neural networks can capture complex system dynamics through training data, empowering the PID controller to adapt to highly non-linear systems. This synergistic approach of amalgamating the classic PID controller with intelligent algorithms represents a potent strategy for pushing the boundaries of control system performance.

This paper will provide a comparative analysis of several control methods: the classic PD gravity compensation controller (PD-G), the Li-Slotine adaptive controller, and the fuzzy logic controller applied to a 4-degree-of-freedom Scara robot. The comparison results are conducted through simulations using Matlab-Simulink software to assess the dynamic characteristics of the system, thereby providing insights into the strengths and weaknesses of each proposed method.

The structure of this scientific paper is presented as follows. Next to the introductory overview, Section 2 provides a concise summary of the mathematical model of the 4-degree-of-freedom Scara robot. Subsequently, Section 3 introduces three control solutions applied to this robot. The subsequent Section 4 presents numerical simulation results and necessary analysis to clarify the effectiveness of the proposed control solutions. Finally, brief conclusions and directions for future research are also provided in Section 5.

2. Modeling of 4-DOF Scara Robots

2.1. Dynamics of a 4-DOF Scara Robot

The SCARA robot is a type of industrial robot characterized by its ability to move quickly and flexibly in two-dimensional space. "SCARA" stands for Selective Compliance Assembly Robot Arm or Selective Compliance Articulated Robot Arm. The distinctive feature of the SCARA robot is its 4-DOF, allowing it to move in the plane and rotate around the vertical axis in a flexible manner. The structure of the SCARA robot typically consists of two parallel arms and an additional degree of freedom, allowing rotation around the third axis.

This robot is commonly used in applications requiring high speed, such as assembly, welding, or product inspection in manufacturing plants. In the study [14], the author presented the configuration of a 4-DOF Scara robot. Here, a concise summary is provided with some basic parameters. The configuration of the 4-DOF Scara robot is of RRPR type, as described in Figure 1.

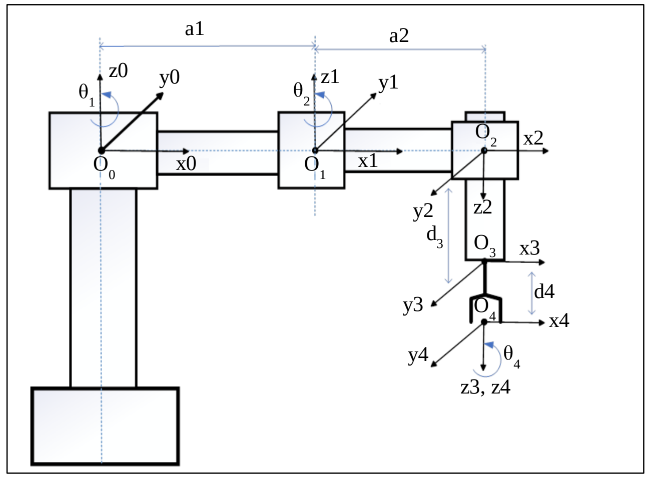


Fig. 1 Typical configuration of a 4-DOF Scara robot

Table 1. Denavit-Hartenberg parameters for the 4-degree-of-freedom Scara robot

Parameters	**Joint 1**	**Joint 2**	**Joint 3**	**Joint 4**
Variable	θ^*_1	θ^*_2	l^*_3	θ^*_4
Length (m)	l_1 (a_1)	l_2 (a_2)	l_3 (d_3)	0 (d_4)
Mass (kg)	m_1	m_2	m_3	m_4
Velocity*	v_1	v_2	v_3	v_4
Length to the Center (m). $l_{gi} = l_i/2$	l_{g1}	l_{g2}	l_{g3}	0
Moment of Inertia	J_1	J_2	J_3	J_4
* m/s: Linear Unit – Joint 3; rad/s: Rotational Units – Joints: 1, 2 and 4				

In fact, there are several methods to solve the kinematics and dynamics problems for robots, and here, the Denavit-Hertaberg method is utilized. With this method, for the robot configuration shown in Figure 1, a set of parameters, as presented in Table 1, can be obtained. With this set of Denavit-Hartenberg parameters, the dynamic equations of the Scara robot can be calculated.

2.2. Dynamics Equations of the 4-DOF Scara Robot

Before proposing control algorithms for the 4-DOF Scara robot, it is imperative to construct dynamic equations for this robot. With the robot's dynamic equations, it is necessary to calculate the kinetic and potential energies of each joint and then employ the Lagrange equations for computation. According to [14], the total kinetic energy of the robot is:

$$K = \frac{1}{2}m_1 l^2_{g1}\dot{\theta}_1^2 + \frac{1}{2}m_{234} l^2_{g1}\dot{\theta}_1^2 + \frac{1}{2}l^2_{g2}m_{234}(\dot{\theta}_1^2+\dot{\theta}_2^2) + l_1 l_{g2} m_{234}(\dot{\theta}_1^2 + \dot{\theta}_1.\dot{\theta}_2)\cos\theta_2 + \frac{1}{2}m_{34}\dot{l}_3^2 + \frac{1}{2}J_1\dot{\theta}_1^2 + \frac{1}{2}J_2(\dot{\theta}_1+\dot{\theta}_2)^2 + \frac{1}{2}J_4(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_4)^2 \quad (1)$$

The potential energy of the entire system is computed as follows:

$$P = - m_{34} g l_3 \quad (2)$$

Where: $m_{234} = m_2 + m_3 + m_4$ and $m_{34} = m_3 + m_4$.

To build the dynamic equation according to the Lagrange method, let us represent the generalized force Mi acting on each joint of the robot as indicated in (3).

$$M_i = \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} \quad (3)$$

Where L= K – P; i = 1,…, 4; q_i represents the *i*th joint.

Finally, the dynamic equations of the Scara robot are expressed in the following form:

$$M = H(q,\dot{q})\ddot{q} + C(q,\dot{q}) + G(q) \quad (4)$$

The above dynamics can be used to apply control laws, which will be presented in the next section.

3. Control Strategies for a Scara Robot

It is evident that the objective of the control method is to ensure the joints of the Scara robot move accurately from the initial point to the desired position. These positions may change after each operational cycle and lie within the physical limits of the robot while ensuring stable operation around the equilibrium point, independent of the mass of the connecting rod and load.

To meet this requirement, the research will initially employ the PD-G control law and the adaptive Li-Slotine law. Both laws utilize the Lyapunov function method to assess stability when applied to the object. Furthermore, to evaluate the effectiveness and suitability of the control algorithms, the paper suggests using fuzzy controllers alongside the PD-G and Li-Slotine control laws.

3.1. PD-G - Based Control Scheme

The PD-G law is a classical control law specifically designed for systems where the physical arrangement of components (system configuration) and the influence of gravity are important factors. It incorporates proportional and derivative control actions, along with a gravity compensation term, to achieve robust performance in these scenarios. This makes the PD-G law well-suited for controlling robots with articulated joints that operate in environments with significant gravitational forces. From the dynamics equation of the Scara robot (5), the proposed control law takes the following form:

$$M = K_P e - K_D\dot{q} + G(q) \quad (5)$$

Where K_p and K_D are positive matrices and diagonal matrices; $e = q_d – q$ denotes the error of joints.

To analyze the stability of the system, select a Lyapunov function in the following form:

$$V = \frac{1}{2}e^T K_P e + \frac{1}{2}\dot{q}^T H\dot{q} \geq 0 \text{ Where } e, \dot{q} \neq 0 \quad (6)$$

K_p is a symmetric positive definite matrix.

$$\frac{dV}{dt} = \frac{1}{2}\dot{q}^T H\dot{q} + \frac{1}{2}\dot{q}^T\dot{H}\dot{q} + \frac{1}{2}\dot{q}^T H\ddot{q} + \frac{1}{2}\dot{e}^T K_P e + \frac{1}{2}e^T K_P\dot{e} \quad (7)$$

Since q_d is a constant, one can be deduced: $\dot{e} = -\dot{q}$. The matrix H is a symmetric positive definite matrix; thus, according to the properties of matrices, one can be obtained below:

$$\ddot{q}^T H\dot{q} = \dot{q}^T H\ddot{q} \quad (8)$$

Let (7) be written as:

$$\dot{V} = \frac{1}{2}\dot{q}^T\dot{H}\dot{q} + \dot{q}^T H\ddot{q} - \dot{q}^T K_P e \quad (9)$$

From (4), the following equation can be taken into account:

$$H\ddot{q} = M - C\dot{q} - G \quad (10)$$

Substituting (10) into (9), the following can be obtained:

$$\dot{V} = \frac{1}{2}\dot{q}^T\dot{H}\dot{q} + \dot{q}^T(M - C\dot{q} - G) - \dot{q}^T K_P e \quad (11)$$

Adding and subtracting the term $\dot{q}^T K_D\dot{q}$ To (11), one can be deduced in (12).

$$\dot{V} = \frac{1}{2}\dot{q}^T[\dot{H} - 2C]\dot{q} + \dot{q}^T[M - G - K_P e + K_D\dot{q}] - \dot{q}^T K_D\dot{q} \quad (12)$$

According to the properties of dynamic equations: $\dot{H} - 2C = 0$.

On the other hand, substituting the selected control law from Equation (5) into Equation (12), the result is achieved in (13).

$$\dot{V} = -\dot{q}^T K_D \dot{q} < 0 \tag{13}$$

Thus, under the chosen conditions, it is observed that $\dot{q} \rightarrow 0$ as $t \rightarrow \infty$ indicating the system's stability around the equilibrium point according to Lyapunov's criterion, i.e., $e = 0$ or $q = q_d$.

With this classical control method, the advantage lies in the simplicity of system computation. However, the drawback is the requirement for precise knowledge of the system's physical parameters (which is often challenging and cannot be accurately determined due to the presence of transmission systems in robots). Moreover, achieving accuracy is unattainable when the robot moves at high speeds, and stability depends on the values of K_D and K_P selected.

3.2. Li-Slotine-Based Control Law

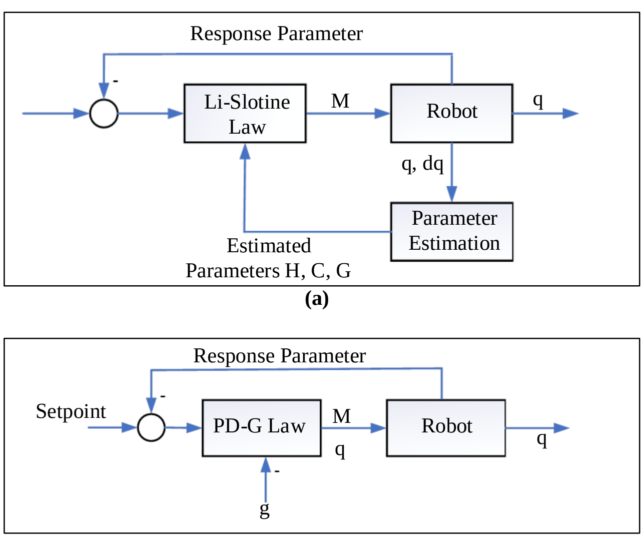
The control law, according to Li-Slotine, is proposed in (14).

$$M = \hat{H}(q)\dot{v} + \hat{C}(q,\dot{q})v + \hat{G}(q) - K_D r \tag{14}$$

The Lyapulov candidate is chosen as given in (15).

$$V = \frac{1}{2} r^T H r + \frac{1}{2} \Delta p^T \Gamma \Delta p \tag{15}$$

Where Γ is a diagonal matrix that is positive definite and $\hat{H}, \hat{C}, \hat{G}$ are matrices estimating the parameters of the system.



(b)
Fig. 2 Diagrams for (a) Li-Slotine control strategy, and (b) PD-G control law.

$$\begin{aligned}
&\Delta H = \hat{H} - H;\ \Delta C = \hat{C} - C;\ \Delta G = \hat{G} - G; \\
&\Delta H\dot{v} + \Delta C v + \Delta G = H\dot{r} + Cr + K_D r \\
&\Delta H\dot{v} + \Delta C v + \Delta G = H(\ddot{q} - \dot{v}) + C(\dot{q} - v) + K_D r \\
&= Y(q,\dot{q},v,\dot{v})\Delta p
\end{aligned} \tag{16}$$

Where Δp denotes the physical parameters of the system such as mass and moment of inertia: $\Delta p = (I_1, m_1, \ldots, I_n, m_n)^T$. $Y(q,\dot{q},v,\dot{v})$ is the system parameter regression matrix.

From (15), in combination with (16), take several computational conversions, one can be obtained as follows:

$$\begin{aligned}
&\dot{V} = \Delta p^T(\Gamma\Delta\dot{p} + Y^T r) - r^T K_D r \\
&\text{Where } -r^T K_D r \leq 0 \ \ (r \rightarrow 0 \text{ when } t \rightarrow \infty)
\end{aligned} \tag{17}$$

From (17), it can be said that the robotic system governed by control law (14) is completely able to stabilize at the operating point according to the Lyapunov criterion.

While the Li-Slotine adaptive control method offers a compelling combination of strong system stability and the ability to adapt to changing system dynamics, it is not without its challenges. Its key advantage lies in its inherent robustness. The controller actively adjusts its internal parameters in response to variations in the system, ensuring continued stability and performance even when faced with unexpected conditions.

This adaptability makes it particularly valuable for controlling systems with uncertain parameters or those operating in dynamic environments. However, this benefit comes at a cost. In fact, the Li-Slotine method demands significant computational resources. The continuous online parameter updates require complex calculations, which can be a burden for resource-constrained control systems. This computational complexity can limit its applicability in real-time control scenarios where processing power is limited. Additionally, parameter selection, such as KD and Γ, significantly affects the system stability. Through the aforementioned calculations, it is significant to derive the block diagram of the two control laws, as shown in Figure 2.

3.3. Fuzzy Logic-Based Control Methodology

The four-degree-of-freedom robot under consideration presents a unique control challenge due to its Multi-Input Multi-Output (MIMO) nature. Unlike simpler systems with single inputs and outputs, MIMO systems exhibit complex interactions between control inputs and resulting outputs. To effectively manage this complexity and achieve precise control of each joint, the principle of decoupling is employed. This strategy decomposes the MIMO system into a series of simpler Single-Input Single-Output (SISO) subsystems.

Essentially, each joint of the robot is treated as an independent system with its own dedicated fuzzy controller. This allows the controllers to focus on regulating the specific joint's position or movement without being overly influenced by the dynamics of other joints. By leveraging decoupling, the overall control scheme becomes more manageable and facilitates the development of individual fuzzy controllers tailored to the specific requirements of each joint. Naturally, the dynamic equations of the Scara robot (4) still need to be ensured.

To effectively control the Scara robot, this study proposes the use of a Mamdani-type fuzzy control model with a 2I/1O structure (two inputs and one output). The two inputs include the error e(t) and its derivative de(t). The output is the direct control signal for the joint torque u(t). Since the Scara robot has 4 degrees of freedom, it is reasonable to use 4 corresponding Mamdani fuzzy structures. Figure 3 illustrates the proposed Mamdani fuzzy controller model built on MATLAB/Simulink.

The establishment of fuzzy rules for controlling a 4-degree-of-freedom Scara robot is depicted in Figures 4, 5, and 6. To ensure the desired quality of the control process, this paper proposes a detailed fuzzy rule set comprising 7 x 7 = 49 rules. This represents a comprehensive fuzzy rule set, encompassing most possible scenarios for each articulated joint. The general structure of a fuzzy rule in the Mamdani model is as follows [20]:

Once the complete set of 49 fuzzy rules is established, the input/output relationships are depicted in a 3D space, as illustrated in Figure 7. This fuzzy logic model holds promise for enhancing the control performance of the system. To fully unlock its potential, three scaling factors have been strategically incorporated. These factors correspond to the two system inputs and the single output, allowing for fine-tuned control over the influence of each variable.

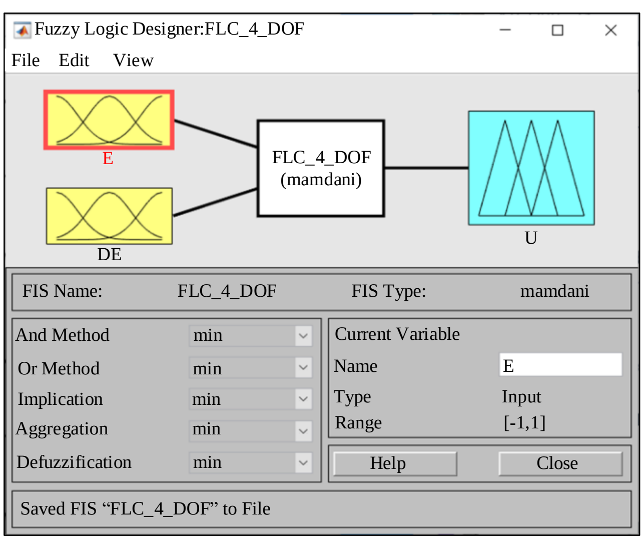


Fig. 3 The 2I/1O fuzzy logic inference built in MATLAB/Simulink

However, merely introducing these scaling factors is insufficient. To achieve optimal performance, a suitable optimization technique is necessary to determine the ideal values for each coefficient. This study employs the Particle Swarm Optimization (PSO) method due to its appealing combination of simplicity and efficiency.

The PSO mimics the collective behaviour of a swarm, iteratively searching for the best solution within the defined parameter space. By incorporating these scaling factors and utilizing PSO for optimization, the control system designed for the 4-DOF SCARA robot can achieve a significant improvement in control quality. This approach enables precise adjustments to the fuzzy logic model, ultimately leading to a more robust and effective control system. The subsequent section of the paper will present simulation results, comparing the performance of the three different control algorithms mentioned above.

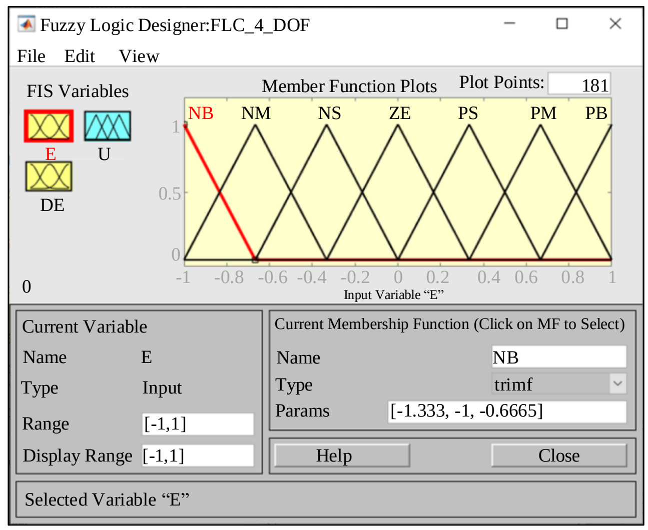


Fig. 4 The membership functions applied to 2 inputs and 1 output of the fuzzy logic model

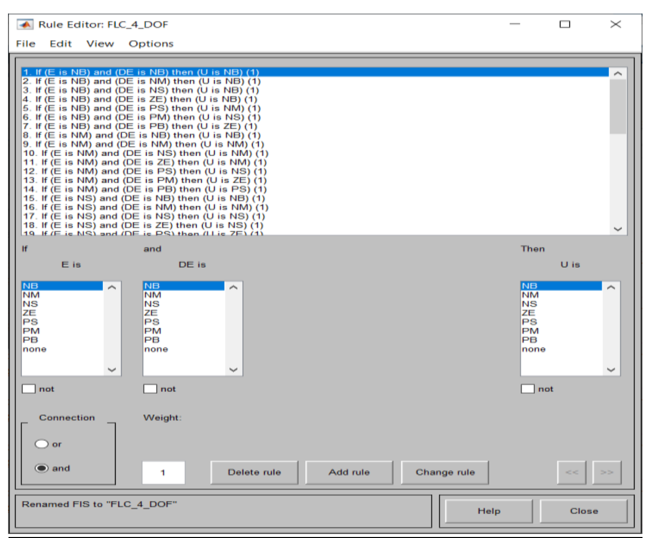


Fig. 5 Logic rules for the proposed fuzzy logic inference

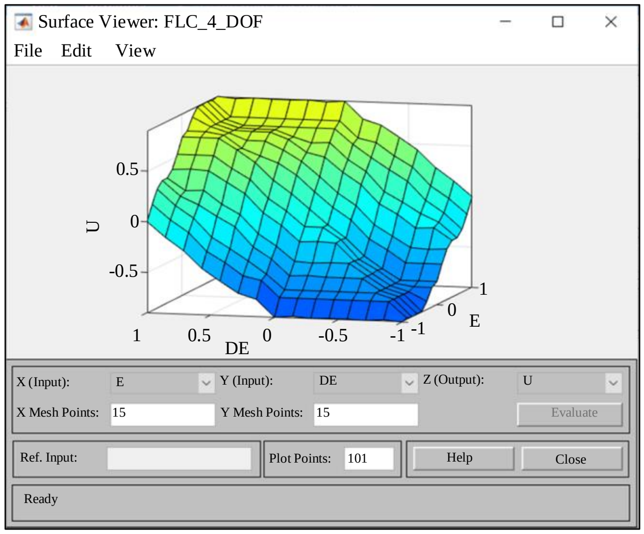


Fig. 6 A representation of the proposed fuzzy rules in 3-D form

4. Simulation Results and Discussion

4.1. Simulation Results

Simulation is an essential process to validate the feasibility of the proposed control solution. It acts as one of the critically final steps before committing resources to building and testing physical prototypes.

By running the control system through simulated scenarios, engineers can identify potential weaknesses, assess its effectiveness under various conditions, and refine its parameters without the cost and time associated with physical experimentation.

This virtual testing environment allows for a wider range of situations to be explored compared to a limited lab setting. In essence, simulation serves as a powerful risk mitigation tool, ensuring the control solution has a strong foundation before the real-world implementation phase.

In this paper, starting from the proposed control concepts discussed earlier (Figure 2 for Li-Slotine control law and PD-G law) and the fuzzy controller presented in Section 3.3, it is feasible to construct a simulation model using MATLAB/Simulink. Simulation parameters are derived from Table 2.

Table 2. Simulation parameters for the Scara robot

Parameters [7]	**Joint 1**	**Joint 2**	**Joint 3**	**Joint 4**
Length (m)	0,25	0.15		
Mass (kg)	2,5	1,5	2	0,6
Moment of Inertia (kg/m^2)	$1{,}5.10^{-4}$	$0{,}32.10^{-4}$	$0{,}32.10^{-4}$	

Table 3. Initial values and reference trajectories used for the simulation process

Initial values	$\theta_1 = 0.7$ (rad)	$\theta_2 = 1.2$ (rad)	$d_3 = 0.7$ (dm)	$\theta_4 = 1.2$ (rad)
Reference Trajectories	$\theta_{d1} = \sin(\omega t)$	θ_{d2} = Pulse Function	$d_{d3} = 1.2$ (dm)	$\theta_{d4} = 1.5$ (rad)

The initial positions of the robot joints relative to the straight-line equilibrium position of the robot arm are illustrated in the table. Different scenarios are provided for each joint to assess the responsiveness of each control method and evaluate its dynamic characteristics.

These scenarios are intended to test the control methods' ability to respond and evaluate their dynamic properties comprehensively. The initial values and set trajectories for the robot joints used for the simulation aim are provided in Table 3. These values and trajectories serve as the starting point for assessing the robot's control methods and dynamic characteristics under various scenarios.

Two figures included in this study (Figures 7 and 8) provide a crucial comparison of the three proposed control laws, specifically examining their behaviour without the influence of external loads. Figure 7 focuses on the joint positions of the robot under each control law, while Figure 8 depicts the corresponding joint velocities.

Analyzing these results it is completely able to assess the effectiveness of each control strategy in achieving the desired performance metrics for the robot under normal operating conditions. This evaluation is essential for selecting the most suitable control law for the specific application.

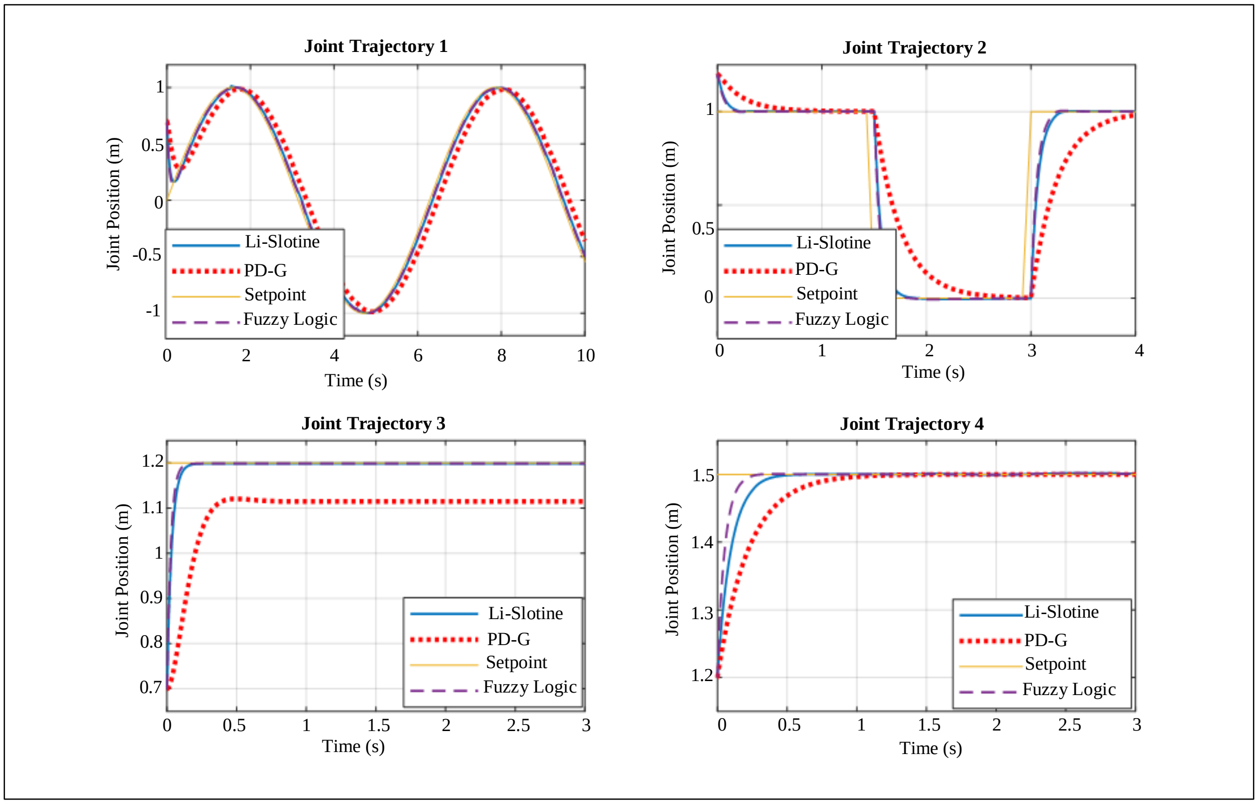


Fig. 7 Joint positions applying various control laws

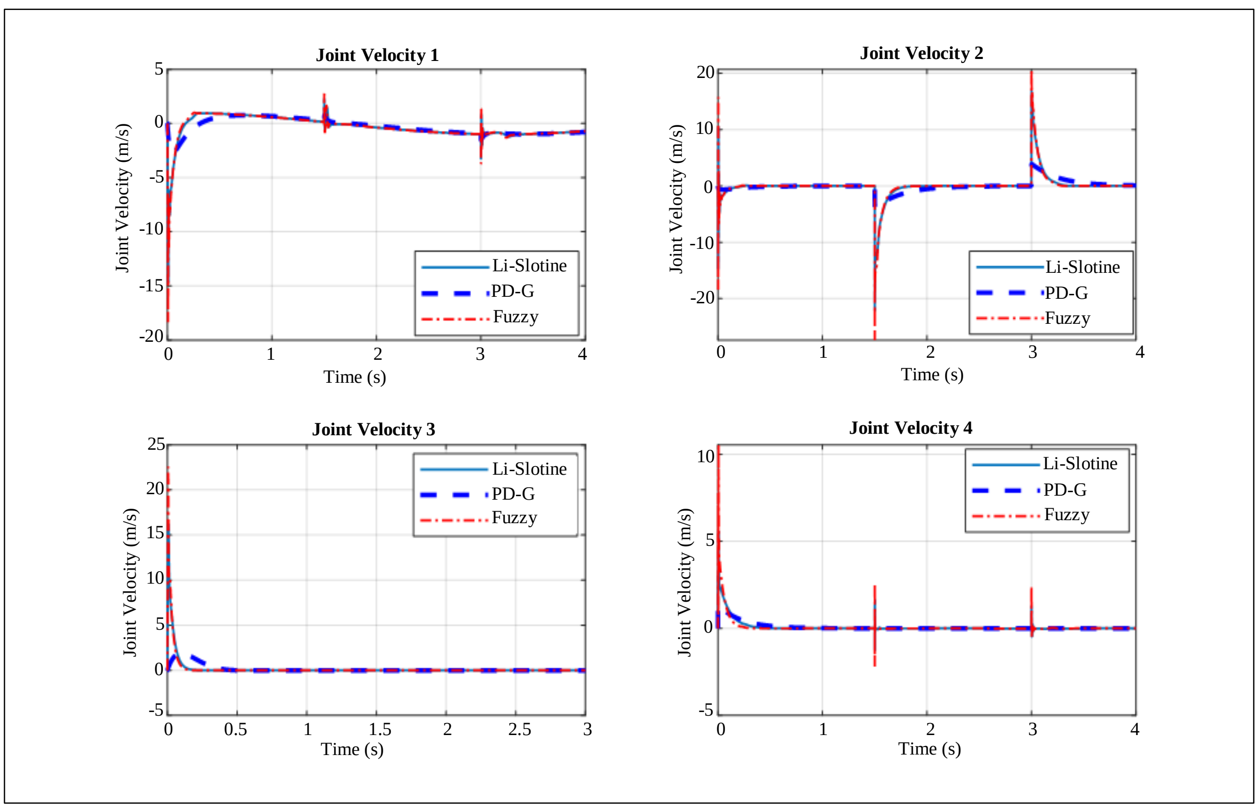


Fig. 8 Joint velocities resulting from different control laws

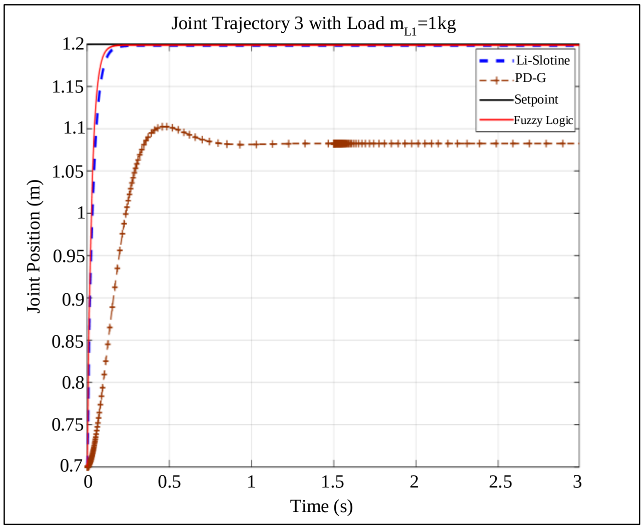


Fig. 9 Joint trajectory 3 with load m_{L1} = 1kg – The first scenario

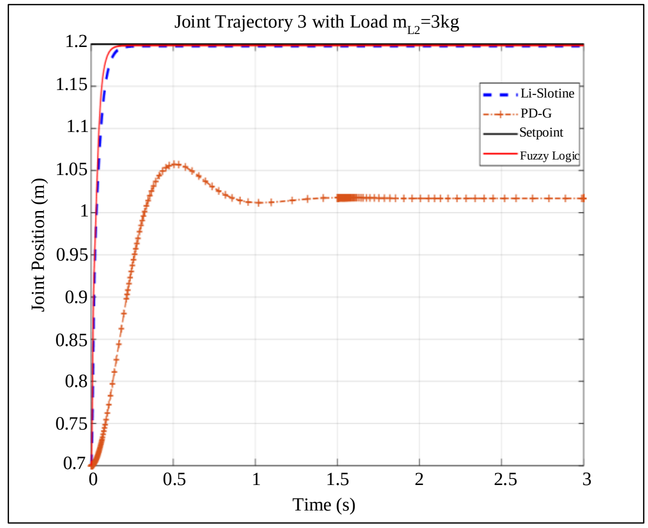


Fig. 10 Joint trajectory 3 with load m_{L1} = 2kg – The second scenario

4.2. Discussions

Figures 9 and 10 draw a clear picture: the PD-G control law struggles mightily when faced with heavy loads. The resulting positional response falls short of expectations, exhibiting significant deviations from the desired trajectory. In stark contrast, the other two control algorithms maintain their composure, delivering accurate positioning even under the burden of heavy loads.

This stark difference in performance highlights a critical limitation of the PD-G law: its susceptibility to variations in load. Robots operating in real-world scenarios often encounter fluctuating loads, making the PD-G law an unsuitable choice for such applications. Its dependence on a constant load renders it ineffective in situations where the payload is constantly changing. Therefore, for robots that must contend with dynamic load conditions, alternative control algorithms, like the ones showcased here, are demonstrably more effective in achieving precise and reliable positioning.

Regarding joint trajectory control, both the response speed and positional error at the time of establishment of the PD-G control law are inferior in quality compared to the Li-Slotine law and fuzzy logic law. When various set trajectories and positions are considered, it can be noted that the responses of the joints under the Li-Slotine and fuzzy logic laws are superior to those under the PD-G law. Particularly, for joint 3, under the influence of gravitational force, the response of the PD-G law still exhibits error.

Additionally, it is observed that the speed response under the Li-Slotine and fuzzy logic laws experiences position alterations due to the selection of a pulsating form for trajectory stage 2; noise from stage 2 affects the remaining stages, especially concerning speed, as stage 2 transitions rapidly. If a simpler trajectory for stage 2 is selected, speed response is subject to such noise.

In computational terms, the PD-G control law is straightforward, whereas the Li-Slotine law is complex, involving multiple calculation steps to yield results. Conversely, the fuzzy logic control law is simpler and easier to implement but depends on the setup function and the number of fuzzy rules utilized. Both the PD-G and Li-Slotine control methods share the common drawback of stability speed depending on the initially selected parameters. Therefore, to optimize computational steps and select suitable parameters, additional parameter selection methods for the control system are required, such as incorporating neural algorithms and alternative calculation approaches. This direction also represents a facet for exploration, development, and application inspired from this study.

5. Conclusion and Future Work

This study conducted a significant investigation regarding control algorithms applicable to 4-DOF Scara robots. These included the gravity compensation PD-G rule, the Li-Slotine adaptive control rule, and the fuzzy control model. The control laws were formulated, analyzed, and notably applied to the Scara robot effectively, as demonstrated through real-time simulations using Matlab/Simulink software.

From the simulation results obtained, related observations and analyses indicated the advantages, disadvantages, and key points of each control solution. Selecting a suitable control algorithm depends on the technological requirements of the Scara robot for a particular distinct operational purpose. The next research direction involves integrating two of the three proposed algorithms, i.e., fuzzy logic and Li-Slotine, to design a more optimal control strategy for the Scara robot, capable of operating under various conditions with good control quality.

Acknowledgments

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