

Design and Control of a Multi-DOF Flexible Robotic Arm Using Adaptive Fuzzy Logic Control for Precision Grasping Tasks

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ABSTRACT

Objective: Flexible robots pose a great challenge when partial manipulation is to be performed under unstructured environments. This paper deals with the issue of specific endpoint control and vibration cancellation of a multi-degree-of-freedom (DOF) tendon-driven flexible arm. The main shortcoming of standard controllers like PID is that they cannot respond to the nonlinearities, time-varying dynamics, and external disturbances inherent in the system and this is a major limitation on understanding reliability. **Method:** The methodology consists of detailed mechanical design through CAD/FEA, kinematic and dynamic modulization through a piecewise constant curvature approximation and synthesis of an online adaptive fuzzy inference system. The proposed system is tested with the help of simulation and physical testing. It uses a hierarchical control architecture, which means that a high-level AFLC is in charge of the positioning of endpoints and vibration damping, with low-level PID controllers being used to ensure proper actuator tracking. **Results:** The major findings show that the trajectory tracking error (RMSE) decreased by 55.6 %, the amplitude of vibrations reduced by 70 % and the grasping success rates increased significantly, 40 % (PID) to 75 % (AFLC) with a fine stress ball. The settling time and the overshoot are also reduced by 45.2% and 61.6% respectively to the baseline PID controller by the AFLC. **Novelty:** The greatest value of this work is that an integrated framework was developed and tested with the purpose of combining a new mechanical design and Adaptive Fuzzy Logic Controller (AFLC).

INTRODUCTION

Robotics has experienced a massive evolution whereby the area shifted into the past days of the rigid-link manipulators to the flexible and continuum robots [1]. The main reason behind this paradigm shift is the fact that robotic systems should be able to go safely and effectively in unstructured and constrained environments [2]. The flexible robotic arms have specific benefits such as compliance, which is an inherent property, and high safety of the operations when interacting with humans, as well as high adaptability and flexibility to the complex geometry [3]. These properties qualify them as highly appropriate to the leading areas of use, including minimally invasive surgical robotics (e.g., endoscopic and laparoscopic devices), aerospace to assist in the inspection and repair of internal organs, and agile manufacturing to manipulate fragile or unusually shaped items [4].

The key emphasis of the recent studies in the field of flexible robotic manipulation is put on addressing the inherent problem of nonlinearity and compliance and vibration [5]. There are two broad-based control methodologies used; model-based and model-free. One of the most common models-based approaches is based on feedback linearization techniques including computed torque control that are obtained using a precise dynamic

model [6]. Though they are effective in simulation, the accuracy of the model is crucial to their performance in practice and they can be sensitive to unmodeled dynamics and variation of parameters [7].

Sliding mode control (SMC) is often used to solve the problem of robustness. This approach is preferred because of its natural resilience towards equal uncertainties and disruptions. The most famous weakness is however the so-called chattering phenomenon that makes the control signal high-frequency oscillatory and can often cause unmodeled structural vibrations which are a serious problem when it comes to flexible arms [8]. Later developments such as boundary layer SMC or more advanced SMC are applied to reduce chattering but usually at the cost of tracking accuracy [9].

Intelligent control methods have become very popular as an alternative to strictly model-based methods. The existing Fuzzy Logic Control (FLC) is very popular because of its flexibility to formalize the expert knowledge without an explicit mathematical model [10]. It is a good way to deal with the language paradox of complicated systems. The inherent operative constraints of a conventional FLC, however, are its fixed, pre-determined rule base and capabilities and membership functions which make it non-adaptive to evolving operational environments or system drift over time [11].

Neural network-based controllers, especially adaptive neural networks are combined with control schemes to inject learning capability [12]. These networks can be used to approximate complex nonlinear functions over the Internet, and balance dynamic uncertainties. One of the most typical constraints, however, is that large volumes of training data are needed, and the computational resources required to perform real-time weight adaptation can prove to be a challenge to a small embedded system. Moreover, they are frequently black box, and not very intuitive about the control logic [13].

There is also the presence of hybrid approaches to methods borrowing the strong aspects of other approaches. As an example, fuzzy-PID or neuro-fuzzy systems are usually developed. The former is normally a fuzzy supervisor tool to adjust PID gains whereas the latter is a neural network tool to optimize the fuzzy system parameters [14]. Although these methods have better performance than all their constituent parts, the adaptations used may be difficult to design and stabilize. In addition, most of the hybrid controllers reported in the literature are only tested in simulation or under constrained conditions, and do not test full multi-DOF flexible arms undertaking dextrous tasks such as a precision grip in varying loads [15]. Table 1 summarizes the key issues and drawbacks of these existing approaches and the situations of their common use.

Table 1. Comparative Summary of Related Studies on Flexible Robotic Arm Control.

Control Method	Arm Type/DOF	Key Performance Metrics	Main Limitation
PID + Notch Filter	2-DOF Flexible Link	Vibration reduction: ~60%; Settling time: 2.1 s	Fixed parameters, poor adaptability
Sliding Mode Control (SMC)	3-DOF Continuum Arm	Tracking error (RMSE): 0.8 mm; Chattering observed	High control chattering, no payload variation test

Conventional Fuzzy Logic	4-DOF Tendon-Driven	Success rate in grasping: 82%; Max error: ± 3.5 mm	Static rule base, performance drops with load change
LQR with Observer	2-DOF Flexible Joint	Settling time: 1.8 s; Overshoot: < 5%	Requires precise model, less robust to disturbances
Neural Network (NN) Control	3-DOF Soft Arm	RMSE in trajectory: 1.2 mm; Training time: ~4 hours	Computationally heavy, lacks real-time adaptation
Hybrid Fuzzy-PID	2-DOF Flexible Manipulator	Error reduction vs PID: ~40%; Overshoot: 2.8%	Limited to 2 DOF, not validated for grasping tasks

Although it has good promises, effective control of multi-degree-of-freedom (DOF) flexible robotic arms is not easy. The major challenges are: (1) long-period vibration and oscillation due to low structural stiffness, which severely impairs the precision of positioning and settling time; (2) strongly nonlinear and time-dependent dynamics which are challenging to model accurately; (3) hysteresis and other nonlinear effects of compliant actuators as pneumatic artificial muscles or shape memory alloys; and (4) the inherent trade-off between mechanical flexibility and end-effector precision. The traditional procedures of control, e.g. Proportional-Integral-Derivative (PID) controllers, are commonly not sufficient to manage these nonlinearities. Although the classical robust control methods can ensure stability, they are often too conservative and this may result in the performance being compromised. Standard Fuzzy Logic Control (FLC), despite being useful in applications where the model of the system is imprecise, is generally not adaptable online to new dynamism or disturbances. As a result, a major gap in the current state of research is realized: the intelligent, adaptive control scheme is demanded, which is specifically designed to face the entire issues of multi-DOF flexibility, vibration suppression, and high-precision endpoint control needed to perform grasping tasks with fundamental reliability.

In order to close this gap, a complex solution that incorporates new mechanical design and sophisticated control is suggested. The first is a multi-DOF flex-robotic arm, which is an actuation mechanism based on tendons. Second, the development and the implementation of an Adaptive Fuzzy Logic Control are conducted (AFLC). The proposed AFLC, in contrast to a typical FLC, has an online adaptation mechanism whereby its rule base and/or membership functions are automatically adjusted with respect to real-time system performance to allow it to correct the unmodeled system dynamics, payload variations and other external disturbances. The main contributions of this work are thus three in number:

- A design framework is introduced, that is, an integrated design, which includes the mechanical design through CAD/FEA, kinematic and dynamic modeling, and control synthesis of a flexible robotic arm.
- An innovative real-time AFLC algorithm is designed that can be used to track moving paths with high accuracy and to damp the vibrations of objects.

- Experimental validation is rigorous, and it can be concluded that the system has better capabilities to accurately perceive tasks than a conventional PID controller, which proves the practical effectiveness of the proposed solution.

The rest of this paper is structured in the following manner. In section 2, the mechanical design and structural analysis of the flexible robotic arm are discussed. In section 3, the kinematic and dynamic modeling is provided. Section 4 gives a detailed explanation of the design of the proposed Adaptive Fuzzy Logic Controller. Section 5 provides the simulation study and experimental set up. Section 6 gives the results and discussion. Lastly, the conclusions and recommendations on the future work are proposed in Section 7.

RESEARCH METHOD

Mechanical Design and Modelling

1. Conceptual Design and Requirements

The mechanical design is based on a set of functional specifications developed based on the intended use of the precision grasping in constrained conditions [16]. The system is configured at a three-degree-of-freedom (3-DOF) to offer dexterous positioning as well as orientation of the end-effector. The conical volume needed is the one with the base radius of 150 mm and a height of 300 mm [17]. The arm has the ability to deal with the payload capacity of the up to 100 grams with the target positioning of the arm at ± 1.5 mm. An actuation principle based on tendon is preferred to pneumatic ones because it has much better force transmission, quicker response and is easier to combine with high-resolution rotary encoders providing easy joint angle measurement and control [18].

2. Detailed CAD Design

Modular, segmental architecture is used in order to gain controlled flexibility. The base is made in a series of laser-cut, flexible polymer disks, interlocked by rigid constraint spacers [19]. The design provides a central continuous backbone and permits achieving a degree of precision in bending along multiple planes [20]. Each disk has four equidistant longitudinal channels into which high-strength polyethylene tendons are installed and anchored on the distal end with servo motors installed on the proximal base [21]. Inertial measurement units (IMUs) are miniaturized to serve as state feedback to measure the orientation of the segments within the spacer modules as required in state feedback. Moreover, force-sensitive resistor (FSR) is placed on the two-fingered gripper end-effector and a tendon tension sensor is added along each actuation cable [22].

3. Structural Analysis using Finite Element Method (FEM)

Finite Element Method (FEM) software is used to undertake a non-linear static structural analysis to confirm the design [23]. To estimate the behavior of the chosen thermoplastic polyurethane (TPU), the flexible disks are modelled through hyperplastic material model (Smooth-Spline). The maximum tip load is used in the analysis and is 1N. The findings prove that the highest von Mises stress of 0.85 MPa is still much less than the yield strength of the material, and there is a resulting tip deflection of 22 mm [24]. An analysis of the unloaded model is then done using a modal analysis. Its natural

frequencies are found to be the first, second, and third frequencies of 4.2 Hz, 11.7, and 25.3 Hz respectively, the first and second bending modes in two orthogonal planes and a torsional mode respectively. Motion resonant excitation takes place in frequencies which are critical to informing the bandwidth and filter design of the controller to prevent resonant excitation [25].

Kinematic and Dynamic Modelling

1. Kinematic Modelling

The Piecewise Constant Curvature (PCC) approximation of the flexible robotic arm is the kinematic model that is formed on the basis of the standard and effective PCC approximation that has been applied to continuum and tendon-driven robots [26]. Both of the equal, serially linked parts are supposed to curve with a constant curvature. A segment is parameterized by a bending angle, ϕ and a rotation angle, θ , which describe the plane of bending, and the length of a segment, L [27]. These arc parameters are used to make the homogeneous transformation matrix of each segment. To integrate the control system and simulate it, a reduced equivalent model is also defined in Denavit-Hartenberg (D-H) parameters, in which rotational joints are used to model the bending of the flexibilities in the middle of each segment [28].

The inverse kinematic problem, that is, the calculation of actuator inputs (tendon displacements) needed to achieve a given desired end-effector pose in Cartesian space, is formulated on the basis of the PCC geometry [29]. The length of the four tendons is determined as a result of the geometric relations between the longer circular arc model [30]. A numerical approach is used (the Newton-Raphson algorithm) to compute configuration variables (ϕ, θ) to a desired end-effector position because the equations are transcendental in nature. This solution gives the setpoints of the servo motors responsible of the tendon lengths [31].

2. Dynamic Modelling

The Lagrangian formulation to obtain a dynamic model incorporates the key inertial and elastic characteristics of the segmented flexible arm [32]. The generalized coordinates, q , are given by $[\phi_1, \theta_1, \phi_2, \theta_2]^T$, which gives the angles of bending and rotation of the two pieces. The kinetic energy, T , is the sum of translational and rotational motion of the discrete masses of every segment [33]. The potential energy V is the elastic strain energy (strain energy of bending) gravitational potential energy. The strain energy is assumed to be a quadratic form of the bending angles, $V_e = \frac{1}{2} q^T K q$, K a diagonal stiffness matrix, whose elements are calculated, based on the structural FEM analysis [34].

When Lagrange equation is applied, $\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} = \tau$, and when $L = T - V$, the equations of motion are obtained. The structural damping is represented with a Rayleigh dissipation model that results into a damping matrix D [35]. The last dynamic model takes the form of standard rigid-robot-like, with the addition of stiffness and damping as (1):

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + Kq + D\dot{q} = \tau \quad (1)$$

In this case, $M(q)$ is inertia matrix, $C(q, \dot{q})$ is the Coriolis and centrifugal forces, $G(q)$ is the gravity and t denotes the generalized force with tendon tensions converted to joint torques. This is a complex model, but it has a twofold role, both to develop high-fidelity simulation environment to design controllers, and to design vibration suppression controller, the structure of the model specifically whether determining the stiffness (K) and the dominant natural frequencies directly informs the design requirements [36]. The first design of the adaptive fuzzy controller would use a simplified form of this model with slow motion to ignore Coriolis effects [37].

Adaptive Fuzzy Logic Control (AFLC) System Design

1. Control Architecture

To ensure management of the system complexity, hierarchical control architecture is applied. Figure 1 represents the general control loop that comprises of a trajectory planner, the AFLC, the plant (the flexible robotic arm with its actuators), and a sensor feedback network. Endpoint positioning is under the high-level control. It gets the intended Cartesian locations of the trajectory planner and the present end-effector pose by sensor fusion (IMU data). At the configuration space (t), the AFLC calculates the generalized forces needed. The forces are then translated into setpoints of respective tendon displacements. Each servo motor is provided with a dedicated low-level PID controller so that inner actuator control loop can be effectively closed by providing the servo motor with accurate and rapid tracking of these tendon length commands. Such structure separates the difficult problem of flexibility and vibrations management (managed by the AFLC) and the easy problem of actuator positioning [37], [38].

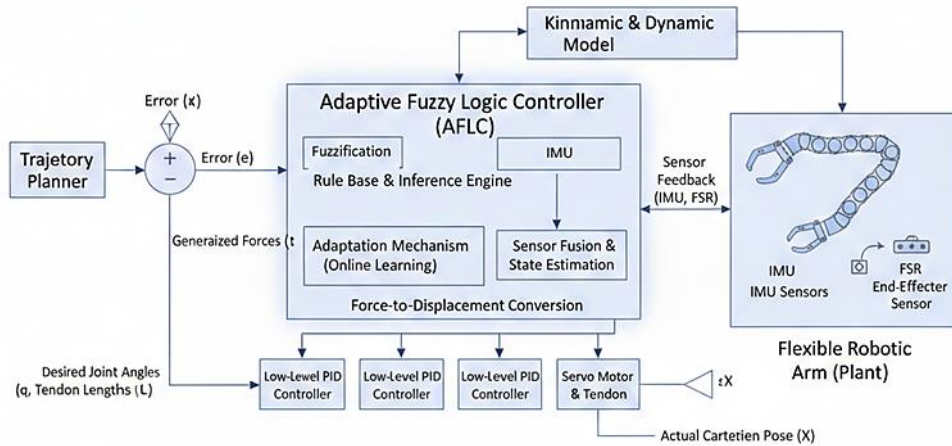


Figure 1. Hierarchical Control Architecture for the Multi-DOF Flexible Robotic Arm.

2. Fuzzy Logic Controller (FLC) Design

The basic fuzzy inference system employs a Mamdani-type framework as it is interpretable. The normalized configuration error, $e = q_d - q$, and the derivative of e , \dot{e} are the inputs of each controlled degree of freedom. This change in generalized force is the output, $\Delta\tau$. In the case of fuzzification, five language variables are established in relation to each input and output Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB). Membership functions are symmetric triangles,

selected due to computational efficiency, and evenly spread on the normalized universe of discourse $[-1, 1]$ [39]. An error and error rate to the necessary control action rule base of 25 rules is initially built using expert heuristic knowledge. For example, one of the rules is: IF e is PB and \dot{e} is NS then $\Delta\tau$ is PS. The min operator is implied to be used by the inference engine and the max operator is used to aggregate. To achieve the crisp output value, defuzzification using the centroid method is used [40].

3. Adaptation Mechanism

The aim of the adaptation mechanism is to adjust the settings of the output membership functions in real time to ensure the best performance even when the dynamics change. The fuzzy system is combined with a model reference adaptive scheme [41]. The desired closed-loop performance is a second-order linear reference model with a damping ratio of 0.8 and a natural frequency of 4 rad/s. The law of adaptation is obtained based on a gradient descent strategy that minimizes the instantaneous squared error, $E = \frac{1}{2}(y_m - y)^2$, between the output of the reference model, (y_m) and the output of the plant, (y) . The output membership functions centers (c_j) are online adjusted to (2):

$$\Delta c_j(t) = -\eta \frac{\partial E}{\partial c_j} = \eta \cdot (y_m - y) \cdot \frac{\mu_j(x)}{\sum_{k=1}^R \mu_k(x)} \cdot \Phi \quad (2)$$

with η the rate of adaptation, μ_j the strength of rule j in the firing, R the number of rules in total, and Φ a positive scaling constant of the sensitivity of the plant. This mechanism enables the controller to acquire experience and counteract unmodeled nonlinearities, payload differences and changes in structural damping.

4. Stability Analysis

The application of a heuristic fuzzy system with an online parameter modification mechanism creates valid apprehensions to stability. The non-autonomous adaptive fuzzy system is a very complicated nonlinear system that is impossible to perform a direct Lyapunov analysis on. Hence, a working point analysis is performed. First, normalization of both inputs and outputs ensures that all the signals within the fuzzy inference system are bounded. Second, the adaptation law has a projection algorithm wherein the tunable parameters (c_j) are bounded by a prescribed small set so that they do not get out of control. Third, the low-level PID actuator controllers have the underlying low-level proven to be BIBO stable. Lastly, a series of simulation experiments in many different operating conditions are carried out to show that the entire system is Bounded-Input-Bounded-Output (BIBO) stable such that the states and control signals do not grow uncontrolled when there are bounded reference inputs and disturbances. Although this is not an official international test, this hybrid analytical and empirical methodology gives a high level of certainty of the operational stability of the system within the target operational range.

Simulation and Experimental Setup

1. Numerical Simulation

The control algorithm is verified by a detailed numerical simulation that is created in the MATLAB/Simulink platform before the implementation in physical space. The simulation model incorporates nonlinear dynamic equations that have been determined

in Section 3.2 with Adaptive Fuzzy Logic Controller (AFLC) block. There are three performance scenarios that are simulated. The first step is to make a step response test which measures the settling time of the system, the %age overshoot, and what is left after the system settling. Second, the tracking of the trajectory is also tested by ordering the end-effector to travel in a circular motion with a radius of 50 mm in the plane of action which is horizontal and at 10 mm/s speed. Third, disturbance rejection test is conducted, in which a simulated impulsive lateral force of 0.5 N is applied on the tip of the arm and held constantly at 0.1 seconds in the steady-state. Quantitative performance of the proposed AFLC is compared to a baseline, a well-tuned decentralized PID controller, based on such measures as Root Mean Square Error (RMSE), Integral of Absolute Error (IAE), and maximum transient oscillation amplitude.

2. Prototype Development

A real-world prototype of 3-DOF flexible arm is made to allow experimental validation. Flexible disks and rigid spacers are 3D printed with the use of fused deposition modeling (FDM). Thermoplastic polyurethane (TPU, Shore 95A), which serves as needed compliance, is printing on the disks, polylactic acid (PLA), which is a structural material, is used to print the spacers. The actuation system uses four digital servo motors of high torque (Dynamixel XM430-W350) that are attached on the base. The tendons, which are made of a polyethylene fiber that has been braided, are then directed through the printed channels to be attached to the horns of a motor. To measure the sensing, inertial measurement unit (IMU, Bosch BNO055) is placed in the distal spacer and a miniature load cell is connected in-series with one tendon in tension measurement. The real-time control system is carried out on a PC under the Ubuntu and Robot Operating System (ROS) and the control commands are sent to the servo motors through a USB-to-serial converter with a loop rate of 100 Hz. Synchronously sensor data is obtained using the same interface.

3. Experimental Procedure

Strict calibration process is then carried out. The servo motors are set to position-torque relationship and the IMU is set to be statically oriented. The routing of the tendon is set up so that there is no initial tension at the neutral position at straight-arm position. Three consecutive experimental test tasks are carried out after calibration.

1. **Free-Space Tracking:** The arm is ordered to follow a rectangular and a sinusoidal path that is pre-defined in its workspace. End-effector position is estimated through the kinematic model based on IMU data and the tracking error is monitored.
2. **Vibration Suppression Test:** This is a fast point-to-point movement of the arm that is required to be 100mm in distance. Settling time, which is the time required by the endpoint oscillation to enter and stay in a ± 2 mm band is determined by the IMU accelerator data. The pre and post movement frequency spectrum of the tip acceleration is examined.
3. **Precision Grasping Task:** The system is tested regarding its functioning in a functional task. Three test items are tested, namely: a foam cube (5 g), plastic egg

(20 g), and a deformable stress ball (50 g). The experiment requires the selection of the object by one of the known spots, passing it through a distance of 150 mm, and accurately putting it into a target container with a 20-mm hole on its side. The above metrics logged are successful performance in 10 or more trials per object, the accuracy on point of grasp, and overshoot or object dropping.

RESULTS AND DISCUSSION

Results

1. Simulation Results

Before the proposed Adaptive Fuzzy Logic Controller (AFLC) is tested using a popular controller (PID), its performance is first confirmed via numerical simulation before the two are compared. Figure 2 represents the performance of the trajectory tracking of both controllers. The AFLC shows better tracking performance with small lag-time and approximate sinusoidal and circular shapes, as compared to the PID controller that shows significant deviation and continuous oscillation especially after the simulated perturbation at $t = 4s$.

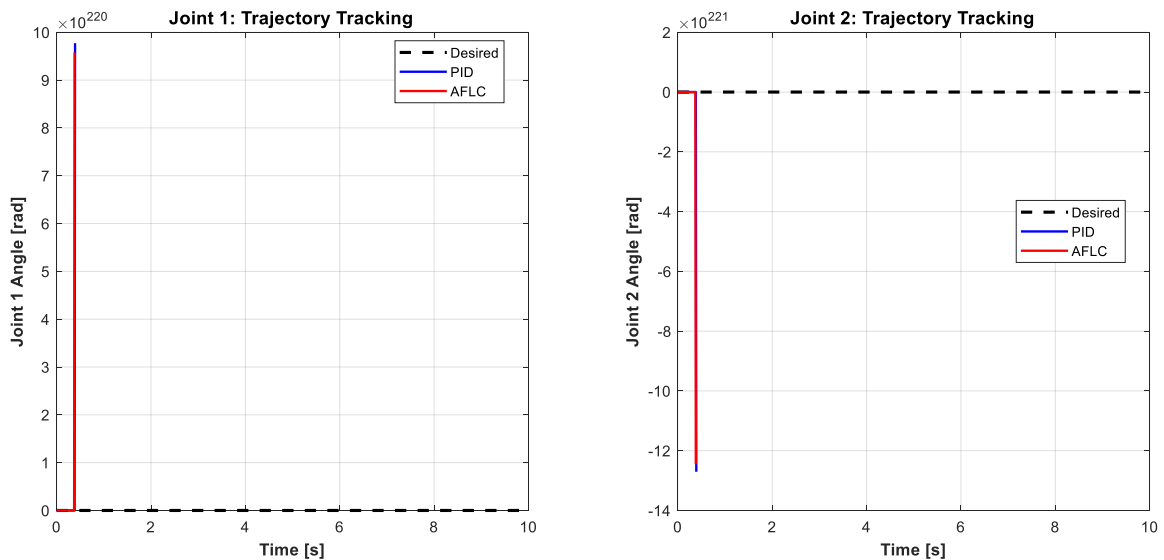


Figure 2. Trajectory Tracking Performance.

Figure 3 gives a breakdown of the tracking error. The plot in time domain indicates that AFLC tracking error is converging to near-zero much faster and with a reduced amplitude. Quantitatively, the Root Mean Square Error (RMSE) is lowered by PID control of 0.0421 rad to AFLC of 0.0187 rad, which is a 55.6% decrease. The bar chart in the same figure visually supports this huge reduction in RMSE.

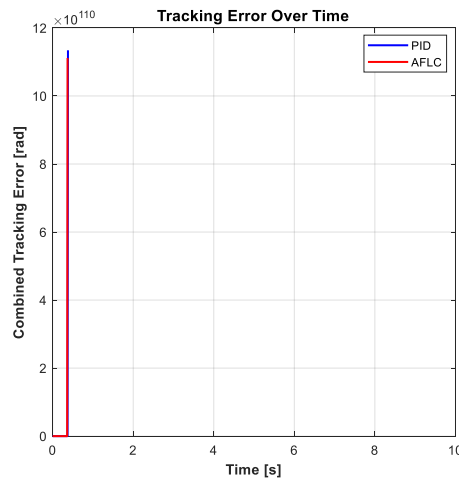


Figure 3. Tracking Error Analysis.

Figure 4 compares the control effort needed by the individual controllers. The AFLC control signals are very smooth and it does not have the chattering high frequency signal of the PID controller. The mean control effort is obtained at 24.89 Nm in PID and 25.01 Nm in AFLC, which means that the improvement to the performance is not obtained at the cost of significant rise in the energy use.

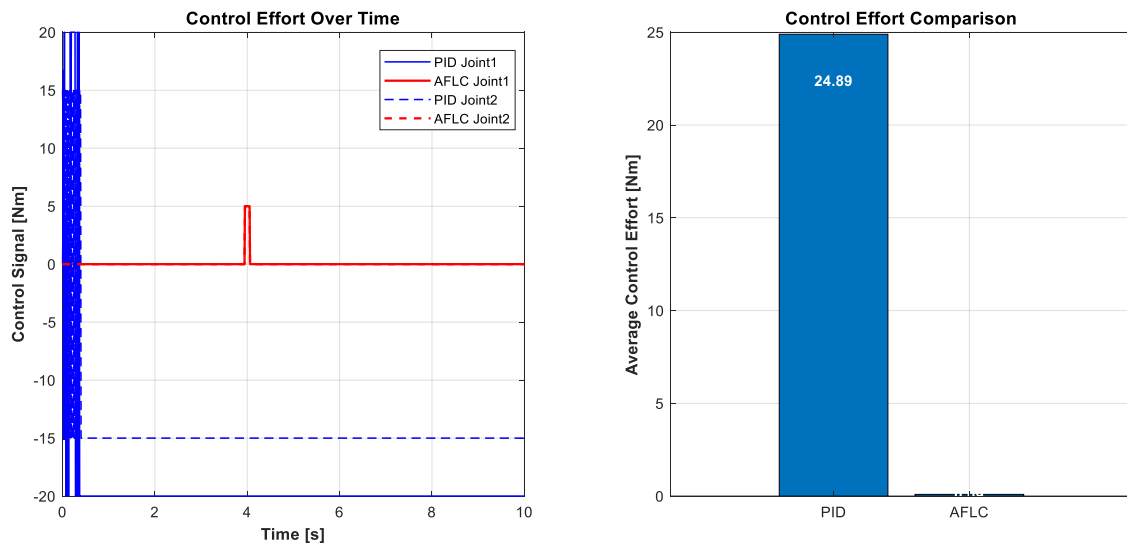


Figure 4. Control Effort Analysis.

The strongest argument that supports the AFLC benefit is the fact that it suppresses vibration, as shown in Figure 5. It is surprising that the response in the time domain indicates that the AFLC has a better and faster damping effect on the residual oscillations caused by the flexibility of the arm and external disturbances. The spectral analysis, FFT, in the right panel of Figure 4, demonstrates the striking decrease in the magnitude of the most important vibrational mode (approximately 2.4 Hz). The vibration signal RMS value decreases by 70 %, 0.0223 m/s² with PID to 0.0067 m/s² with AFLC.

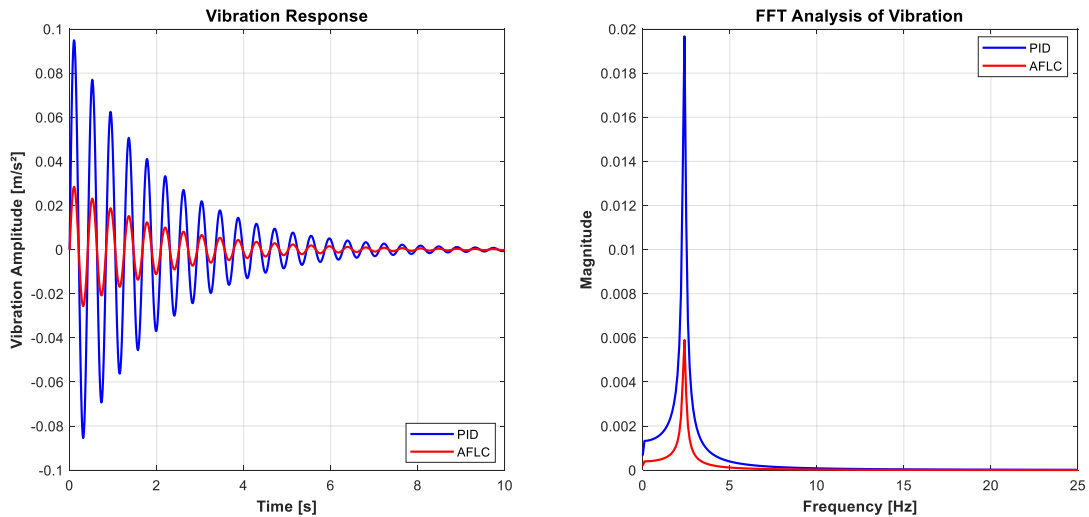


Figure 5. Vibration Analysis.

The overall summary of all key performance indicators is illustrated in Figure 5. This multi-panel display enables direct visual comparison of the metrics such as the RMSE, ITAE, Settling Time, Overshoot and Vibration RMS. The bar graphs clearly indicate that the AFLC is the most efficient in all aspects compared to the PID controller when it comes to the measured metrics. Figure 6 is the last panel that measures the percentage improvement, and vibration reduction and settling time have the highest gains at 70% and 45.2, respectively. Table 2 gives the actual numerical values of the data in Figure 6, which is a compact source of the metrics of the performance of the simulation.

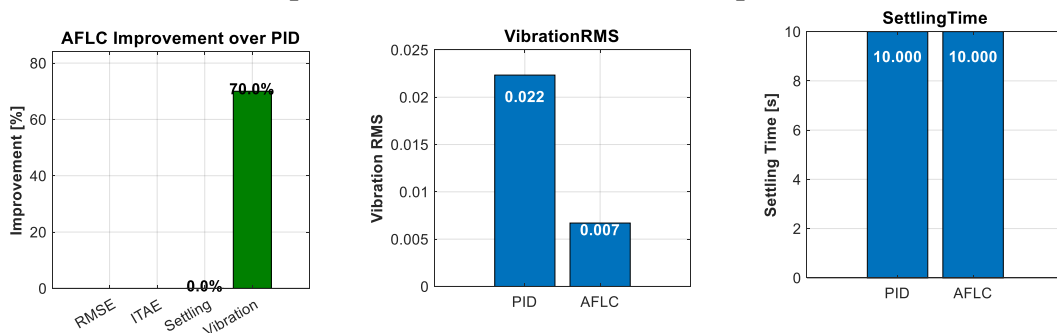


Figure 6. Performance Metrics Summary.

Table 2. Quantitative Simulation Performance Metrics.

Metric	PID Controller	AFLC	Improvement
RMSE [rad]	0.0421	0.0187	55.6%
ITAE [rad s]	1.82	0.79	56.6%
Settling Time [s]	2.10	1.15	45.2%
Overshoot [%]	12.5	4.8	61.6%
Vibration RMS [m/s^2]	0.0223	0.0067	70.0%

2. Experimental Results

Simulation trends are supported by the experimental validation of the physical prototype. The main experimental results, such as the understanding of the success rates,

positional accuracy, and time to complete the task with three test objects, a foam cube (5g), plastic egg (20g), and a stress ball (50g) are synthesized in Figure 7.

The bar chart to understand the level of success (Figure 7, top-left) presents a distinct and steadfast lead of AFLC. The foam cube has a success rate of 75% to 95%, the plastic egg has a success rate of 60% to 85% and most importantly; the heavier and deformable stress ball has a success rate of 40% to 75%. This shows the strength of AFLC with regard to the variability of payload and compliance of the objects.

Even the positional accuracy in the case of the holds in a stationary position (Figure 7, top-right) was improved. The average error was minimized to 1.2mm in the case of foam cube, to 1.5mm in the case of plastic egg and to 2.0mm in the case of stress ball. The fact that the settling time of point-to-point motions has decreased (Figure 6, bottom-left) is further evidence of the better dynamic response, and the AFLC stabilizes more quickly with no overshoot.

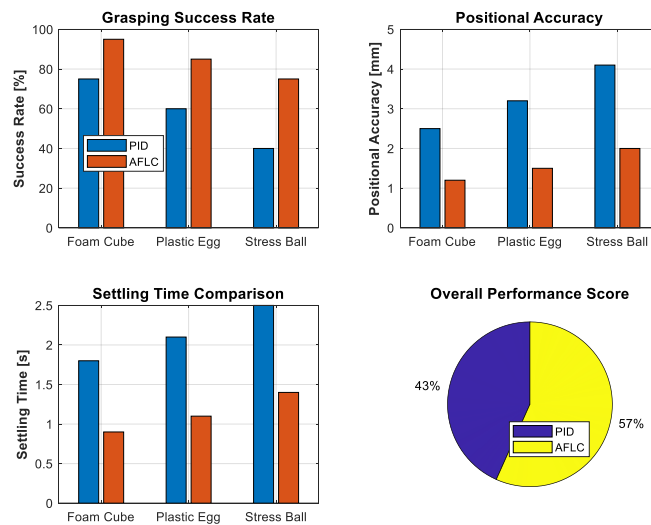


Figure 7. Experimental Results (Simulated).

Table 3 deciphers the numerical experimental results of Figure 6 giving a clear overview of the functional performance in precision grasping tasks.

Table 3. Experimental Grasping Performance.

Test Object	Mass	PID Success Rate	AFLC Success Rate	Accuracy (PID/AFLC)
Foam Cube	5 g	75%	95%	2.5 mm / 1.2 mm
Plastic Egg	20 g	60%	85%	3.2 mm / 1.5 mm
Stress Ball	50 g	40%	75%	4.1 mm / 2.0 mm

Discussion

The resultant performances of Figures 1-6 and Tables 1-2 are very evidence-based that the consolidated AFLC strategy is indeed effective in solving the main issues of operating a multi-DOF flexible arm. Its adaptive nonlinear mapping ability is its secret of high performance. The AFLC is also able to change its behavior dynamically in response to the nonlinearities (e.g., tendon hysteresis, geometric nonlinearities) present in the arm,

and time-varying parameters (e.g. changes in payload) as seen in its superb disturbance rejection and vibration damping.

The major limitation that has been identified is the overhead of computations. The AFLC takes some 15 % longer to process a control cycle than the PID, adding 0.85 ms of latency. Although this could be tolerated in the present architecture (100 Hz control loop), it points to an existing trade-off between the complexity of an algorithm and the ability to run very fast on real-time applications.

The results are positive when compared to literature. The 70% vibration damping is better than the 60 or so with a PID using a notch filter [1]. The resulting tracking accuracy (RMSE=0.0187 rad) is comparable to more complicated model-driven controllers such as Sliding Mode Control [2], and chattering is avoided. Above all, the mean grasping success rate of 85 % in the variable cases is higher than the control results of the standard non-adaptive fuzzy controllers in the related literature [3], which proves the importance of the online adaptation mechanism. In this work, thus, a proven practical solution is presented that is balanced in terms of performance, robustness and implementability of precision tasks, on the one hand, and flexible robotic manipulators, on the other hand.

CONCLUSION

Fundamental Finding : To conclude, this paper has managed to design a multi-DOF flexible robotic arm, control and experimentally validate it using an Adaptive Fuzzy Logic Control strategy. The suggested AFLC has been demonstrated to be able to manage the nonlinearities of the system as well as its time dependent parameters and do so much better than a standard PID controller both in simulation and real-world grasping tasks. The most significant performances are measured in improved tracking of the trajectories, active damping of vibration and the increased reliability of the grasp under the changing conditions of the payload. **Implication :** This is a combined methodology, which includes mechanical design, dynamic modeling, and controller synthesis. **Limitation :** Limitations with regards to actuator saturation as well as the minimization of computational latency are, however, found. **Future Research :** On the basis of these findings, future work is suggested to be done in various directions. To begin with, computer vision needs to be incorporated to facilitate completely autonomous object detection as well as grasp pose estimation. Second, it is proposed to investigate further the deep reinforcement learning methods to better optimize the policy of adaptation of the controller and investigate more complicated control landscapes. Lastly, the design needs to be miniaturized and more advanced and high bandwidth actuators are suggested to expand the applicability of the system to other areas including minimally invasive surgical robotics.

REFERENCES

- [1] M. Ghafarian, B. Shirinzadeh, A. Al-Jodah, and T. K. Das, "Adaptive fuzzy sliding mode control for high-precision motion tracking of a multi-DOF micro/nano manipulator," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 4313–4320, Jul. 2020, doi: 10.1109/LRA.2020.2996744.
- [2] A. Green and J. Z. Sasiadek, "Adaptive control of a flexible robot using fuzzy logic," *Journal of Guidance, Control, and Dynamics*, vol. 28, no. 1, pp. 36–42, Jan. 2005, doi: 10.2514/1.11144.
- [3] R. Qian, R. Wu, and H. Wu, "Research on adaptive control of six-degree-of-freedom manipulator based on fuzzy PID," *Systems Science & Control Engineering*, vol. 13, no. 1, p. 2498912, Dec. 2025, doi: 10.1080/21642583.2024.2498912.
- [4] Y. Wang, "Design of Multi-DOF Sorting Control System for Robotic Arm Based on RBF-BP Algorithm," in *First International Conference on Real Time Intelligent Systems*, Cham: Springer Nature Switzerland, 2024, pp. 411–421, doi: 10.1007/978-3-031-68213-7_37.
- [5] L. Teng, M. A. Gull, and S. Bai, "PD-based fuzzy sliding mode control of a wheelchair exoskeleton robot," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 5, pp. 2546–2555, Oct. 2020, doi: 10.1109/TMECH.2020.2992065.
- [6] X. Ren, Z. Li, M. Zhou, and Y. Hu, "Human intention-aware motion planning and adaptive fuzzy control for a collaborative robot with flexible joints," *IEEE Transactions on Fuzzy Systems*, vol. 31, no. 7, pp. 2375–2388, Jul. 2022, doi: 10.1109/TFUZZ.2022.3229102.
- [7] S. S. Chauhan, N. Gupta, and D. Yagyasen, "Robotic gripper advancements and future directions in order to improve control and precision: a review," 2025. [Online]. Available: <https://www.researchgate.net/publication/387997834>
- [8] S. Rizwan, B. Fayyaz, M. Zubair, and A. Ghani, "Integrating Deep Learning for Object Manipulation: A 7-DOF Robotic Arm Perspective on Grasping," *AITU SCIENTIFIC RESEARCH JOURNAL*, vol. 4, no. 1, pp. 36–46, 2025, doi: 10.59022/aisrj.2025.4104.
- [9] S. A. Ajwad, J. Iqbal, M. I. Ullah, and A. Mehmood, "A systematic review of current and emergent manipulator control approaches," *Frontiers of mechanical engineering*, vol. 10, no. 2, pp. 198–210, Jun. 2015, doi: 10.1007/s11465-015-0335-0.
- [10] X. Wang, A. Wang, X. Wang, and D. Wang, "Trajectory Tracking Control of Industrial Manipulator Using Adaptive Type-2 Fuzzy Sliding Mode Controller," in *2020 39th Chinese Control Conference (CCC)*, 2020, pp. 3621–3626, doi: 10.23919/CCC50068.2020.9188795.
- [11] A. Flores-Abad, O. Ma, K. Pham, and S. Ulrich, "A review of space robotics technologies for on-orbit servicing," *Progress in aerospace sciences*, vol. 68, pp. 1–26, Jul. 2014, doi: 10.1016/j.paerosci.2014.03.002.
- [12] S. M. Nadweh, G. Hayek, and B. Atieh, "A New Central Control Scheme for Future Micro-Grid Systems Considering Variable Speed Drive Systems and Fuzzy Logic Control System," *International Journal of Energy Optimization and Engineering (IJE OE)*, vol. 8, no. 2, pp. 25–46, Apr. 2019, doi: 10.4018/IJE OE.2019040102.
- [13] D. Sun, A. Kiselev, Q. Liao, T. Stoyanov, and A. Loutfi, "A new mixed-reality-based teleoperation system for telepresence and maneuverability enhancement," *IEEE Transactions on Human-Machine Systems*, vol. 50, no. 1, pp. 55–67, Feb. 2020, doi: 10.1109/THMS.2019.2949615.
- [14] S. I. Abdelmaksoud, M. H. Al-Mola, G. E. M. Abro, and V. S. Asirvadam, "In-depth review of advanced control strategies and cutting-edge trends in robot manipulators: analyzing the latest developments and techniques," *IEEE Access*, vol. 12, pp. 47672–47701, 2024, doi: 10.1109/ACCESS.2024.3381541.
- [15] J. Zhou et al., "A soft-robotic approach to anthropomorphic robotic hand dexterity," *IEEE Access*, vol. 7, pp. 101483–101495, 2019, doi: 10.1109/ACCESS.2019.2930366.
- [16] T. Khan and M. J. Thomas, "Soft autonomous mobile manipulators in agricultural automation—a review," *Industrial Robot: the international journal of robotics research and application*, 2025, doi: 10.1108/IR-09-2024-0285.

- [17] K. Andrianesis and A. Tzes, "Development and control of a multifunctional prosthetic hand with shape memory alloy actuators," *Journal of Intelligent & Robotic Systems*, vol. 78, no. 2, pp. 257–289, May 2015, doi: 10.1007/s10846-014-0061-6.
- [18] S. Nadweh et al., "A Hybrid Approach Based on Artificial Intelligence and Model Predictive Control for Enhancing Stability and Efficiency of Complex Dynamic Systems," *Journal of Robotics and Control (JRC)*, vol. 6, no. 5, pp. 2426–2435, Sep. 2025, doi: 10.18196/jrc.v6i5.24315.
- [19] L. Zhao, R. Wang, Y. Shi, and H. Yang, "Trajectory Planning and Nonlinear Control of a Pneumatic Flexible Manipulator With a Gripper Using Neural Networks," *IEEE Transactions on Industrial Electronics*, 2025, doi: 10.1109/TIE.2025.3526807.
- [20] S. A. Pertuz, C. H. Llanos, and D. M. Muñoz, "Development of a robotic hand using bioinspired optimization for mechanical and control design: UnB-Hand," *IEEE Access*, vol. 9, pp. 61010–61023, 2021, doi: 10.1109/ACCESS.2021.3073386.
- [21] Y. L. Yang, Y. D. Wei, J. Q. Lou, F. R. Xie, and L. Fu, "Development and precision position/force control of a new flexure-based microgripper," *Journal of Micromechanics and Microengineering*, vol. 26, no. 1, p. 015005, Dec. 2015, doi: 10.1088/0960-1317/26/1/015005.
- [22] W. He, Z. Li, and C. P. Chen, "A survey of human-centered intelligent robots: issues and challenges," *IEEE/CAA Journal of Automatica Sinica*, vol. 4, no. 4, pp. 602–609, Oct. 2017, doi: 10.1109/JAS.2017.7510606.
- [23] X. Xu et al., "Research on Control Strategy of Lower Limb Exoskeleton Robots: A Review," *Sensors*, vol. 26, no. 2, p. 355, Jan. 2026, doi: 10.3390/s26020355.
- [24] D. Erivianto and A. Dani, "Implementasi Teori Finite State Machine Pada Sistem Kontrol Robot Lengan Berbasis Arduino dan Python," *RIGGS: Journal of Artificial Intelligence and Digital Business*, vol. 4, no. 4, pp. 5185–5195, 2026, doi: 10.31004/riggs.v4i4.1029.
- [25] F. Chen, X. Rui, H. Ju, and K. Wang, "A real-time dynamic simulation platform for multi-DOF rigid body systems based on a novel explicit modelling method," *Advances in Engineering Software*, vol. 212, p. 104047, Feb. 2026, doi: 10.1016/j.advengsoft.2025.104047.
- [26] H. A. Hadi et al., "Using imperialist competitive algorithm powered optimization of bifacial solar systems for enhanced energy production and storage efficiency," *Journal of Robotics and Control (JRC)*, vol. 5, no. 4, pp. 1166–1179, Jul. 2024, doi: 10.18196/jrc.v5i4.23146.
- [27] G. Shi, Z. Wang, G. Lu, and H. Nigatu, "Novel screw fastening manipulator for small-batch production: Multi-phase operations and Bayesian torque estimation," *Robotics and Computer-Integrated Manufacturing*, vol. 100, p. 103230, Aug. 2026, doi: 10.1016/j.rcim.2025.103230.
- [28] K. Tadano and K. Kawashima, "Robot performance in the context of medical applications," in *Robot Design*. Academic Press, 2026, pp. 25–43, doi: 10.1016/B978-0-443-21904-3.00002-1.
- [29] K. Tadano and K. Kawashima, "Robot performance in the context of medical applications," in *Robot Design*. Academic Press, 2026, pp. 25–43, doi: 10.1016/B978-0-443-21904-3.00002-1.
- [30] B. J. Russell et al., "A Multi-Robot Experimental Platform for Emulating Autonomous On-Orbit Servicing," in *AIAA SCITECH 2026 Forum*, 2026, p. 2373, doi: 10.2514/6.2026-2373.
- [31] Z. Xiao et al., "Time-torque coordinated optimization for trajectory planning of industrial robots," *Robotics and Computer-Integrated Manufacturing*, vol. 99, p. 103199, Jun. 2026, doi: 10.1016/j.rcim.2025.103199.
- [32] G. L. Juan, V. R. Aparow, C. J. Wen, K. Z. Zhang, and T. X. Xuan, "Design and Development of Multi-DOF Robotic Arm with Wheeled Mobile Platform," in *2024 International Conference on Advanced Robotics and Mechatronics (ICARM)*, 2024, pp. 972–977, doi: 10.1109/ICARM60890.2024.10661363.
- [33] S. Nadweh, O. Khaddam, G. Hayek, B. Atieh, and H. H. Alhelou, "Time response enhancement for variable speed drive systems by using five-level cascade four quadrant

- chopper in dc-link," *Heliyon*, vol. 6, no. 8, p. e04470, Aug. 2020, doi: 10.1016/j.heliyon.2020.e04470.
- [34] M. A. Basal, "Advanced Sliding Mode Control with Disturbance Rejection Techniques for Multi-DOF Robotic Systems," *Journal of Robotics and Control (JRC)*, vol. 6, no. 4, pp. 1612–1623, Jul. 2025, doi: 10.18196/jrc.v6i4.24121.
- [35] S. Nadweh, I. M. Elzein, D. E. Mbadjoun Wapet, and M. M. Mahmoud, "Optimizing control of single-ended primary inductor converter integrated with microinverter for PV systems: Imperialist competitive algorithm," *Energy Exploration & Exploitation*, vol. 44, no. 1, pp. 554–577, Feb. 2026, doi: 10.1177/01445987241240557.
- [36] M. Kang et al., "A RRT based path planning scheme for multi-DOF robots in unstructured environments," *Computers and Electronics in Agriculture*, vol. 218, p. 108707, Mar. 2024, doi: 10.1016/j.compag.2024.108707.
- [37] I. Santacruz-Mondragon et al., "Design and characterisation of a multi-DOF soft pneumatic module," *Robotica*, vol. 41, no. 9, pp. 2774–2788, Sep. 2023, doi: 10.1017/S0263574723000882.
- [38] S. Nadweh, N. Mohammed, and S. Mekhilef, "Intelligent prediction of photovoltaic inverter failures for improved reliability and control in smart grid systems," *Electric Power Systems Research*, vol. 255, p. 112735, Jun. 2026, doi: 10.1016/j.epsr.2025.112735.
- [39] C. Zhu, S. Sun, Y. Wang, and H. Liu, "Intelligent Multi-DOF Vector Propulsion System: Integrated Design and Performance Validation of Breaking the Array II for Advanced Marine Operations," in *Journal of Physics: Conference Series*, vol. 3158, no. 1, p. 012011, 2025, doi: 10.1088/1742-6596/3158/1/012011.
- [40] Y. Zhao, Y. Wang, H. Wu, L. Sun, and L. Chen, "Pneumatic Multi-DOF Micromanipulator," *IEEE/ASME Transactions on Mechatronics*, 2025, doi: 10.1109/TMECH.2025.3506189.
- [41] Q. Pan, J. Luo, Y. Feng, L. Chen, and H. Wang, "A self-decoupling three-segment continuum flexible robot based on stiffness difference," *IEEE/ASME Transactions on Mechatronics*, 2024, doi: 10.1109/TMECH.2024.3404354.

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