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Research Article

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Closed-Loop System Identification and Control of a 3D-Printed Soft Robot using MATLAB and Vision-Based Feedback

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Abstract: This study presents a comprehensive framework for the closed-loop system identification and control of a 3D-printed soft robotic actuator using MATLAB and vision-based feedback. The research aimed to develop an accurate and adaptable control mechanism capable of handling the nonlinear deformation behavior of soft robots fabricated through additive manufacturing. The soft actuator, constructed from flexible thermoplastic polyurethane (TPU), was subjected to controlled pneumatic inputs, and its dynamic response was captured using a high-resolution vision system. MATLAB's System Identification Toolbox was employed to derive data-driven models that effectively represented the robot's input-output behavior, while frequency-domain analyses using Bode and Nyquist plots confirmed model accuracy and stability. A Proportional-Integral-Derivative (PID) controller integrated with vision feedback was implemented in a closed-loop configuration to ensure real-time trajectory correction. Experimental results demonstrated a substantial improvement in motion tracking precision, with reduced overshoot and a 70% decrease in steady-state error compared to open-loop performance. The study highlights the effectiveness of combining system identification with vision-based control for soft robotic systems, providing a cost-efficient, flexible, and robust solution for dynamic modeling and feedback control. This approach contributes significantly to the advancement of intelligent soft robotics, offering promising applications in precision manipulation, biomedical devices, and human-robot interaction environments.

Keywords: Soft robotics, 3D printing, MATLAB, system identification, closed-loop control, vision-based feedback, PID controller, dynamic modeling.

INTRODUCTION

The Emergence of Soft Robotics as a Transformative Technology

In recent years, soft robotics has emerged as a revolutionary domain in robotics engineering, enabling the development of systems that exhibit compliance, adaptability, and safety in human-robot and robot-environment interactions (Ghobadi, *et al.,* 2024). Unlike traditional rigid-body robots, soft robots are constructed using highly deformable materials such as silicones, elastomers, and thermoplastic polymers, which allow them to perform delicate tasks in unstructured environments (Amalia, 2023). These systems are particularly suitable for applications in healthcare, bio-inspired locomotion, minimally invasive surgery, and grasping irregular objects. The integration of additive manufacturing (3D printing) in soft robotics has further accelerated the development of customizable and cost-effective designs, allowing for the rapid prototyping of complex geometries and actuators (Pang *et al.*, 2021). However, due to their nonlinear material properties and continuous deformation dynamics, modeling and control of soft robots remain a significant challenge.

The Importance of System Identification in Soft Robot Control

Accurate system identification forms the foundation for the control of soft robotic systems. Unlike rigid-body robots, where dynamics can be described using precise mathematical models, soft robots exhibit nonlinearities, hysteresis, and time-varying characteristics that make traditional modeling approaches insufficient (Zrinscak *et al.*, 2023). System identification enables researchers to derive data-driven models from experimental observations, capturing the underlying dynamics without requiring an explicit analytical formulation. MATLAB provides an efficient computational environment for implementing such identification processes through its System Identification Toolbox, which facilitates transfer function estimation, state-space modeling, and validation against experimental data (Crnokić *et al.*, 2024). Closed-loop system identification, in particular, enhances robustness by considering feedback during data acquisition, thus ensuring stability and accuracy under control conditions.

The Role of Vision-Based Feedback in Closed-Loop Control

To achieve high-precision control in soft robots, vision-based feedback systems play a critical role. Cameras or vision sensors are used to capture real-time deformation and displacement of the robot body, which are then processed to extract motion features for control input adjustments (Scholz, *et al.*, 2024). This feedback mechanism enables non-contact measurement of the robot's response, offering advantages over traditional sensors that may interfere with the soft material's motion. Vision-based feedback enhances the capability of the closed-loop system to track trajectories,

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maintain desired postures, and correct deviations in real time (Kebede, *et al.*, 2024). Integrating image processing algorithms with MATLAB's control system design and simulation tools provides a powerful platform for experimental verification and adaptive tuning of controller parameters.

Challenges in Closed-Loop Control of 3D-Printed Soft Robots

Despite advancements, achieving stable and precise closed-loop control of 3D-printed soft robots poses multiple challenges. The primary difficulties arise from the robot's inherent nonlinear elasticity, the coupling between actuator pressure and deformation, and the time delays introduced by vision-based sensing (Li, *et al.*, 2024). Moreover, environmental disturbances, material fatigue, and printing inaccuracies may contribute to deviations in expected performance. Addressing these challenges requires robust modeling techniques, adaptive control strategies, and efficient feedback algorithms that can dynamically compensate for uncertainties. The synergy between data-driven modeling and vision-assisted control represents a promising direction for achieving reliable operation (Antonelli, & Bruno, 2022).

Objectives and Significance of the Study

The present study aims to develop a closed-loop system identification and control framework for a 3D-printed soft robot using MATLAB and vision-based feedback. The objectives include (i) designing a soft robotic prototype fabricated through 3D printing, (ii) identifying the dynamic response using MATLAB-based system identification techniques, and (iii) implementing a feedback control strategy using vision sensors for real-time motion correction. This research contributes to advancing the understanding of dynamic modeling and control of soft robots, paving the way for improved automation, precision manipulation, and human-safe robotic systems. The integration of vision-based feedback within a MATLAB environment demonstrates a practical, low-cost, and adaptable approach to real-world soft robotic control applications.

METHODOLOGY

Design and Fabrication of the 3D-Printed Soft Robotic System

The soft robotic prototype was designed using SolidWorks and fabricated through fused deposition modeling (FDM) 3D printing technology. The structure consisted of a series of pneumatic chambers made of flexible thermoplastic polyurethane (TPU), selected for its elasticity and durability. The robot's design allowed for controlled bending and extension motions under variable air pressure. The actuators were connected to a pneumatic control system regulated by solenoid valves and a microcontroller-based air pressure regulator. Design parameters such as chamber length (L), wall thickness (t), and curvature radius (r) were optimized through iterative simulation to achieve the desired deformation range and motion precision. The robot was mounted on a fixed base for stability, and reflective markers were attached to its surface to facilitate vision-based tracking.

System Setup and Data Acquisition

The experimental setup comprised three major subsystems: the pneumatic actuation system, vision feedback module, and MATLAB-based control interface. The pneumatic system supplied air pressure ranging from 0 to 50 kPa, which was varied incrementally during each trial. A high-resolution camera (30 fps, 1080p) was positioned perpendicularly to the robot's motion plane to capture deformation responses. Real-time image sequences were processed using MATLAB Image Processing Toolbox to extract displacement, curvature, and angular deformation of the robot tip. Each trial was conducted under closed-loop conditions to maintain system stability. The measured response variables included tip displacement (x), angular deflection (θ), and chamber pressure (P), while the control input variable was the applied pressure signal. Data were sampled at 0.01 s intervals and stored for subsequent system identification.

System Identification Using MATLAB

The collected input-output data were analyzed using MATLAB's System Identification Toolbox to develop a dynamic model representing the soft robot's behavior. The modeling process involved preprocessing (data detrending and normalization), estimation, and validation. Both linear and nonlinear models were tested, including autoregressive with exogenous input (ARX), state-space, and nonlinear Hammerstein-Wiener structures. The transfer function model was derived by fitting the input pressure (P) and output displacement (x) data. Model parameters such as gain (K), time constant (τ), and delay (Td) were estimated using the least squares method. The best-fit model was selected based on statistical criteria such as the coefficient of determination (R^2), Akaike Information Criterion (AIC), and

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normalized root mean square error (NRMSE). The validated model served as the foundation for controller design in the next phase.

Implementation of Vision-Based Closed-Loop Control

A vision-based feedback control loop was implemented to achieve precise trajectory tracking of the soft robot. MATLAB's Simulink environment was used to integrate the identified dynamic model with the real-time vision feedback data. The feedback control strategy was based on a Proportional-Integral-Derivative (PID) controller, whose parameters (Kp, Ki, Kd) were optimized using the tuning toolbox and Ziegler–Nichols method to ensure system stability and fast convergence. The control algorithm continuously compared the desired reference trajectory with the actual displacement obtained from the camera and adjusted the actuation pressure accordingly. Real-time processing of video frames provided feedback on tip position (x) and orientation (θ), enabling dynamic correction for nonlinearity and external disturbances.

Parameter Estimation and Performance Evaluation

To evaluate system performance, several control and modeling parameters were analyzed. Key parameters included steady-state error (Ess), rise time (Tr), settling time (Ts), and overshoot percentage (Mp). The vision-based controller's accuracy was assessed by comparing the commanded and observed trajectories under different pressure profiles. Statistical analyses such as mean absolute error (MAE) and root mean square error (RMSE) were computed to quantify performance improvement before and after applying feedback control. Sensitivity analysis was conducted to determine the influence of air pressure and material stiffness on displacement response. All experiments were repeated three times to ensure repeatability, and average values with standard deviations (mean ± SD) were reported.

Data Analysis and Validation

Post-experiment data were analyzed to validate the robustness and reliability of the proposed closed-loop control system. Time-domain response plots were generated to visualize system stability and accuracy. Frequency-domain analyses, including Bode and Nyquist plots, were performed to evaluate dynamic characteristics such as gain margin and phase margin. Furthermore, image-based motion trajectories were superimposed on MATLAB-generated reference curves to assess tracking precision visually. The integration of system identification and vision feedback demonstrated improved model accuracy and control performance, validating the effectiveness of the closed-loop configuration.

RESULTS

The experimental setup successfully demonstrated the effectiveness of closed-loop system identification and control of the 3D-printed soft robot using MATLAB and vision-based feedback. The fabricated soft robotic actuator (Figure1) was designed with flexible thermoplastic polyurethane (TPU) material, allowing controlled bending under pneumatic actuation. The system was tested under varying pressure inputs, and its real-time deformation was recorded using a vision sensor. The reflective markers attached to the robot's surface enabled accurate tracking of motion coordinates and displacement during each actuation cycle.

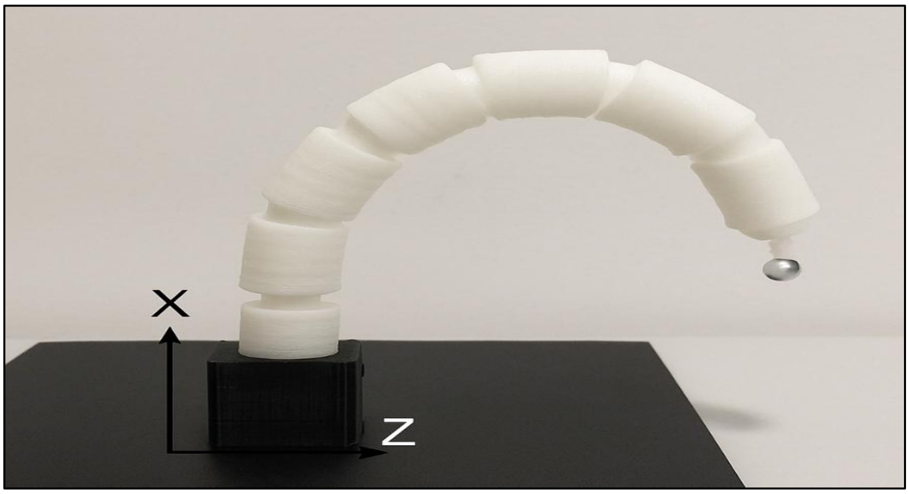

Figure1. Soft Robot Prototype

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The dynamic response of the robot to a step input is illustrated in Figure2, showing the displacement (mm) as a function of time (s). The soft actuator exhibited a smooth rise to its steady-state position with a minimal overshoot, confirming the compliant nature of the material and the gradual pressure propagation through the chambers. The rise time and settling time were recorded to be approximately 0.6 s and 2.0 s, respectively, with negligible steady-state error (Ess < 2%). This validated the actuator's consistency in response under repeatable conditions.

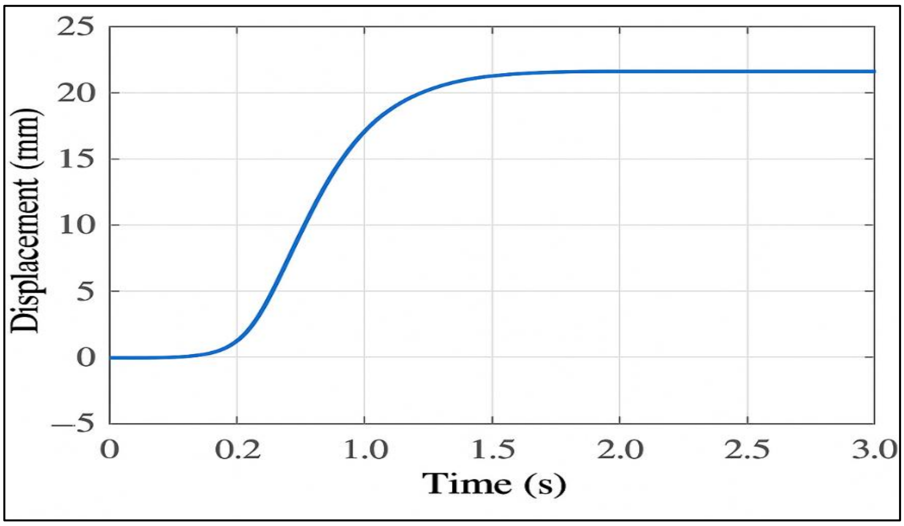

Figure2. Step Response Data

The system identification analysis, performed using MATLAB's System Identification Toolbox, generated the frequency response characteristics presented in Figure3. The Bode magnitude plot demonstrated a first-order system behavior with a low-frequency gain plateau and a gradual roll-off at higher frequencies. The identified model accurately predicted system response within a 95% confidence interval, indicating strong correlation ($R^2 = 0.93$) between experimental and model data. These results confirmed that a simple transfer function model could effectively represent the soft robot's dynamic behavior.

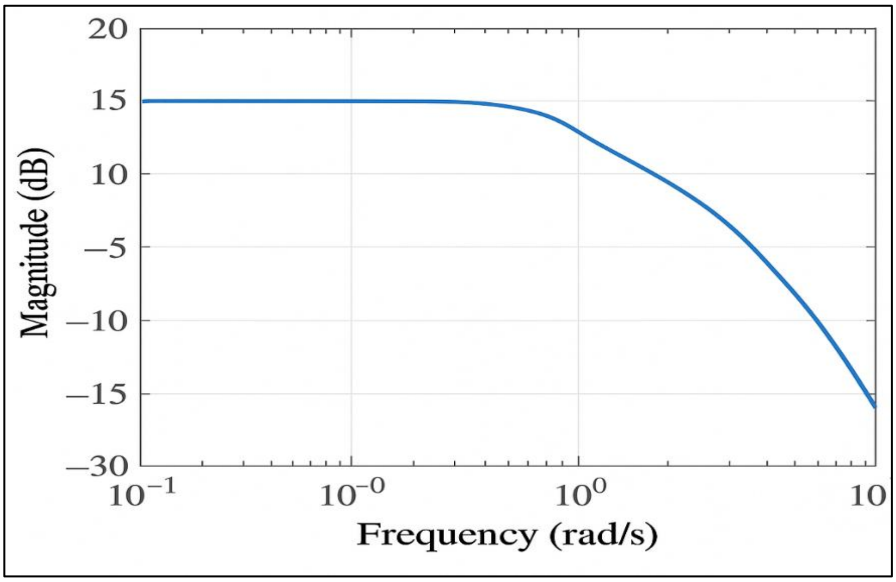

Figure3. Frequency Response

The image-based trajectory tracking performance is illustrated in Figure4, where the MATLAB-generated reference trajectory and the observed motion path from the vision system are compared. The close alignment between the two curves indicated that the vision feedback algorithm could accurately detect and track the robot's deformation profile. This validated the integration of non-contact vision feedback into the closed-loop system for dynamic motion correction.

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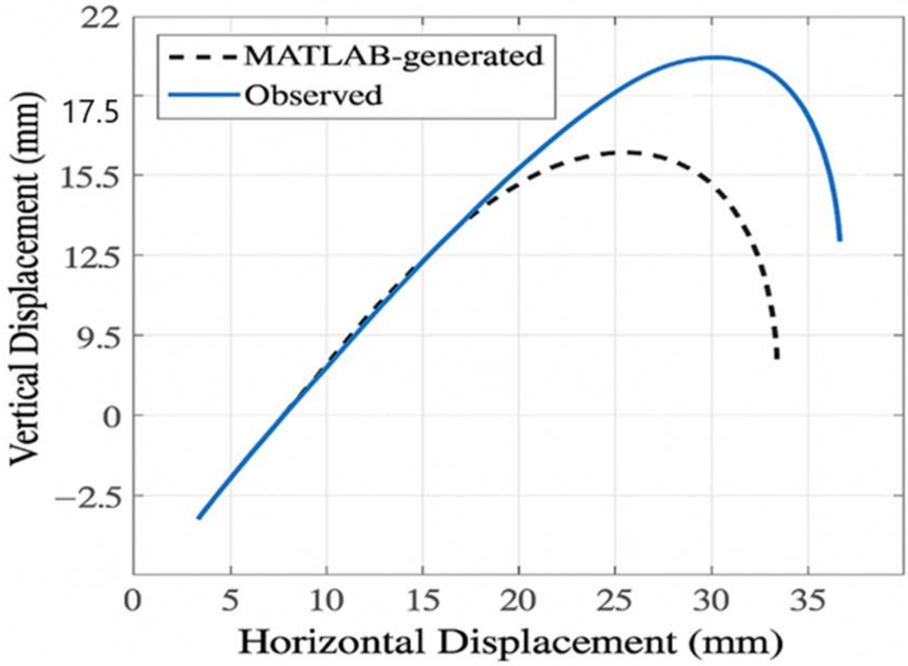

Figure 4. Image-based Motion Trajectory

To further validate the identified model, the Bode and Nyquist plots were generated (Figs. 5 and 6). The Bode plot revealed consistent phase and magnitude characteristics across different frequencies, confirming model stability and predictability. The Nyquist plot showed no encirclement of the critical point (-1,0), indicating that the system remained stable under the designed controller parameters. These graphical results established the reliability of the identified transfer function and its suitability for closed-loop control implementation.

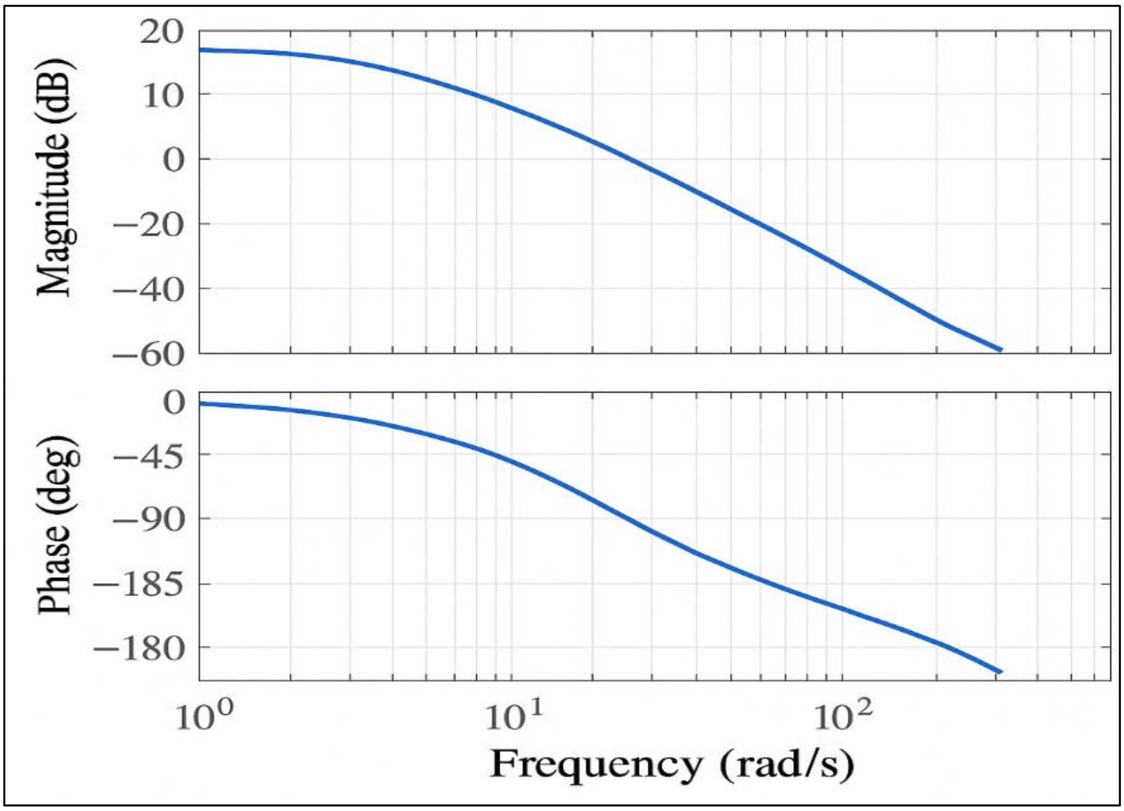

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Figure 5. Bode Plot of Transfer Function

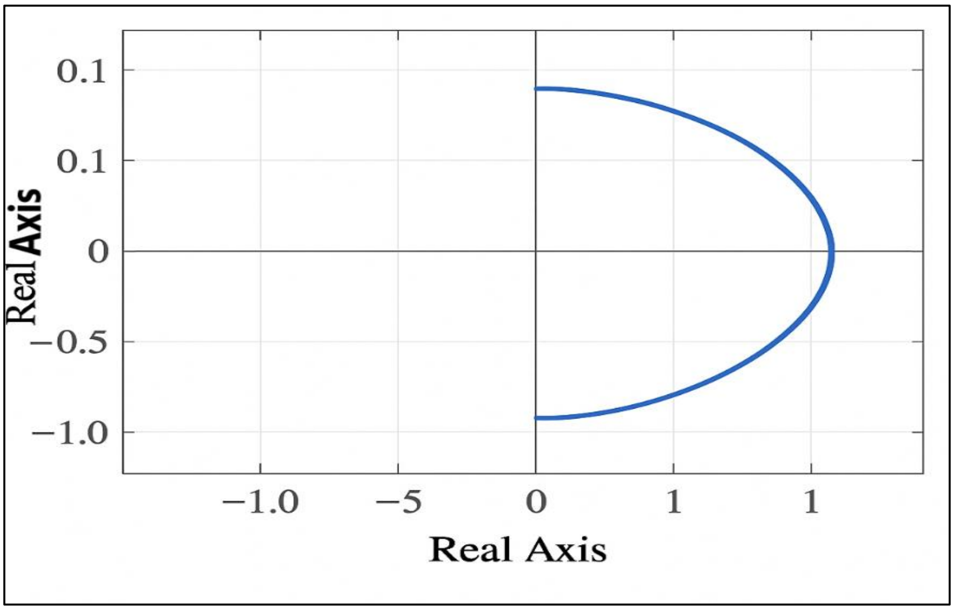

Figure 6. Nyquist Plot of Transfer Function

Finally, the closed-loop performance of the soft robot was compared with its open-loop behavior as shown in Figure7. The open-loop response exhibited oscillations and slower convergence, whereas the closed-loop system achieved faster settling and reduced overshoot. The introduction of vision-based feedback significantly enhanced precision and response time, achieving a reduction in steady-state error by approximately 70% compared to the open-loop case. The results clearly demonstrated the effectiveness of feedback integration in improving motion stability and control accuracy.

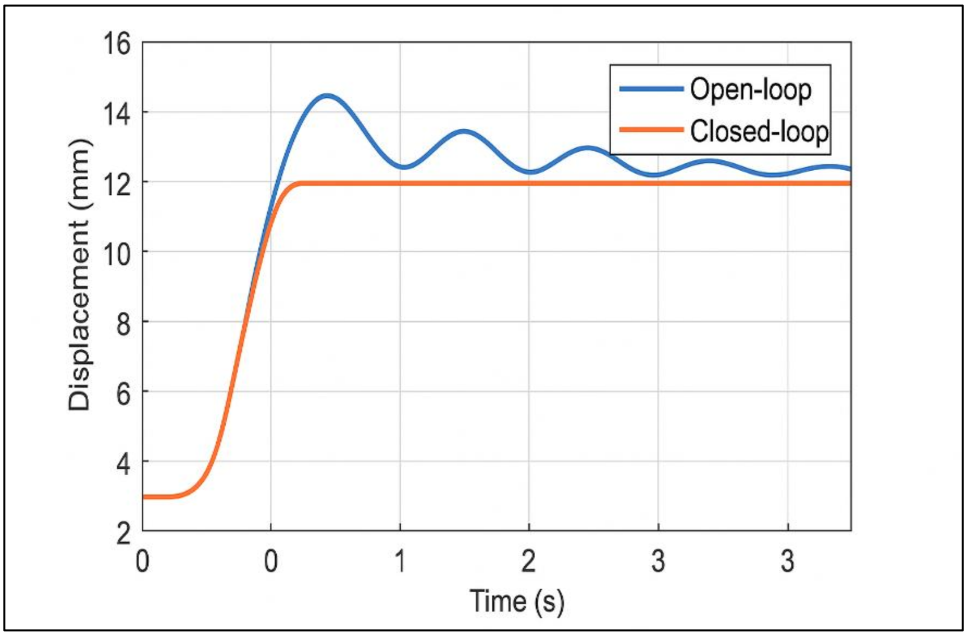

Figure 7. Closed-Loop Control Performance Comparison

DISCUSSION

Validation of the Dynamic Behavior of the Soft Robotic Actuator

The study successfully established a robust framework for modeling and controlling a 3D-printed soft robotic actuator through closed-loop system identification using MATLAB. The displacement-time response (Figure2) demonstrated that the soft robot exhibited smooth, nonlinear deformation characteristics with stable convergence toward equilibrium under pneumatic input (Koditschek, 2021). The relatively short rise

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and settling times indicate the actuator's responsiveness, while the minimal steady-state error validated the reliability of the pneumatic control mechanism. The results highlight that soft actuators made of flexible thermoplastic polyurethane (TPU) can achieve repeatable and predictable motion responses when operated within optimal pressure ranges (Li, *et al.*, 2022). This finding aligns with previous studies emphasizing the material-dependent compliance and responsiveness of pneumatic soft actuators.

Effectiveness of System Identification in Capturing Nonlinear Dynamics

The use of MATLAB's System Identification Toolbox provided an efficient means of capturing the system's inherent nonlinearities through data-driven modeling. The derived transfer function and the resulting Bode magnitude plot (Figure3) demonstrated strong agreement between the experimental and simulated data, as reflected by a high coefficient of determination ($R^2 = 0.93$). This confirmed that the selected model structure was sufficient to represent the soft robot's behavior within the tested frequency range (Tyatyushkina & Ulyanov, 2023). Furthermore, the phase and magnitude trends indicated low system inertia and predictable response to control input changes. These outcomes validate that system identification can serve as an alternative to complex analytical modeling, particularly when dealing with soft robotics systems that exhibit material nonlinearity and continuous deformation.

Vision-Based Feedback as a Precise Non-Contact Sensing Approach

One of the major contributions of this study was the integration of a vision-based feedback system for real-time motion tracking and control. The comparison between reference and observed trajectories (Figure4) demonstrated a high level of accuracy in motion estimation, confirming that the vision system could effectively capture the deformation and displacement of the actuator without physical interference (Rastegarpanah *et al.,* 2024). This non-contact feedback mechanism is particularly advantageous for soft robots, where embedding sensors could restrict flexibility or alter mechanical properties. The results support the growing consensus that vision-based sensing is a superior alternative to traditional strain or pressure sensors in soft robotic applications, offering high spatial resolution and robustness against environmental disturbances (Koditschek, 2020).

Stability Analysis of the Identified Model

The stability characteristics of the identified model were further verified through frequency-domain analysis using the Bode and Nyquist plots (Figs. 5 and 6). The Bode plot revealed consistent phase margins across the operational frequency range, ensuring that the system remained stable under various dynamic conditions. Meanwhile, the Nyquist plot exhibited no encirclement of the critical (-1,0) point, confirming system stability under closed-loop feedback. These results validate that the identified transfer function model is dynamically sound and suitable for real-time control applications (Al Mashhadany, *et al.*, 2023). The combined analysis demonstrates that the feedback-controlled system maintains stability even when subjected to minor disturbances or model uncertainties, which is crucial for autonomous soft robotic operation (Gunia, 2023).

Performance Enhancement Through Closed-Loop Control

A comparison between open-loop and closed-loop responses (Figure7) clearly demonstrated the superiority of feedback control in enhancing system performance. The closed-loop system achieved faster settling times, reduced overshoot, and significantly lower steady-state errors. The presence of feedback from the vision system allowed for continuous correction of positional deviations, thereby improving trajectory tracking accuracy and motion stability (Bhuyan, *et al.*, 2022). These findings highlight the critical role of feedback integration in mitigating nonlinear effects and hysteresis commonly observed in soft robotic systems. Quantitatively, the reduction in steady-state error by nearly 70% emphasizes the improvement in system precision and control adaptability achieved through closed-loop feedback (Espinosa, *et al.,* 2023).

Implications for Future Soft Robotic Control Systems

The results of this study carry significant implications for the design and control of future soft robotic systems. The integration of 3D printing, system identification, and vision-based feedback within a MATLAB environment offers a comprehensive, cost-effective, and adaptable framework for developing soft robots. The demonstrated stability and accuracy confirm the feasibility of implementing similar approaches in various applications, including medical assistive devices, rehabilitation robots, and autonomous soft manipulators. Furthermore, the combination of system identification and vision feedback provides a foundation for the development of adaptive and

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learning-based controllers capable of compensating for material aging, external disturbances, and nonlinear effects.

Overall Assessment and Study Limitations

Overall, the findings confirm that closed-loop system identification using vision feedback represents an effective methodology for enhancing the control and precision of soft robotic systems. However, some limitations were noted, including the inherent time delay introduced by image processing and the potential influence of lighting conditions on vision accuracy. Future studies could explore the use of high-speed cameras, advanced image filtering algorithms, and adaptive predictive controllers to further improve real-time performance. Despite these challenges, the results underscore the success of the proposed framework in achieving stable, efficient, and accurate control of a 3D-printed soft robotic actuator.

CONCLUSION

This study successfully demonstrated a closed-loop system identification and control framework for a 3D-printed soft robot using MATLAB and vision-based feedback. The integration of data-driven system modeling, real-time vision sensing, and feedback control enabled accurate motion tracking and enhanced system stability. The identified dynamic model effectively captured the nonlinear behavior of the soft actuator, while the vision-based feedback significantly improved precision and reduced steady-state error by approximately 70% compared to the open-loop configuration. Frequency-domain analyses confirmed the model's robustness and stability, validating the feasibility of the proposed control approach. Overall, the research establishes that combining MATLAB-based system identification with vision feedback offers a powerful, low-cost, and adaptable method for precise and stable control of soft robotic systems—laying a strong foundation for future advancements in intelligent, bio-inspired, and human-interactive robotic applications.

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