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Climbing Pipe and Gripper Control Mechanisms for Bionic Snake Robots in Constrained Environments

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Abstract

This paper presents the development and optimization of climbing pipe and gripper control mechanisms for a 10-degree-of-freedom (10-DOF) servo-driven bionic snake robot in constrained pipe environments. A MATLAB/Simulink simulation framework is employed to model robot kinematics, dynamics, gait generation, and friction-based distributed gripping. Five simulation scenarios varying pipe diameter (50–150 mm), inclination (0°–90°), and friction coefficient (0.35–0.60) are evaluated. Results demonstrate that the distributed friction-based gripper provides reliable performance under moderate conditions, while slip ratio escalates sharply above 60° inclination and energy consumption increases monotonically with pipe difficulty. A phase-wise vertical climbing analysis reveals five sequential stages: initial anchoring, body bending, upward propulsion, rear pull-up, and re-anchoring. The proposed framework contributes a unified simulation-based methodology for analysing pipe-climbing snake robots and validates distributed friction gripping as a viable, lightweight strategy for constrained-environment robotic inspection.

KEYWORDS

snake robot; pipe climbing; friction-based gripper; constrained environment;
MATLAB/Simulink; biomimetic robotics

1 | INTRODUCTION

Bionic snake robots exploit long, articulated bodies to navigate narrow, hazardous environments inaccessible to wheeled or legged robots [1, 2]. Industrial pipeline inspection, search-and-rescue, and maintenance operations represent high-value applications where snake robots offer advantages through distributed body contact, flexible posture control, and multiple locomotion modes [3, 4]. Despite significant research progress, achieving stable, energy-efficient pipe climbing with reliable gripping remains challenging. Key difficulties include maintaining sufficient contact forces across varying pipe geometries, surface conditions, and inclinations while integrating locomotion and gripping as a unified control system [5, 6].

Existing work has addressed friction-based locomotion [7], contact feedback for propulsion improvement [8], and snake robots with integrated grippers for narrow-space inspection [5]. However, a comprehensive simulation framework combining climbing mechanics, friction-based distributed gripping, and systematic performance evaluation across varied pipe conditions

remains absent from the literature [9, 14]. This paper addresses these gaps with three primary contributions: (i) a unified MATLAB/Simulink framework integrating kinematics, dynamics, friction-based gripping, and gait generation; (ii) a novel distributed friction-based gripper mechanism enabling continuous locomotion without discrete clamp-release cycles; and (iii) systematic performance evaluation including phase-wise vertical climbing analysis across five pipe-condition scenarios.

2 | RELATED WORK

Snake locomotion research has identified serpentine, rectilinear, concertina, and sidewinding gaits, each offering distinct advantages for constrained-environment navigation [1, 2, 10]. Hatton and Choset (2009) demonstrated wave-based gait generation, while Marvi et al. (2014) showed that controlled body contact minimises slip during sidewinding on inclined surfaces. Contact feedback through vertical bending was shown by Fu and Li (2023) to significantly improve propulsion on irregular terrain.

Snake robot design has evolved to incorporate modularity, compliance, and task-specific functionality [9]. Series-elastic actuators [9] and tendon-driven compliant mechanisms [15] have improved terrain adaptability. Ji et al. (2023) demonstrated that combining grippers with snake robots substantially improves narrow-space inspection performance. Gripper technology research spanning soft adaptive grippers [16, 17], pneumatic systems [18, 19], and underactuated grippers [20, 21] provides design principles applicable to friction-based snake robot contact systems.

3 | SYSTEM DESIGN AND MATHEMATICAL MODELLING

3.1 | Mechanical Design

The proposed robot is a 10-DOF servo-driven modular snake robot. Each degree of freedom is a controlled rotational joint enabling coordinated body bending. Rigid body segments are connected by servo-powered joints, permitting the robot to form pipe-climbing postures through distributed multi-point contact rather than single-point clamping. Figure 1 illustrates the robot model inside pipe boundaries and the general climbing configuration.

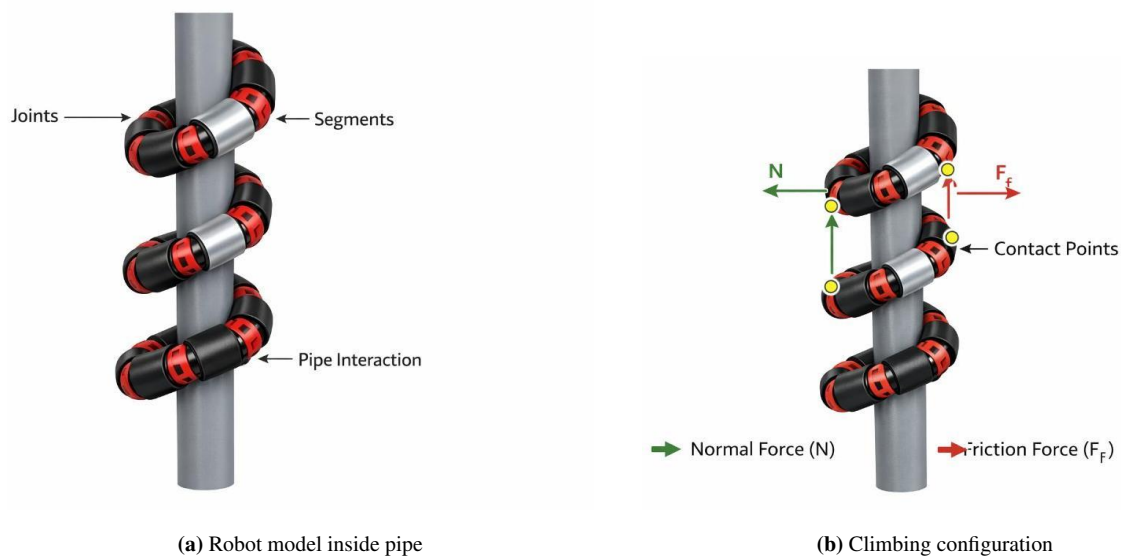


FIGURE 1 2D representation of the 10-DOF snake robot inside pipe boundaries; (b) general climbing movement configuration.

3.2 | Kinematic Modelling

The robot is modelled as an articulated chain. Joint angle trajectories follow sinusoidal functions generating travelling body waves consistent with wave-based gait generation (Hatton and Choset, 2009):

$$\theta_i(t) = A \sin(2\pi f t + (i-1)\varphi), \quad i = 1, 2, \dots, 10 \quad (1)$$

where A is amplitude, f is gait frequency, and φ is the phase shift between adjacent joints. Link orientation and node coordinates are computed cumulatively:

$$\psi_k = \sum_{i=1}^k \theta_i, \quad x_k = x_{k-1} + l \cos \psi_k, \quad y_k = y_{k-1} + l \sin \psi_k \quad (2)$$

The vertical coordinate y_k quantifies upward climbing progress. Joint angle trajectories for selected and all 10 joints are shown in Figure 2.

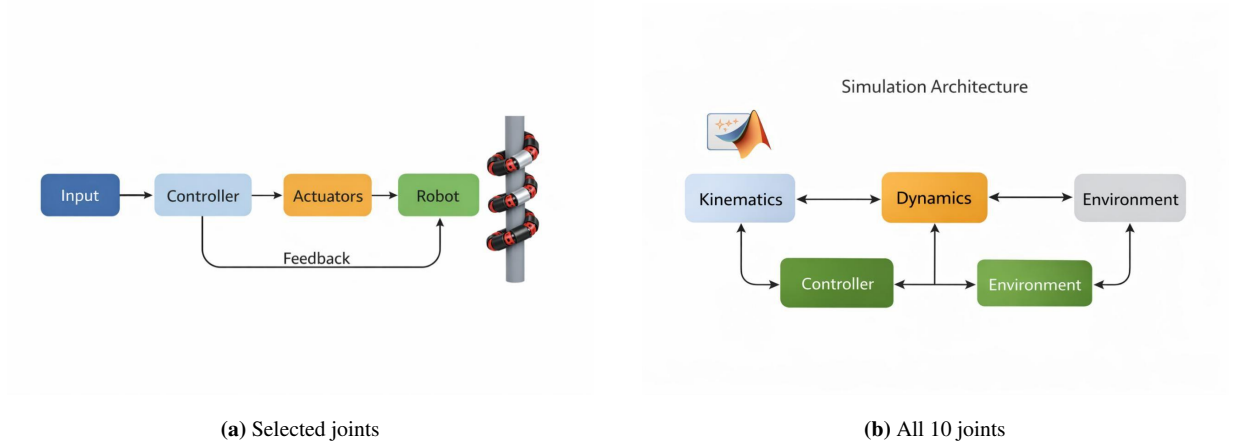


FIGURE 2 Joint angle trajectories: (a) selected joints; (b) all 10 joints showing coordinated phase-shifted wave.

3.3 | Dynamic Modelling and Force Analysis

The pipe interaction model (Figure 3) relates normal force N , friction force F_n , and gravitational resistance F_g :

$$F_n = \mu N \geq F_g = mg \sin \alpha \quad (3)$$

$$\tau_i = I_i \ddot{\theta}_i + b_i \dot{\theta}_i + \tau_{\text{load},i} \quad (4)$$

$$E = \int_0^T \sum |\tau_i \omega_i| dt \quad (5)$$

Slip prevention requires $\mu N \geq mg \sin \alpha$. Low μ or high α reduces available friction below gravitational resistance, causing slip.

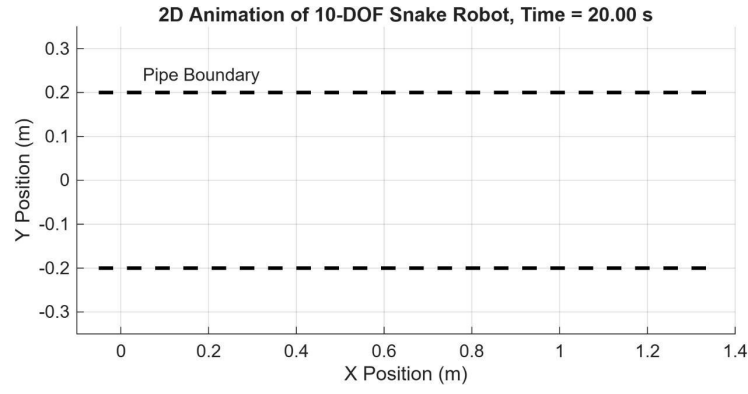


FIGURE 3 Pipe interaction model.

3.4 | Friction-Based Distributed Gripper

The proposed gripper is a distributed friction-based contact system rather than a mechanical clamp. Selected body segments function as temporary anchors while others advance, enabling simultaneous gripping and locomotion. Normal force is generated by body curvature pressing against the pipe wall; the resulting friction prevents slip. This approach eliminates discrete clamp-release cycles, offering mechanical simplicity and locomotion continuity. Performance is evaluated through slip ratio, stability index, grip reliability, and energy consumption.

4 | SIMULATION SETUP AND CONTROL ARCHITECTURE

The system is implemented in MATLAB/Simulink comprising five subsystems: kinematic (sinusoidal joint trajectories), dynamic (force and torque calculations), pipe environment (geometry and surface conditions), controller (PID with adaptive feedback), and output evaluation. The control architecture is shown in Figure 4. Five simulation scenarios with systematically increasing difficulty are defined in Table 1. Input parameters (amplitude $A = 25^\circ$, frequency $f = 0.5$ Hz, phase shift $\phi = \pi/5$) are held constant across all scenarios.

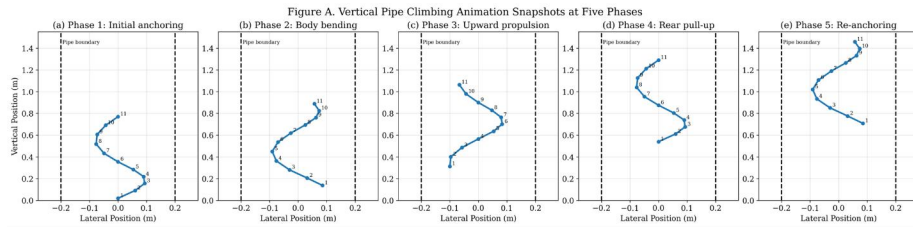


FIGURE 4 General movement configuration of the snake robot during pipe-climbing simulation.

TABLE 1 Simulation scenarios with varying pipe conditions.

Scenario	Diameter (mm)	Inclination ($^\circ$)	Friction (μ)	Difficulty
S1	50	0	0.60	Easy
S2	75	30	0.55	Low-Moderate
S3	100	60	0.45	Moderate
S4	125	75	0.40	Difficult
S5	150	90	0.35	Very Difficult

5 | RESULTS AND DISCUSSION

5.1 | Climbing Performance

Climbing distance results (Figure 5) confirm that maximum distance is achieved under S1 conditions (smallest diameter, horizontal, highest friction), with performance decreasing progressively through S2–S5. The most significant drop occurs between S3 and S4–S5, where combined high inclination, large diameter, and low friction substantially reduce climbing effectiveness.

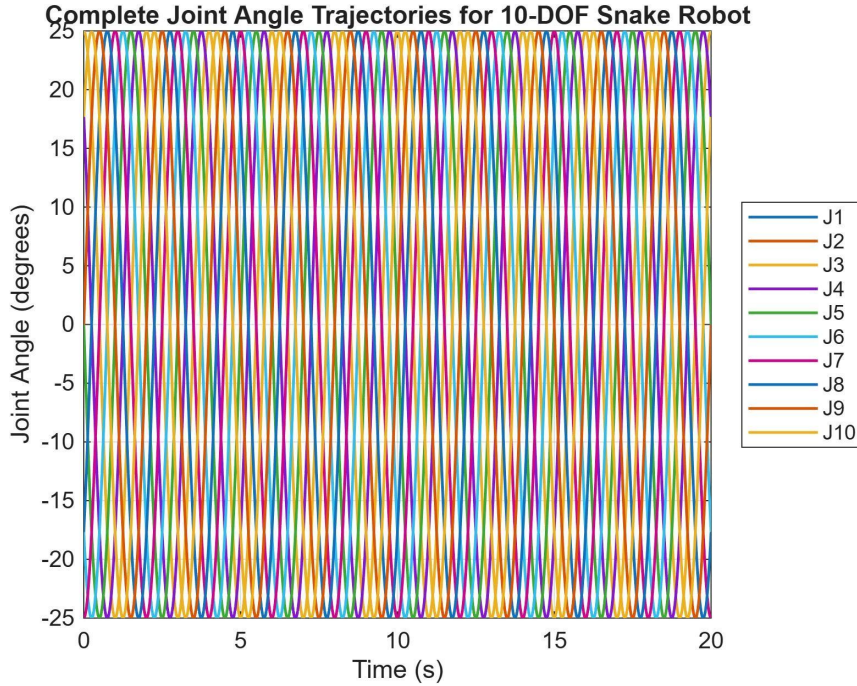


FIGURE 5 Sample joint angle trajectories for selected joints of the 10-DOF snake robot.

5.2 | Speed Analysis

Climbing speed decreases monotonically with inclination (Figure 6a), with the sharpest decline above 60° where gravitational resistance dominates. Larger pipe diameters also reduce speed (Figure 6b) by diminishing contact force effectiveness per unit body length.

5.3 | Stability and Slip Analysis

Slip ratio increases monotonically with inclination (Figure 7a), remaining low below 60° and escalating sharply at 75° – 90° as the gravitational component exceeds available friction. The stability index (Figure 7b) decreases in inverse proportion. Diameter-based analysis (Figure 7c) confirms that larger pipes produce higher slip due to reduced contact force effectiveness.

5.4 | Grip Reliability and Energy Consumption

Grip reliability (Figure 8a) remains high for S1–S3 and falls markedly in S4–S5, where the combination of large diameter, steep inclination, and low friction approaches the fundamental limits of friction-only gripping. Energy consumption (Figure 8b) increases monotonically from S1 to S5, driven by greater actuator effort for contact maintenance and anti-slip correction. Figure 8c shows that increasing friction coefficient directly reduces energy consumption, confirming that surface quality governs energetic efficiency.

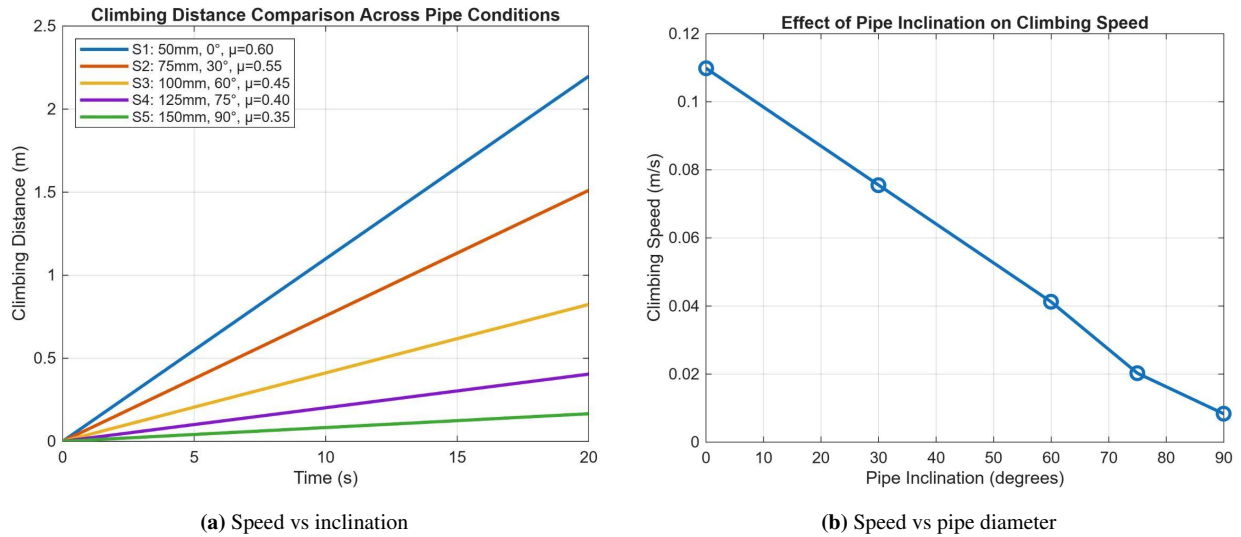


FIGURE 6 Speed performance: (a) effect of inclination; (b) sensitivity to pipe diameter.

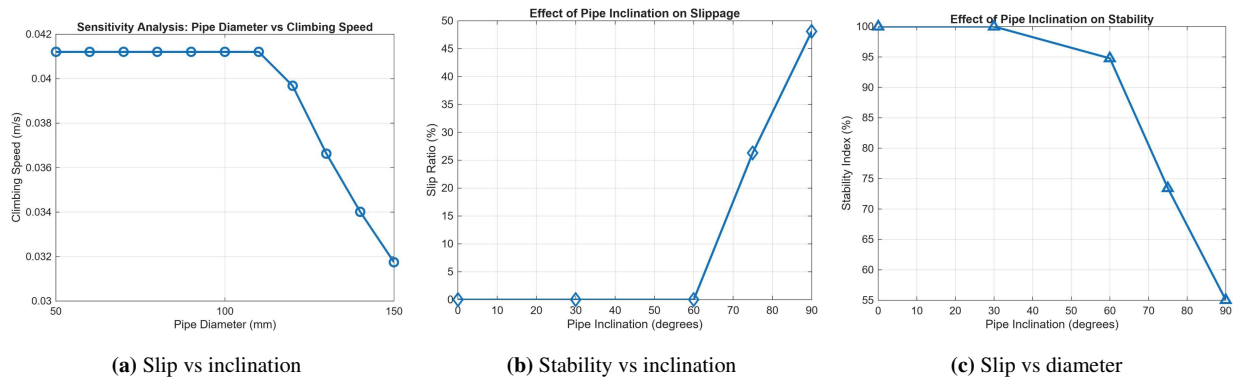


FIGURE 7 Stability and slip: (a) slip ratio vs. inclination; (b) stability index vs. inclination; (c) slip ratio vs. pipe diameter.

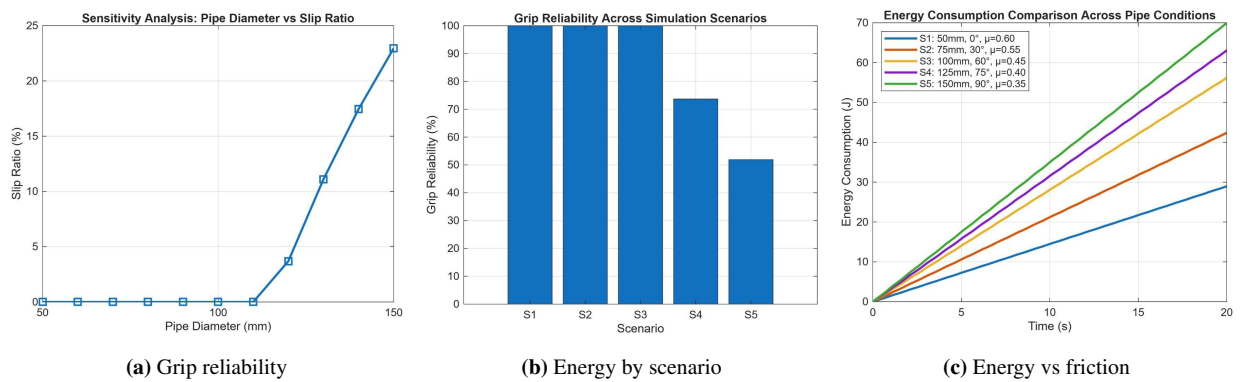


FIGURE 8 Grip reliability across scenarios; (b) energy consumption by scenario; (c) energy vs. friction coefficient.

5.5 | Sensitivity Analysis

Sensitivity analysis (Figure 9) confirms that friction coefficient and pipe inclination are the dominant performance drivers. Climbing speed is maximised at high friction and low inclination, while slip is minimised under the same conditions. The operational envelope within which friction-based gripping is reliable is clearly bounded by $\alpha < 60^\circ$ and $\mu > 0.45$.

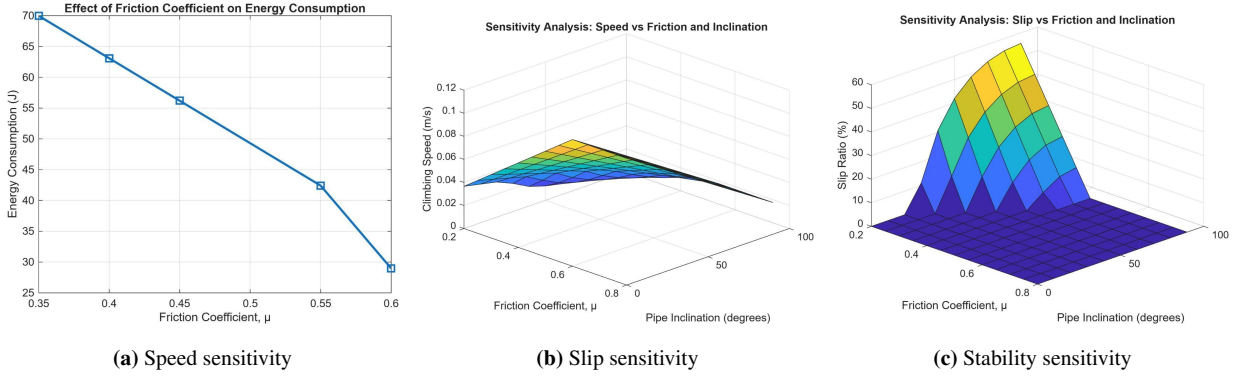


FIGURE 9 Sensitivity analysis: (a) climbing speed; (b) slip ratio; (c) stability index — all vs. friction coefficient and pipe inclination.

5.6 | Phase-Wise Vertical Climbing Analysis

Vertical climbing is decomposed into five sequential stages (Figure 10): (1) Initial Anchoring—selected segments contact the pipe wall, generating friction to prevent downslip; (2) Body Bending—servo joints increase curvature, raising normal force and friction; (3) Upward Propulsion—travelling body wave displaces the centre of mass vertically; (4) Rear Pull-Up—posterior segments advance following front-segment progression; (5) Re-Anchoring—a new stable contact pattern is established at a higher vertical position. Slip ratio is minimised during anchoring phases and peaks during propulsion, while stability is lowest during rear pull-up as contact redistributes across the body.

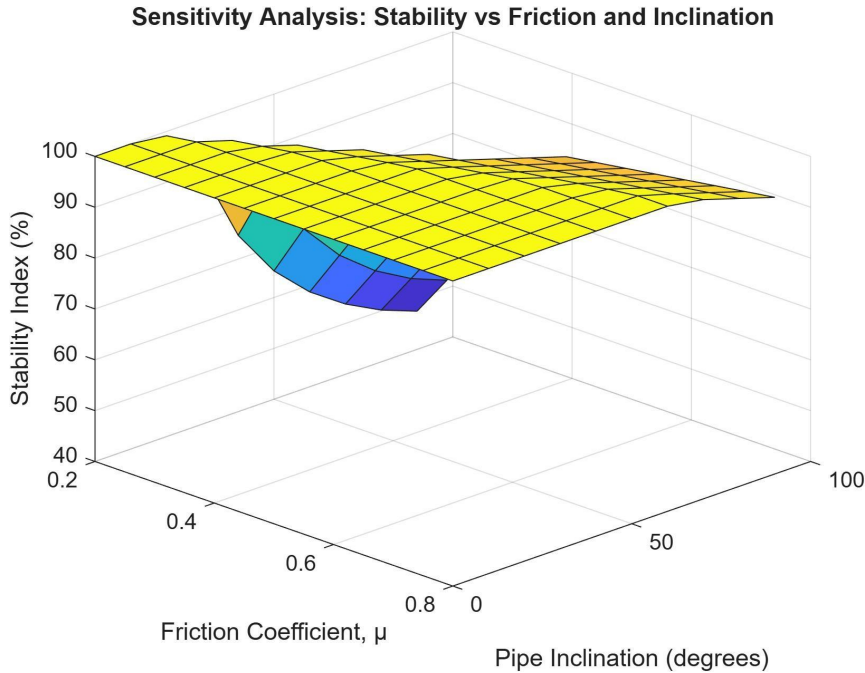


FIGURE 10 Sensitivity analysis of stability index against friction coefficient and pipe inclination.

6 | CONCLUSION

This paper presented a simulation-based framework for climbing pipe and gripper control mechanisms for a 10-DOF bionic snake robot. The distributed friction-based gripper provides reliable performance under moderate pipe conditions ($\alpha \leq 60^\circ$, $\mu \geq 0.45$) but degrades under high-inclination, low-friction, large-diameter conditions. Slip escalates sharply above 60° , energy consumption increases with pipe difficulty, and five-stage phase analysis characterises the anchoring-propulsion cycle. Future work should prioritise physical prototype development, integration of contact force sensing for adaptive control, and investigation of hybrid gripper designs combining friction-based and compliant contact to extend reliable operation into high-inclination, low-friction environments.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Abu Nasher Md Nazibullah: Conceptualization, methodology, software, simulation, formal analysis, investigation, data curation, writing — original draft preparation and writing — review and editing. Xingguo Song: resources, visualization, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY

Data available on request from the authors.

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