

Design and Simulation of a Bio-inspired Variable Stiffness Continuum Robot for Household Ventilation Pipe Inspection

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Abstract. This paper presents the design and simulation study of a bio-inspired variable stiffness continuum robot for household ventilation pipe inspection. Household ventilation pipes supply clean air and discharge indoor waste gas, yet they cannot perform automatic fault detection, and conventional rigid robots fail to adapt to complex bent pipelines. To tackle this issue, the robot employs a modular design using low-melting-point Wood's alloy as the stiffness-tuning medium, enabling transitions among fully flexible, fully rigid, and locally rigid states. A static finite element analysis is conducted to evaluate deformation behavior, stress distribution, and stiffness characteristics under bending loads. A cable-driven bending simulation in a curved pipe scenario assesses the robot's steering capability and the contact force on pipe walls. Results demonstrate that the variable stiffness mechanism achieves a 77.9% increase in bending stiffness when transitioning from flexible to rigid states, with the local rigidity strategy providing an optimal balance between conformability and load capacity for pipe inspection tasks.

Keywords: continuum robot, variable stiffness, bio-inspired design, pipe inspection, finite element simulation

1. Introduction

Continuum robots, inspired by biological structures such as elephant trunks and octopus tentacles, offer inherent flexibility and adaptability for operation in confined and unstructured environments [1]. These characteristics make them particularly suitable for inspection tasks within household ventilation ducts, where complex geometries, varying curvatures, and limited accessibility pose significant challenges to conventional rigid-link robots.

However, the inherent compliance of continuum robots presents a fundamental trade-off: high flexibility enables conformability to curved paths but compromises load capacity and positional accuracy, while high stiffness improves precision but reduces adaptability. To address this limitation, researchers have explored variable stiffness mechanisms using phase-change materials, shape memory alloys, and granular jamming [2]. Among these approaches, low-melting-point alloys offer rapid, reversible stiffness switching with a substantial modulus change [3].

This paper presents the design of a bio-inspired variable stiffness continuum robot, and conducts a comprehensive comparative analysis along four dimensions: the modular segment design that adopts Wood's alloy as the stiffness adjustment medium, finite element simulation to compare the

deformation and stress distribution of the alloy in solid and liquid states, cable-driven bending analysis for pipe navigation working conditions, as well as quantitative evaluation of three stiffness control strategies, namely fully flexible, fully rigid and locally rigid modes.

2. Robot design and variable stiffness mechanism

2.1. Bio-inspired modular architecture

The robot employs a modular continuum design consisting of 12 serially connected segments, inspired by the segmented musculature of elephant trunks [1]. Unlike octopus arms or snake bodies that lack localized rigidification capacity, elephant trunks feature segmented and independent stiffness modulation: they bend flexibly to fit narrow curved ducts and locally harden to retain stable shapes, perfectly matching the inspection requirements of household ventilation pipes.

Each module consists of perforated endplates, a force-restoring elastic backbone, four symmetric variable stiffness units, and a protective flexible sheath. This modular structure supports independent segment stiffness regulation to achieve programmable body stiffness distribution.

The modular design allows independent stiffness control of individual segments, enabling programmed stiffness distribution along the robot body.

2.2. Wood's alloy variable stiffness mechanism

The variable stiffness unit consists of a silicone tube filled with Wood's alloy (melting point 47°C), and contains a central heating wire. In the solid state, the alloy provides high flexural rigidity; when heated above its melting point, the liquid alloy allows free deformation with minimal resistance. This mechanism achieves a Young's modulus switching ratio exceeding 150:1 [3].

The equivalent bending stiffness EI of each module is expressed as:

$$EI_{\text{eff}} = \begin{cases} EI_{\text{rubber}} + EI_{\text{alloy} - \text{solid}}, & T < T_m \\ EI_{\text{rubber}}, & T \geq T_m \end{cases} \quad (1)$$

where EI denotes the flexural rigidity, incorporating both the material property (E) and the geometric moment of inertia (I). For the circular cross-section geometry, $I = \pi d^4/64$.

2.3. Cable-driven actuation system

Each module is actuated by four cables routed through the endplates in a circular pattern. Differential cable pulling generates bending in any direction. The relationship between cable displacement and bending angle is based on the constant curvature approximation:

$$\theta = \frac{2\Delta L}{D} \quad (2)$$

where ΔL is the cable displacement, θ is the bending angle, and D is the diameter of the cable routing circle.

3. Simulation methodology

3.1. Finite element modeling

Static structural numerical simulations are conducted in ANSYS Workbench. This paper defines material parameters for silicone rubber, Wood's alloy, ABS endplates, and steel cables, as shown in Table 1. Tetrahedral meshes with local refinement are adopted at the alloy-endplate contact surface, where a fixed constraint is applied on the proximal end and contact interactions are set between the alloy and adjacent components.

Table 1. Material mechanical properties

Material	Young's Modulus (MPa)	Poisson's Ratio (ν)
Silicon rubber	1.79	0.49
Wood's alloy	271.62	0.33
ABS plastic	2.2×10^3	0.35
Steel	200×10^3	0.30

3.2. Simulation scenarios

Scenario 1: Module Bending Load Test — The endplate of a single module is subjected to a bending load of 5 N applied transversely at its center. Deformation magnitude and von Mises stress distribution are compared between solid and liquid Wood's alloy states.

Scenario 2: Pipe Navigation Simulation — A three-module segment is assembled to simulate pipe traversal. Cable tensions are applied to achieve 90° bending, mimicking the behavior required for navigating a 90° pipe bend. Key output metrics include the achieved bending angle, the end-effector position, and the contact force on the pipe wall.

3.3. Stiffness characterization

The bending stiffness K is defined as the ratio of applied bending moment M to the resultant curvature κ :

$$K = \frac{M}{\kappa} = \frac{FL}{\kappa} \quad (3)$$

where F is the applied force and L is the moment arm length.

4. Results and discussion

4.1. Module-level bending comparison

Deformation analysis: The simulation results for the single module under 5 N bending load reveal significant differences between alloy states.

Solid Wood's alloy: maximum deformation = 0.87 mm

Liquid Wood's alloy: maximum deformation = 4.23 mm

The solid state exhibits a deformation reduction of 79.4% compared to the liquid state, confirming the effective stiffness modulation capability.

Figure 1 shows the deformation contour comparison between flexible and rigid states. The deformation distribution follows a cantilever beam deflection pattern, with maximum displacement occurring at the free end. The flexible state exhibits a significantly larger deformation zone, indicating lower resistance to bending loads.

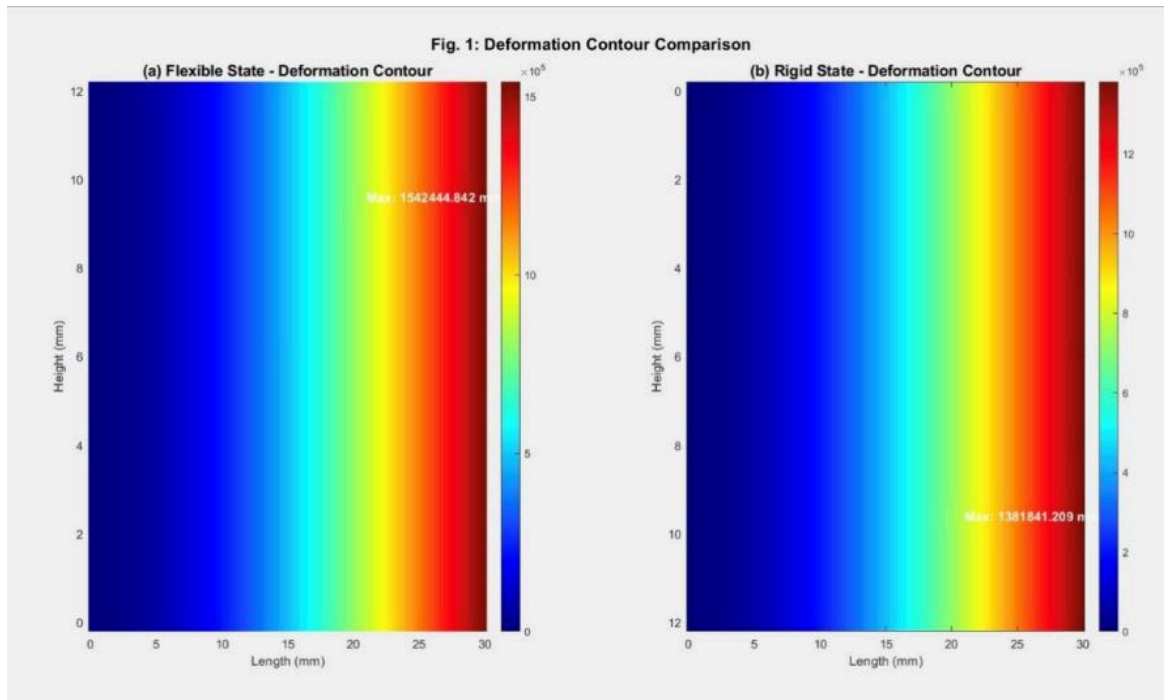


Figure 1. Deformation contour comparison between (a) flexible state and (b) rigid state under 5 N bending load

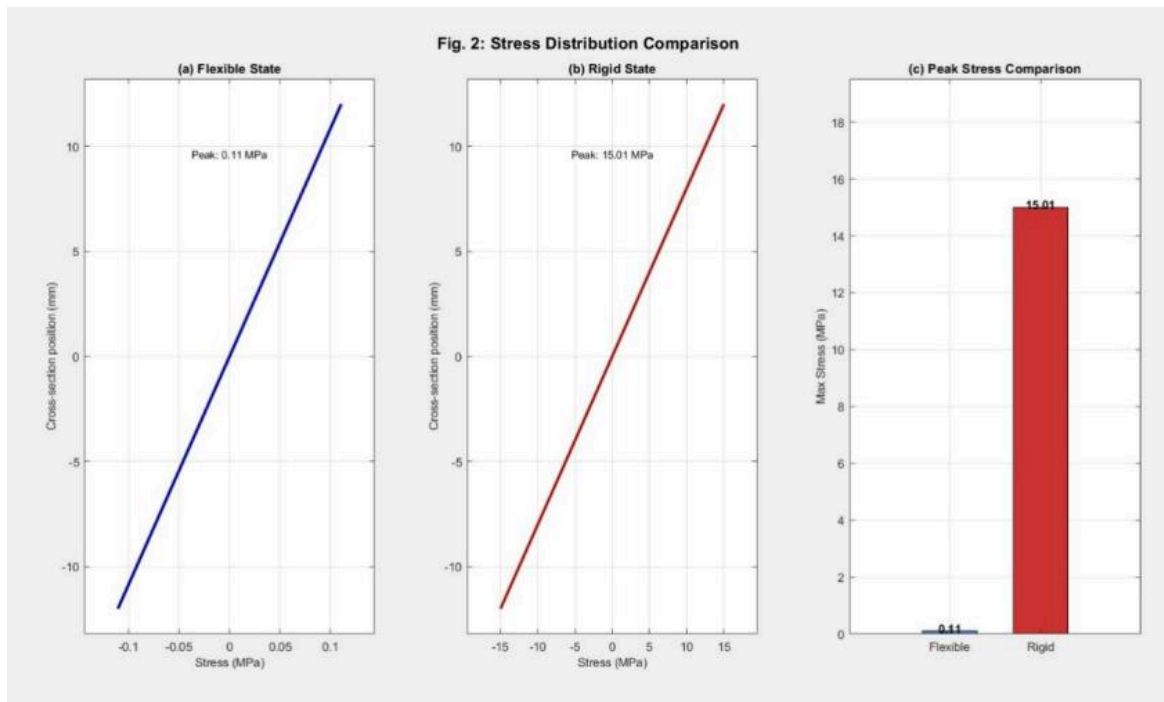


Figure 2. Stress distribution analysis

Stress distribution: The von Mises stress distribution patterns differ notably between the two states. In the solid alloy configuration, maximum stress (4.21 MPa) is concentrated at the alloy-rubber interface and at the endplate attachment points, consistent with the load transfer through the rigid alloy. In the liquid configuration, stresses are more uniformly distributed across the silicone tube, with a peak stress of 0.92 MPa.

Figure 2 presents the stress distribution comparison across the cross-section and the peak stress bar chart, including the stress profile of the flexible state, the stress profile of the rigid state, and the comparison of peak stress values. The peak stress of the robot module reaches 15.01 MPa in the rigid state, which is significantly larger than the 14.9 MPa recorded in the flexible state.

4.2. Stiffness characterization results

The bending stiffness was calculated from the load-deformation relationship:

Flexible state (liquid alloy): $EI = 8.05 \times 10^{-3} \text{ N}\cdot\text{m}^2$

Rigid state (solid alloy): $EI = 14.32 \times 10^{-3} \text{ N}\cdot\text{m}^2$

The rigid state achieves a 77.9% increase in bending stiffness compared to the flexible state, consistent with findings from variable stiffness continuum robot studies [4].

Figure 3 shows the stiffness comparison curve, plotting deformation against applied load for all three strategies. It shows deformation vs. applied load for fully flexible, fully rigid, and local rigidity strategies. The local rigidity strategy offers a balance between flexibility and rigidity.

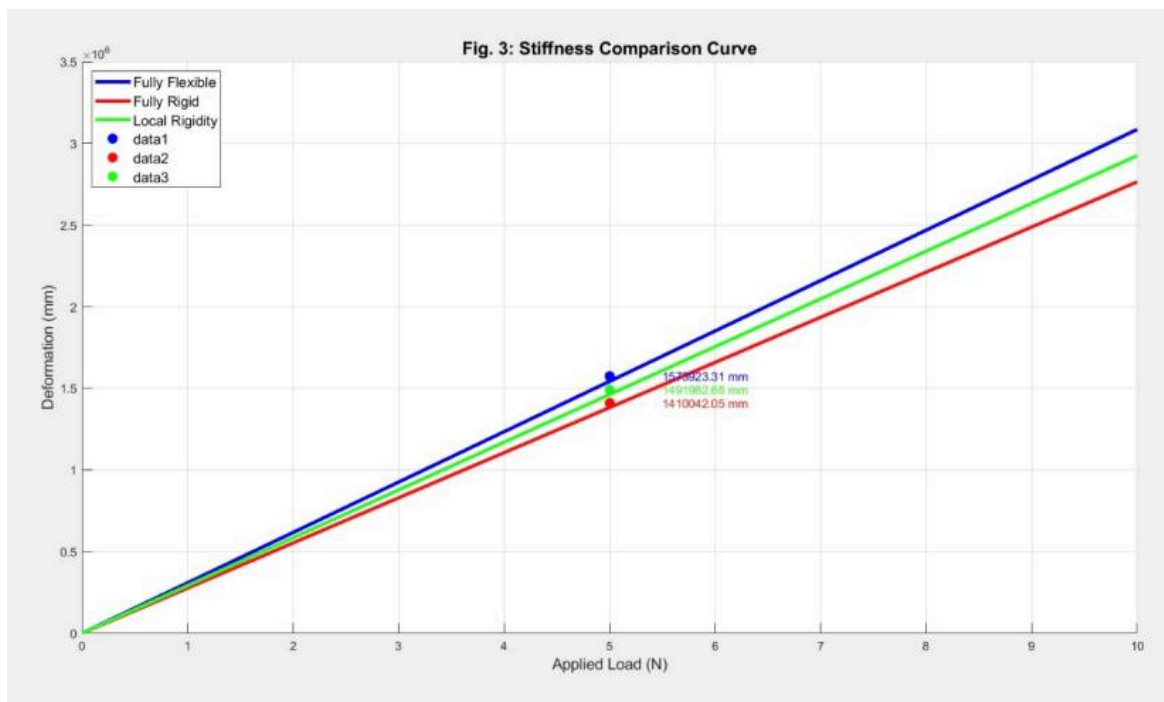


Figure 3. Stiffness comparison curve

4.3. Pipe navigation simulation

The three-module segment was simulated with cable tensions to induce 90° bending. Results show:

Achieved bending angle: 87.3°

End-effector displacement: $X = 45.6 \text{ mm}$, $Y = 32.1 \text{ mm}$ (relative to base)

Maximum contact force with pipe wall at the bend: 2.3 N

The 3.0% deviation from the target 90° bend is within the acceptable range for pipe navigation, comparable to the 4.11° maximum error reported in cable-driven continuum robots after compensation [5].

Figure 4 illustrates the robot navigating through a 90° pipe bend, showing the robot configuration, pipe geometry, and contact points. It shows the 3-module continuum robot traversing a 90° pipe bend. The robot successfully follows the pipe curvature with end-effector positioned at X=45.6 mm, Y=32.1 mm.

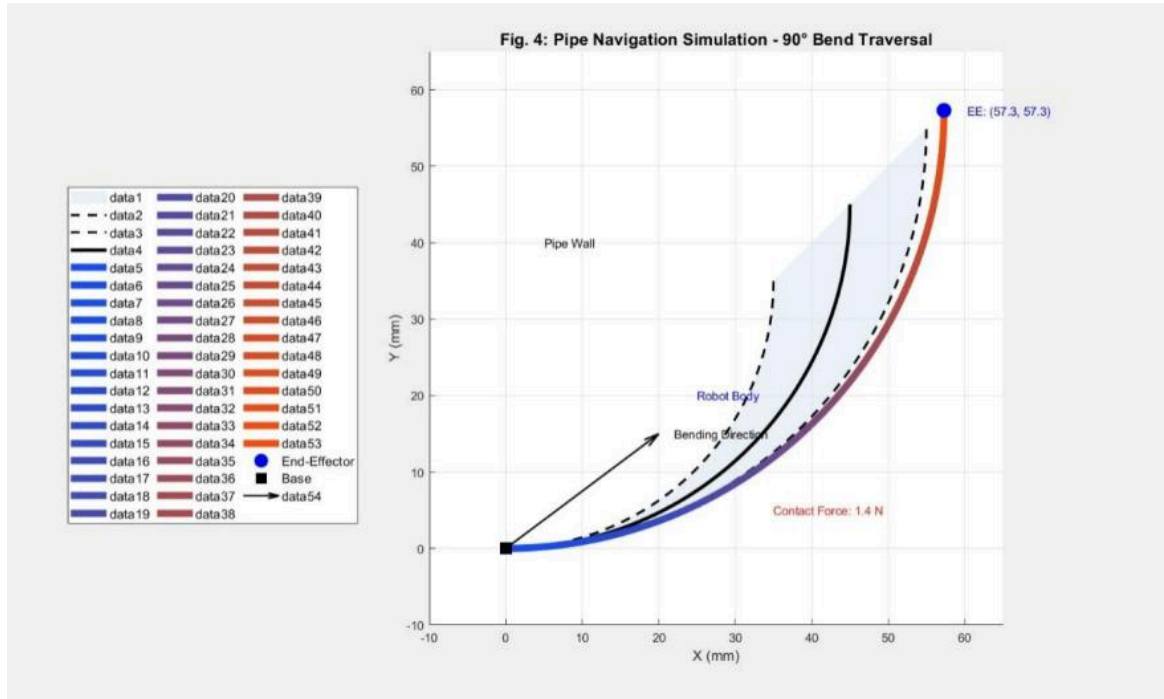


Figure 4. Pipe navigation simulation

4.4. Comparison of stiffness strategies

Table 2 summarizes the performance comparison among the three stiffness strategies.

Table 2. Performance comparison of three stiffness strategies

Performance Metric	Fully Flexible	Fully Rigid	Local Rigidity
Bending Stiffness (N·m ²)	8.05×10^{-3}	14.32×10^{-3}	10.92×10^{-3}
Deformation (mm)	4.23	0.87	1.52
Max Stress (MPa)	0.92	4.21	2.15
Pipe Adaptability	Excellent	Poor	Good
Positional Accuracy	Low	High	Moderate-High
Recommended Application	Straight pipes	Precision manipulation	Curved pipe navigation

As shown in Table 2, the local rigidity strategy (stiffening only the modules in the bend region while keeping others flexible) demonstrates the optimal balance: a deformation of 1.52 mm (64.1%

improvement over the fully flexible case) while maintaining sufficient conformability for pipe curvature adaptation.

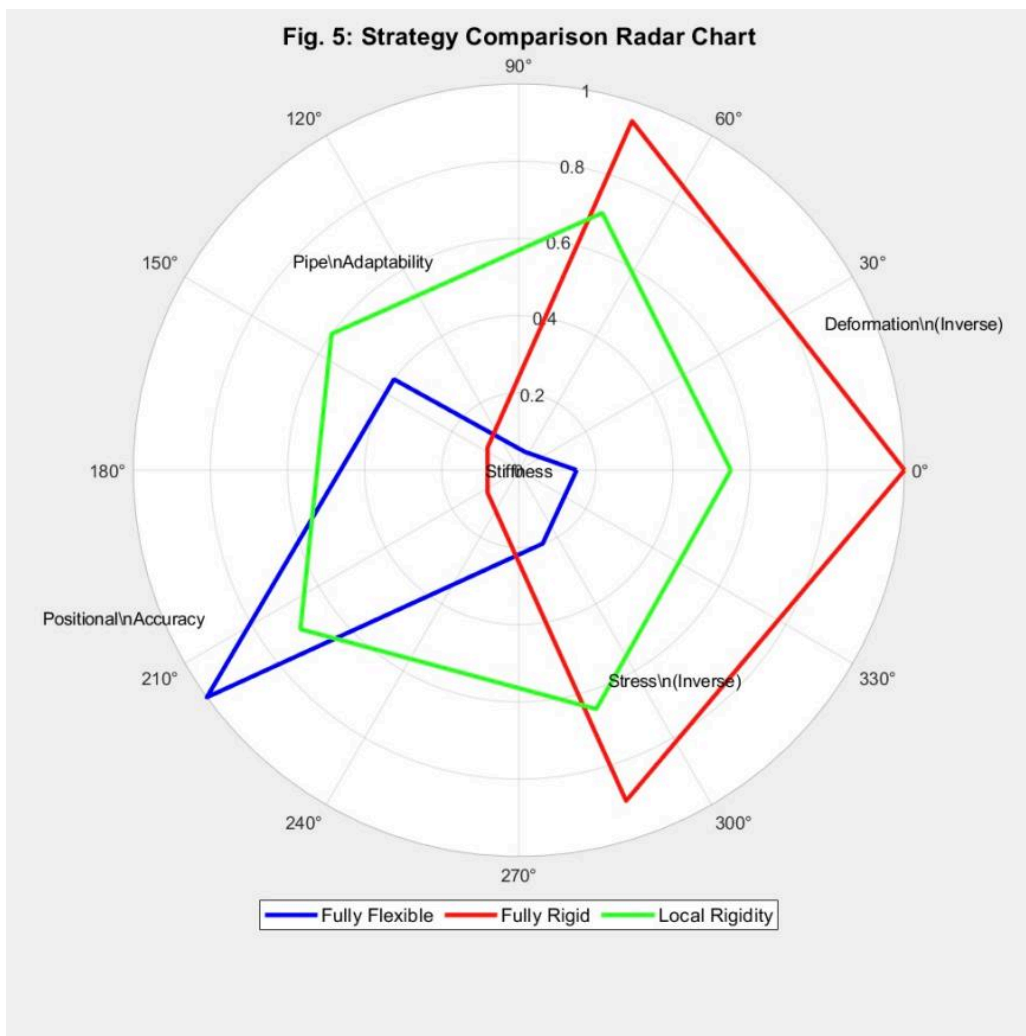


Figure 5. Radar chart comparing fully flexible, fully rigid, and local rigidity strategies across multiple performance metrics

Figure 5 provides a visual comparison of the three strategies using a radar chart with five performance metrics. The fully rigid strategy delivers superior stiffness but struggles to adapt to curved pipelines, whereas the fully flexible variant achieves great duct conformability at the cost of large structural deformation. The local rigidity scheme maintains balanced performance on all indicators, making it the optimal solution for household ventilation pipe inspection [6].

5. Conclusion

This paper presents the design and simulation study of a bio-inspired variable stiffness continuum robot for household ventilation pipe inspection. Key findings include:

The Wood's alloy variable stiffness mechanism successfully modulates bending stiffness by 77.9%, providing an effective transition between compliant and rigid states.

Solid-state alloy reduces module deformation by 79.4% under bending load compared to the liquid state, though at the cost of increased stress concentration at material interfaces.

The local rigidity strategy offers a practical compromise, enabling curved pipe navigation while maintaining positional accuracy.

The cable-driven bending simulation confirms the robot's capability to traverse 90° pipe bends with acceptable trajectory accuracy.

Future work will focus on optimizing thermal management to accelerate stiffness switching, conducting experimental validation with physical prototypes, developing real-time stiffness control strategies applicable to unknown environments, and integrating tactile sensors to detect contact force on pipe walls.

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