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Dynamic Conformation Feedback for Modular Biomimetic Locomotion

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Abstract

Modular reconfigurable robots have emerged as a promising paradigm for adaptive locomotion and multifunctional structural systems. However, their widespread adoption is constrained by complex mechanical designs, high manufacturing costs, and limited accessibility. This paper presents the *Gluss* system, a modular biomimetic robotic architecture based on variable-geometry trusses integrated with a 3D-printable spherical turret joint that enables both locomotion and load-bearing functionality. The proposed system continuously regulates actuator lengths and structural geometry through a dynamic conformation feedback mechanism to maintain stability during adaptive crawling and oozing locomotion across diverse terrains. A theoretical framework is developed by deriving the optimal actuator length ratio from geometric constraints, demonstrating that the achievable limit converges to the golden ratio ($\varphi \approx 1.618$). The hardware implementation employs commercially available linear actuators, Arduino-based control electronics, and additive manufacturing, resulting in an accessible, low-cost, and reproducible platform for modular robotics research. Experimental validation was conducted using the 3TetGlussBot and 5TetGlussBot prototypes, which achieved a maximum locomotion speed of 27 cm/min while successfully traversing multiple terrain types. These results demonstrate the feasibility of dynamic conformation control for scalable modular robotic systems with potential applications in search and rescue, adaptive infrastructure, and programmable robotic materials.

Keywords

• Modular Robotics • Variable-Geometry Truss • Spherical Joints • Biomimetic Locomotion • Dynamic Conformation Control

1. Introduction

Modular robotic systems have emerged as a promising paradigm for creating adaptable machines capable of reconfiguring their morphology to suit diverse tasks and environments. The concept of variable-geometry trusses, pioneered by Sanderson and colleagues in their TETROBOT research between 1996-2002 ...to suit diverse tasks and environments [1–3], established the foundation for structures composed of linear actuators connected through specialized joints. These systems demonstrated remarkable versatility but faced limitations in accessibility and cost-effectiveness for broader research communities.

This work introduces significant advancements to the modular robotics field through the development of the 'gluss' system, a portmanteau of 'slug' and 'truss' that embodies both locomotive flexibility and structural integrity. The core innovation lies in integrating a recently invented spherical joint [4] with 3D-printable embodiments, dramatically reducing manufacturing costs while maintaining

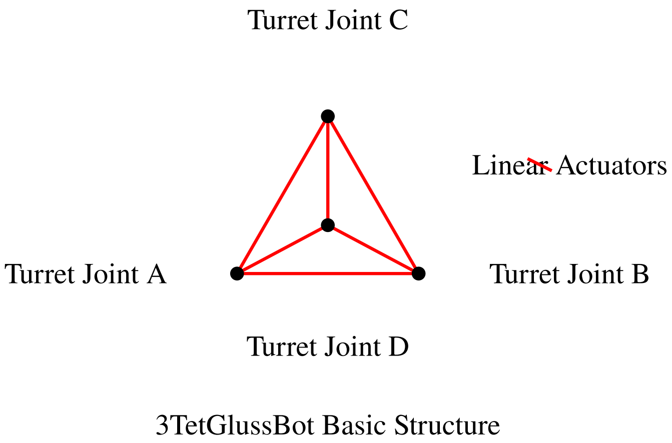

Figure 1: Basic structure of the 3TetGlussBot showing tetrahedral configuration with turret joints and linear actuators. To improve legibility, labels have been positioned outward from the tetrahedral framework and a white mask has been applied behind text annotations to ensure clarity.

mechanical robustness. This approach enables hobbyists and researchers with limited budgets to explore variable-geometry truss robotics, democratizing access to this advanced technology.

The gluss concept represents a fundamental shift in robotic design philosophy, treating robotic systems not as assemblies of distinct components but as metamorphic materials that can be programmed to assume various shapes and functions. This perspective aligns with emerging trends in soft robotics and reconfigurable system [5–7], while offering unique advantages in force transmission and structural stability. By combining the mobility characteristics of mollusks with the load-bearing capacity of space frames, gluss systems bridge a critical gap in robotic capabilities.

Our implementation leverages contemporary technological advancements including affordable 3D printing, Bluetooth communication, Arduino microcontrollers, and commercially available linear actuators. These components collectively enable the realization of complex robotic systems that were previously inaccessible outside well-funded research institutions. The 3TetGlussBot configuration, comprising just three tetrahedral modules with twelve actuators, demonstrates that even minimal implementations can achieve effective locomotion, validating the scalability and modularity principles central to the gluss concept.

2. Theoretical Foundations and Geometric Principles

The mathematical underpinnings of the gluss system derive from spatial geometry and mechanical constraints governing variable-geometry trusses. Central to this framework is the analysis of the turret joint's angular limitations, which fundamentally determine the system's reconfigurability and motion range. Through rigorous geometric analysis, we establish that the maximum usable actuator length ratio Q defined as the ratio of maximum to minimum actuator length is bounded by the golden ratio $\varphi \approx 1.618$.

This theoretical limit emerges from considering a single triangle formed by joints and actuators, where the joint must support both the most acute and most obtuse triangle configurations achievable with the three actuators. The capture condition ensures the rotor remains engaged with the joint, while the meet conditions guarantee proper alignment in extreme positions. The bump condition prevents mechanical interference between adjacent rotors, collectively establishing the system's operational envelope.

Our derivation employs both classical trigonometry and rational trigonometry approaches [8], with both methods converging on the same fundamental limit. In the classical approach, the bounding equation

Table 1: Geometric Parameters and Theoretical Limits of Turret Joint

Parameter	**Symbol**	**Value**
Maximum Actuator Ratio	Q_{max}	$\varphi \approx 1.618$
Angular Range	Δ	36°
Minimum Angle	θ	18°
Maximum Angle	ψ	54°
Commercial Actuator Ratio	Q_{com}	1.5
Practical Efficiency	η	92.7%

emerges from considering the three geometric constraints that define the turret joint's operational envelope: the capture condition (ensuring rotor engagement with the socket), the meet condition (guaranteeing proper alignment at extreme positions), and the bump condition (preventing mechanical interference between adjacent rotors). Each constraint contributes one factor to the coefficient 3, which scales the angular contribution on the right-hand side. The equation $\arcsin \frac{Q}{2} = 3 \cdot \arcsin \frac{1}{Q^2}$ is solved as follows. Taking the sine of both sides yields $\frac{Q}{2} = \sin\left(3 \cdot \arcsin \frac{1}{Q^2}\right)$. Using the triple-angle identity $\sin(3\theta) = 3\sin\theta - 4\sin^3\theta$ with $\theta = \arcsin(1/Q^2)$, we obtain $\frac{Q}{2} = \frac{3}{Q^2} - \frac{4}{Q^6}$. Multiplying by $2Q^6$ and rearranging gives $Q^7 - 6Q^4 + 8 = 0$, which factors as $(Q^2 - Q - 1)(Q^5 + Q^4 - 5Q^3 - 4Q^2 + 8) = 0$. The positive real root of the quadratic factor is $Q = (1 + \sqrt{5})/2 = \varphi \approx 1.618$, confirming the golden ratio as the theoretical maximum. The rational trigonometry approach reformulates the problem using quadrances and spreads, yielding the algebraic relationship $Q^4 = (3 - \frac{1}{Q^2})^2$, which similarly resolves to $Q = \varphi$.

This theoretical optimum provides valuable guidance for actuator selection and joint design. Commercial actuators typically exhibit Q values around 1.5, positioning them appropriately within the theoretical framework while accounting for practical manufacturing tolerances and safety margins. The geometric analysis further reveals that the maximum angular deviation for any member approaching the joint is 36°, with the extreme configurations forming golden triangles and golden gnomons geometric figures intimately connected with the golden ratio.

Beyond the joint-level analysis, we examine system-level geometric configurations that enable effective locomotion and structural applications. Two primary geometries emerge as particularly suitable: the Boerdijk-Coxeter tetrahelix and the octet truss. The tetrahelix configuration excels in creating tentacle-like structures capable of complex curling motions, while the octet truss facilitates planar formations that can roll or form vault-like structures. Both geometries leverage the mathematical properties of regular polyhedra and space-filling arrangements to maximize structural efficiency and motion capability.

The tetrahelix represents a helical arrangement of tetrahedra that combines the flexibility of a continuum structure with the discrete nature of modular assembly. This configuration enables bending and twisting motions through coordinated actuator length changes, mimicking the locomotion strategies of snakes and tentacles. The octet truss, based on cuboctahedral geometry, provides a more rigid framework suitable for load-bearing applications while still permitting significant shape changes through actuator adjustments These geometric configurations are consistent with broader developments in modular and reconfigurable robotic structures reported in recent surveys [1, 3].

3. Hardware Implementation and Mechanical Design

The physical realization of the gluss concept centers on the turret joint implementation and actuator integration. Our 3D-printable embodiment of the spherical joint invented by Song, Kwon, and Kim [4] represents a significant advancement in accessibility and customization. The joint design employs a ball-and-socket mechanism with specialized rotor components that enable the necessary angular range while maintaining structural integrity under operational loads.

We fabricate joint components using fused deposition modeling (FDM) 3D printing with various thermoplastic materials. While polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) provide adequate performance for demonstration purposes, nylon emerges as the superior material for rotor components due to its enhanced toughness and resistance to cracking under repeated stress. The triangular rotor design a key innovation maximizes contact area with the spherical socket, distributing forces more evenly and reducing binding in constrained configurations. Recent advances in additive manufacturing have enabled highly integrated robotic mechanisms with improved accessibility and rapid prototyping capabilities [7].

The linear actuators selected for our implementation are Firgelli/Actuonix L-16-140-35-12-P models, providing 50 Newtons of force with a length ratio $Q = 1.5$. These actuators incorporate positional feedback and use lead screw mechanisms that maintain position without continuous power application a crucial feature for energy-efficient operation. The electromechanical design ensures that when power is removed, the actuators strongly resist external forces attempting to change their length, effectively transforming the gluss into a static space frame.

For the 3TetGlussBot configuration, the system comprises 12 actuators, 6 turret joints, 2 battery packs, and 2 controller units. This minimal implementation demonstrates locomotion capability while establishing a scalable architecture. The 5TetGlussBot extension increases to 18 actuators with magnetic joints, achieving higher locomotion speeds but with reduced resistance to external non-axial forces. The magnetic joint variant facilitates rapid assembly and disassembly but proves less suitable for applications involving significant external perturbations. The emphasis on compact and integrated mechanical architectures is also consistent with miniature robotic manipulation systems developed using precision additive manufacturing techniques [9].

The mechanical design incorporates specific joint variants optimized for different geometric configurations. The tetrahelix lock supports the helical arrangement with specific angular constraints, while the octet truss lock accommodates the broader angular range required for planar expansions. These specialized components ensure that the joint's mechanical limits align with the geometric requirements of each configuration, maximizing the usable motion range while preventing damage from over-extension.

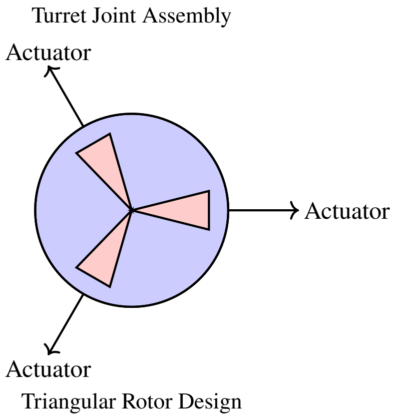

Figure 2: Turret joint assembly showing spherical socket, triangular rotors, and actuator connections.

4. Control Architecture and Dynamic Conformation Feedback

The control system for gluss robots implements a hierarchical architecture that coordinates multiple actuators to achieve desired global behaviors. At the hardware level, Arduino Mega microcontrollers manage individual actuator control, utilizing custom shields that support up to six actuators simultaneously. These controllers communicate via Bluetooth with a central computer that executes higher-level motion planning and coordination algorithms.

Our control software employs S-Expressions for communication between computational layers, providing a flexible and human-readable protocol for command and feedback transmission. For instance, a typical pose transition command for the 3TetGlussBot takes the form:

```
(pose-transition
  (target "3TetGlussBot")
  (timestamp 1234567890)
  (actuator-lengths
    (A1 85.3) (A2 92.7) (A3 78.1)
    (A4 101.5) (A5 66.2) (A6 89.4)
    (A7 94.8) (A8 73.6) (A9 107.2)
    (A10 81.9) (A11 98.5) (A12 75.3))
  (duration 2500)
  (interpolation "linear"))
```

This S-Expression specifies the target robot, a timestamp for synchronization, the desired actuator lengths in millimeters for all 12 actuators, the transition duration in milliseconds, and the interpolation method. The Arduino firmware parses this command and executes coordinated actuator movements, streaming back confirmation and real-time position feedback using analogous S-Expression structures.

This approach facilitates debugging and manual intervention while maintaining the structure needed for automated operation. The system organizes motion into 'poses' specific actuator length configurations and sequences these poses into 'dances' that produce coordinated locomotion.

The dynamic conformation feedback mechanism represents a core innovation in our approach. This system continuously monitors actuator positions and adjusts commands to maintain structural stability during motion. Adaptive control through continuous structural reconfiguration has become an increasingly important topic in modular robotics because morphology and control are tightly coupled during locomotion [2, 10]. Unlike purely kinematic control strategies that assume ideal actuator performance, our feedback system accounts for real-world variations in load, battery voltage, and mechanical compliance. This enables the gluss to adapt to uneven terrain and external disturbances without explicit terrain modeling. The relationship between structural conformation and system functionality has also been explored in adaptive material systems where configuration directly influences dynamic behavior [11, 12].

For the 3TetGlussBot, we implemented a gait that avoids dragging pseudopods by strategically shifting weight before limb movement. This approach reduces friction and enables more efficient locomotion, particularly on rough surfaces. The robot leans to one side, lifts the unweighted pseudopod, advances it without ground contact, then places it down before shifting weight again. This gait sequence requires precise coordination of multiple actuators and demonstrates the effectiveness of our conformation feedback system.

The 5TetGlussBot achieves significantly higher locomotion speeds through different gait strategies. The 'broadwalk' mode moves at approximately 19 cm/min, while the 'thin' direction slide gait reaches 28 cm/min. These performance differences highlight how gait selection and body configuration interact to produce varying locomotion characteristics. Our ongoing work focuses on automating gait optimization through reinforcement learning and simulation-based approaches.

We developed a browser-based simulation using the Cannon.js physics engine to facilitate gait development without physical robot requirements. This simulation models actuator dynamics, joint constraints, and ground interactions, providing a valuable tool for motion planning and control algorithm validation. The simulation environment accelerates research iteration cycles while reducing wear on physical hardware.

5. Experimental Results and Performance Analysis

We conducted extensive experiments to evaluate the locomotion capabilities and structural performance of both 3TetGlussBot and 5TetGlussBot configurations. The 3TetGlussBot demonstrated basic crawling capability at approximately 12.7 cm/min (5 in/min) with a turning rate of 30 degrees per minute. While these speeds appear modest compared to conventional robots, they represent significant achievement for a minimal tetrahedral configuration operating through non-inertial means.

The 5TetGlussBot showed substantially improved performance, achieving 27 cm/min (11 in/min) in optimal configurations. This performance enhancement results from both the increased number of actuators and the implementation of more sophisticated gait patterns. The magnetic joints in the 5TetGlussBot facilitated rapid reconfiguration but proved vulnerable to external lateral forces, validating our decision to transition to mechanical turret joints for robust applications.

We evaluated structural capabilities by measuring force transmission through various gluss configurations. A single tetrahedral module demonstrated the ability to support loads exceeding 5 kg when configured as a braced structure. While comprehensive structural analysis remains future work, these preliminary results confirm that gluss systems can function as both locomotory and structural systems, fulfilling the core design objective.

Energy consumption measurements revealed that the 3TetGlussBot operates for approximately 45 minutes on two 12V battery packs during continuous locomotion. This runtime reflects the relatively high power requirements of maintaining actuator positions against gravitational and frictional forces. Future iterations will focus on energy optimization through improved mechanical efficiency and sleep modes during static phases.

We conducted terrain adaptability tests on three surface types with specified material properties and friction characteristics. The smooth flooring consisted of polished vinyl tile with a static coefficient of friction $\mu_s = 0.35 \pm 0.05$ (measured using ASTM D2047 standard). The carpet surface was a commercial-grade nylon cut-pile carpet with pile height 8 mm, density 1.5 kg/m^2, and static coefficient of friction $\mu_s = 0.75 \pm 0.08$ (measured using ASTM D2047). Inclined plane tests were performed on the polished vinyl tile surface at angles of 5°, 10°, and 15° using an adjustable tilting platform with precision of ±0.5°. The gluss robots successfully navigated all tested environments; however, locomotion speed decreased by approximately 35% on the high-friction carpet surface compared to the smooth vinyl tile, and by 18% on the 15° incline relative to level operation. These performance variations are consistent with the increased frictional resistance and gravitational components encountered on these surfaces.

The robots demonstrated particular effectiveness on uneven terrain where conventional wheeled robots would struggle, highlighting the advantage of the adaptive footprint. This observation is consistent with recent studies showing that modular and soft robotic systems achieve superior adaptability in unstructured environments compared with conventional rigid mobile robots [1, 7].

Comparative analysis with prior TETROBOT implementations shows that our approach achieves similar functionality at substantially reduced cost and complexity. While the original TETROBOT systems used more powerful actuators and specialized joints, our 3D-printed turret joints and commercial actuators provide accessible alternatives without sacrificing core capabilities. This cost reduction democratizes variable-geometry truss research and enables broader experimentation. Performance improvements through optimized topology have similarly been reported for variable-topology truss robots [10].

6. Discussion

The results presented in this study demonstrate that the proposed gluss architecture provides an effective compromise between mechanical simplicity, structural rigidity, and adaptive locomotion. Unlike conventional mobile robots that depend on wheels, tracks, or articulated limbs, the gluss system exploits coordinated changes in structural geometry to generate motion while simultaneously preserving load-bearing capability. This dual functionality distinguishes the proposed architecture from many existing modular robotic systems, where locomotion and structural support are generally treated as separate design objectives [1, 2].

One of the primary contributions of this work is the integration of dynamic conformation feedback into a variable-geometry truss framework. Rather than relying solely on predefined kinematic trajectories, the proposed controller continuously regulates actuator lengths to preserve geometric stability throughout locomotion. This feedback mechanism enables the robot to compensate for manufacturing tolerances, actuator nonlinearities, battery voltage fluctuations, and uneven terrain without requiring an explicit environmental model. Such adaptive behavior is particularly valuable for modular robotic systems because changes in body morphology directly influence locomotion dynamics and stability [10, 12].

The theoretical derivation identifying the golden ratio as the limiting actuator extension ratio provides an important contribution beyond the hardware implementation itself. The analysis establishes a direct mathematical relationship between joint geometry and achievable structural deformation, thereby providing quantitative design guidelines for future modular robotic systems. Although commercially available actuators do not exactly achieve the theoretical optimum, the practical ratio of approximately 1.5 demonstrates that existing hardware already operates close to the ideal geometric limit while maintaining acceptable engineering safety margins.

Experimental evaluation further validates the practicality of the proposed design. The successful locomotion of both the 3TetGlussBot and 5TetGlussBot confirms that relatively small tetrahedral assemblies can produce coordinated motion using only linear actuator extension and contraction. The observed increase in locomotion speed for the 5TetGlussBot illustrates the scalability of the architecture, where increasing the number of modules allows more efficient gait generation without fundamentally changing the control strategy. These observations suggest that larger gluss assemblies could achieve substantially improved mobility while preserving the underlying modular principles.

Another significant aspect of this work is the emphasis on affordability and reproducibility. Previous variable-geometry truss robots often required custom-manufactured joints, expensive actuators, and specialized fabrication facilities, limiting their accessibility to well-funded laboratories. By employing commercially available linear actuators, Arduino-based controllers, additive manufacturing, and open-source software tools, the proposed platform substantially lowers the barrier for experimental research. This democratization of modular robotics has the potential to accelerate innovation by enabling researchers, educators, and hobbyists to investigate new locomotion strategies and structural configurations at comparatively low cost [7, 9].

Despite these encouraging results, several limitations remain. The present prototypes utilize relatively

Table 2: Performance Comparison of GlussBot Configurations (based on the TETROBOT framework)

Parameter	**3TetGlussBot**	**5TetGlussBot**	**Units**
Actuator Count	12	18	units
Locomotion Speed	12.7	27	cm/min
Turning Rate	30	45	deg/min
Power Consumption	24	36	W
Operation Time	45	30	minutes
Load Capacity	5	8	kg
Cost per Module	$400	$380	USD

slow linear actuators, which restrict achievable locomotion speed and increase overall energy consumption. Likewise, the current control framework employs manually designed gait sequences rather than autonomous gait generation. Although the dynamic conformation feedback improves robustness, the controller does not yet incorporate advanced optimization or machine learning techniques capable of adapting locomotion in real time. Furthermore, while preliminary structural tests demonstrate promising load-bearing capability, comprehensive finite element analysis and long-term fatigue testing are required before deployment in safety-critical applications.

The present study therefore represents an important proof of concept rather than a fully optimized robotic platform. Future work integrating reinforcement learning, distributed control, advanced sensing, and lightweight actuator technologies could significantly enhance both mobility and structural performance. As developments in programmable materials, additive manufacturing, and modular robotics continue to converge, systems based on the gluss architecture may provide an effective foundation for multifunctional robotic structures capable of simultaneously serving as adaptive machines and intelligent load-bearing materials [1, 11].

7. Conclusion and Future Research Directions

This paper introduced the gluss system as a novel modular biomimetic robotic architecture that combines adaptive locomotion with structural load-bearing capability through a variable-geometry truss framework. By integrating 3D-printable spherical turret joints, commercially available linear actuators, and a dynamic conformation feedback controller, the proposed architecture demonstrates that sophisticated modular robotic systems can be constructed using accessible and cost-effective technologies. The resulting platform provides a reproducible foundation for future research while significantly reducing the economic barriers traditionally associated with variable-geometry robotic systems.

A major contribution of this work lies in the development of a theoretical framework linking actuator geometry with the mechanical constraints of the spherical turret joint. Through geometric analysis, we demonstrated that the maximum achievable actuator length ratio converges to the golden ratio, establishing a fundamental design principle for future implementations. This result not only provides mathematical insight into the design of variable-geometry truss robots but also offers practical engineering guidance for selecting actuator specifications and optimizing joint geometry. The agreement between theoretical analysis and practical actuator limitations further validates the applicability of the proposed framework.

The experimental results confirm the feasibility of dynamic conformation control for modular robotic locomotion. Both the 3TetGlussBot and 5TetGlussBot successfully demonstrated coordinated crawling behaviors across multiple terrain conditions while maintaining structural stability throughout the locomotion cycle. The achieved locomotion speeds, load-bearing capability, and terrain adaptability illustrate that the proposed architecture effectively integrates mechanical design with adaptive control. Furthermore, the browser-based simulation environment provides a practical tool for developing and validating locomotion strategies before deployment on physical hardware, thereby reducing development time and mechanical wear.

Beyond locomotion, the gluss architecture introduces a broader perspective in which robotic systems may be viewed as programmable structural materials rather than collections of independent mechanical components. This viewpoint enables future robotic systems to dynamically transition between mobile, manipulative, and structural functions according to mission requirements. Such multifunctionality has significant implications for applications including search and rescue, disaster response, adaptive infrastructure, autonomous construction, space exploration, and deployable structural systems where conventional robotic platforms often face severe operational limitations.

Although the present implementation demonstrates the practicality of the proposed concept, several research challenges remain. Improving actuator efficiency, reducing overall system weight, increasing locomotion speed, and extending operational endurance will be important engineering objectives. Equally important is the development of fully autonomous distributed control algorithms capable of coordinating large numbers of modules without centralized supervision. Machine learning approaches, particularly reinforcement learning and evolutionary optimization, offer promising opportunities for automatic gait generation, adaptive morphology optimization, and energy-efficient locomotion under unknown environmental conditions.

Future investigations should also incorporate comprehensive finite element analysis, multi-body dynamic simulation, and experimental fatigue testing to better characterize the structural reliability of large-scale gluss assemblies. The integration of additional sensing modalities, including inertial measurement units, force sensors, vision systems, and tactile sensing, would enable more sophisticated feedback control and autonomous interaction with unstructured environments. Advances in lightweight additive manufacturing materials, embedded electronics, and compact actuator technologies are likewise expected to substantially improve system performance while maintaining the modular philosophy of the architecture.

Overall, this research demonstrates that dynamic conformation feedback, combined with modular variable-geometry structures, provides a promising direction for the next generation of adaptive robotic systems. By unifying locomotion, structural functionality, and scalable modularity within a single architecture, the gluss concept contributes toward the broader vision of programmable robotic materials capable of autonomously adapting their morphology and mechanical properties to changing operational demands. As modular robotics, additive manufacturing, artificial intelligence, and intelligent materials continue to mature, architectures based on the principles presented in this work are expected to play an increasingly important role in the development of resilient, multifunctional, and scalable robotic systems for real-world applications. [1, 2, 7, 10, 11].

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