A BIOMIMETIC ROBOTIC SYSTEM WITH TENSEGRITY-BASED COMPLIANT MECHANISM

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Abstract. Biomimicry has played a pivotal role in robotics. In contrast to rigid robots, bio-inspired robots exhibit an inherent compliance, facilitating versatile movements and operations in constrained spaces. The robot implementation in fabrication, however, has posed technical challenges and mechanical complexity, thereby underscoring a noticeable gap between research and practice. To address the limitation, the research draws inspiration from the unique musculoskeletal feature of vertebrate physiology, which displays significant capabilities for sophisticated locomotion. The research converts the biological paradigm into a tensegrity-based robotic system, which is formed by the design of rigid-flex coupling and a compliant mechanism. This integrated technique enables the robot to achieve a wide range of motions with variable stiffness and adaptability, holding great potential for advanced performance in ill-defined environments. In summation, the research aims to provide a robust foundation for tensegrity-based biomimetic robots in practice, enhancing the feasibility of undertaking intricate robotic constructions.

Keywords. Biomimetic, Adaptive Robot, Tensegrity, Compliant Mechanism, Rigid-Flex Coupling

1. Introduction

In recent decades, digital fabrication has relied on robotics for mechanical precision and technological efficiency. The traditional use of rigid robots has been exploited in various applications, especially manufacturing, due to their competence in dealing with massive and repetitive workloads in fixed spaces (Trivedi et al., 2008). Nevertheless, their inability to conform to external impacts or environmental changes is evident. As more advanced demands, such as operation and exploration in extreme terrains (Kobayashi et al., 2022), gradually increased, the inspiration from nature has led to the emergence of biomimicry in robotics. Developers across disciplines, including biology, engineering, and architecture, seek solutions to replicate the adaptability and mobility observed in biological systems.

To address the existing constraints of rigid robots and explore the implementation

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of biomimetic robotics, this research draws inspiration from biomechanics, specifically vertebrate physiology (Zappetti et al., 2020). The structural composition allows vertebrates to possess inherent mechanical advantages, including versatile movement and effective adaptability. This biological system relies on an integrated framework between rigid and soft bodies, which can be characterized by a discrete set of compressed components and a continuum of tensional network. The structural amalgamation provides high compliance, flexibility, driving efficiency, and effective force distribution with a self-balancing mechanism (Liu et al., 2022). Moreover, depending on their current condition or intention, vertebrates can switch the structural stiffness to change their configuration, which enhances the environmental adaptability. Research has confirmed that this biological system aligns with the tensegrity structure, providing an effective basis for robotic bodies (Lessard et al., 2016). Similar to vertebrate appendages, this unique structure is also comprised of rigid and soft components (Motro, 2003) with dexterous reconfigurability. Building upon this anatomical and mechanical concept, the research has developed a hybrid robotic system based on a numerical form of tensegrity structure. This proposed structure is derived from a linear augmentation of prismatic tensegrity units (Zhang and Ohsaki, 2015), imitating the spine-like attributes commonly seen in vertebrates. Furthermore, the research presents comprehensive information about the robot implementation, grafting the tensegrity-based compliant mechanism onto a mechatronic control system with programmable tendon-driven actuators. This innovation allows the robot to perform variable motions, demonstrating a feasible framework for tensegrity-based robots in architecture, engineering, and construction (AEC) industries.

2. Related Works

Biomimetic robots based on tensegrity structures are constructed by mimicking the geometric form, function, and kinematic principles found in the nature world. Researchers in the field of architecture and mechanical engineering have conducted scientific projects attempting to graft the structural properties onto robotics. The principal goal of these bio-inspired robots is to represent the structure and behavior of specific living organism or appendages, such as fish (Chen and Jiang, 2019), human shoulder (Li et al., 2022), bird neck (Fasquelle et al., 2019), and snakes (Hirose and Mori, 2004), broadening the application of biomimetic robots in practice. Research has indicated that tensegrity structures can be manipulated by either changing the length of compressive components or pulling on certain segment of tensional members (Hanaor and Levy, 2001). The former method provides a deployable capability, while the latter allows the robot to achieve variable movements. To further explore the mobility and optimize the driving efficiency, the research adopts the pulling approach and converts it into the tensegrity-based compliant mechanism.

3. Robot Implementation

3.1. BIOMIMETICS

Unlike conventional rigid robots, most biological structures rely on a harmonious blend of rigid and soft components. In vertebrates, the appendages are based on a musculoskeletal system composed of bones, muscles, tendons, and joints. The integration of rigid and soft elements constitutes a dynamic form, displaying versatile mobility and high compliance in degrees-of-freedom. Rigid bones undergo compression and comprise the framework of the entire structure. The muscles, on the contrary, maintain the stability of the system via a tensional network. This rigid-flex connection between bones and muscles, driven by tendons as actuators, is a crucial feature of this bio-inspired system.

In terms of biomechanics, the tendon-driven actuation allows precise, centralized control over bone movements through a continuous force distribution. Once the structure is pulled by tension from the tendons, the stress will be distributed through the tensional network. The configuration therefore changes to match the new equilibrated form. In comparison with the rigid counterpart, this bio-inspired mechanism excels in driving efficiency and range of motions, offering a paradigm shift in robotic design.

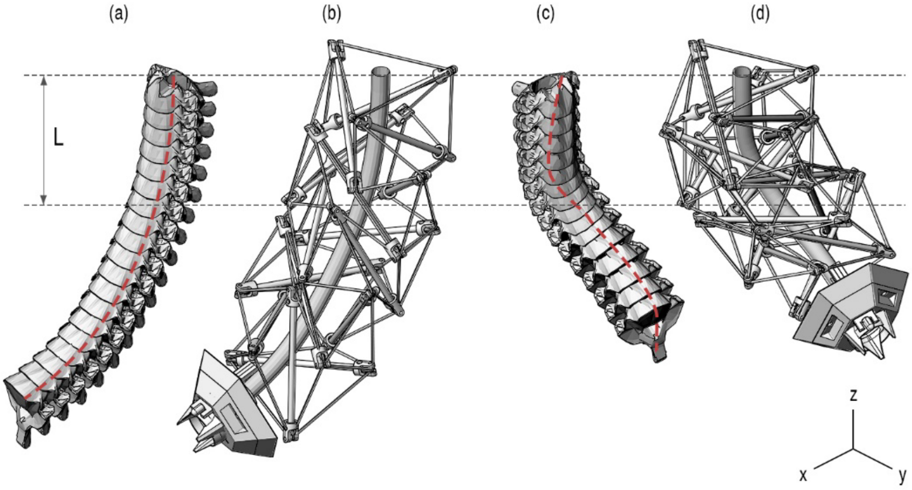


Figure 1. Biomimetic Motions Presented by Kinematic Simulations (a) Bending in Vertebrates (b) Bending Performed by Proposed Robot Model (c) Torsion in Vertebrates (d) Torsion Performed by Proposed Robot Model (L: Length of Each Tensegrity Unit)

3.2. NEMERICAL TENSEGRITY

To imitate the biological system based on tensegrity structures, the research employs the adaptive force density approach to deal with the form-finding issues. The design starts with the prismatic tensegrity. Through the application of external forces, the structure reconfigures with flexibility, displaying its inherent compliance. By augmenting the form with multiple tensegrity units, a spine-like topology is generated and its deformability is amplified as demonstrated in Figure 1. This robot structure is comprised of triangular plates on both ends, hexagonal plates in the middle, and a rhombic network in a circumferential pattern. The rhombic network allows force distributions to achieve on the primary axis, sharing a similarity with the muscles in vertebrates (Figure 2). The proposed numerical robot model is adjustable in dimensions and composition with parametric design process. This provides a customizable foundation and reduces the mechanical complexity of biomimetic robots.

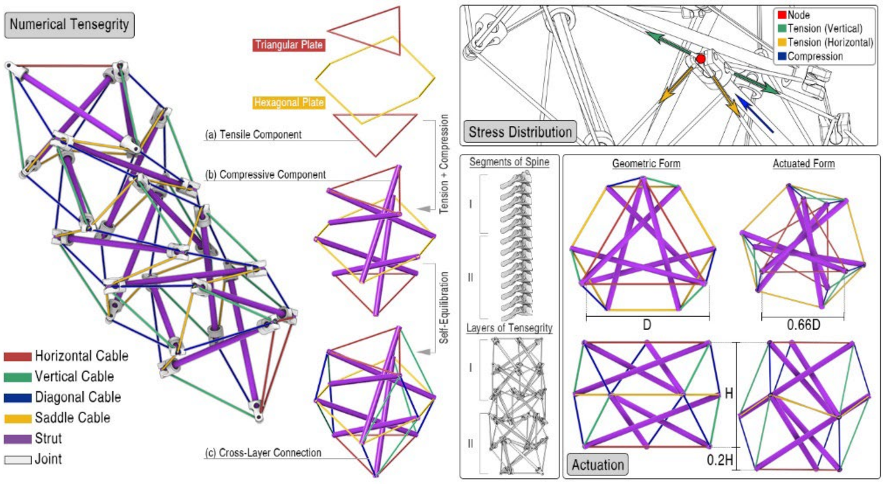


Figure 2. Geometric Form and Structural Performance of The Numerical Tensegrity Robot

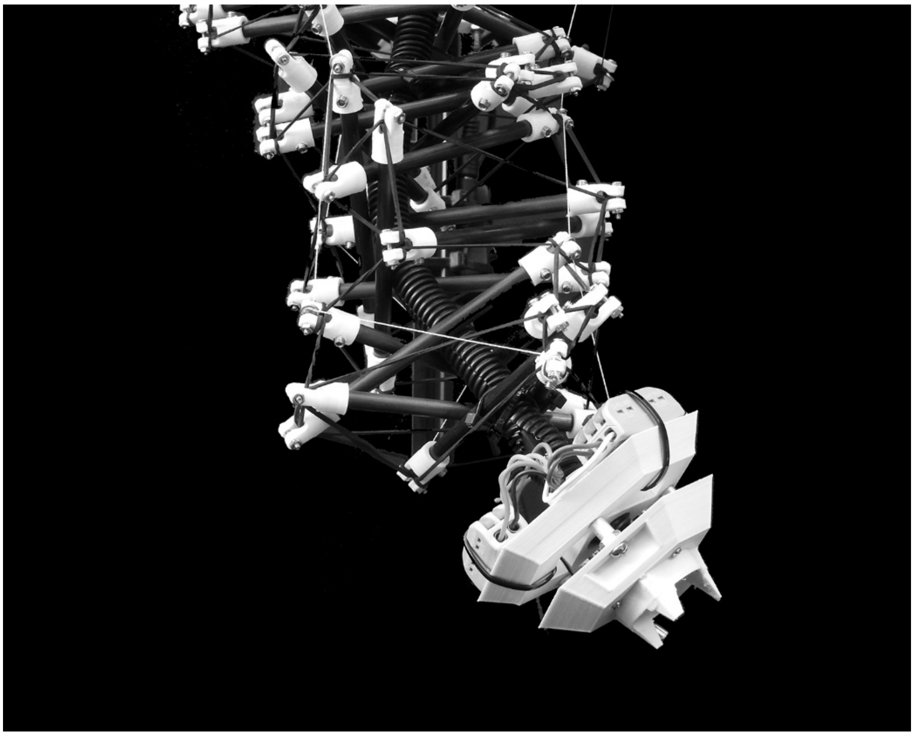


Figure 3. Mechanical Design Detail of The Tensegrity-Based Biomimetic Robotic System

4. Mechanical Design

4.1. RIGID-FLEX COUPLING AND COMPLIANT MECHANISM

The efficacy of the mechanical system has a profound influence on robotic performance, tensegrity-based robots in particular. To achieve versatile mobility and precise manipulation, the self-equilibration based on tensegrity joints needs to be effectively carried out. Thus, the research has developed a rigid-flex coupling as presented in Figure 2 and Figure 3, transforming the entire robot body into a dynamic form with compliant mechanism. Combining the mechanical advantages of both rigid and soft structures, the coupling ensures force distributions on each node. The coupling also allows adaptive changes in the structural stiffness, facilitating advanced movements or load-bearing operations. In terms of materials and interchangeability, the proposed coupling can be easily applied to or dismantled from the compressive struts, as shown in Figure 4. In addition, it can be rapidly fabricated through 3D-printing technology, reducing the entry-level of biomimetic robots with cost-effective implementations and high feasibility.

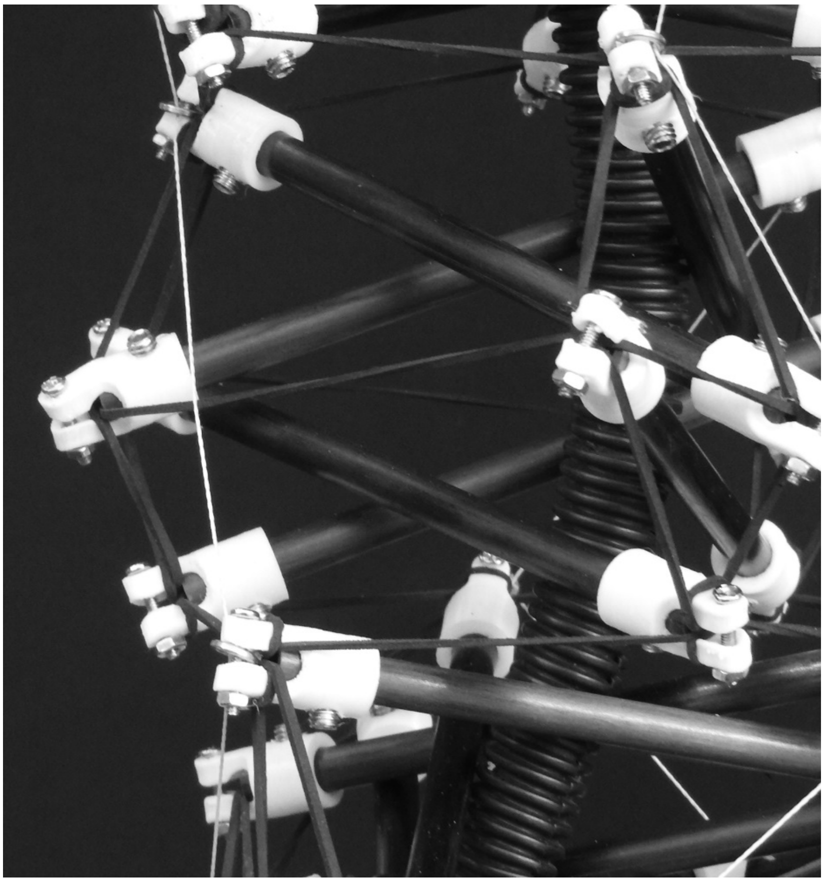


Figure 4. Detail of The Rigid-Flex Coupling With Actuation

4.2. MECHATRONIC CONTROL SYSTEM

As demonstrated in Figure 5 and Figure 6, the research presents an integrated mechatronic system, including parametric control, real-time simulations, and mechanical actuation, to employ the tensegrity-based compliant mechanism. The robot is controlled by a stepper motor set linked to the computational tools, ensuring distributed cooperative control. Using inverse kinematics and delta robotics, the software platform can calculate the control parameters of each motor to achieve the desired position or configuration. The software toolkit, based on Kangaroo and Firefly in Grasshopper, can conduct real-time simulations according to these control parameters and thus establish relationships between current robot configurations and corresponding data from the actuator.

To enhance the trajectory tracking capabilities and other related performance, the entire framework employs a closed-loop control strategy, connecting controller to an infrared sensor. By entering the thermal property of the target, the proposed robot can track the objective and moves adaptively to achieve the trajectory by using the relationship data collected previously. This approach optimizes dexterous mobility and inherent compliance of the tensegrity-based robot body. In addition, equipped with various sensors on the end effector, the robot can be triggered by diverse types of data to fit in its current environment.

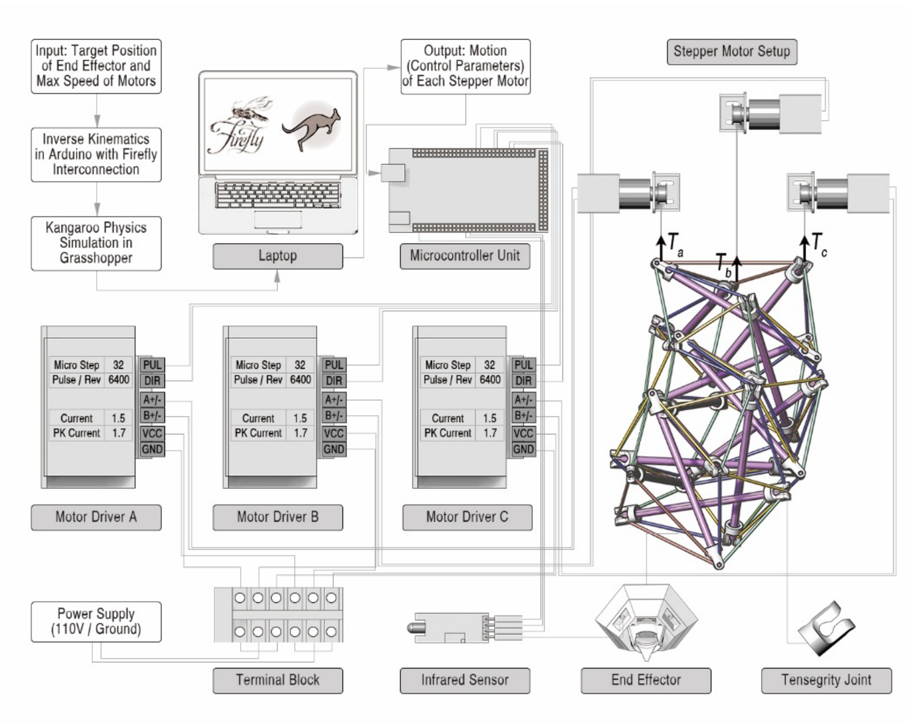


Figure 5. Tensegrity-Based Compliant Mechanism with Mechatronic Control System (Grasshopper / Arduino)

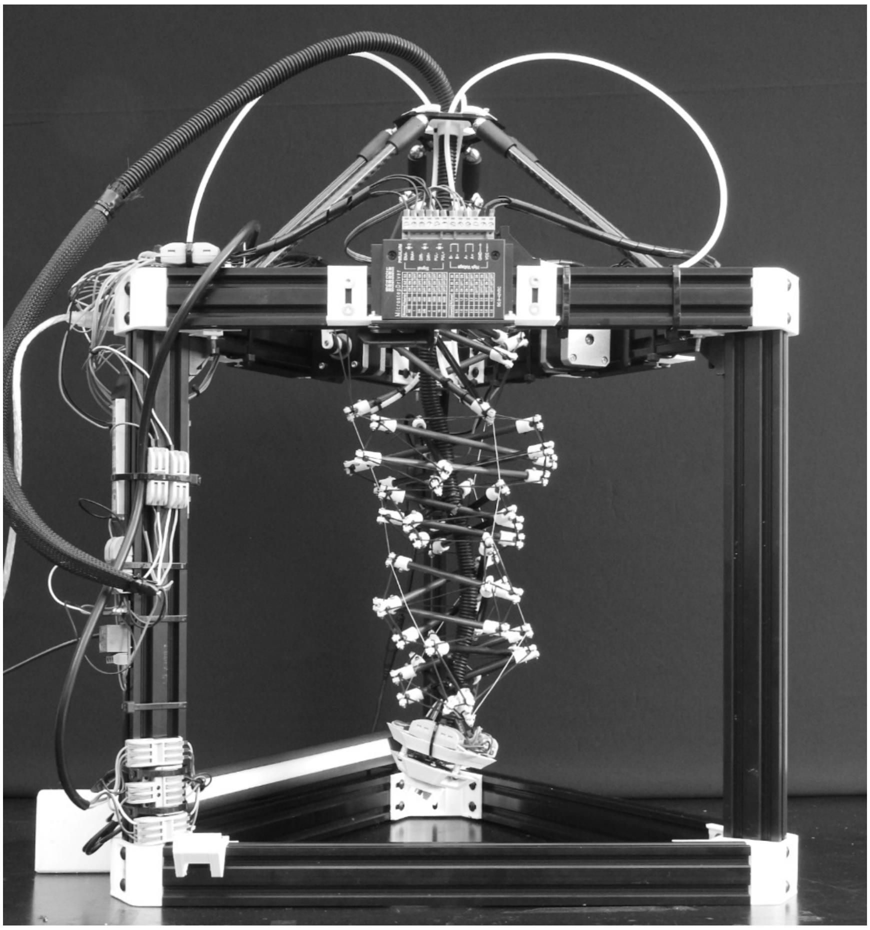


Figure 6. Hardware Setup of The Mechatronic Control System

5. Results and Discussions

5.1. KINEMATICS

In this research, the mobility of the proposed robot has been explored by leveraging the compliant mechanism. Based on the experimental results, it is validated that the rigid-flex coupling design enhances robotic adaptability. The tensegrity-based robot displays high compliance in degrees-of-freedom, enabling a wide range of motions (Figure 7).

The research has developed a programmable tendon-driven technique, enabling biomimetic locomotion. The self-equilibrating ability allows diverse configuration by applying differential tension force on the actuator. Each set of the control parameters corresponds to a specific configuration, including multidirectional (bending, rotation, and torsion) and unidirectional (buckling, contraction and extension) movements, as shown in Figure 8.

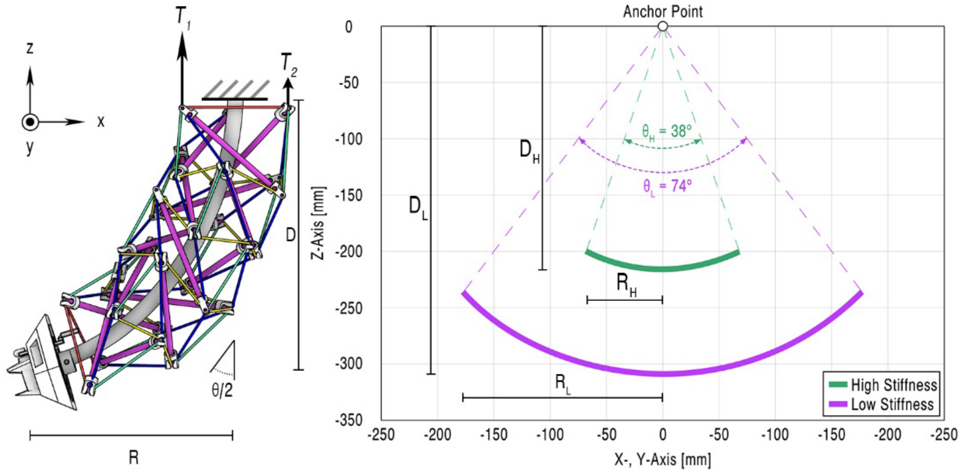
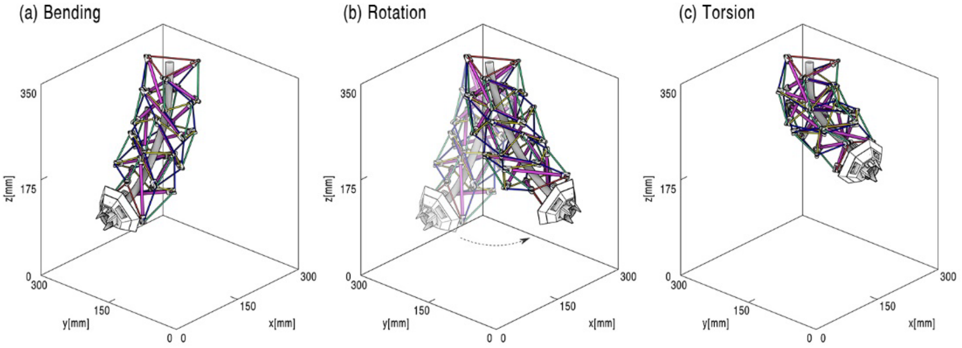


Figure 7. Range of Motions (H: High Stiffness State. L: Low Stiffness State)


(a) Bending (b) Rotation (c) Torsion

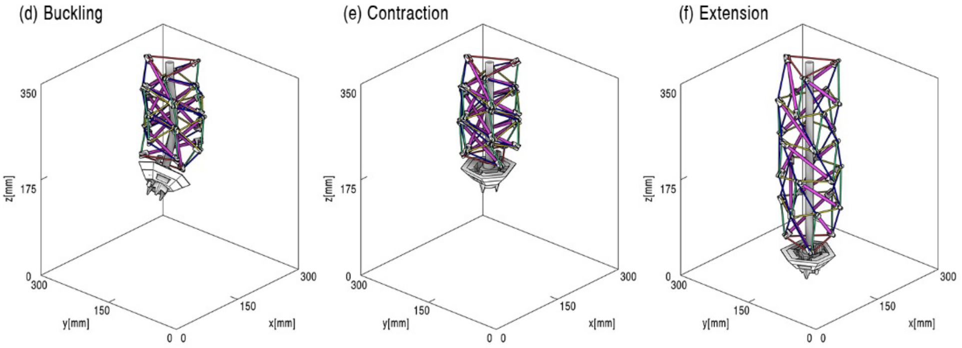

(d) Buckling (e) Contraction (f) Extension

Figure 8. Kinematic Simulations of Tensegrity-Based Robot

5.2. MAINTENANCE

The prestress in the tensional network of tensegrity structures facilitates impact resistance and versatile movement through effective stress distribution. Nevertheless, consideration must be given to the time-dependent prestress loss resulting from cable relaxation. Even slight loss may cause deviation from the simulation results.

5.3. ACCURACY

Although the proposed robot validates the effectiveness of the rigid-flex coupling, there are several challenges to be completed before further applications. In fact, the intrinsic mechanical properties of materials may potentially interfere the operation. First, friction between cables and joints may disrupt the movement of the robot, leading to inaccuracies. Second, the risk of cable fracture when exceeding ultimate strength requires attention. This issue may cause the failure of entire tensional network.

6. Conclusion and Potential Applications

To address the constraints encountered by current robots when confronted with external impacts and confined spaces, the research draws inspiration from biological paradigms and explores the implementation of biomimetic robots. By leveraging the musculoskeletal characteristic observed in vertebrate physiology, the research develops a robotic system based on tensegrity structures. This bio-inspired robot embodies a fusion of rigidity and flexibility, actuated by the proposed compliant mechanism. The design not only augments the adaptability to varying environmental conditions but also enhances its kinematic performance. Furthermore, the research introduces a mechatronic control system, integrating computational tools and hardware setup. Utilizing inverse kinematics and physics simulations, the robot can be manipulated to achieve versatile movements and execute diverse missions.

The overall robotic performance is evaluated in the research. With variable sets of control parameters, the robot can perform multidirectional and unidirectional movements. Moreover, the passively reconfigurability allows the robot to buffer collisions, attenuating damage from environmental impacts. In terms of future applications, this inherent adaptability enables the robot to complete sophisticated operations in confined environments, such as plumbing shafts, rehabilitation after natural disasters, and underground explorations, demonstrating significant potential for advanced robotic construction.

The research also listed several latent issues, such as material deterioration and intrinsic mechanical limitations. However, design iterations with innovative materials, characterized by high tensile strength and durability, still possess a promising trajectory for addressing these challenges.

In summation, the research demonstrates a robust foundation for tensegrity-based robots, aiming to explore the robot implementation of biomimicry. The proposed robotic system exhibits noticeable potential to undertake complex tasks in challenging environments, contributing to advancements in digital fabrication.

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