Design and Implementation of Novel Underactuated Geometric Compliant (UGC) Robotic Modules with Resizable Bodies

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***Abstract*— This paper introduces a novel underactuated geometric compliant (UGC) robot and explores the behavior of modules with variable radial stiffness to enhance UGC robot versatility. We design and fabricate semi-rigid geometric joints tailored to specific objectives, validating their stiffness and durability through physical testing. A Gaussian process regression model incorporates joint characteristics, including thickness, facilitating the development of easily 3D-printable prototypes. We present various configurations for constructing the overall UGC module, demonstrating a prototype that dynamically reduces its radius while maintaining structural integrity. This study also discusses the potential, challenges, and limitations of UGC modules, providing insights for future UGC robotics research.**

I. Introduction

The robotics field increasingly adopts soft and compliant mechanisms, recognizing their research significance [1]. These attributes, offering flexibility and safety, enhance robotic platform capabilities. However, achieving compliance and flexibility usually necessitates complex actuation with numerous actuators, posing challenges for practical implementation in designs with limited actuators, a concept known as underactuation [2].

Compliance and softness are crucial for safer, more flexible mechanisms [3] and robotic systems [4], offering advantages in various applications. For instance, in challenging environments like power plant inspection where traditional methods are costly and difficult [5], adaptable robots combining softness with durability can operate directly within systems without disassembly [6]. Similarly, navigating sharp environments such as caves or pipes poses challenges for both soft and traditional robots, highlighting the importance of selecting suitable semi-rigid materials like Polylactic acid (PLA) for resilient yet adaptable robot structures [7].

Underactuated robotics, despite their greater complexity compared to fully actuated counterparts, offer numerous advantages including enhanced energy efficiency, material conservation, and space optimization [2], [8]. These robots demonstrate increased efficiency and flexibility, particularly effective with precise control mechanisms in scenarios such as locomotion [9] or shape transformation [10] in constrained environments. Their reduced actuation requirements contribute to conservation efforts by minimizing mass, volume, and energy consumption [8], [11], resembling biological structures like snakes or birds that use minimal actuation for complex morphological transformations. In robotics, integrating geometric compliance with underactuation remains a challenge for achieving adaptive size or form changes efficiently with fewer actuators.

In this paper, our motivation stems from creating geometrically simple-to-3D print bodies that possess compliance and deformability while utilizing underactuated systems to reshape or resize. Our contributions include conducting an in-depth study on compliant geometric plastic (semi-rigid PLA) joint designs and their ease of 3D printing, analyzing the behavior of joints concerning stiffness and recovery angle, developing a model using the Gaussian Regression Process to identify variable stiffness and return angle with varying thickness, and proposing the final compact printable design, including various module design variations, of an underactuated geometric compliant (UGC) module with a motor actuator.

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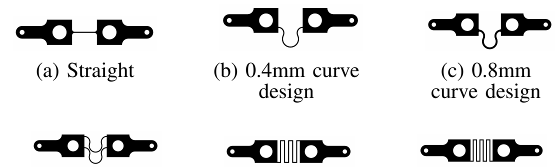


(a) Straight (b) 0.4mm curve design (c) 0.8mm curve design

(d) Double joint design (e) Symmetrical square Wave (f) Non-symmetrical square Wave

Fig. 1: Series of designed geometric compliant joints.

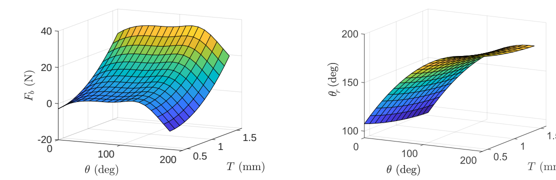
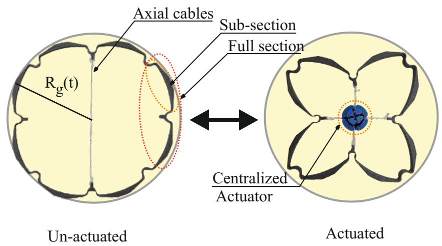


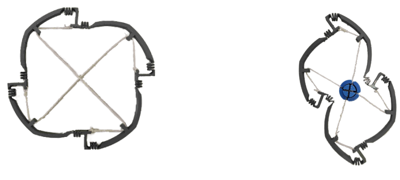
Fig. 2: The trained GP model for angle θ and joint thickness T inputs and output of body force F_b and return angle θ_r of curve joint.

II. Geometric Compliant Joint Design and Tests

This section studies compliance and flexibility across various geometric joint designs. By examining how geometry impacts joint stiffness and recovery, we lay the groundwork for understanding the best combinations necessary to achieve a variable radius module design.

We have proposed various geometric joint forms fabricated using 3D-printed PLA materials, as shown in Fig. Fig. 1. Each joint was analyzed by measuring the force exerted using a Force Gauss sensor and the angular bending θ with computer vision techniques (ImageJ Fiji). The initial straight linear connection exhibited a predictable stress-strain relationship with a defined yield point. The studies present that joints with curve geometries have semi-linear behaviors (see Fig. 1(b)-(d)) in their stiffness model; however, symmetrical square wave models present nonlinear stiffness and return angle behaviour. The square wave geometric joints demonstrate better returnable angles and preserve their deformability, while curve designs lose their plasticity with a high number of rotations.





(a) Un-actuated (b) Actuated

Fig. 3: Example passive prototypes using curved joints and square wave joints in singular distribution form.

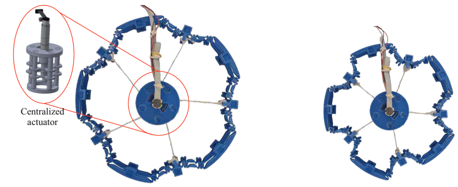
Due to these nonlinearities, the stiffness and return angle is modelled using the Gaussian Regression Process, as shown in Fig. 2, considering curve joints with different thickness parametric values. The Gaussian regression model, effectively encapsulates the recorded data and serves as a reliable tool for calculating the expected force based on angle deformation and joint thickness. This model demonstrates high accuracy within the tested range. However, it becomes less reliable for angle values above 150°or below 30°due to insufficient recorded data in these regions. The only limitation is particularly evident with the extremely high force values observed in the T =1.2 mm and T =1.6 mm tests, where data scarcity leads to reduced prediction accuracy. We have done similar modeling for other geometrical joints presented in Fig. 1 with different thicknesses.

III. Underactuated Geometric Compliant Module

In this section, we present our finalized single 3D-printed UGC modules and compare their results. Lastly, we discuss the successful development of our UGC module results and analyze their behaviour.

One of our passive designs is shown in Fig. 3, using curved joints with cable connections in the centre. This design required a large amount of force to actuate and did not decrease in radius efficiently. This is due to the shape change that caused part of the geometry to bloom outwards while the rest moved in. Our targeted aim is to reduce the R_g outer radius of the module based on a contraction of beams/cables. Another passive compression UGC design using square wave joints, shown in Fig. 3, was tested using a pulley system to drag one layer under another. This design worked but required constant manual rotation from the central actuator and wasn't naturally stable due to inconsistent actuation and dependency on cable contraction order. Additionally, redirection added friction, significantly increasing the required force.

For the final active successful prototype featuring an actuator as the UGC module, the objective was to achieve approximately an 80-85% reduction in diameter to demonstrate the effectiveness of UGC models. Based on hierarchical test



(a) Un-actuated (b) Actuated

Fig. 4: Showing both actuate and not actuated states showing around 80% radius change

designs and experiments conducted with passive modules, it was determined that employing a 5-section ring (as depicted in Fig. 4) would enable more consistent deformation throughout the ring, drawing from our experience with the perpendicular square wave mode. In order to prevent the bending that appeared in previous prototypes, two layers of these rings were printed and connected using vertical connectors that would slot together and keep the centralized actuator properly balanced in the centre of the modular total body. This would also allow for internal space inside the structure to better integrate the motor mounting components.

IV. Conclusion

This study introduces a novel underactuated geometric compliant (UGC) module capable of adjusting its radius, achieving a reduction to around 80% of its initial value. The research also analyzes various geometries for compliant joints, optimizing the design to enhance strength and actuation consistency while minimizing components. Future work will focus on incorporating the UGC into shape and size-changing snake robots, transitioning joints from 2D to 3D forms with curvature-based feedback control.

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