Reconfigurable Multimodal Robots Using Programmable Origami with Variable Stiffness Joints

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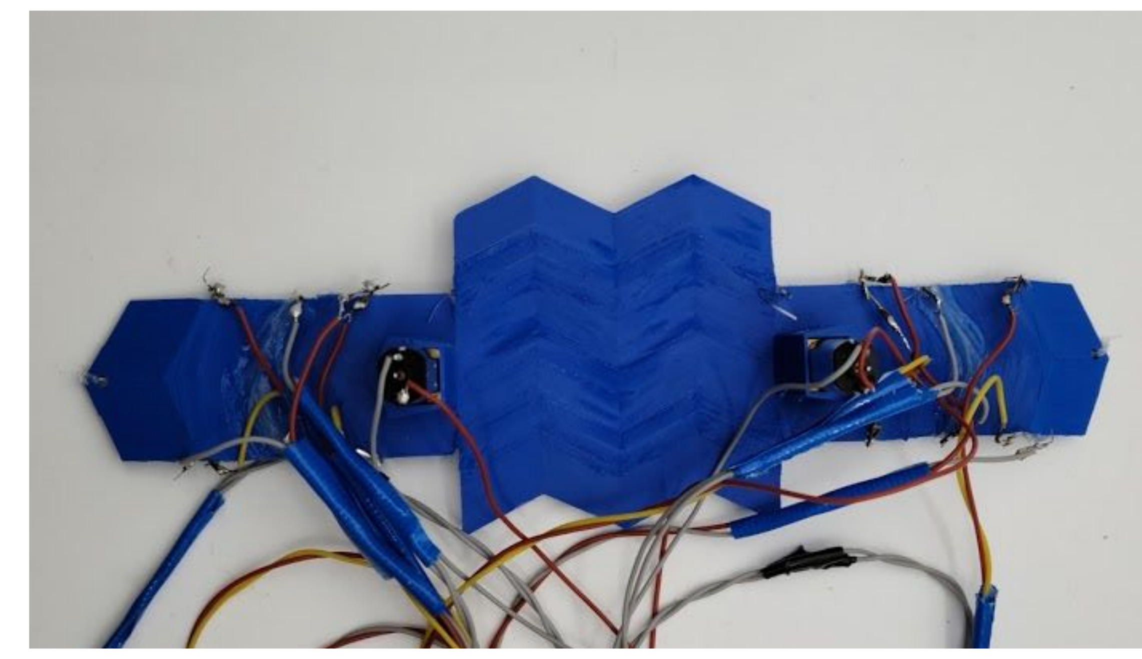
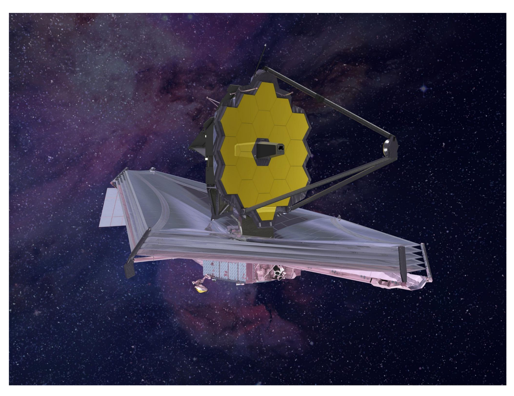


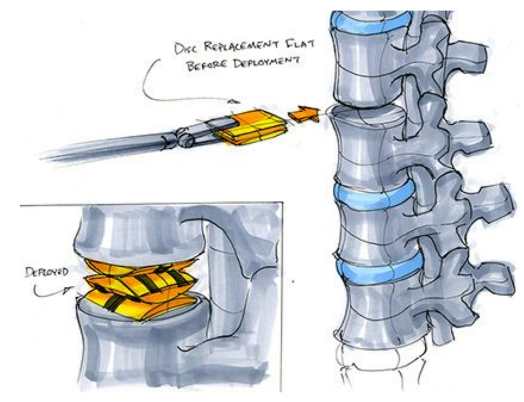
Introduction:

Simple, multi-functional robotics are heavily desired in almost every scientific field. The vast majority of technologies in use today that provide these features come with heavy drawback associated with exchanging parts, high costs, and maintenance requirements that make them impractical. This research focuses on a cheap, easy to manufacture origami base that can accomplish many motions without changing parts or extensive actuation systems. This poses several design challenges that are likely to be met with a robot that has reconfigurable geometry and variable stiffness.
A robotic origami with changing stiffness patterns is used to fulfill these requirements. The changing stiffness patterns allows the base to adjust its motion even with simple actuation that does not change between different motions. Simple 3D printed materials are used to provide ease of manufacturing and keep the cost low.

Origami solar panels for satellites used by NASA [Popular Science].



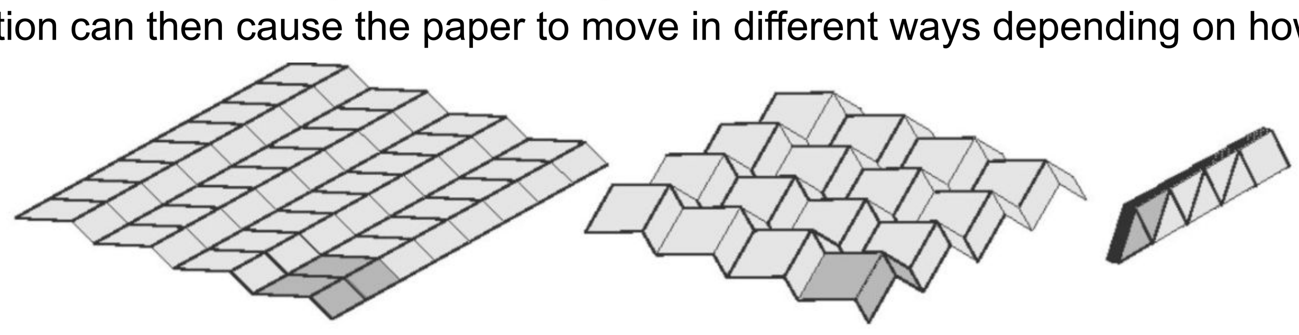
New James Webb space telescope with origami used to unfurl [SciTech Daily].



Disk replacement using origami [MedGadget].

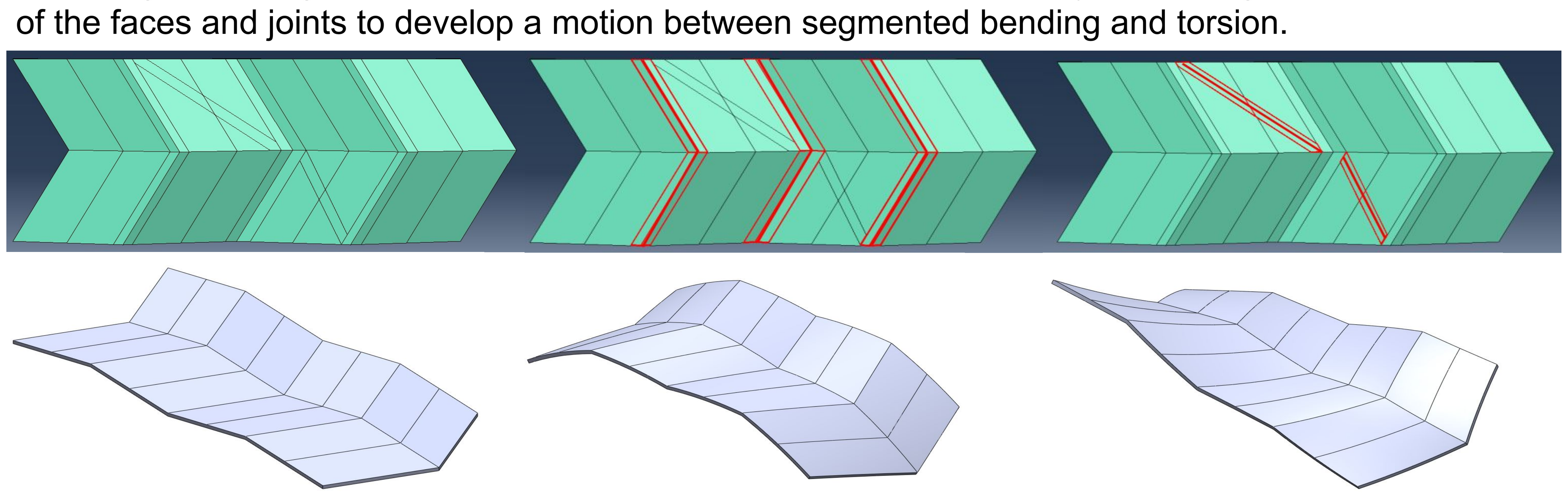
Working Concept:

In order to understand this research, it is first fundamental to understand the glass transition temperature. The glass transition temperature is a temperature range where a polymer's stiffness is several orders of magnitude lower than its stiffness is normally. This is heavily utilized in this research to create a robot that can rapidly change between softened and frozen states for different functions.
This robot is based off of Miura origami. Miura origami is a folding pattern that allows a sheet of paper to flatten vertically if compressed or horizontally if expanded, allowing for dynamic states in between. The general theory is that an entirely new folding pattern can be created by changing the stiffness of different joints and faces. One could imagine it as adding new creases to a piece of paper and seeing how it folds. The same action can then cause the paper to move in different ways depending on how it was creased.



Example of Miura origami folding [Geometry of Miura-folded Metamaterials].

In this robot, these new folding patterns are utilized to produce two primary movements with more planned in the future. The current producible movements are "segmented bending" and "torsion." Segmented bending is a result of heating each joint in the origami creating a base that folds similarly to a finger. Torsion is a result of heating a diagonal line across the faces of the origami that encourages twisting motion. Both of these motions can be combined by fine tuning the stiffness ratios of the faces and joints to develop a motion between segmented bending and torsion.



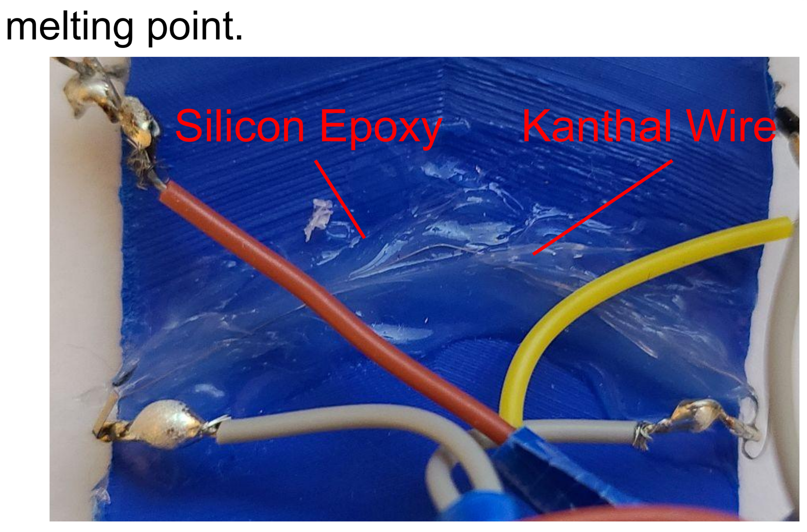
Flat Origami | Segmented Bending | Torsion

Robotic Locomotion and Results:

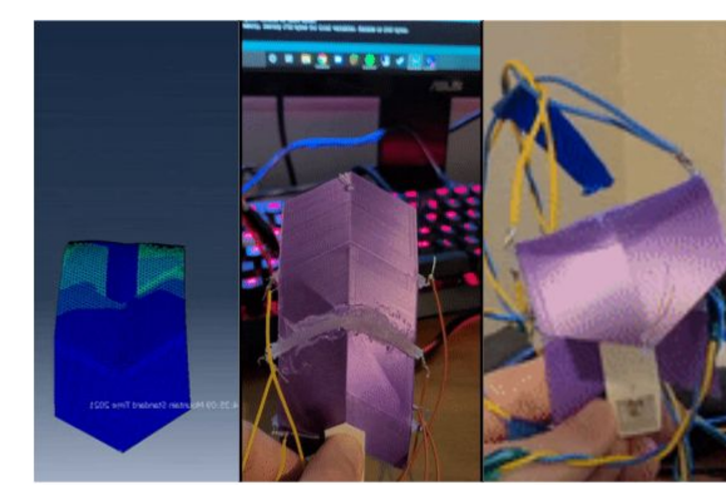
The result of these experiments were several forms of robotic locomotion and a robot with the ability to drastically change its movement patterns without changes in actuation. In total we were able to demonstrate segmented crawling with one joint versus three joints, torsional turtle walking, torsional turning, slanted walking, as well as crab walking by utilizing and combining the varying stiffness patterns achievable with this origami.
Each of these motions contributes to the robot's locomotion. Together they allow the robot to turn, walk forward and backward, crawl left and right, as well as move at an angle all with two motors and no actuation change. These are impressive results based entirely on heating different sections of the origami. Some examples are shown below.

Methods and Design:

The origami was evaluated in a number of ways culminating in a functional robotic base and predictive trends for the origami's movement. This was done through first using finite element analysis (FEA) as well as an topology optimization process in MATlab to develop the best possible geometry and variable stiffness sections for reliable, impactful movement. FEA allowed for accurate motion prediction and the ability to determine if any actuation would cause the PLA base to be put under stresses greater than its yield strength (26 MPa). This was used as a rough guideline for the geometry design.
Resistive heating elements were made using flat kanthal wire and a silicon epoxy adhesive. The adhesive worked as a thermal barrier between the heating wire and the origami such that the PLA would not reach its melting point.

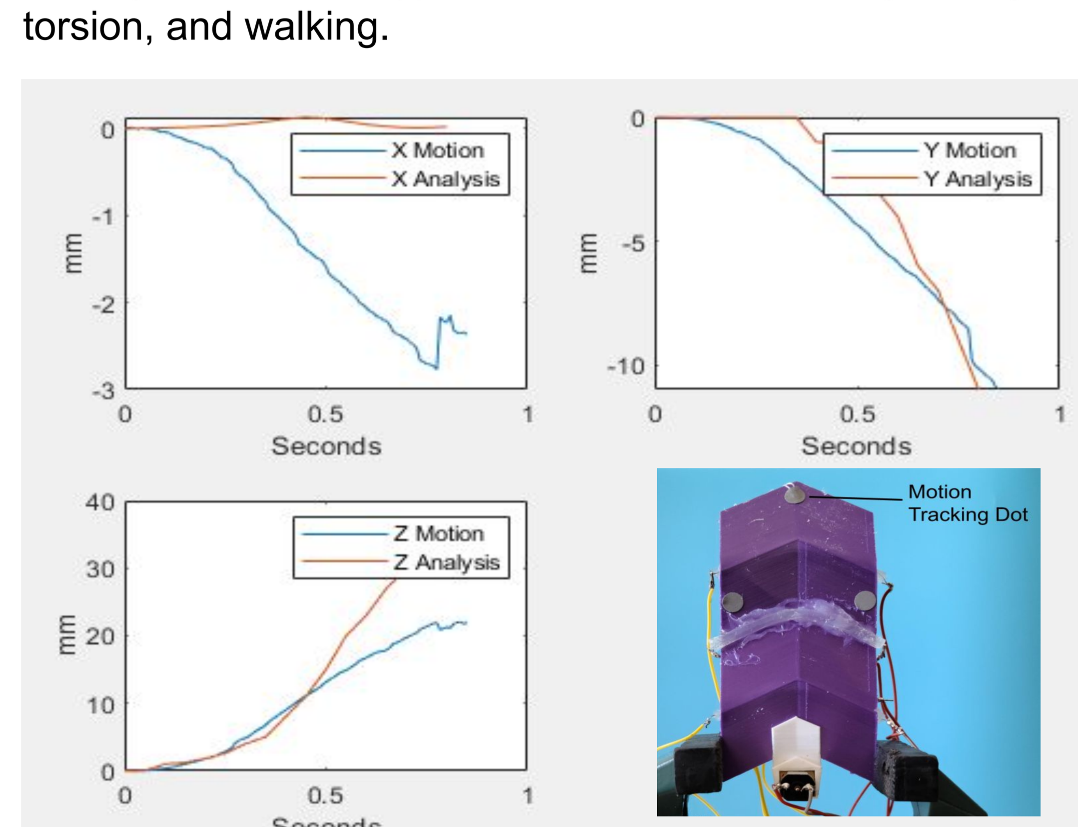


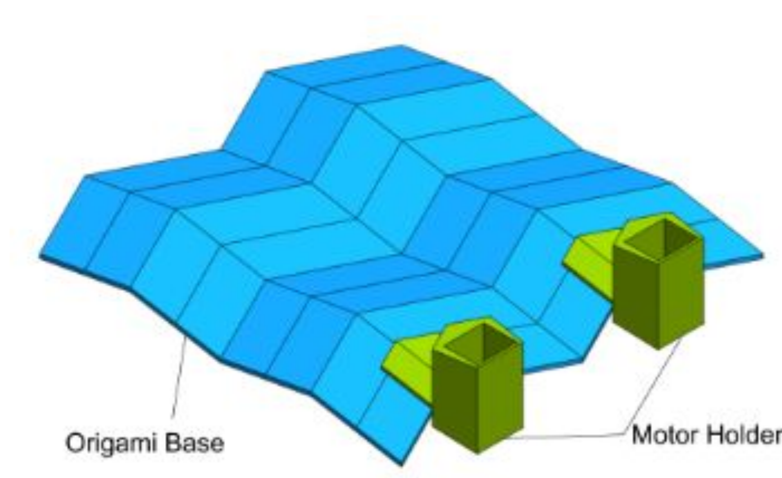
Resistive heating element configuration.



Origami FEA compared with experimental torsion.

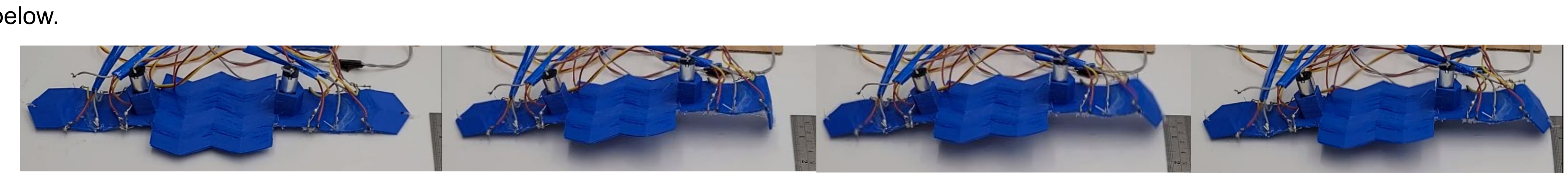
Several base prototypes were then fabricated based on the acceptable designs reached through FEA and MATlab topology optimization. These bases were fitted with heating elements and put to the test using a robotic test bench. The robotic test bench was fitted with motor actuation and precise high-amperage heating control. Specialized motor holders were designed for this purpose and affixed to the bases.The bases were then compared on a basis of the degree of motion generated, stiffness change, and toughness. A base thickness of 1.25 mm was determined to be the sweet spot between resisting heat deformation and having impactful movements.
Motion tracking was also in order to determine the accuracy of the FEA simulation. The results of the simulated and real origami proved to be relatively close and accurate enough for the purpose of our testing. Three infrared reflective dots were placed on an origami base and saddle bending was recorded with an infrared motion tracking camera. The movement of these dots were then compared to the movement of related points on simulated origami in an FEA.
Once the base geometry was settled and it was determined what movements it could make, a robot was created using the robotic test bench and a 3D printed origami body. This robot was made to undergo three main types of locomotion: crawling through segmented bending, crawling through torsion, and walking.



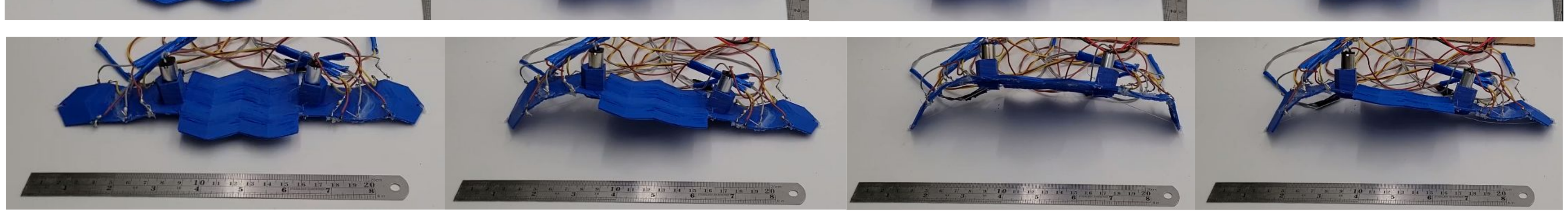


Movement Direction

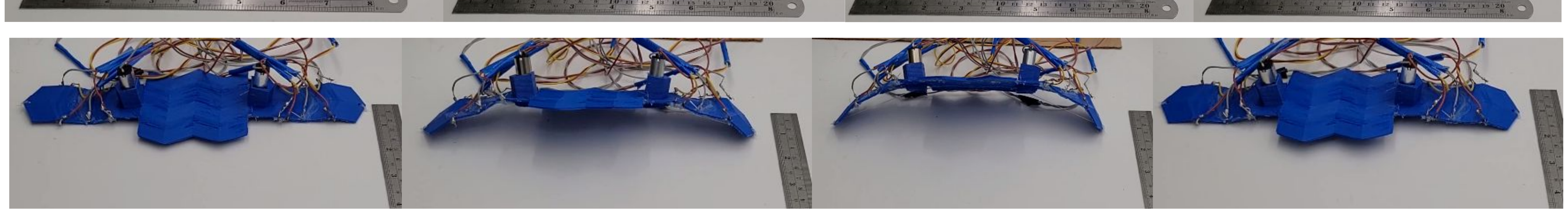
Single Segment-Crawling



Slanted Triple Segmented-Walking



Torsional Movement



Conclusion:

The results of this research proved that low cost, simple robots can utilize the glass transition temperature of 3D printed PLA to significantly increase adaptability and movement possibilities. This research can serve as a basis for future research into low cost, easy to manufacture adaptive robotics.The practical application of this design can be extended to many fields as is and has a lot of room to grow with many more possible movements and stiffness patterns that have yet to be tested.