Development of a Modular Multi-Material Multistable Linkage and Analysis of Mechanical Factors and Their Effect on Restoring Force

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Abstract

Compliant mechanisms move via the deflection of flexible members, allowing them to be designed with reduced part count, fewer points of failure, and increased durability. Bistable devices are compliant mechanisms characterized by two stable fixed positions separated by an unstable equilibrium position. Complex bistable devices can be developed by modularizing mechanisms into individual components, improving testing timelines and technology accessibility. With the advent of commercially available additive manufacturing technologies, chains of bistable mechanisms (modular linkages) have created the opportunity for more complex actuation profiles.

In this investigation, a modular, multi-material, multistable mechanism was designed and tested. This bistable mechanism was investigated because of its ease of manufacture and reduced design-iteration timeframe. The mechanism acted as a spring with a nonlinear spring constant, such that it had several stable positions along its travel length. A linear actuator attached to a force sensor was used to measure the restoring force of the mechanism at a given displacement from the mechanism's natural length. Restoring force as a function of distance was measured for several devices with different spacings between flexible units (defined as the intermediate arm length). Testing revealed that restoring force increased as intermediate arm length increased. Moreover, the modular system was quite durable, with force vs. displacement profiles remaining similar over more than three hundred tests.

Bistable linkages require no energy input when not in actuation phase, and the units developed during this study were quite flexible and durable. Therefore, these systems could be used for robotics applications, providing low energy movement and the capability to navigate complex terrain.

Introduction

The goal of this study was to investigate the variations in actuation force of a novel, modular-design type, bistable linkage compliant mechanism. Compliant mechanisms that operate via partial or complete deflection of flexible members, have myriad applications. Mechanisms are designed with a reduced part count, reduced manufacturing cost, increased repeatability, decreased frictional wear on joints, and inherent scalability.

Stable State

Deflected State

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A bistable mechanism is one that is characterized by having two stable states with a nonstable equilibrium.
Bistable mechanisms are most commonly used as switching mechanisms. In this study, the actuation force of various bistable mechanisms was studied as an application for robotics actuators. As a result of its two stable states, bistable mechanisms both do not require energy input when in a stable state, and then require only a finite amount of energy to actuate. This study predicted that bistable mechanisms could outperform actuators in long term durability, manufacturability, and overall energy requirement.

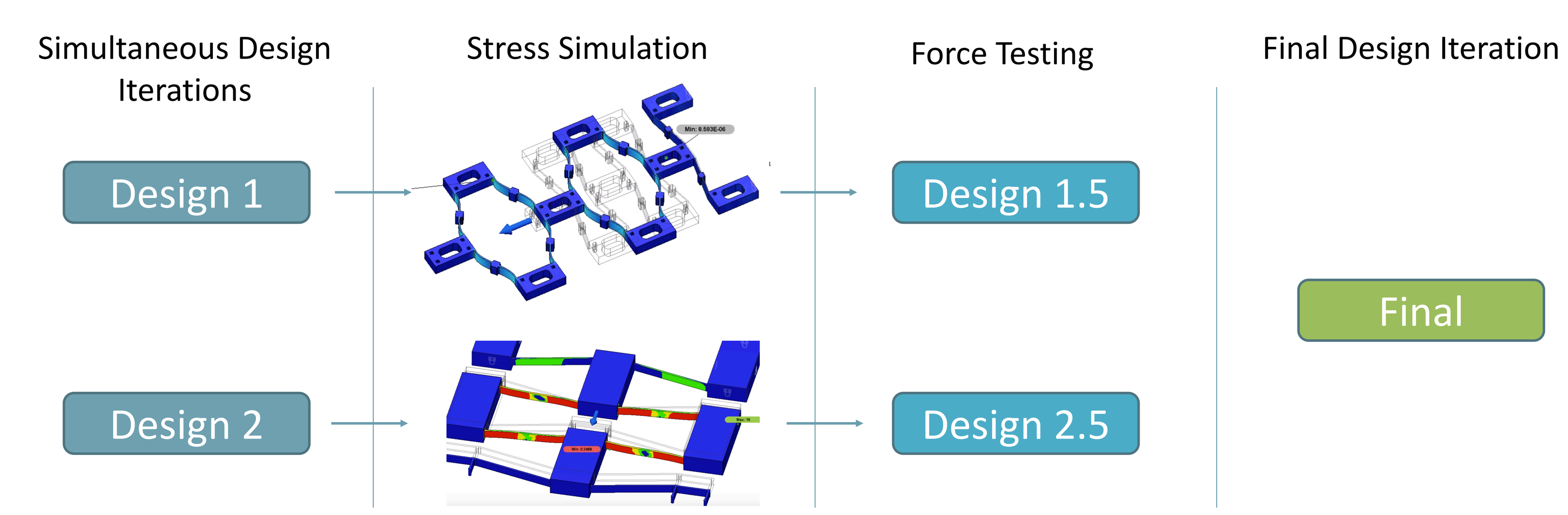
It became necessary to evaluate the actuation force of the mechanism to accurately predict the scale of the robotic actuator that would be feasible given other system requirements like batteries, motors, and circuitry. To accomplish this task, a series of "arms" were developed with varying intermediate lengths. These arms were incorporated as part of a larger "bistable linkage" a series of connected bistable mechanisms. The intermediate length dimension was hypothesized to affect actuation force as a result of the research conducted at NASA JPL.

Research Questions

The goal of this study was to investigate the variations in actuation force of a novel, modular-design type, bistable linkage compliant mechanism. Some questions were evident during design and testing.

- How does **actuation** change with respect to *intermediate arm length?*
- In what way will **mechanism durability** impact actuation profiles?
- How is the **maximum force** related to intermediate arm length

Methods



Part 1 – *Printing*:

a. The solid models were printed on the LulzBot TAZ 6 using PolyLite PLA filament and the standard extruder head. The nozzle temperature was 220° F and the bed temperature was 60° F. The movement speed was decreased to 70% to increase resolution. After printing, the solid models were cooled for 20 minutes at room temperature. The infill was 50% and the layer height was 0.18 mm.
b. The flexible models were printed on the LulzBot TAZ6 using PolyFlex filament and the standard extruder head. The nozzle temperature was 225° F and the bed temperature was 40° F. After printing, the solid models were cooled for 20 minutes at room temperature. The movement speed was decreased to 80% to increase resolution. The infill was 90% and the layer height was 0.18 mm.

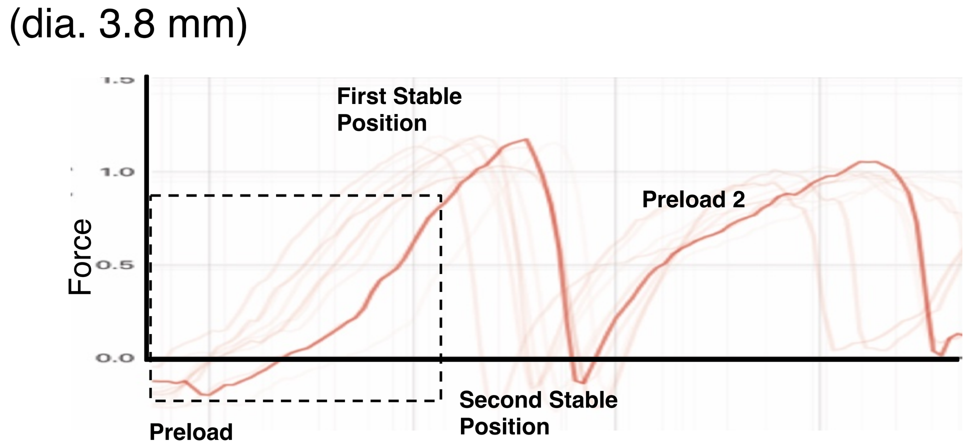
Part 2 – *Print Modifications*

a. After a PLA print was finished, each piece was sanded to smooth out any imperfections.
b. After a PolyFlex print was finished, both a knife and tweezers were used to detach any strands and/or bubbles that formed between the print layers. If any imperfections impaired their fit, the PolyFlex pieces were reprinted.

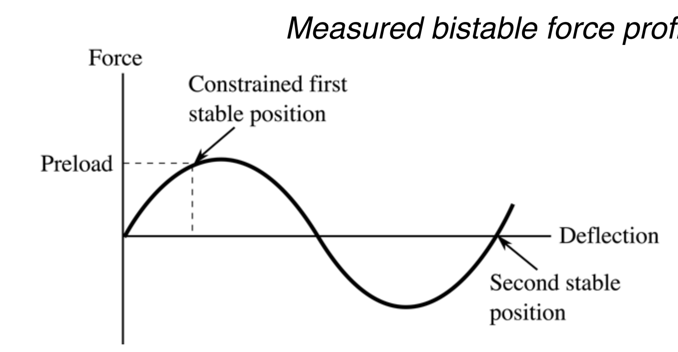
Part 3 – *Assembly*

a. The PolyFlex pieces were gently pushed into place in the slots of the PLA pieces. Each PolyFlex arm was seated fully.
b. The PLA node covers were also friction-fit over each node
c. A piece of 12-gauge wire was fashioned into a force-transferring linkage between the measurement node and the force sensor. The wire was fashioned into a triangular shape with a circle at the top (dia. 3.8 mm)

Using Dremel to modify fit of 3D print

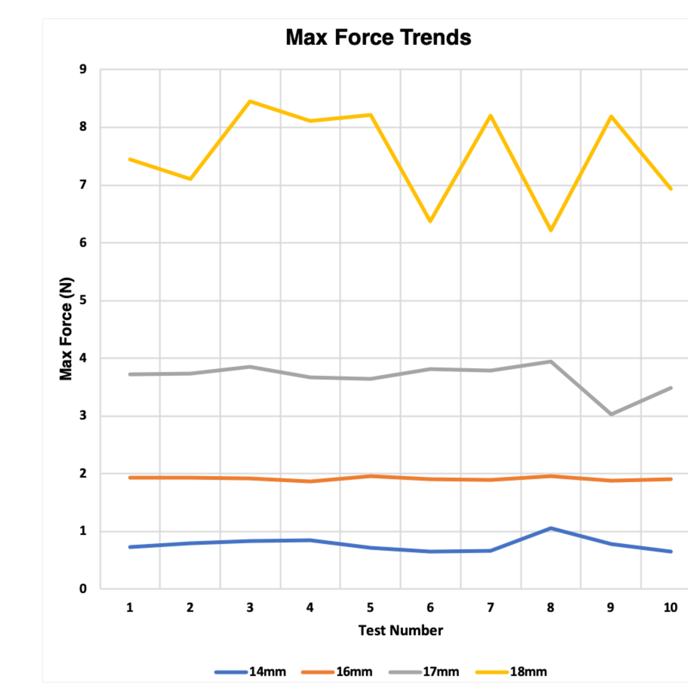


Measured bistable force profile

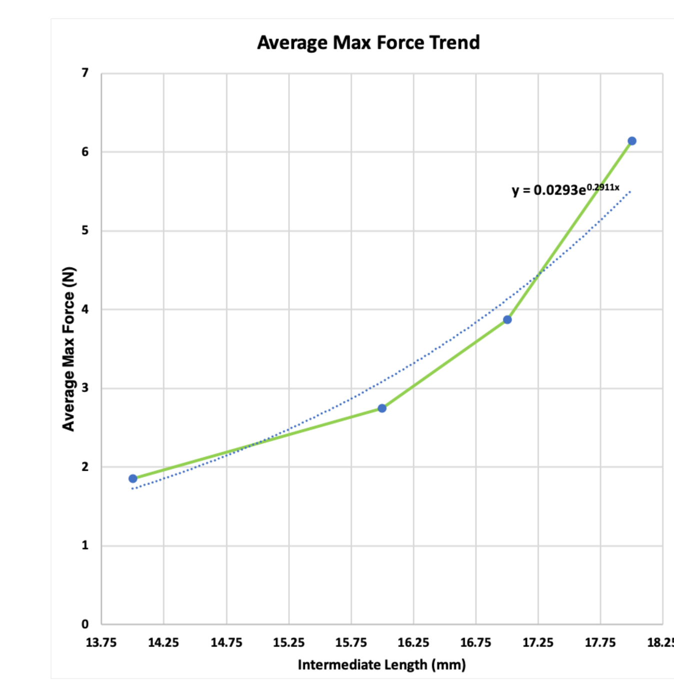


Example bistable force profile

Data – Quantitative and Empirical



Variability across tests is apparent in the above. As intermediate length increases, inconsistencies in design and testing setup become more apparent. The yellow line (representing an intermediate length of 18 mm) has more variability during testing than other lengths.



Due to inconsistencies in measurement equipment and mechanism design, there is variability in the actuation force across tests. However, the max force trends suggest that there is a relationship between intermediate length and actuation force.

Discussion and Results

Data collected support the hypothesis that actuation force increases with intermediate length. Although some variability in actuation and off axis warping occurred, the design featured a typical bistable actuation profile and was durable. Although it appears that there were significant variations in actuation force between different trials of the same intermediate length, there are a few factors that impeded the collection of precise and accurate data.

Variability in linear actuation
After reviewing footage collected during testing, it became clear that the linkage was not actuating in a linear fashion. In many cases, likely due to friction, mechanical wear on flex arms, and alignment inconsistencies, the linkage would move to the left or right of the test area, impacting the side walls. This increased friction would increase the force required to actuate the linkage.

Off-Axis warping
After reviewing footage collected during testing, in many of the 18 mm trials it seemed that the mechanism was not staying flat on the test bench. As a result of the increased intermediate length, the connected nodes would follow the path of least resistance guided by the flex arms, resulting in off-axis warping. This caused the mechanism to impact the Lexan sheet placed above the test area, increasing friction, and thus increasing force required to actuate the linkage.

Data collected support the following.

Design
- Successful actuation of individual linkages
- Increasing actuation force
- Bistable force profile

Principles of compliant mechanisms

Durability
- 300+ actuations, and no components have failed.

Cost Effectiveness
- ~100 grams of each filament was bringing total material cost to less than $7.

Acknowledgements

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