Design and Characterization of a Tunable-Stiffness Pneumatic Legged Hopping Robot

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Introduction and Goals

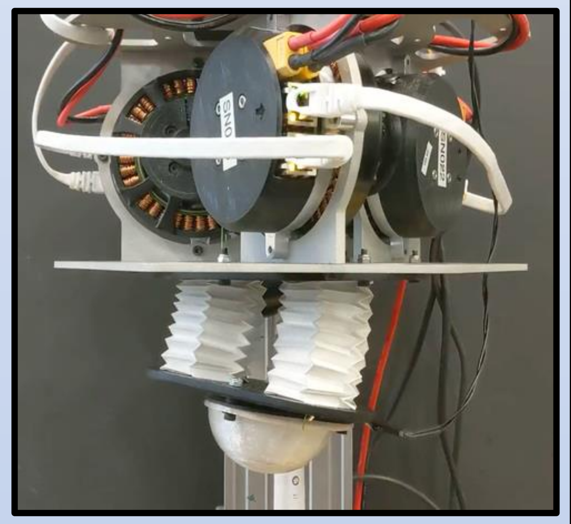
Introduction

- Tunable-stiffness actuators have seen increased use as legs as they mimic the behavior of animals who modulate their joint stiffness to adapt to different terrains. This adaptation allows for more efficient and stable locomotion [1].
- Pneumatic actuators are desirable for dynamic situations for their inherent compliance, but current solutions require energy expensive air pumps and valves [2].

Goals

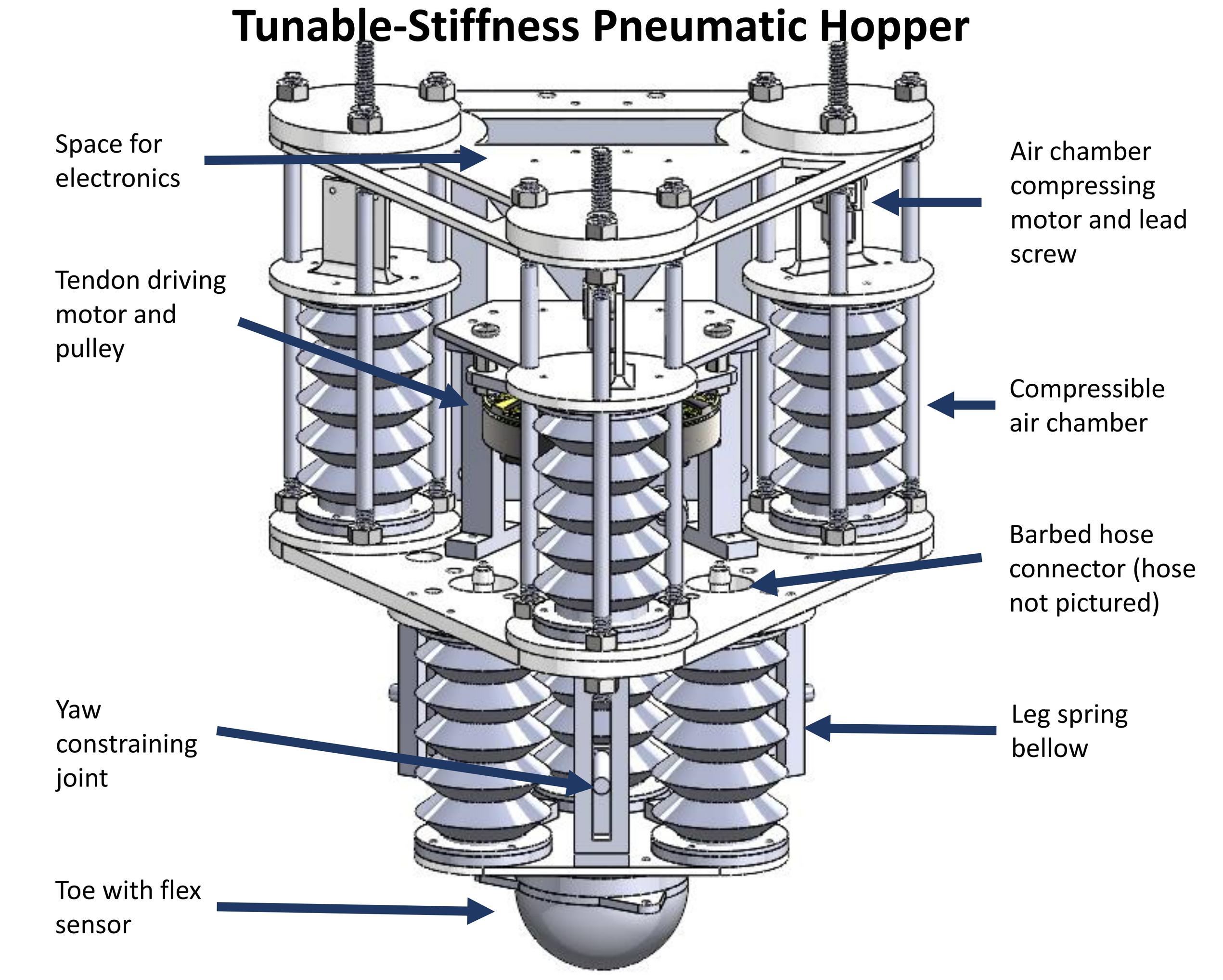
- Design and characterize a pneumatic tunable-stiffness actuator with a continuous and large stiffness range and precise control, which doesn't require air pumps.
- Integrate the actuator into a robotic platform like the REBO hopper[3] that is capable of rapid hopping to study energy consumption on various terrains.

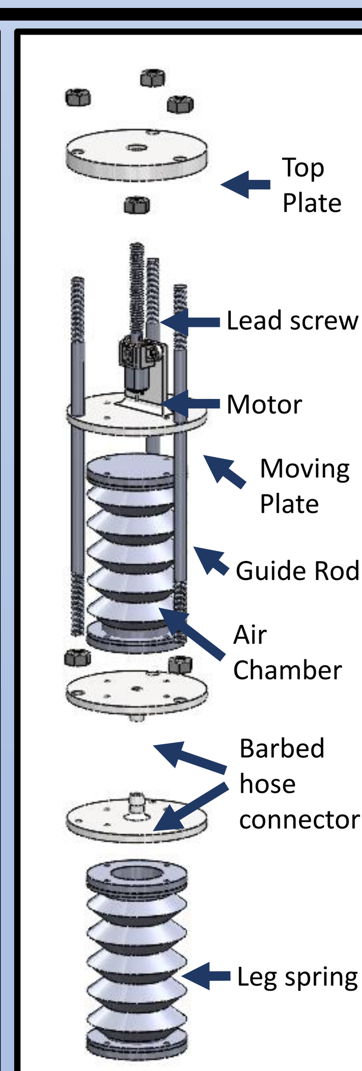
REBO Hopper



Design Overview

Tunable-Stiffness Pneumatic Hopper





Dimensions

- 240mm x 240 mm x 320 mm
- 2.7 kgs

Motors

- 1x U8 KV100 Motor to drive central tendon
- 3x Pololu DC Motors with a 100:1 reduction to compress air chambers, changing spring stiffness

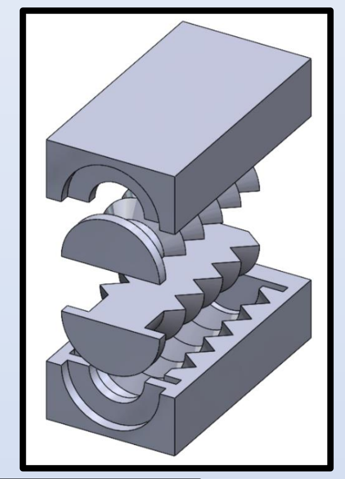
Sensors

- 1x IMU for acceleration data
- 3x pressure sensors, one connected to each spring/air chamber pair
- 1x flex sensor to detect ground contact
- 1x power monitoring module to record motor energy cost

Bellow Design

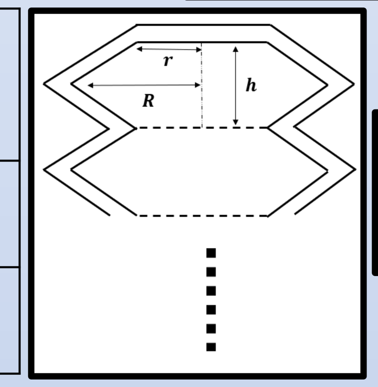
Bellows

- Silicone bellows with a shore hardness of 30A
- Chosen for its material stiffness, airtightness, and ease of fabrication
- TPU, flexible filament, lower hardness silicone tested



Parameters

	Segment Height (h)	Large Radius (R)	Small Radius (r)	Segment Count (n)
Air Chamber	7.46 mm	20.10 mm	10.58 mm	5
Leg Spring	7.46 mm	18.47 mm	9.00 mm	5



$$V_c(h_c) = \frac{2}{3}\pi n_c h_c (R_c^2 + r_c^2 + R_c r_c)$$

$$V_s(h_s) = \frac{2}{3}\pi n_s h_s (R_s^2 + r_s^2 + R_s r_s)$$

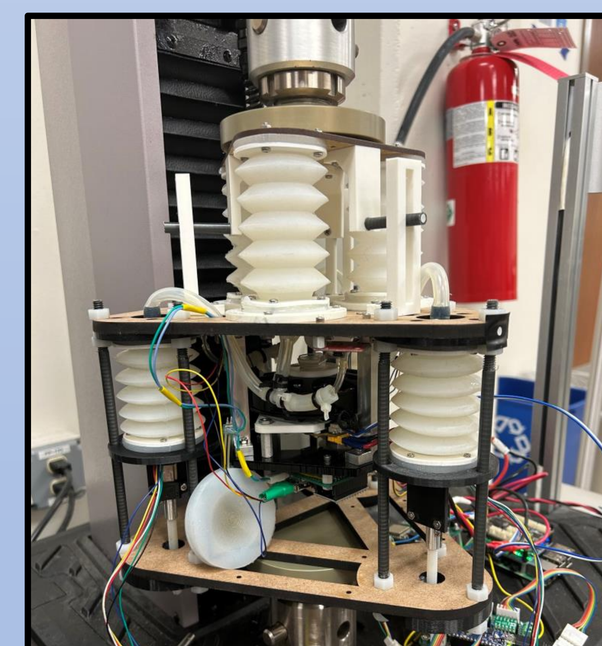
Experimental Setup

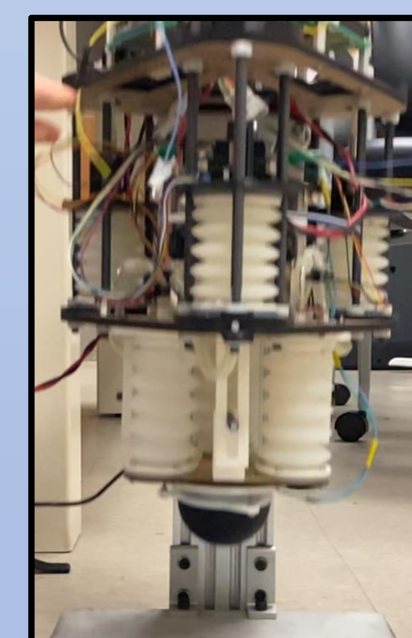
MTS Stiffness Test

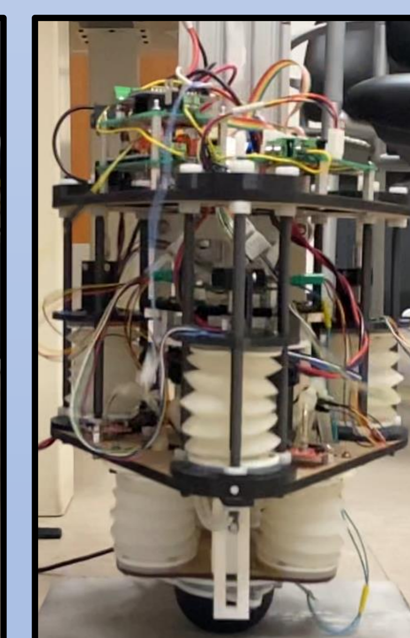
- MTS compression test to characterize the stiffness of the hopper legs
- 9 air chamber compressions with 3 trials per compression

Damping Test

- Hopper free dropped and trajectory tracked
- Damping coefficient calculated using the peaks of each bounce

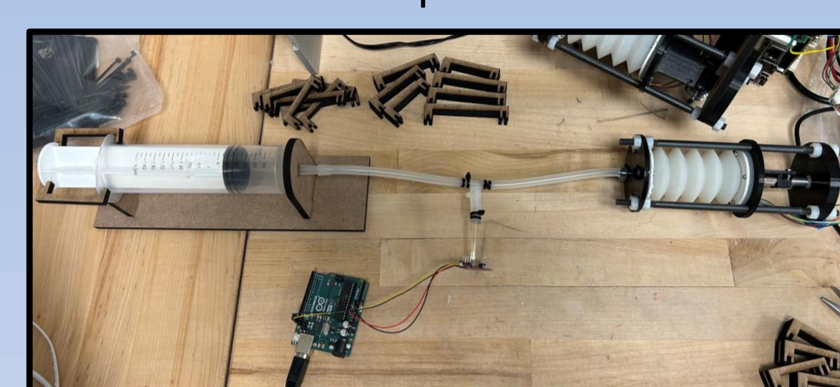






Wall Deformation Test

- Wall deformation occurs at the bellows due to internal pressure, causing it to behave differently than the geometric model
- Bellow compressed at different starting pressures
- Real bellow volume extracted from pressure sensor readings using Boyle's Law



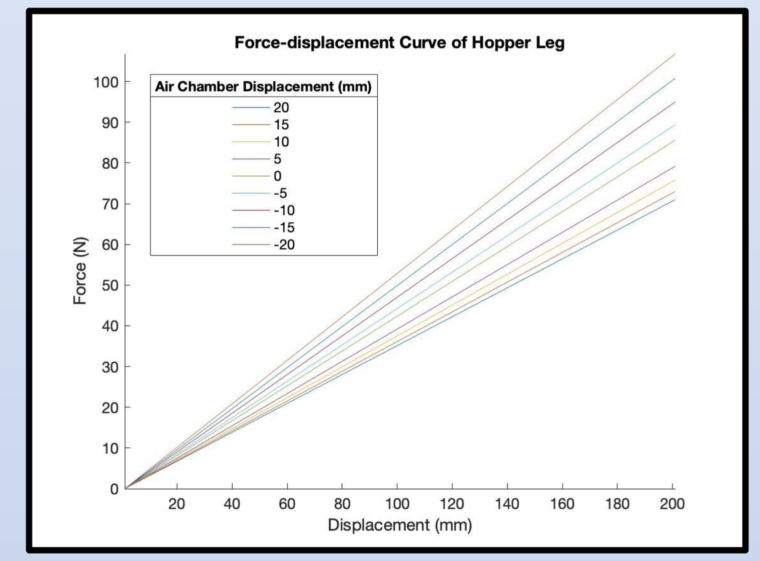
Bellow Characterization Results

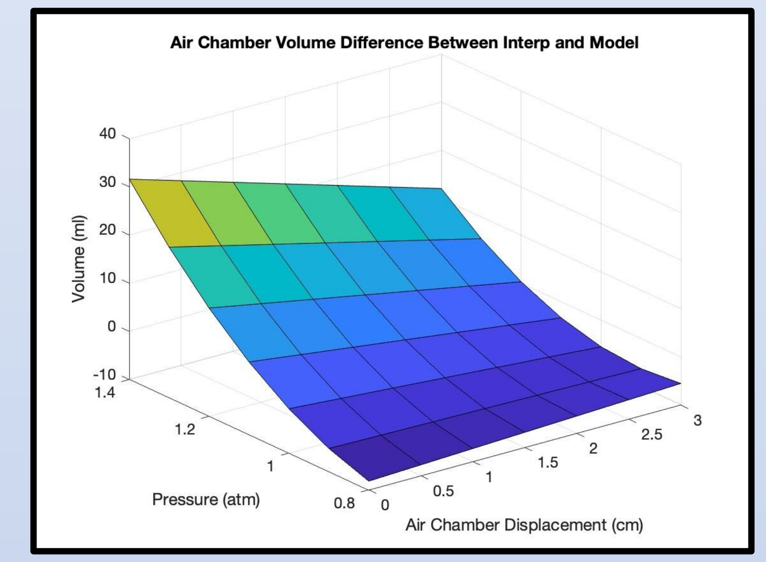
Stiffness and Damping

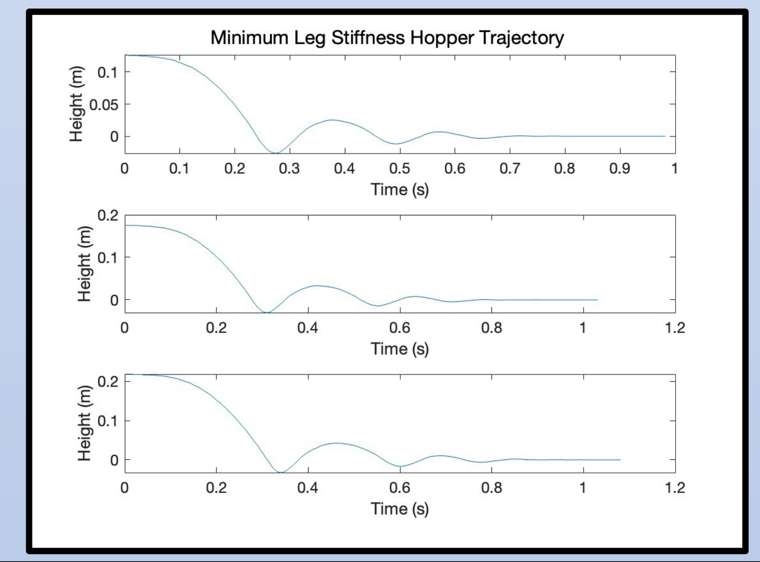
- Leg stiffness of 3.55 N/mm to 5.34 N/mm, 1.5x stiffness range
- Leg damping coefficient of 48.74 kg/s to 60.45 kg/s

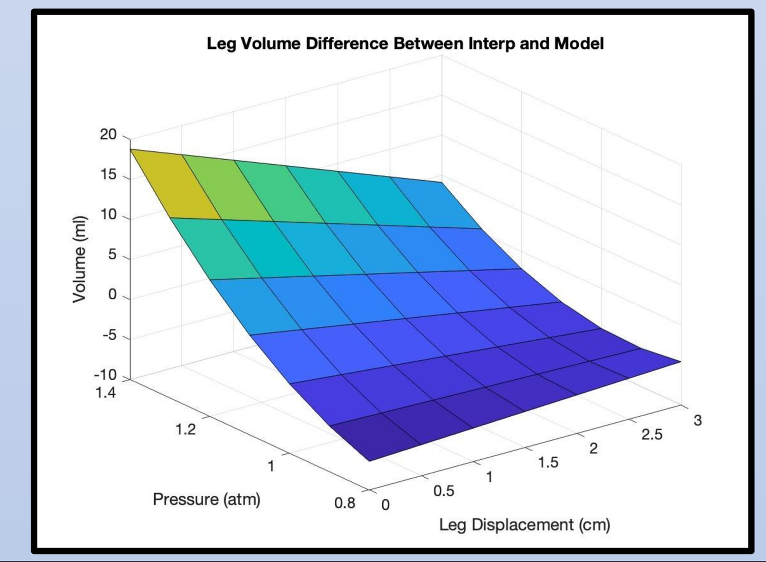
Wall Deformation

- Bellow volume increases with pressure, not solely a function of displacement like the geometric model









Future Work

- Incorporate a pressure term into the bellow model to account for irregular wall deformation
- Characterize the hopping energy cost of different spring stiffnesses on various emulated terrain
- Hop with the assistance of boom to confirm leg altitude model
- Develop a neural network to enable the robot to identify the terrain it is hopping on from sensor data

Acknowledgements and References

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References

[1] Farley CT, Houdijk HH, Van Strien C, Louie M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. J Appl Physiol (1985). 1998 Sep;85(3):1044-55. doi: 10.1152/jappl.1998.85.3.1044. PMID: 9729582.
[2] M. F. Hale, J. L. Du Bois and P. Iravani, "Agile and Adaptive Hopping Height Control for a Pneumatic Robot," 2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, QLD, Australia, 2018, pp. 5755-5760, doi: 10.1109/ICRA.2018.8460557.
[3] W. -H. Chen, S. Misra, J. D. Caporale, D. E. Koditschek, S. Yang and C. R. Sung, "A Tendon-Driven Origami Hopper Triggered by Proprioceptive Contact Detection," 2020 3rd IEEE International Conference on Soft Robotics (RoboSoft), New Haven, CT, USA, 2020, pp. 373-380, doi: 10.1109/RoboSoft48309.2020.9116040.