# Body Lift and Drag for a Legged Millirobot in Compliant Beam Environment

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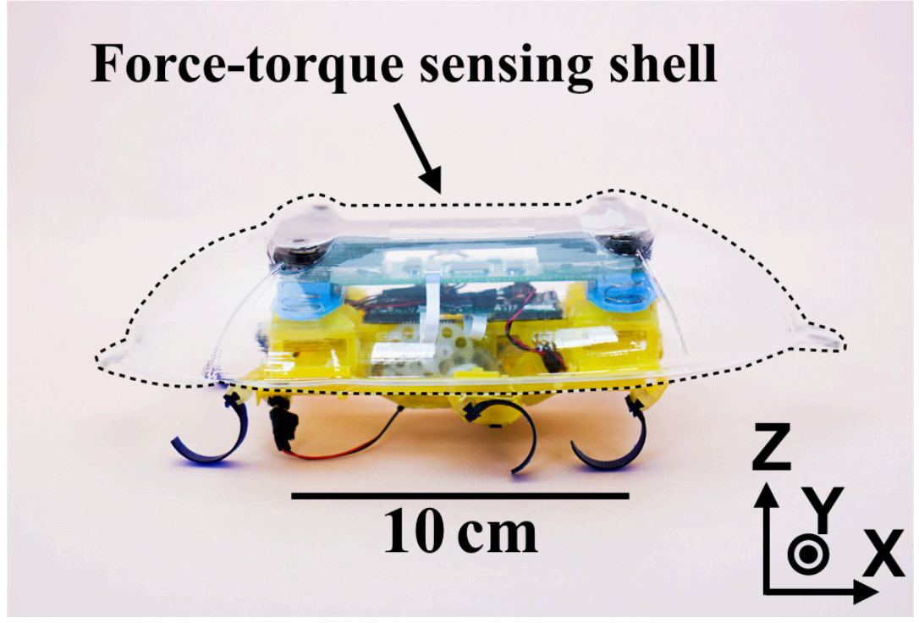
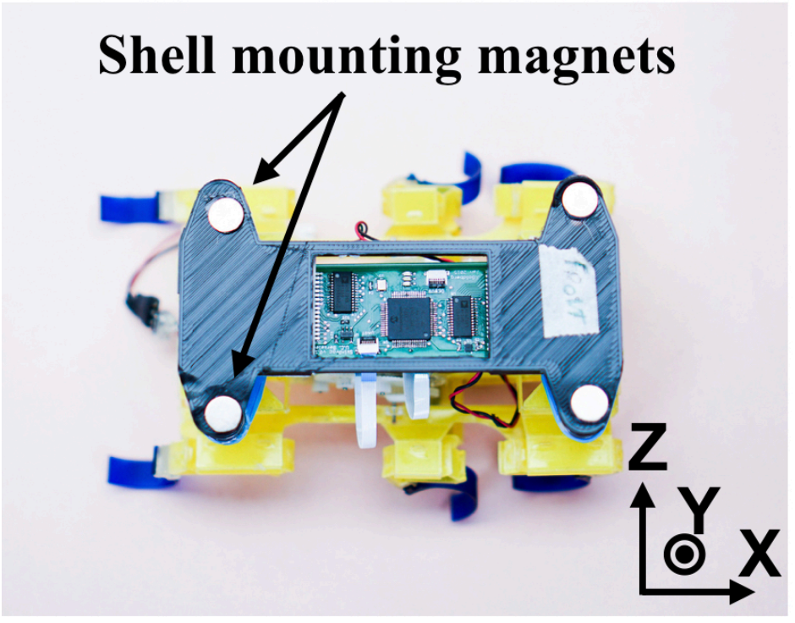
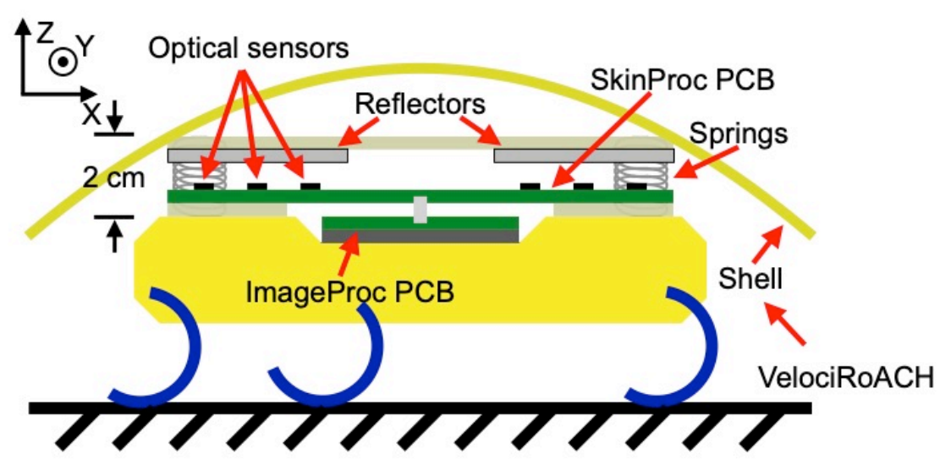
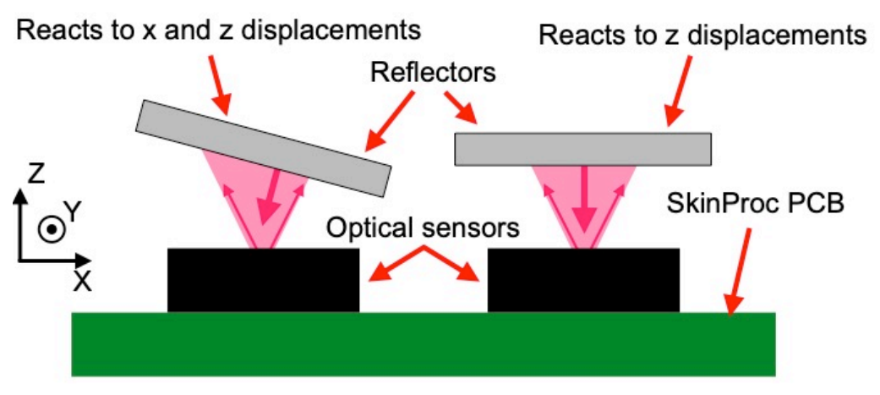
## Introduction

- Previous work in millirobot locomotion through grass-like terrain focused on characterizing effect of body shapes in traversal [1], [2]. However, these studies did not focus on measuring environmental drag energy or forces.
- In this work, we use a previously developed force-torque sensor [3] mounted on a hexapedal millirobot to measure contact forces.
- These forces are exerted on the shell while traversing a channel with grass-like beams at varying clutter densities. We collect and analyze these forces to directly measure drag, lift, and specific resistance of legged locomotion.


Force-torque sensing shell


Shell mounting magnets





## Specific Resistance & Drag Energy

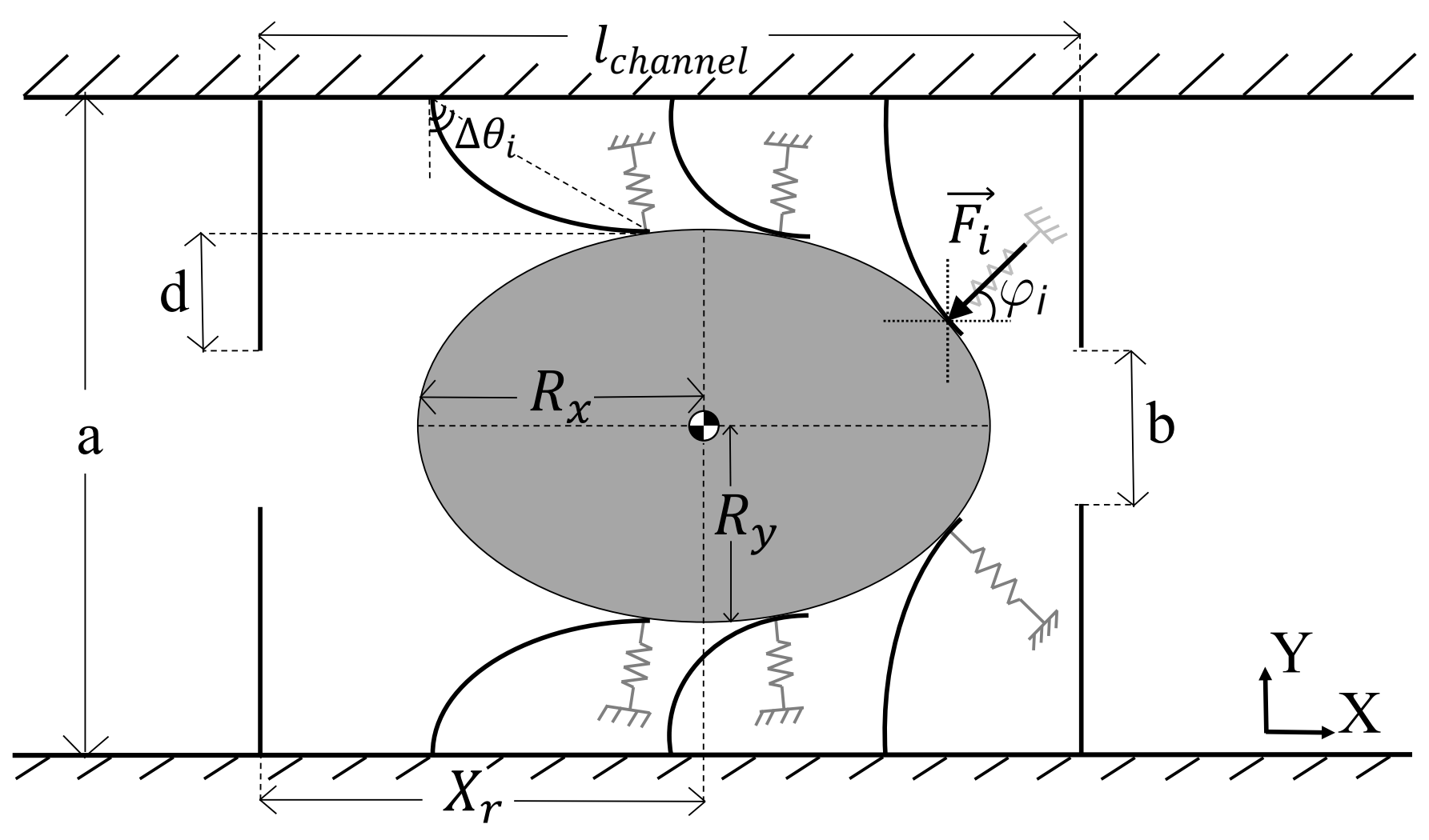
- We characterize the traversal of the hexapedal millirobot through the cluttered terrain by its drag energy and specific resistance to motion.
- Drag energy measures the amount of energy the robot exerts when traversing the given terrain and specific resistance is a dimensionless quantity that describes the energy efficiency of moving from one point to another.

$$E_{drag} = \overline{F_x} l_{channel}$$

- $\overline{F_x}$ is the average drag force, $l_{channel}$ is the length of the channel.

$$Specific\ Resistance\ (\eta) = \frac{\overline{P}}{mg\overline{v}}$$

- $\overline{P}$ is the average power consumption for both leg motors. $\overline{v}$ is the average velocity of the robot during experiment.



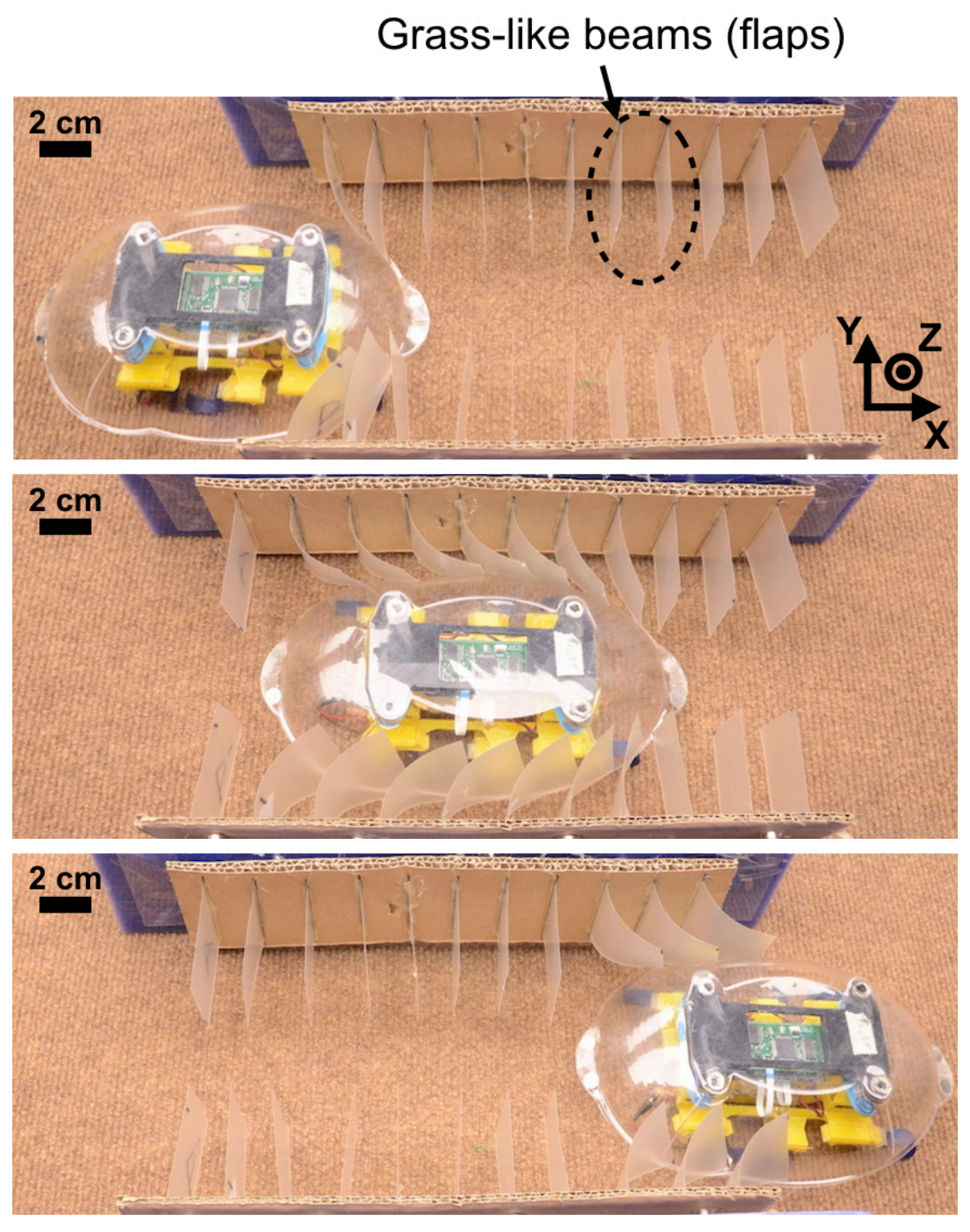
## Experiment Design

*Beam obstacle track*

- Inspired by the cluttered terrain model from Li et al. [1], thin sheets of fiberglass were cut to form flaps (3cm x 3cm x 0.012 cm) and were glued onto blue wax blocks to create a beam obstacle track which is 71cm long of which 28cm is filled with obstacles.

*Open-loop trials in variable channel width*

- To create interaction forces of differing magnitudes we varied the lateral width $b$ of the channel and ran open-loop experiments for 5 possible values: free, 10cm, 8cm, 6cm and 4cm.



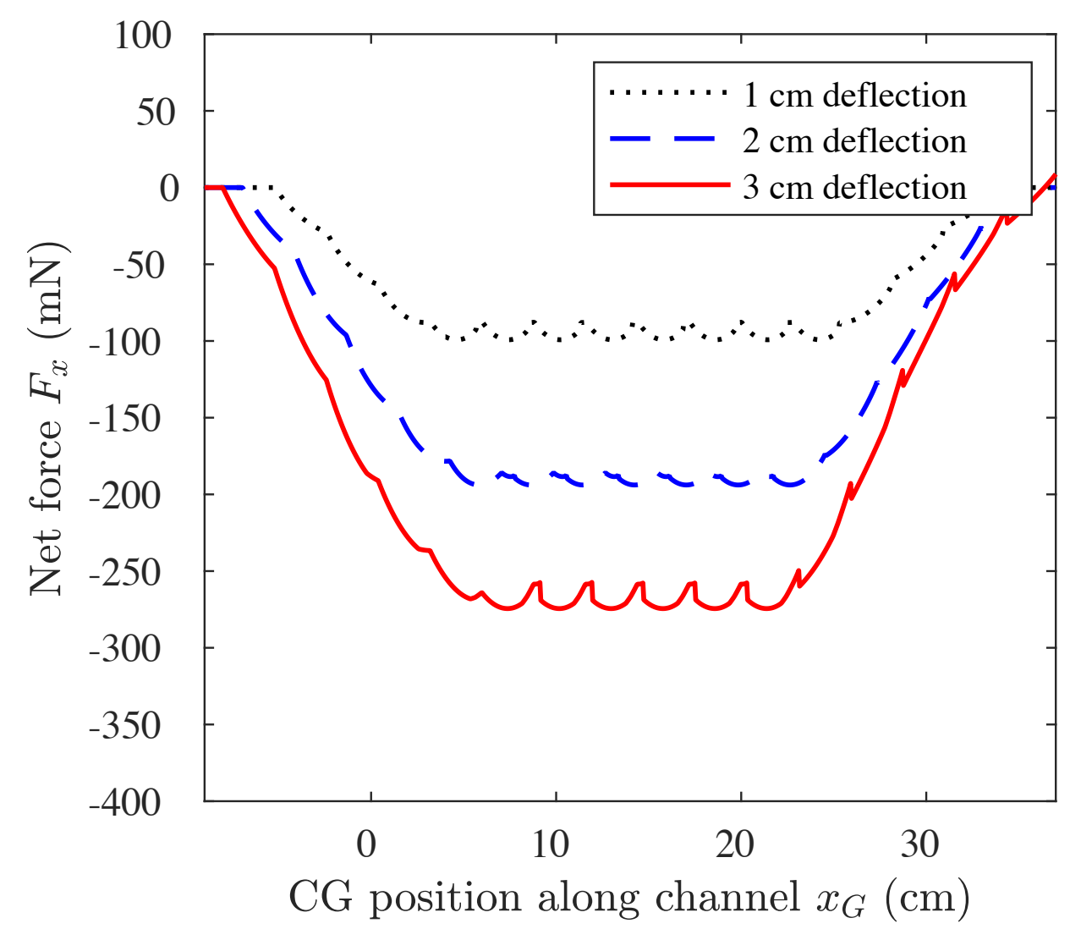
*Quasi-static contact forces*

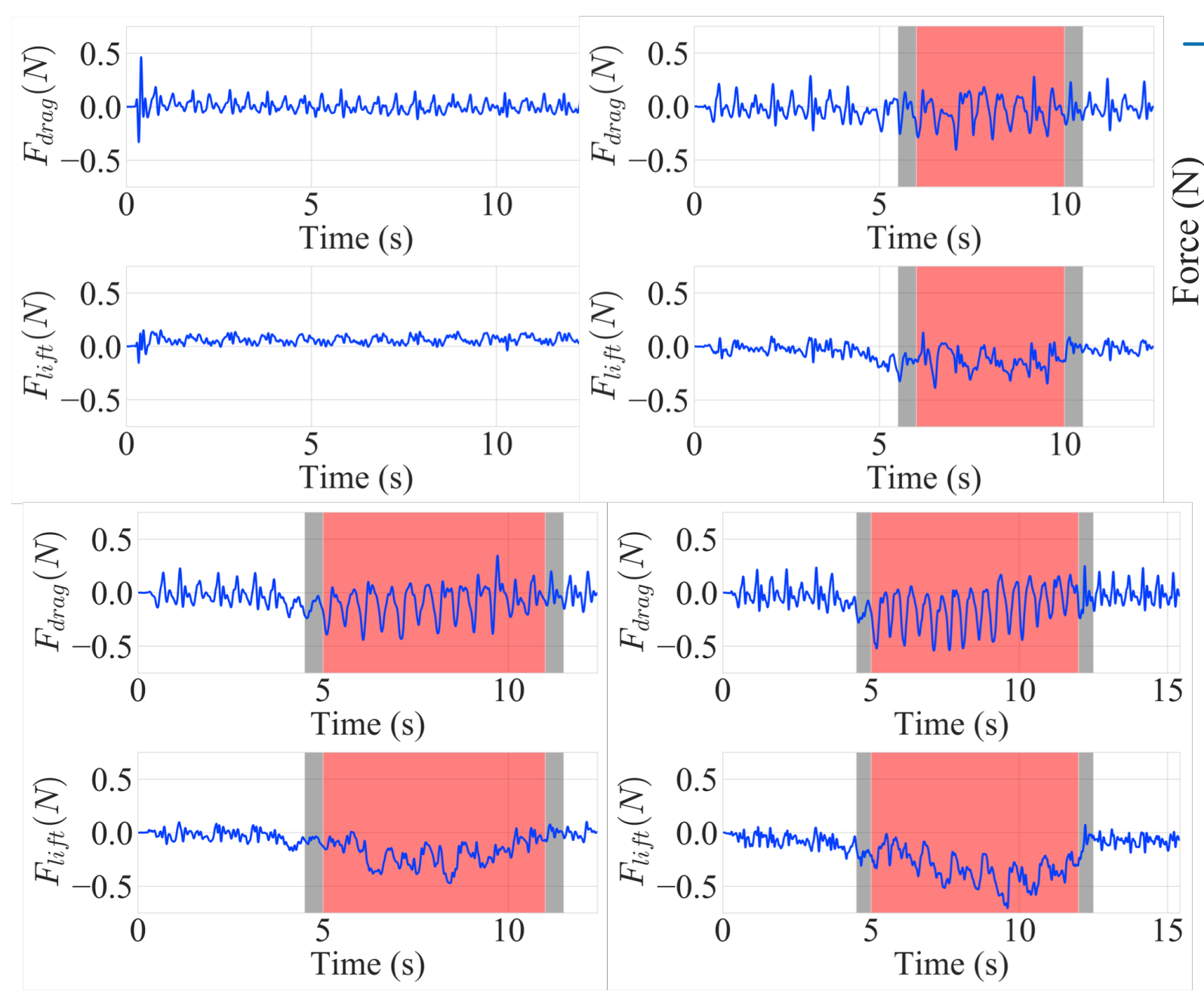
- Each grass-like beam is modeled as a torsional spring that produces a force in the XY plane according to the angular deflection of the beam ΔΘ.
- As shown in the video, the millirobot moves very slowly within the cluttered section of the channel, this allows us to model the contact forces using:

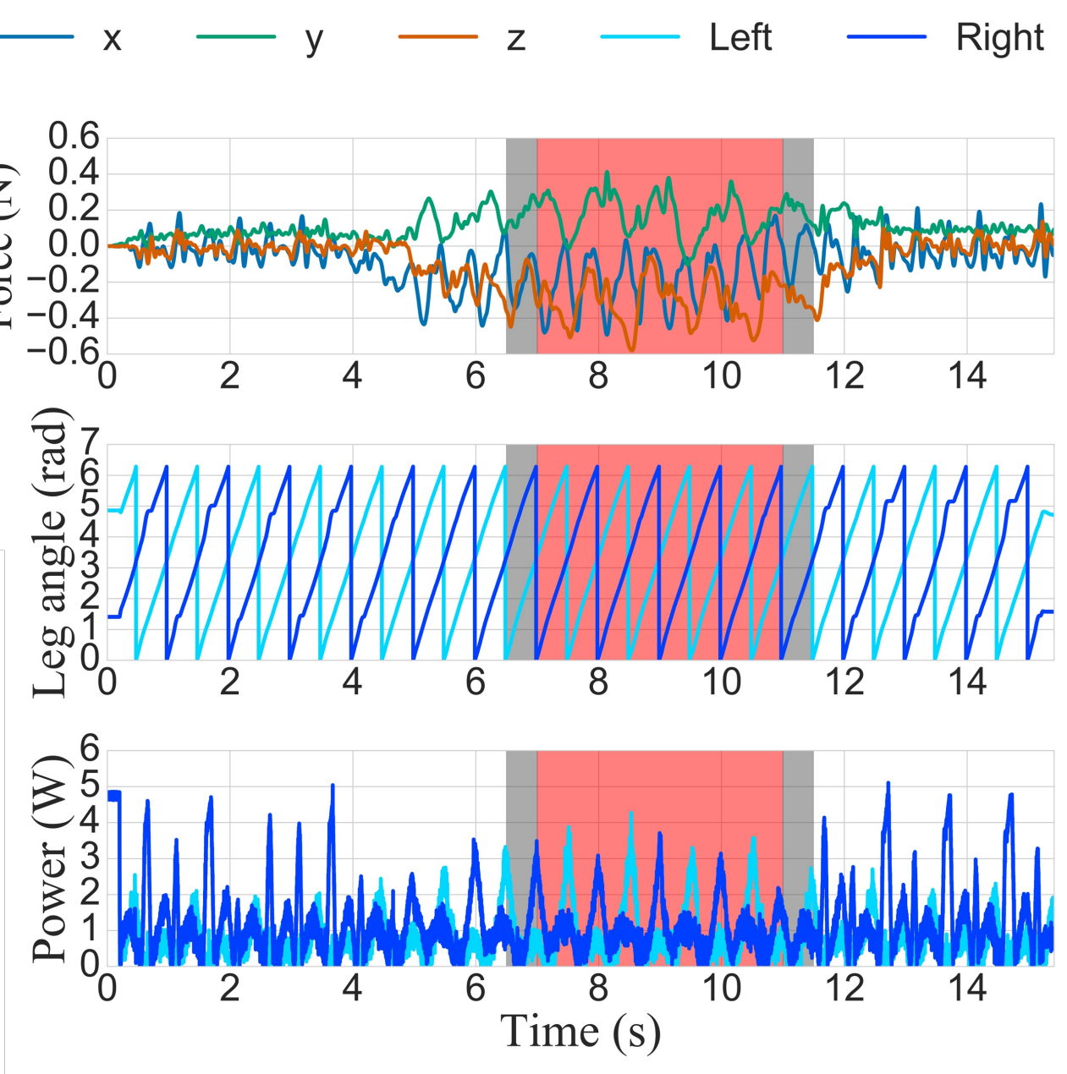
$$F_{drag} = 2\sum_{i=1}^{n} \mathbf{F_i}\cdot\hat{\mathbf{x}}. \qquad \mathbf{F_i} = \frac{k_t}{L}\Delta\theta_i\left(\hat{\mathbf{n}}_\mathbf{i} + \mu_k\hat{\mathbf{t}}_\mathbf{i}\right)$$

## Results

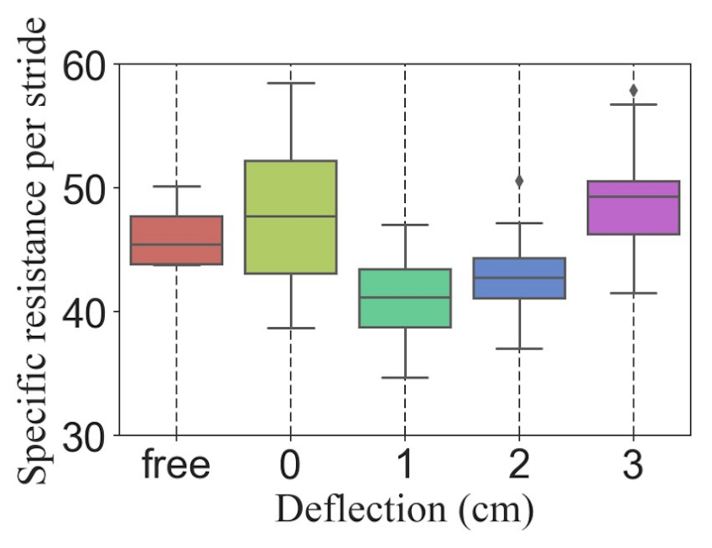
- Dynamic numerical simulation based on the quasi-static force analysis was made that captures the increase in drag forces as number of beams in contact increase.
- Figure below shows the measured $F_{drag}$ and $F_{lift}$ as the robot traverses the channel.
- Drag forces increase while the negative lift forces pushing on the shell also increases which causes greater traction in the legs of the robot.
- Electrical energy plots shows no trend with respect to channel deflection however, drag energy plots shows a non-linear increase which could be used to quantify terrain densities.

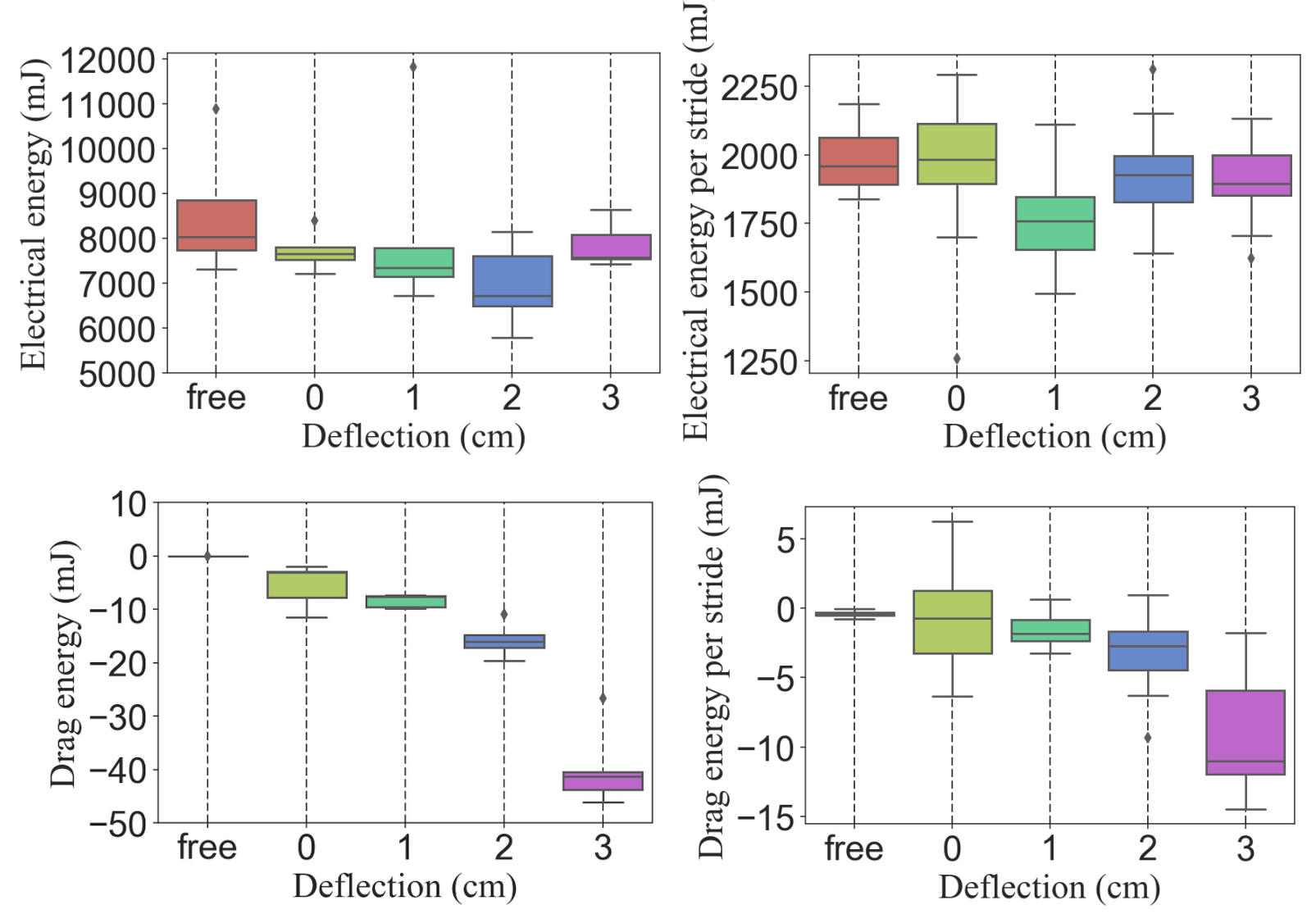






- Experiments show specific resistance doesn't monotonically increase as the channel width decreases.
- This suggests squeezing through a channel can result in less energetic cost than running free.
- Box plot shows the average specific resistance is lower in 1cm deflection than free experiment.
- However, if the channel is narrow then running through the channel becomes more costly than running outside the channel.





## Discussion & Future Work

- This work presents a method to experimentally quantify specific resistance and drag energy of traversing a cluttered terrain.
- Experimental trials show, while drag and lift forces increased with decreasing channel width, specific resistance did not monotonically increase which suggests some contact between robot and clutter terrain could lower specific resistance and increase traction compared to free running.
- Reliance on typical telemetry data such as motor power, joint torques or back EMF is insufficient to distinguish beam deflection conditions.
- Furthermore, calculating drag energy could provide a better measure in quantifying optimum locomotor paths for cluttered terrains.
- Future direction of this work could explore developing closed loop control of this millirobot using the net forces exerted on robot's body.

## References

- [1] C.Li,A.O.Pullin,D.W.Haldane,H.K.Lam,R.S.Fearing,and R. J. Full, "Terradynamically streamlined shapes in animals and robots enhance traversability through densely cluttered terrain," *Bioinspiration & Biomimetics*, vol. 10, no. 4, p. 046003, 2015.
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- [3] J. D. Goldberg and R. S. Fearing, "Force sensing shell using a planar sensor for miniature legged robots," in *IEEE/RSJ Inter- national Conference on Intelligent Robots and Systems (IROS)*, pp. 1494–1500, 2015.