Dynamics of Millimeter-scale Robotics with Thin-film Piezoelectric and High-Aspect Ratio Polymer Leg Mechanisms

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Introduction

Micro-robots have potential applications to disaster response, exploration and defense. Microscale walking robots, typically with maximum dimensions on the order of a centimeter or smaller, have been proposed or developed based on a variety of electromechanical actuation principles. Among these, in thin-film materials piezoelectric actuation can be achieved with modest actuation voltages (typically 5-20 V) and over comparatively large deflections via beam bending.

The millimeter-scale micro-robot described in this work integrates thin-film lead-zirconate-titanate (PZT) piezoelectric micro-actuators with high-aspect from parylene-C polymers in micro-robotic leg joint mechanisms. The sample hexapod micro-robot at right is 5mm x 2.4mm x 0.15mm.

A dynamic model for robot and ground interaction is presented to explain robot locomotion in a vibrating field using in-chip measurements of actuator dynamics and additional dynamic properties obtained from finite element analysis (FEA) and other design information.

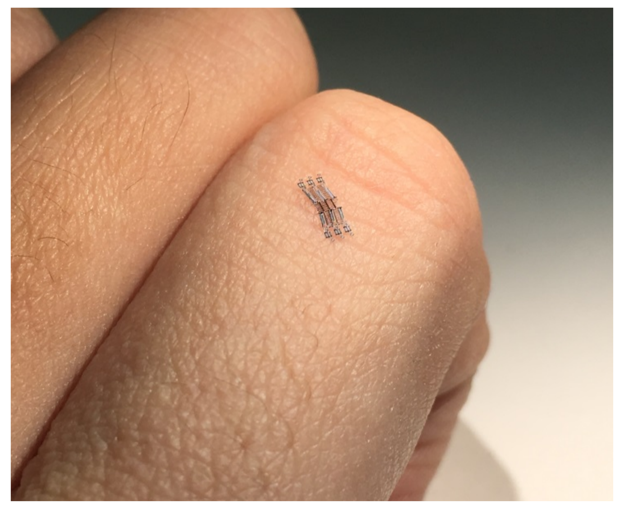


Figure 1: A hexapod micro-robot on a finger (fabricated in Prof. Oldham's Lab)

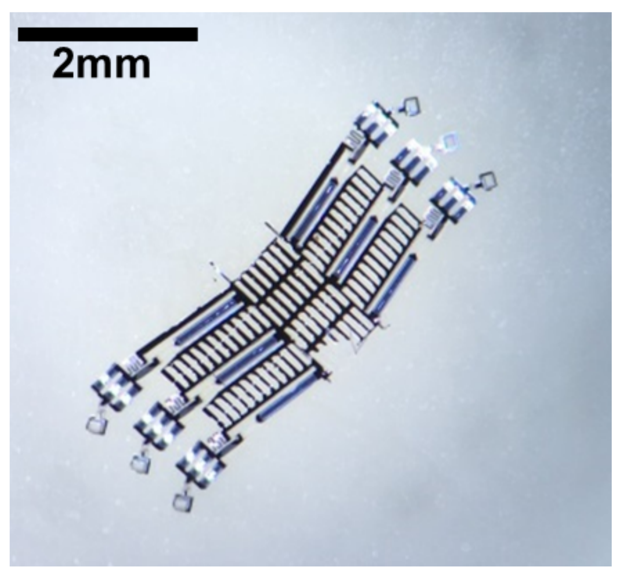


Figure 2: Photo of a detached hexapod micro-robot under microscope.

Actuation Design

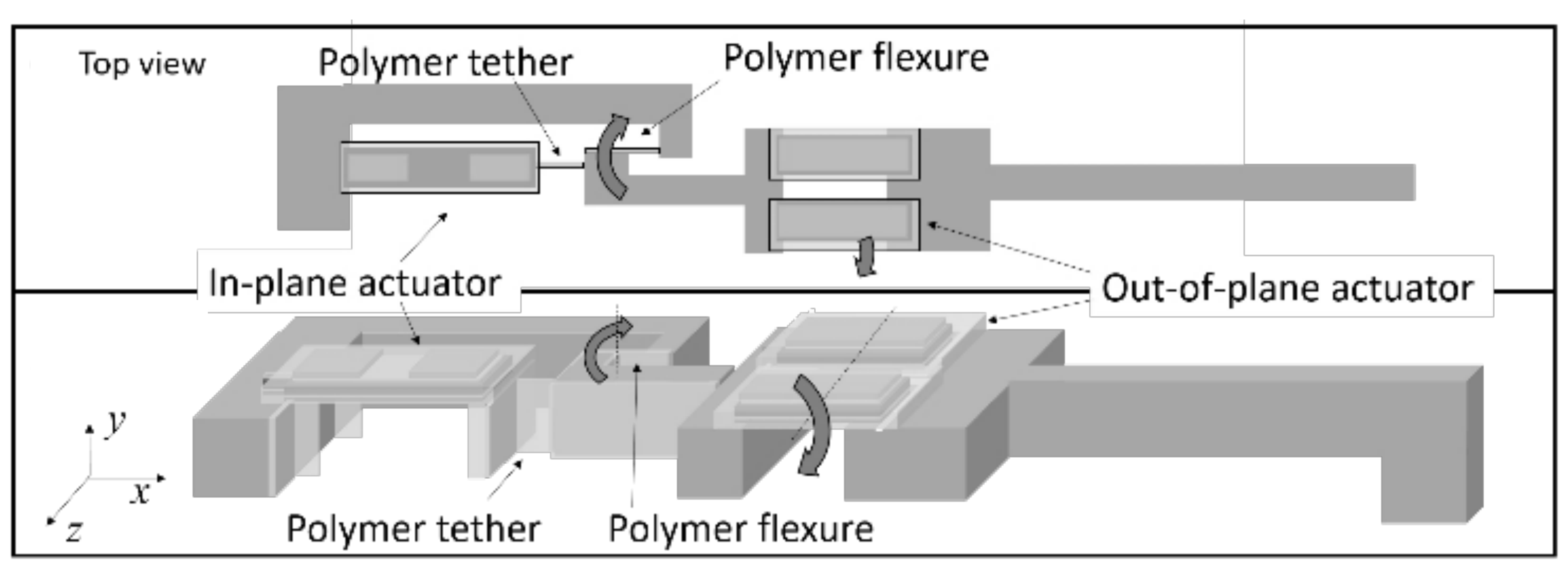
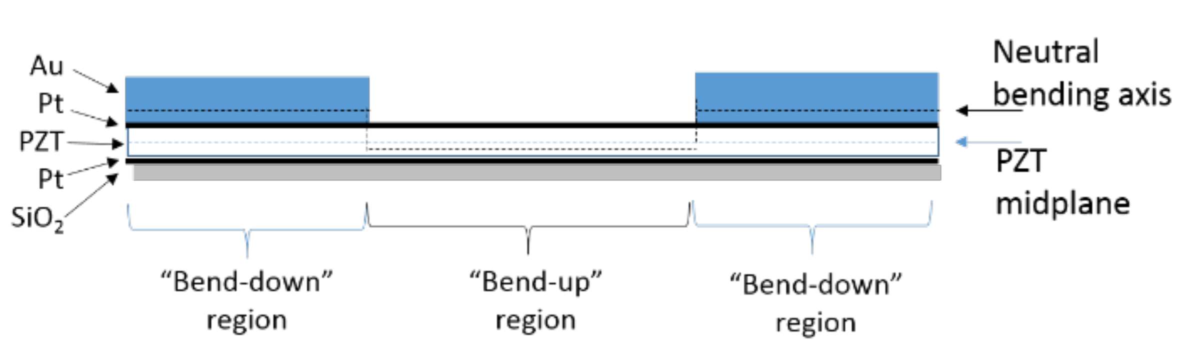


Figure 3: (a) top-view and (b) oblique view of a single leg with high-aspect ratio polymer for in-plane rotation, and thin-film piezoelectric unimorphs for both in-plane and out-of-plane motion [1]

Elastic leg joints based on thin-film piezoelectric actuation are designed for both out-of-plane and in-plane rotation.

The basic actuation unit of a thin-film piezoelectric device is a multi-layer, unimorph beam or membrane containing the piezoelectric layer between two metal electrodes. Simple piezoelectric cantilevers generate out-of-plane bending motion. As a given piezoelectric cantilever will tend to deflect either upwards or downwards, piezoelectric beams for lateral actuation in this arrangement are constructed of a combination of bend-up and bend-down elements.

Figure 4: Schematic (side view) of bend-down/bend-up piezoelectric cantilever designed to generate in-plane tip displacement [1]



Static & Modal Performance

The static motion (~70 µm) of the hexapod micro-robot foot is observed with a microscope at 19 Vpp. The motion of three different locations on the micro-robot, body, hip and knee, are measured in the frequency domain.

The mode shapes[2] associated with the hip near 438 Hz, uniformly generated on the body near 830 Hz, and most strongly associated with the knee near 3.4 kHz.

The out-of-plane rotation is measured to be 4.9±0.5°, while the in-plane-rotation is measured as 4.2±1.4°.

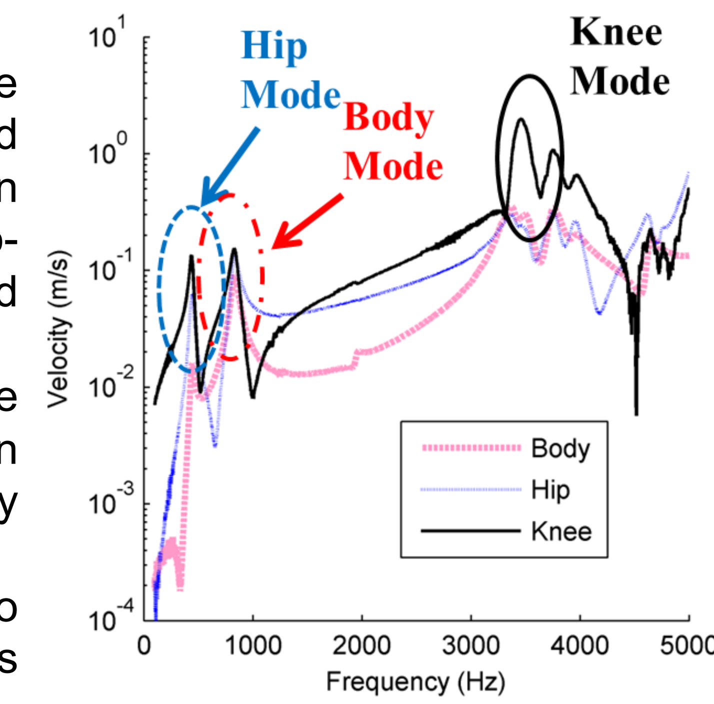


Figure 4: Resonance measurement of three different locations on the micro-robot: body (pink dash), hip (blue dotted) and knee (black solid)

Dynamics Model

A dynamic model[3] is developed for small-scale robots with multiple high-frequency-actuated compliant elastic legs and a rigid body. The motion of the small-scale robots results from dual-direction motion of piezoelectric actuators attached to the legs, with impact dynamics increasing robot locomotion complexity. The dynamic model is tested with two different centimeter-scale robot prototypes having an analogous actuation scheme to the millimeter-scale micro-robots.

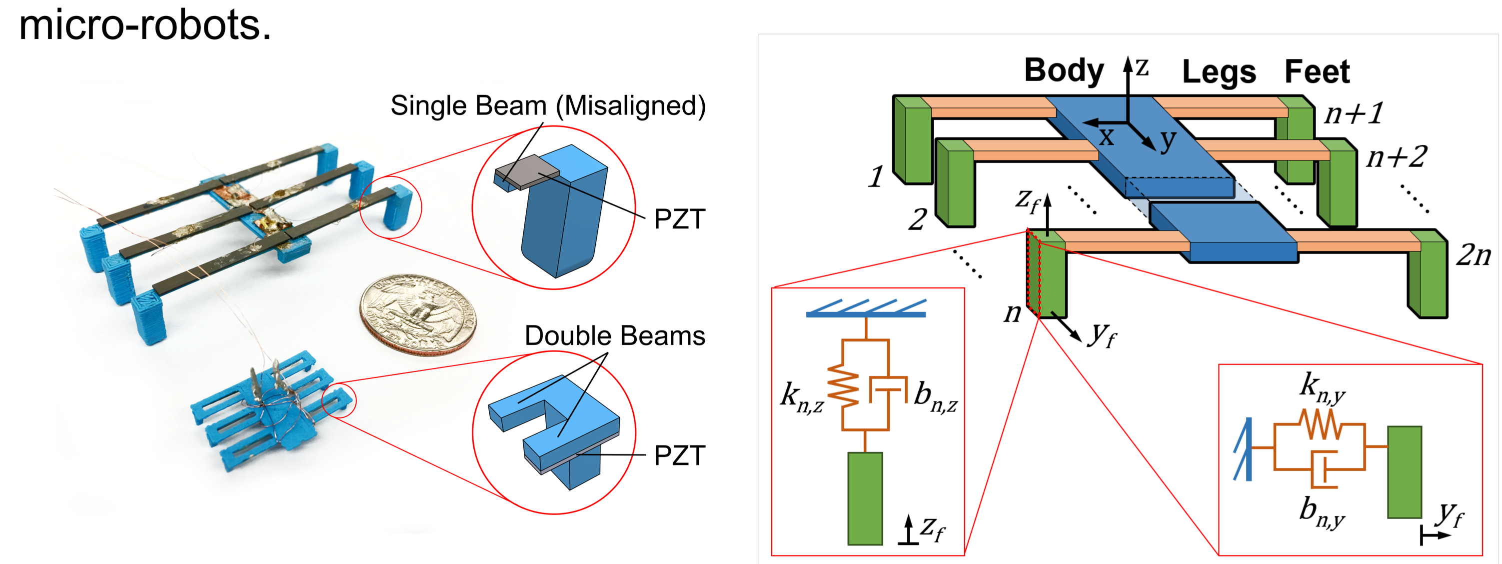


Figure 5: (Left) Photograph of both centimeter-scale prototypes with schematics of leg construction for each; (Right) Schematic of a generic micro-robot with 2n elastic legs connected to a rigid body. The motion of each foot in the y and z-directions is modeled independently. [2]

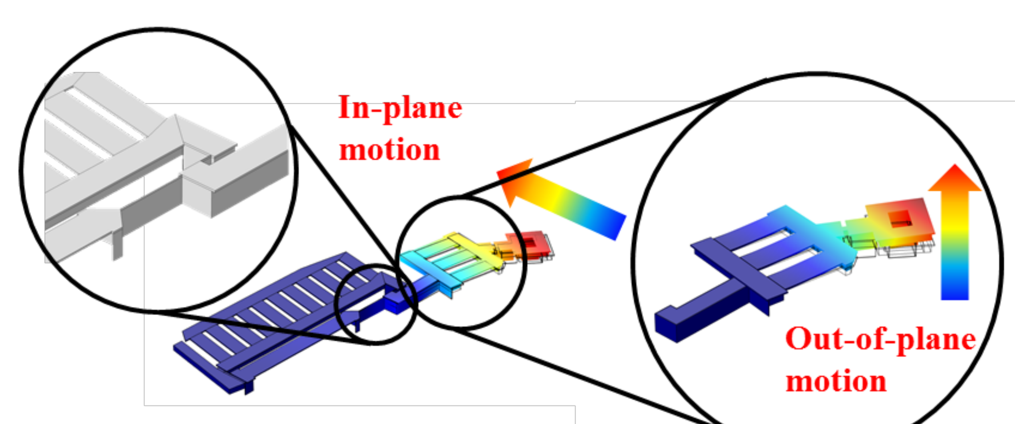


Figure 6. (left) The compliant structure of a robot leg with a high aspect ratio link connecting the hip and knee actuators; also shown are the COMSOL-simulated mode shapes of the first lateral mode of the leg (middle), originating in pivot about the hip actuator, and the first vertical mode of the leg (right), originating in bending of knee actuators.

The dynamics of a sample silicon hexapod micro-robot are studied as an example for understanding the legged micro-robots based on thin-film piezoelectric actuation. These robots have structural dynamics featuring elastic, linear resonances, light damping, and resulting high sensitivity to ground impact interactions. A dynamic model is modified, further integrating micro-scale feature such as adhesion and squeeze damping. The model is validated with passive out-of-chip locomotion, both lateral and vertical, of the detached hexapod micro-robot, using model information extracted from design parameters, finite element analysis results, and in-chip characterization.

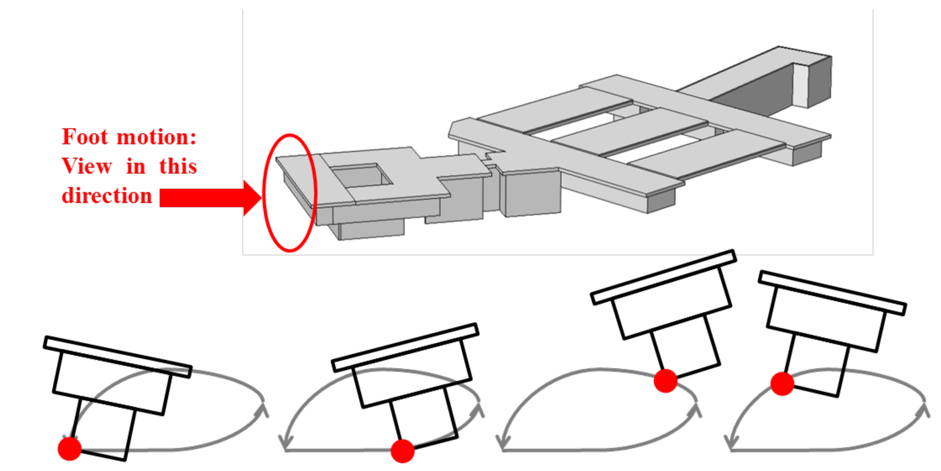


Figure 7. Side view of nominal robot foot motion when ground is present; the foot remains stationary with respect to the ground for a certain period of time when actuated downward and moves in air when actuated upward.

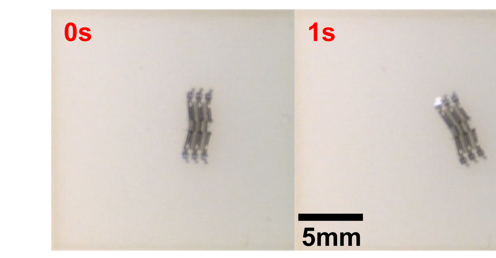


Figure 8. Hexapod microrobot location at (left) time = 0s and (right) time = 1s when the tray is externally vibrated by the shaker at 240 Hz.

Key features of small-scale motion near resonance examined in this work include squeeze-film damping and adhesion forces, with substantial effects for accuracy of foot motion and forward locomotion predictions, respectively. The model permits simulation of robot motion both with external vibration and on-board electrical actuation, allowing some exploration of potential robot-ground interactions should it operate under on-board electrical power. However, some mismatch between simulation and measurements that can be taken still exists, possibly due to remaining complexities of foot-terrain interaction that are not been fully studied.

Robot performances are estimated with this dynamic model. The current micro-robot with structure and actuators is about 0.3 mg. In simulation, when the robot total mass is larger than 1.7 mg, the robot stop moving. In some cases, locomotion is predicted to achieve a higher speed with a payload, as it improves uniformity of foot impact during simulation of a tripod gait.

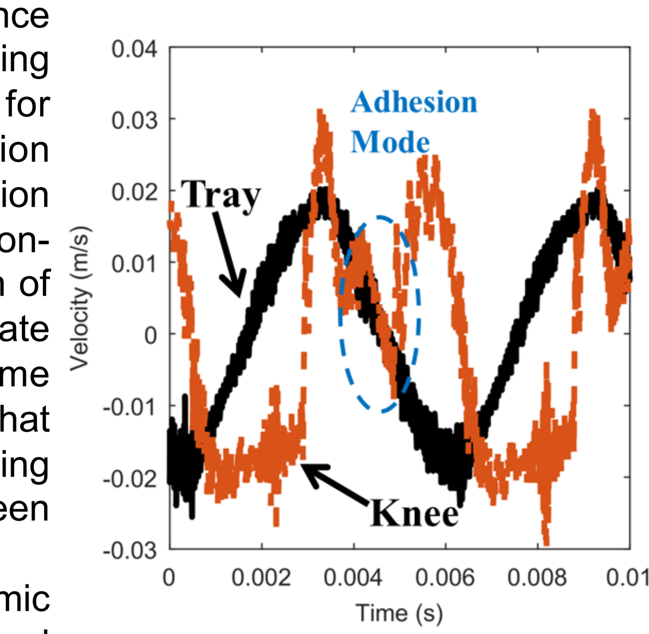


Figure 9. The vertical motion of the robot knee (dashed red) and tray (solid black), measured with the LDV when the shaker is actuated with 4V input voltage.

Conclusion & Future Work

We have demonstrated an actuation design for a thin-film piezoelectric micro-robot with high-aspect ratio polymer from a silicon wafer. With the static and dynamic performance of the micro-robot, we could further implement a dynamic model that has been validated with a millimeter-scale hexapod robot and scaled prototypes to micro-scale for better design, estimation and control of efficient micro-robot locomotion.

Further discussion on the robot motion with on-board electrical actuation was presented to understand possible scenarios for locomotion of micro-robots based on thin-film piezoelectric actuation principles. Further details of other contributing factors to microscale surface interactions, such as electrostatic forces and foot and/or ground plastic deformation, may improve the accuracy of dynamic model prediction. Further analysis will also examine and optimize other actuator inputs having potential for sustained efficient locomotion. Future tasks for micro-robot development include the validation of payload capability and integration with on-board battery or wirelessly-coupled power supplies.

References

[1] Choi, Jongsoo, Minchul Shin, Ryan Q. Rudy, Christopher Kao, Jeffrey S. Pulskamp, Ronald G. Polcawich, and Kenn R. Oldham "Thin-film piezoelectric and high-aspect ratio polymer leg mechanisms for millimeter-scale robotics." *International Journal of Intelligent Robotics and Applications* 1.2 (2017): 180-194.

[2] Qu, Jinhong, and Kenn R. Oldham. "Dynamic Structural and Contact modeling for a Silicon Hexapod Microrobot." *Journal of Mechanisms and Robotics* (2017).

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