NRI: FND: Light-Powered Microrobots for Future Microfactories (NRI #1734383)

Sri Sukanta Chowdhury, Andriy Sherehiy, Ruoshi Zhang, Zhong Yang, Danming Wei, Dan O. Popa(PI)

Louisville Automation and Robotics Research Institute (LARRI)

Next Generation Systems Group Lab, University of Louisville

http://www.ece.louisville.edu/ngs

Abstract

The goal of this research to study light powered microrobots that can accomplish precision nano-scale positioning and manipulation tasks. This study will provide new knowledge for programming multiactuator locomotors with a single beam, using differential responses of the robot limbs to generate multi-legged gaits. FEA simulations of 7 microrobots designed from asymmetric Chevron actuators are presented with in depth analysis of their resonance behavior due to fixed, as well as elastic supports at their contact points with underlying substrate. Experimental resonance frequencies of 3 different designs identified by frequency sweep experiments, excited by a 532 nm pulse laser, are in close agreement with the simulated values. Contact stiffness is estimated by comparing simulated and experimental resonance frequencies. Both in-plane and out of plane motion due to resonance is found in all of these structures that can be used to predict the stick-slip step size (locomotion mechanism) of these robots. In addition, modeling of differential thermal expansion is conducted to optimize the laser spot size that is used to drive these microrobots. Simulations of elliptic and circular laser spots with varying size suggest that covering only the actuators of the robot is sufficient for successful actuation. Using a circular laser spot increase the thermal expansion of the overall microrobot by 3.3 nm resulting in no significant gain in step size/gait of the robotic locomotion. This finding proves that the shape and size of the laser spot are insignificant as long as the actuators are under the laser beam.

Introduction and Objective

Remote-powered microrobot (Type-R):

- Design optimization by differential leg design using FEA simulations to improve steering capability of microrobots.
- Determining resonance frequencies of actuators for fixed and elastic boundary conditions to mimic real world environment.
- Simulation of thermal expansion of individual actuators as well as the whole robot structure to estimate the stick-slip step size.
- Optimize the laser spot size and shape to ensure maximum energy transfer.
- Determining the best dry media via atomic force microscope (AFM) surface roughness measurement.
- Experimental validation of effect of surface roughness on the locomotion of the microrobots.

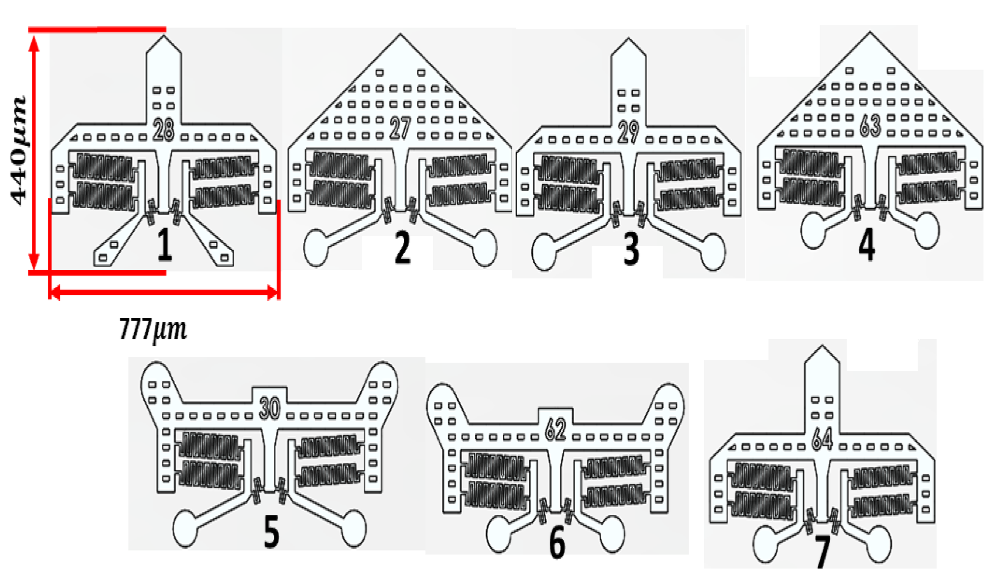

Fig. 1. Top view of 7 type-R microrobots designed from asymmetric actuators. Each microrobot is unique in terms of actuator length, length and width of body frame, length of legs and shape and number of dimples attached.

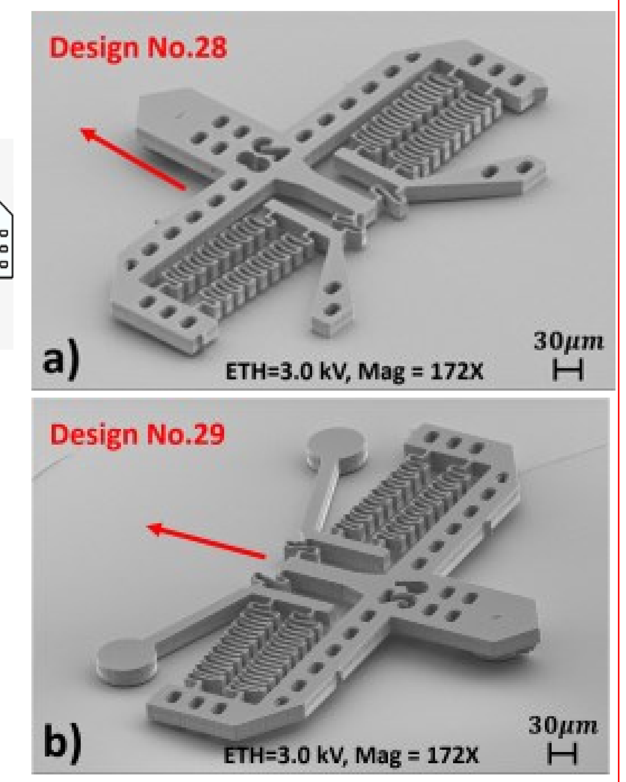

Fig. 2. SEM images of assembled ChevBot

Microrobot Models

- Spring-mass-damper model of microrobots:

$$m\frac{d^2x}{dt^2}+\gamma\frac{dx}{dt}+kx=F$$

- Resonance frequency:

$$\omega_n=2\pi f_n=A_n\sqrt{\frac{EI}{mL^3}}$$

- Brownian motion driven Lorentzian power spectral density:

$$S_x(f)=\frac{\bar{x}^2/(\pi Q f_0)}{\left(1-\left(\frac{f}{f_0}\right)^2\right)^2+\left(\frac{f}{Qf_0}\right)^2}$$

- Contact stiffness for perfectly smooth surfaces:

$$k_{CH}=\frac{dF}{dy}=\frac{3}{2}\left(\frac{16RE_*^2}{9}\right)^{1/3}F^{1/3}$$

- Modified Contact stiffness for small load:

$$k_{CHR}=\frac{k_{CH}}{3}$$

FEA Simulations of Resonance Frequencies

Fixed Support

Table 1

Modal frequencies for 7 microrobots using fixed supports at dimple and legs positions.

Modal number	Design number						
	27	28	29	30	62	63	64
f_1	43.3	50.0	14.7	28.4	15.8	21.4	68.1
f_2	46.9	19.7	16.4	56.5	16.8	50.0	16.1
f_3	12.7	22.6	28.4	12.7	32.8	53.8	18.1
f_4	14.4	16.2	16.9	13.7	30.3	16.2	31.6
f_5	23.8	21.1	17.1	28.5	13.8	16.9	18.7
f_6	14.8		29.6	14.4	14.9	28.0	19.5
f_7	14.9		52.5	15.0	31.3	13.8	33.4
f_8	25.0			29.7	29.8	15.7	

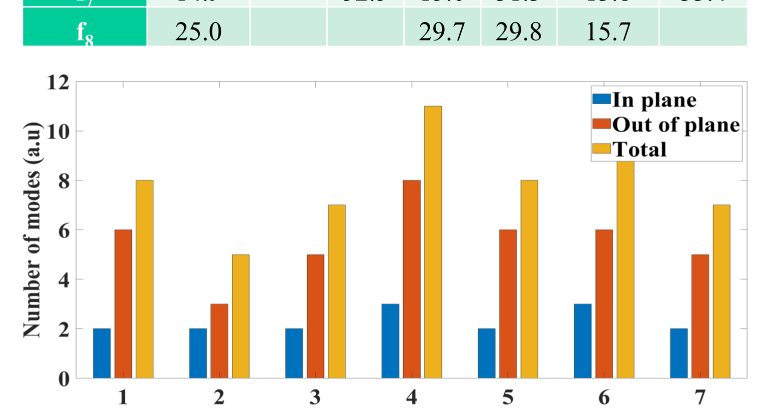

Fig. 3. Distribution of modal frequencies of microrobots toward in-plane and out of plane.

Elastic Support

Table 2

Modal frequencies for 7 microrobots using elastic supports with a contact stiffness of 100 MN/m at dimple and legs positions

Modal number	Design number						
	27	28	29	30	62	63	64
f_1	69.82	23.81	53.26	51.23	53.36	73.96	56.89
f_2	154.5	92.89	113	139.4	155.6	167.8	123.5
f_3	1524	551.3	1441	1890	1919	1417	1357
f_4	2694	1282	1899	2025	2060	2738	1937
f_5	3236	1505	2557	2756	2520	3121	2206

Table 3

Modal frequencies for design 29 microrobot with varying elastic supports at dimple and legs positions

Elastic Stiffness (MN/m)	Modal frequencies (Hz)				
	f_1	f_2	f_3	f_4	f_5
10	16.8	35.6	455.6	600.96	809.5
100	53.2	112.9	1440.7	1898.8	2557.4
200	75.3	159.7	2037.3	2682.7	3612.9
500	119.1	252.6	3220.4	4229.8	5694.3
1000	168.4	357.3	4552.3	5954.1	8010.6

Thermal Expansion Simulation

- Thermal simulation of Individual actuators as well as whole robot structure is performed.
- Expansion in vertical and horizontal direction is estimated to determine stick and slip step size.
- Gradually increasing size of a circular and an elliptical heat source is used to optimize optical beam delivery system.
- A 0.5 μm thick layer on the top surface of the robot is defined as the active area.
- A convection current around the structure is set to mimic the actual laboratory environment.
- Expansion along the thickness (z-axis) of the robot is ignored because any expansion in this direction will not contribute to the locomotion.

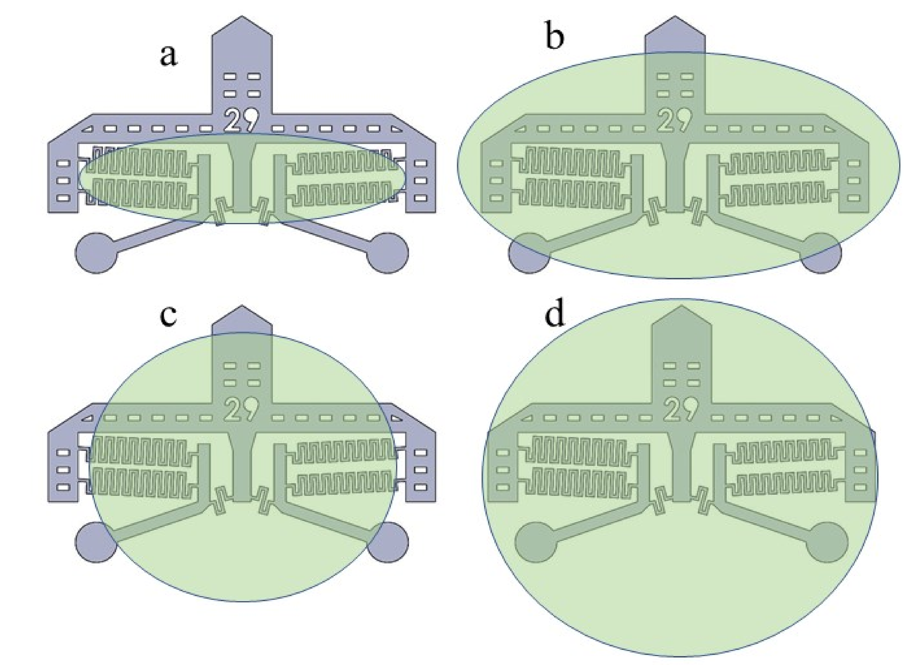

Fig. 4. Orientation of circular and elliptical laser beam on microrobot

Table 4

Thermal expansion of design 29 microrobot in vertical and horizontal direction

Laser spot shape	Vertical Expansion (μm)	Horizontal Expansion (μm)
Circle	1.4687	2.0280
Ellipse	1.4654	2.0277

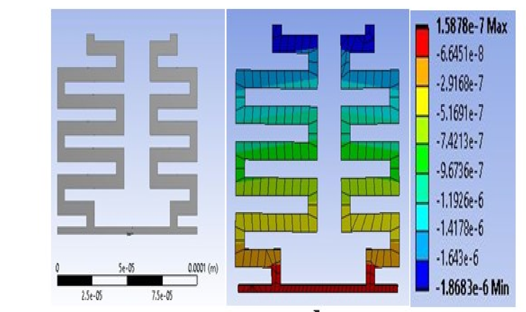

Fig. 5. Thermal expansions of isolated actuators

Experimental validation of resonance frequencies

Experimental setup

A high-power Nd:YAG pulse laser (Spectra-Physics Explorer® one) operates at 532 nm, is used as the actuating source. The repetition rate of the pulses can be adjusted between 0.5-60 KHz. A National Instrument smart camera (ISC-1772C) is used for real-time position tracking of the microrobots. A second camera (Pixelink PL-D734) is used as guidance during sample positioning. The microrobots are placed on a sample chuck, positioned on top of five cascaded linear stages. Three of stages are manually controlled and the rest two (PI Q-521) are controlled by LabVIEW

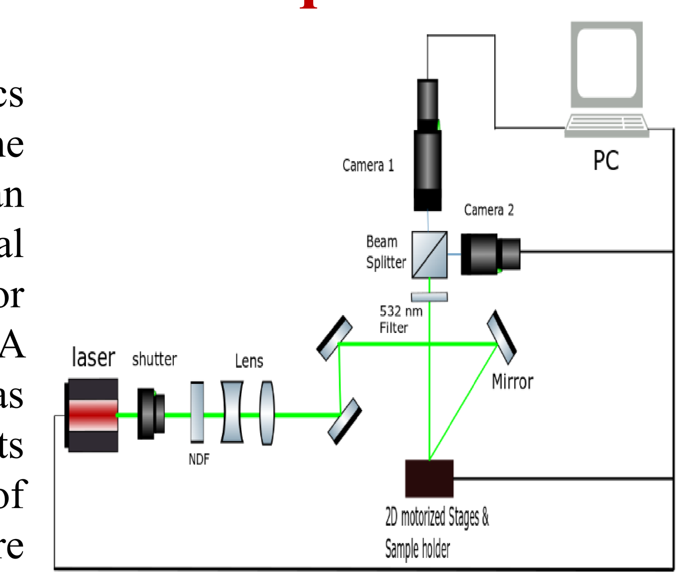

Fig. 6. Schematic of experimental setup

- A total of 6 robots consists of 3 different designs (out of 7) tested for their resonance frequency.
- Driving current of the laser is set at 4.5 A with an elliptical spot size of approximately 0.3 mm^2.
- Burst mode is used with 30-50 pulses per burst and a loop delay of 200-300 ms

Table 5

Thermal expansion of design 29 microrobot in vertical and horizontal direction

Modal number	Design number					
	28	28	29	29	64	64
f_1	600	700	800	700	1000	1000
f_2	1000	1300	1500	1100	1700	2000
f_3	1700	1900	2000	2000	2400	2500

Dry Media Surface Roughness Measurement

Mode of operation:

- Non-contact (AC)

AFM probe:

- Cantilever resonant frequency: ~155 kHz

AFM scan parameters

- Scanned area 40 μm x 40 μm
- Scan speed: 20 μm/s
- 256 lines per area
- Surface scanned at 5 different locations

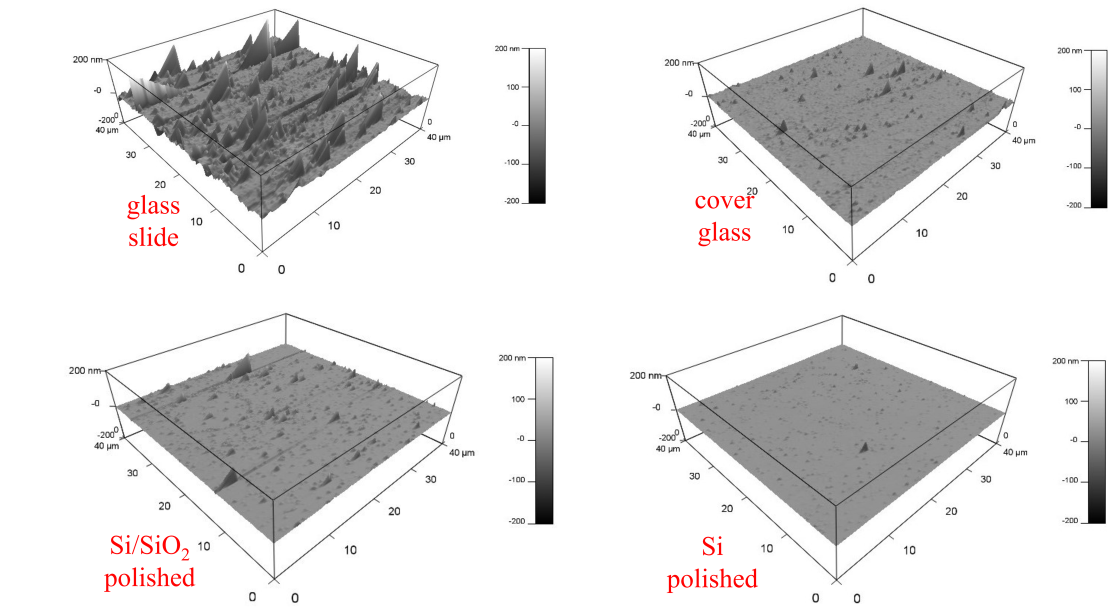

Fig. 7. Roughness of different dry surface

- **Surface Roughness - Root mean squared (RMS):** $RMS=\sqrt{\frac{1}{N}\sum_{i=1}^{N} z_i^2}$

Where z_i is a height at specific point on the substrate's surface (given pixel i in the image).

Table 6

Surface roughness parameters for different dry media

	RMS [nm]	RMS (Min) [nm]	RMS (Max) [nm]
glass slide	27.5	21.5	36.8
cover glass	5.9	3.7	8
Si polished	2.2	1.4	2.7
SiO_2	6.5	3.9	8.8
Si/Au	13.0	11.9	15.4
Si dimples	5.4	0.5	10.8

Conclusion

- we analyzed the predicted behavior of laser -driven microrobot based on dynamic models of intermittent contact.
- FEA modal analysis of 7 different untethered microrobots was carried out for both fixed and elastic support at their contact points.
- Resonance frequencies of 3 robots were also measured experimentally, showing close agreement with the simulated values using an elastic stiffness of 100 MN/m at the contact points.
- Simulation results also confirm that the shape of the laser beam has no significant impact on the step size of the stick-slip locomotion mechanism of these microrobots due to their thermal expansion.
- In the future, we will experimentally identify the best dry media and use a dynamic controller for closed-loop in-plane locomotion.

[1] S. S. Chowdhury, Z. Yang, A. Sherehiy, D. Wei, R. Zhang, and D. O. Popa, "Parametric investigation of laser-driven microrobot maneuverability on dry substrates " in *2020 International Conference on MARSS,* 2020.

[3] Z. Yang, A. Sherehiy, S. S. Chowdhury, D. Wei, R. Zhang, and D. O. Popa, "Design, fabrication and experimental validation of a steerable, laser-driven microrobot in dry environments," in *CASE*, 2020, pp. 882-887.

[2] S. S. Chowdhury, Z. Yang, P. W. Clapacs, and D. O. Popa, "Untethered microrobots with serpentine actuators: The role of elastic point contact & laser beam shape on their locomotion" in *ASME MSEC,* 2021.

NSF grant #CMMI 1734383

NATIONAL INSTRUMENTS

J.B. SPEED SCHOOL OF ENGINEERING

Next Generation Systems Group (NGS) at University of Louisville, USA

NEXT GEN SYSTEMS

UNIVERSITY OF LOUISVILLE