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Manipulation of Microrobots Using Chladni Plates and Multimode Membrane Resonators

MIDN Lillian Usadi *, LT Steven Yee, Dr. Hatem Elbidweihy, Dr. Samara Firebaugh

United States Naval Academy, 121 Blake Rd, Annapolis, MD 21402

* Corresponding author: lillian.usadi@gmail.com

Abstract: The advent of micro/nanorobotics promises to transform the physical, chemical, and biological domains by harnessing opportunities otherwise limited by size. Most notable is the biomedical field in which the ability to manipulate micro/nanoparticles has numerous applications in biophysics, drug delivery, tissue engineering, and microsurgery.

Acoustics, the physics of vibrational waves through matter, offers a precise, accurate, and minimally invasive technique to manipulate microrobots or microparticles (stand-ins for microrobots). One example is through the use of flexural vibrations induced in resonant structures such as Chladni plates.

In this research, we developed a platform for precise two-dimensional microparticle manipulation via acoustic forces arising from Chladni figures and resonating microscale membranes. The project included two distinct phases: (1) macroscale manipulation with a Chladni plate in air and (2) microscale manipulation using microscale membranes in liquid. In the first phase (macroscale in air), we reproduced previous studies in order to gain a better understanding of the underlying physics and to develop control algorithms based on statistical modeling techniques. In the second phase (microscale in liquid), we developed and tested a new setup using custom microfabricated structures. The macroscale statistical modeling techniques were integrated with microscale autonomous control systems. It is shown that control methods developed on the macroscale can be implemented and used on the microscale with good precision and accuracy.

Keywords: Chladni Plates; Microscale Membranes; Acoustic Actuation; Displacement Maps

Motivation:

- Microrobots (~10-100 μm) are able to interact with biological structures on their same size scale that macroscale robots cannot.
- Biomedical applications: Lab on a Chip (2-D), drug delivery, tissue repair
- There are various ways to manipulate microrobots: optical, chemical, electrical, magnetic, and acoustical.
- Acoustic actuation is a non-invasive way to manipulate microrobots.

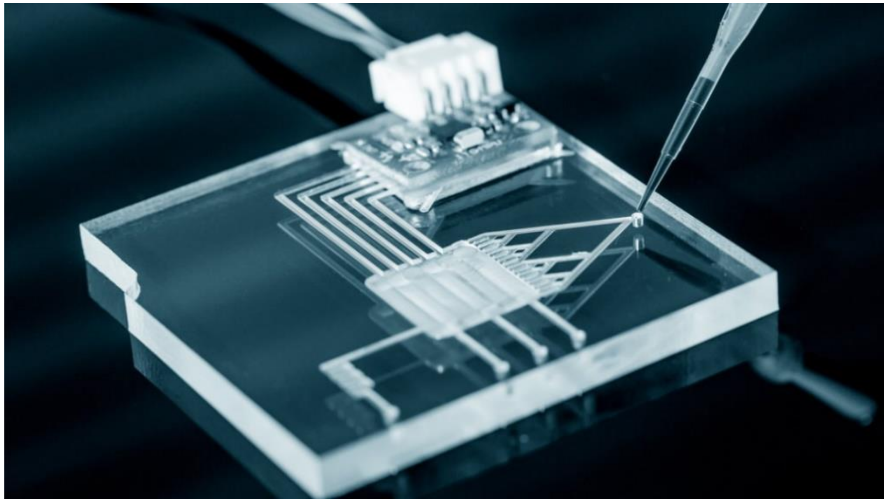

Fig. 1. Lab on a Chip [3]

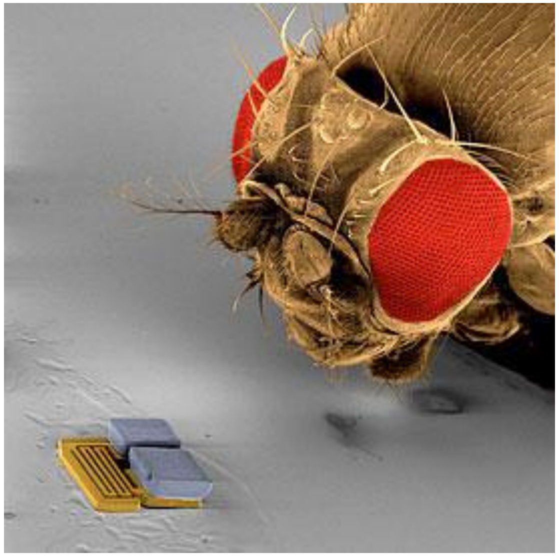

Fig. 2. Microbot next to a fly [2]

References:
[2] NIST and Nanosoccer .https://www.nist.gov/topics/nanotechnology/nist-and-nanosoccer . Accessed: 2020-11-24.
[3] This One-Cent Lab-on-a-Chip Can Diagnose Cancer and Infections.https://singularityhub.com/2017/02/19/one-cent-lab-on-a-chip-can-detect-cancer-and-infections . Accessed: 2020-11-24.

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Background:

- Chladni Plates are thin, metal plates that have natural resonant frequencies with standing wave patterns visualized by particles displaced on the plate.
- Chladni figures are complex patterns formed in response to vibrations. See Figs. 3-4.

Fig. 3. Chladni plate with the sand on top forming a Chladni Figure [4]

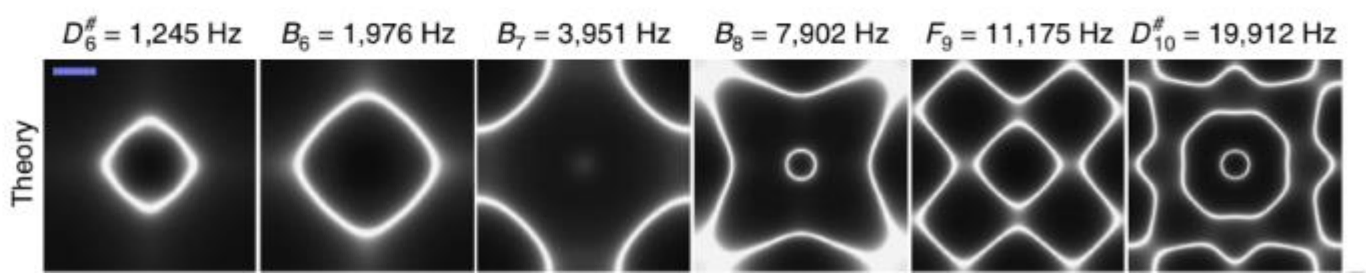

Fig. 4. Chladni plate resonating at various resonant frequencies [1]

References:
[1] Quan Zhou, Veikko Sariola, Kourosh Latifi, and Ville Liimatainen. Controlling the motion of multiple objects on a chladni plate. Nature communications, 7:12764, 09 2016
.com/2017/02/19/one-cent-lab-on-a-chip-can-detect-cancer-and-infections . Accessed: 2020-11-24.
[4] Chladni Plates.https://www.pasco.com/products/lab-apparatus/waves-and-sound/ripple-tank-and-standing-waves/wa-9607

Background:

- Displacement maps show the direction of movement of a particle at every single point on the Chladni plate as a result of plate oscillation at the indicated frequency.
- Displacement maps are referenced as tables by a control algorithm to control movement of a microrobot or other particle.

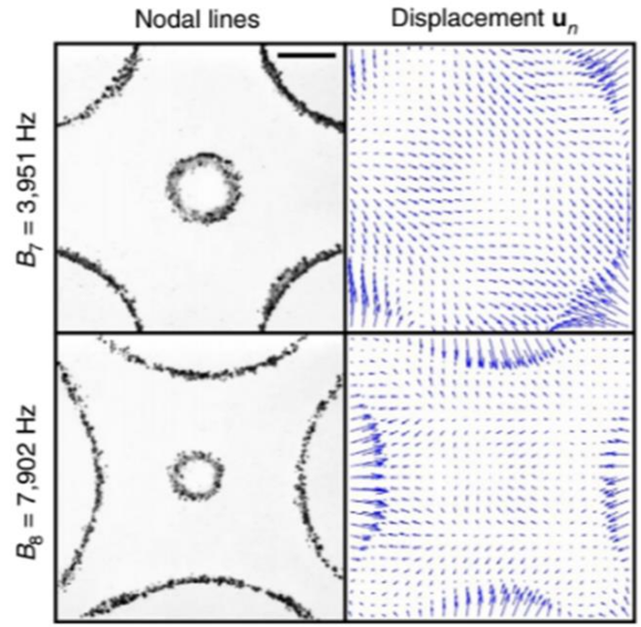

Fig. 5. Visual representations of the nodal lines and displacement maps resulting from driving a 50mm square Chladni plate with two different frequencies. [1]

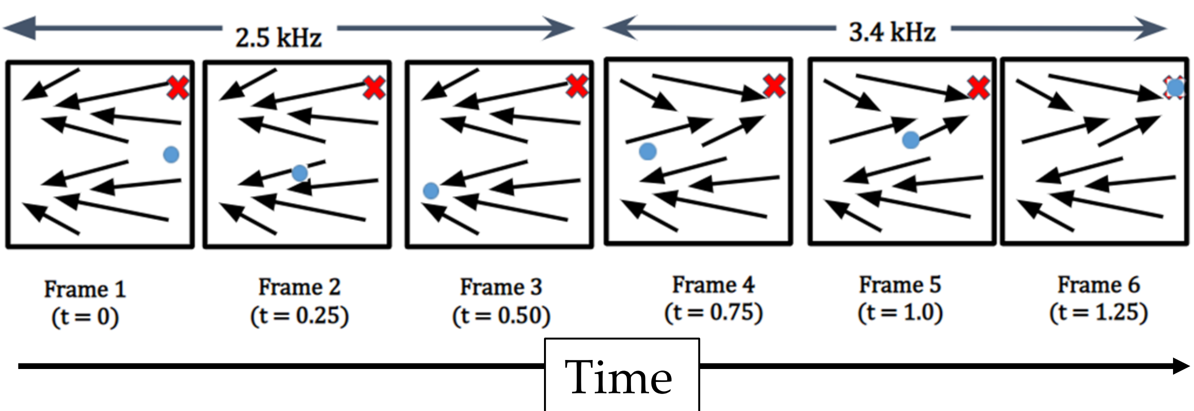

Fig. 6. Notional schematic that shows the movement of the blue bead over time by using the displacement maps of two different frequencies.

References:
[1] Quan Zhou, Veikko Sariola, Kourosh Latifi, and Ville Liimatainen. Controlling the motion of multiple objects on a chladni plate. Nature communications, 7:12764, 09 2016
.com/2017/02/19/one-cent-lab-on-a-chip-can-detect-cancer-and-infections . Accessed: 2020-11-24

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Project Phasing

- Experiment has two parts: macroscale manipulation in air and microscale in water.
- Macroscale manipulation in water will be performed if necessary to understand microscale experiment.

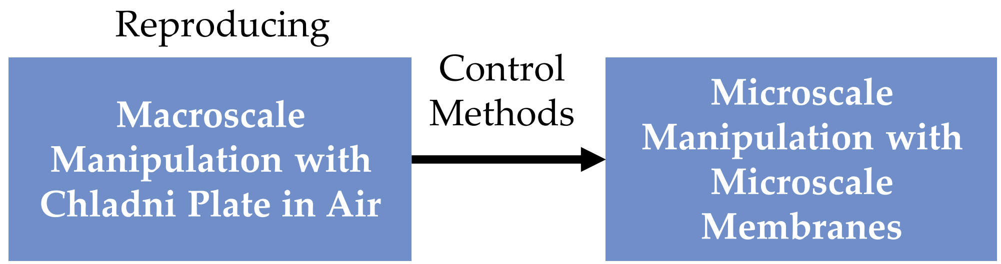


Fig. 7. Project phasing

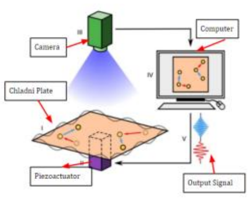
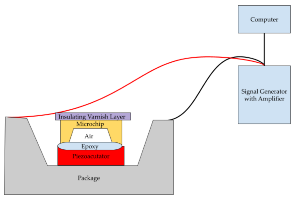
	Particle Size	Frequency	Picture
Macroscale Manipulation with Chladni Plate in Air	~750 um (Solder Beads)	~1 kHz – 20 kHz	
Microscale Manipulation with Microscale Membranes	~50 um (Microbeads)	~10 kHz - 1 MHz	

Table 1. Table shows the various stages of this experiment [1]

References:
[1] Quan Zhou, Veikko Sariola, Kourosh Latifi, and Ville Liimatainen. Controlling the motion of multiple objects on a chladni plate. Nature communications, 7:12764, 09 2016
.com/2017/02/19/one-cent-lab-on-a-chip-can-detect-cancer-and-infections . Accessed: 2020-11-24.

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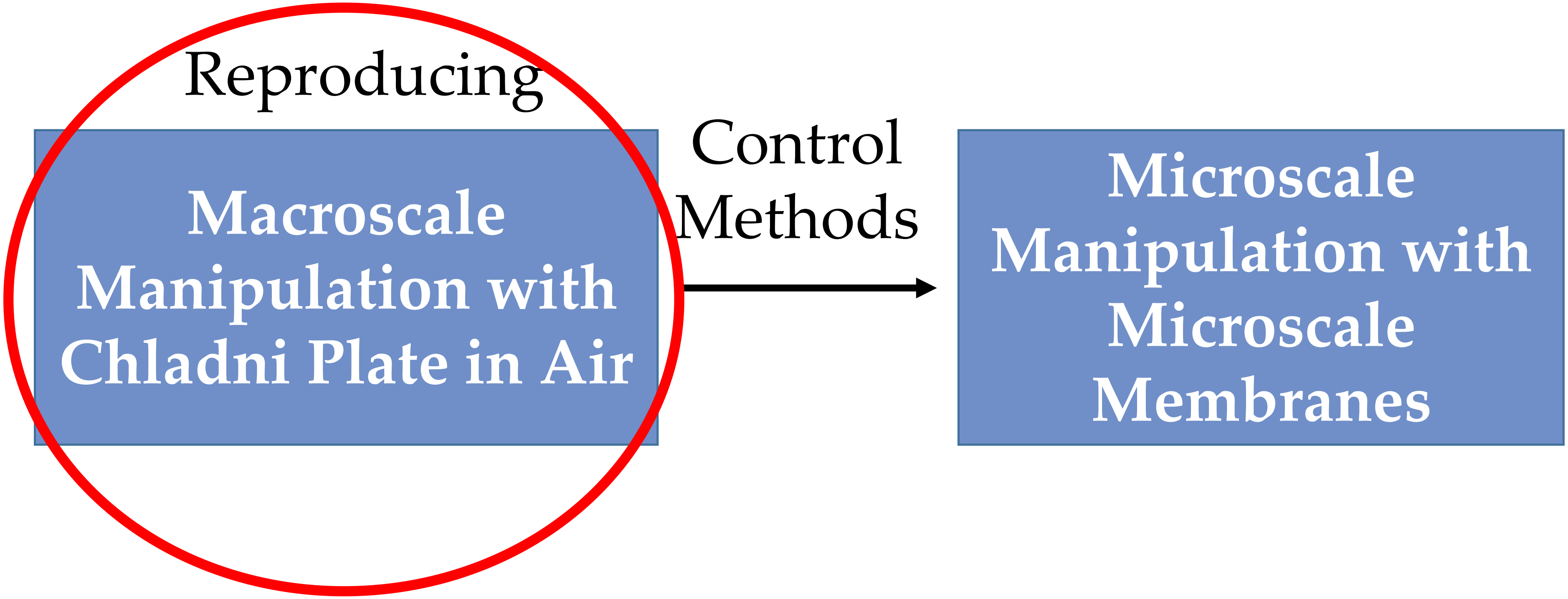


Fig. 8. Project phasing

Macroscale Experiment

- Random frequencies from Fig. 4 were played via MATLAB-controlled signal generator to drive a piezoelectric actuator and a 50mm square Chladni plate.
- Images were acquired concurrently using a USB microscope.

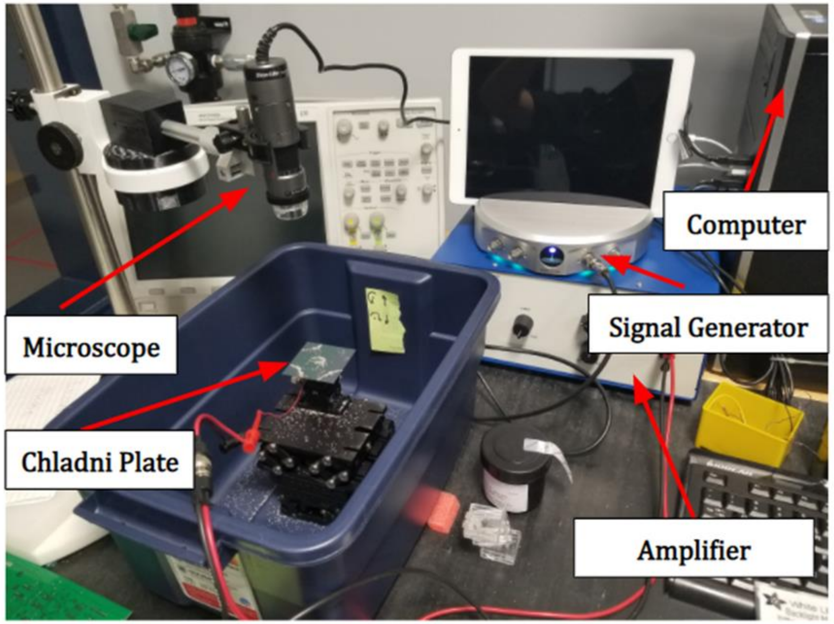


Fig. 9. Macroscale manipulation with Chladni plate in air experimental setup

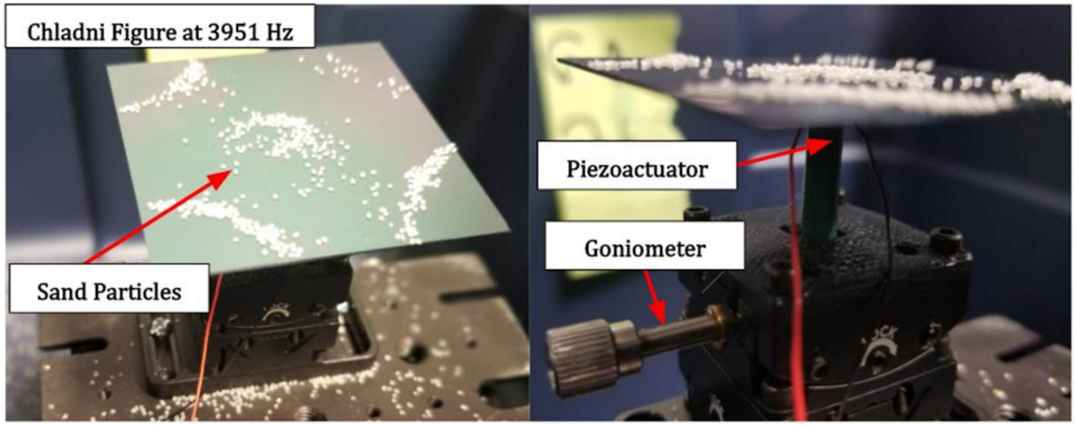


Fig. 10. Picture of Chladni figure developed at 3951 Hz

References:
[1] Quan Zhou, Veikko Sariola, Kourosh Latifi, and Ville Liimatainen. Controlling the motion of multiple objects on a chladni plate. Nature communications, 7:12764, 09 2016
.com/2017/02/19/one-cent-lab-on-a-chip-can-detect-cancer-and-infections . Accessed: 2020-11-24.
[4] Chladni Plates.https://www.pasco.com/products/lab-apparatus/waves-and-sound/ripple-tank-and-standing-waves/wa-9607

Macroscale Experiment – Displacement Maps

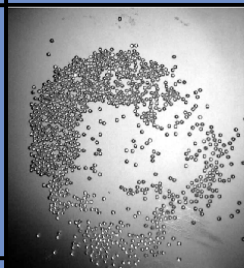
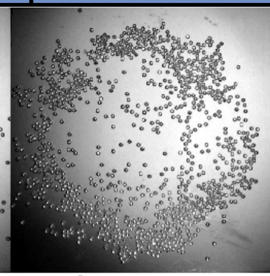
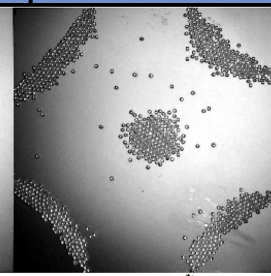
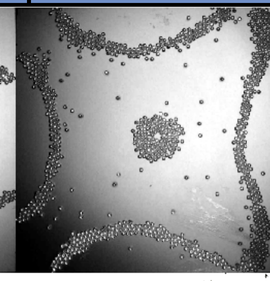
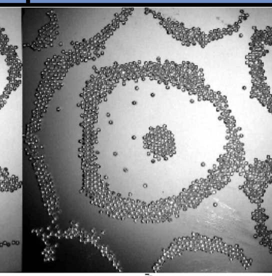
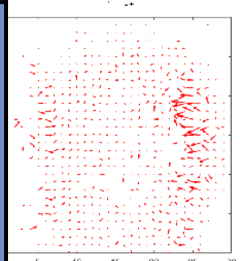
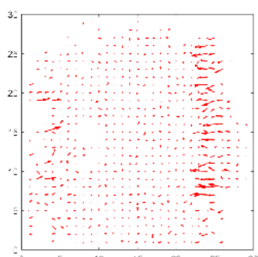
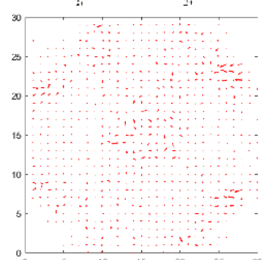
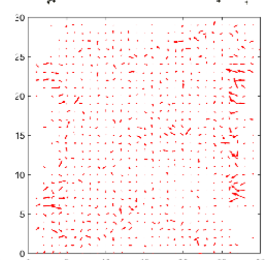
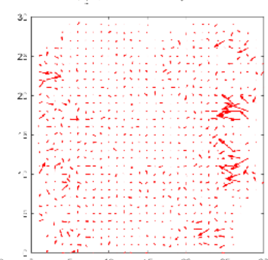
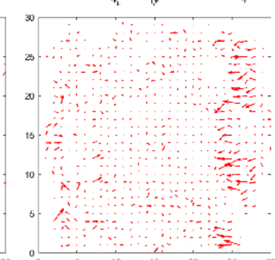
	1245 Hz	1976 Hz	3951 Hz	7902 Hz	11175 Hz	19912 Hz
(a) Grayscale Images						
(b) Object Identified Particles						
(c) Displacement Maps						

Table 2. Images Acquired and Post-Processed

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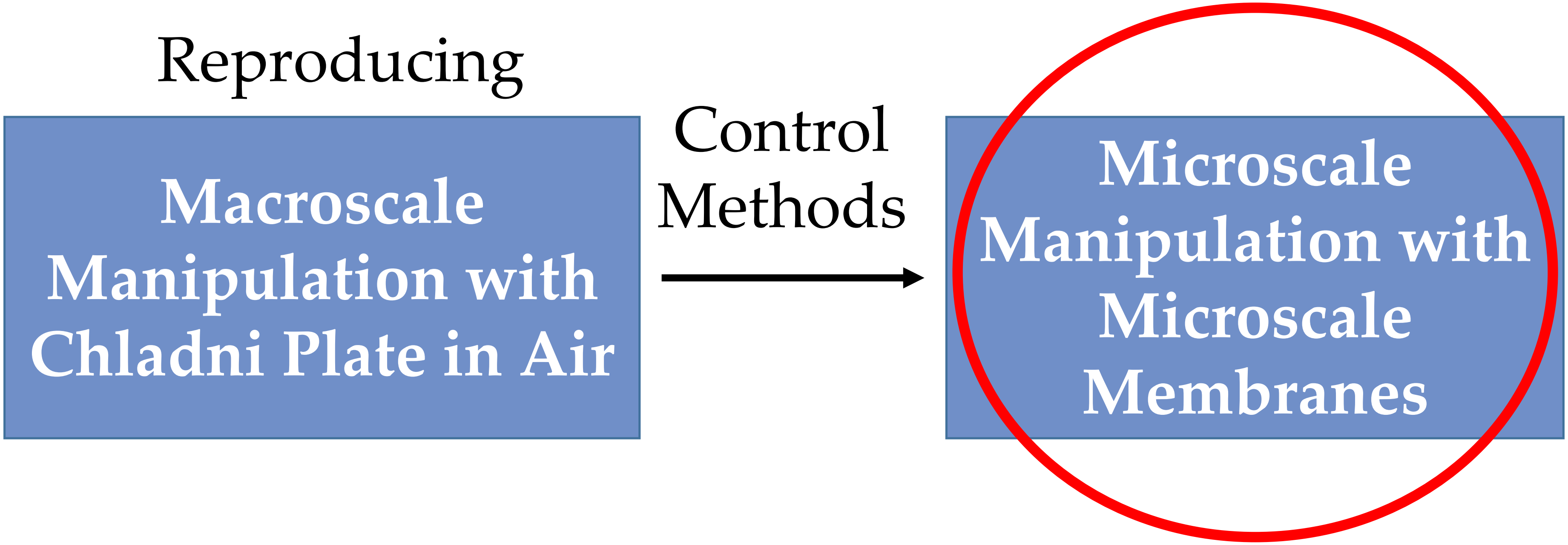

Fig. 11. Project phasing

Microscale Experimental Setup

- Frequencies to drive the piezoelectric actuator and multimode membrane resonator were chosen based off of [5] and prior analytical computations.
- Images were acquired concurrently using a USB microscope.

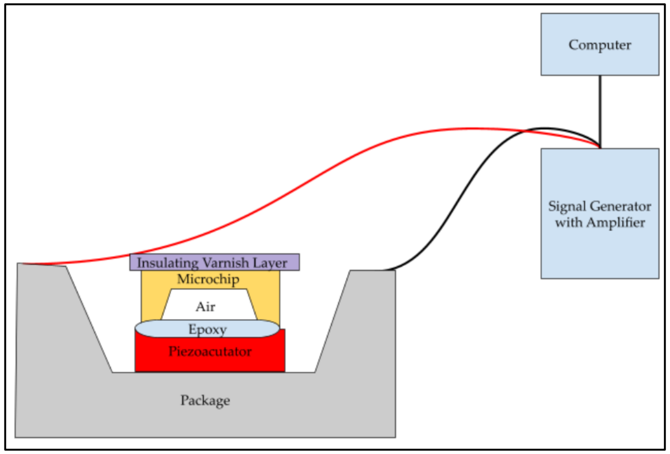

Fig. 12. Sketch of the microscale setup

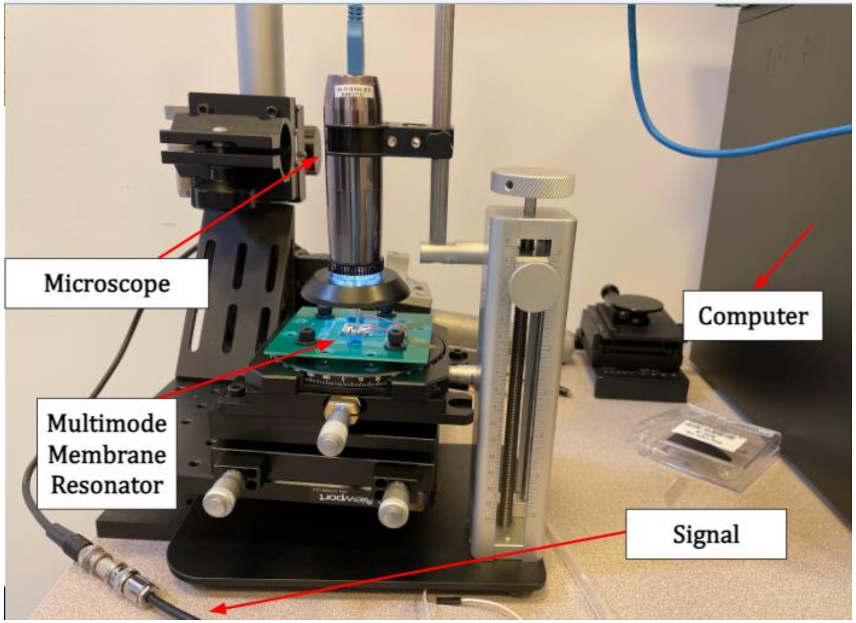

Fig. 13. Experimental microscale setup including the multimode membrane resonator

References:
[5] H. Jia, X. Liu and P. X. -. Feng, "Manipulating and Patterning Micro/Nanoparticles in Liquid Using Multimode Membrane Resonators," 2018 IEEE Biomedical Circuits and Systems Conference (BioCAS), Cleveland, OH, USA, 2018, pp. 1-4, doi: 10.1109/BIOCAS.2018.8584705.

Design of Microchip

- 10μm-thick silicon microscale membranes were designed in-house and then manufactured by MEMSCAP.
- Each chip quadrant contains different membrane shapes and boundary conditions.

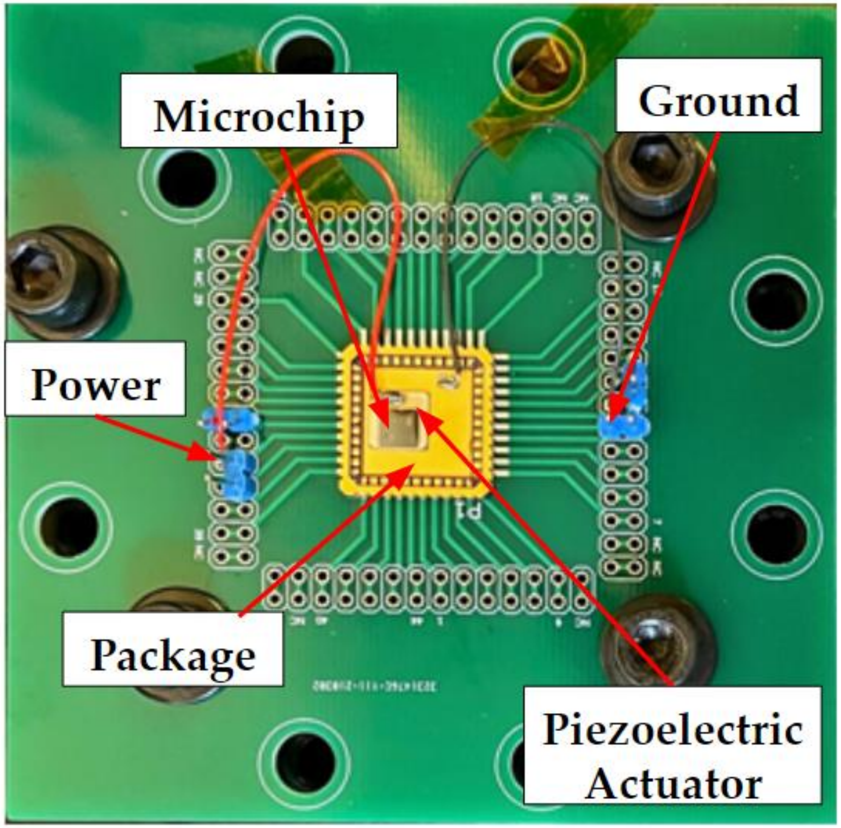

Fig. 14. Picture of multi-mode membrane resonator on a PCB

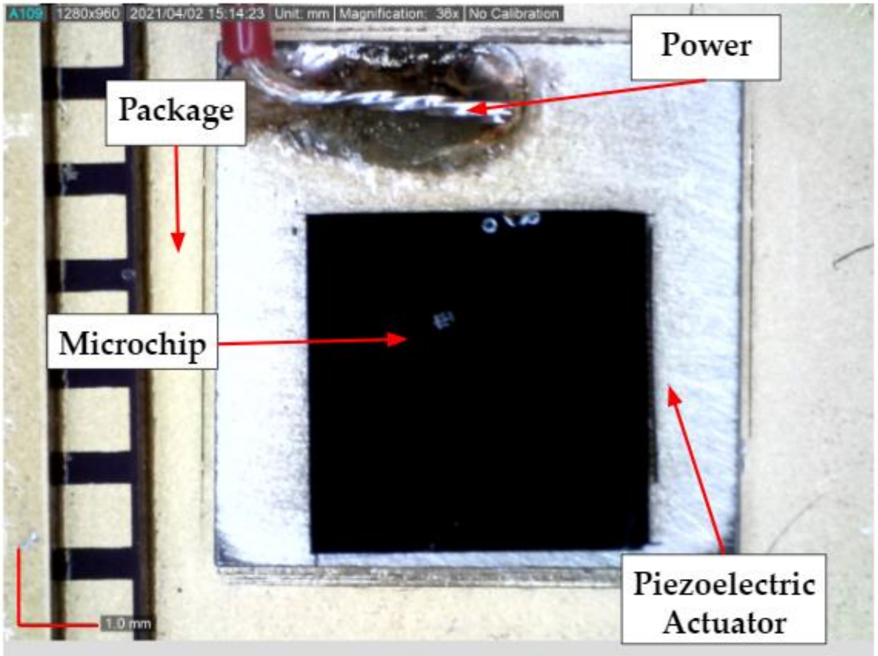

Fig. 15. Picture of multi-mode membrane resonator, piezoelectric actuator, and chip package

2-D Drumhead (Clamped)

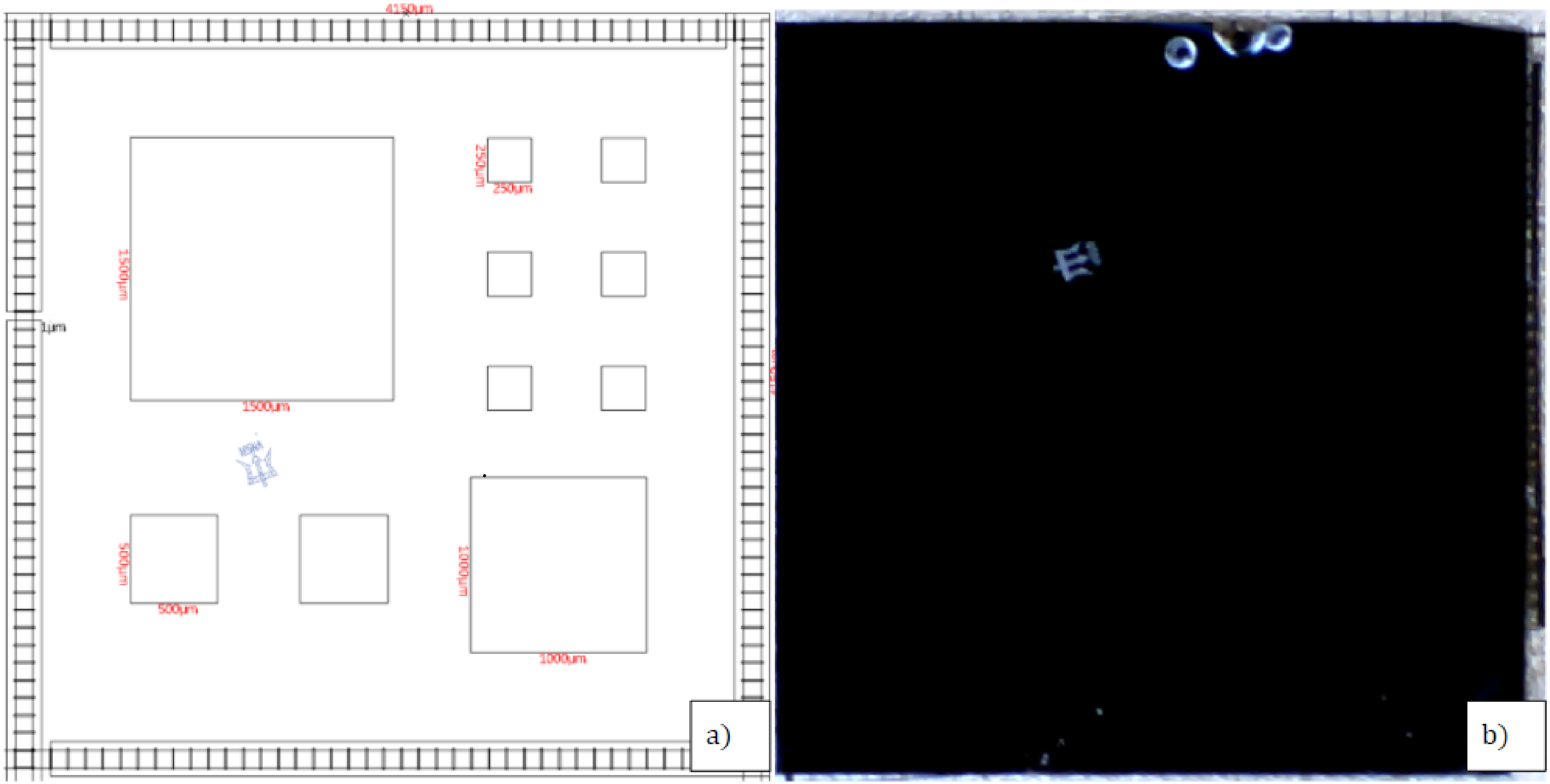

Fig. 16. Drumhead (Clamped)
a) Layout Editor Design b) Actual Photograph

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2-D Trampoline (Unclamped)

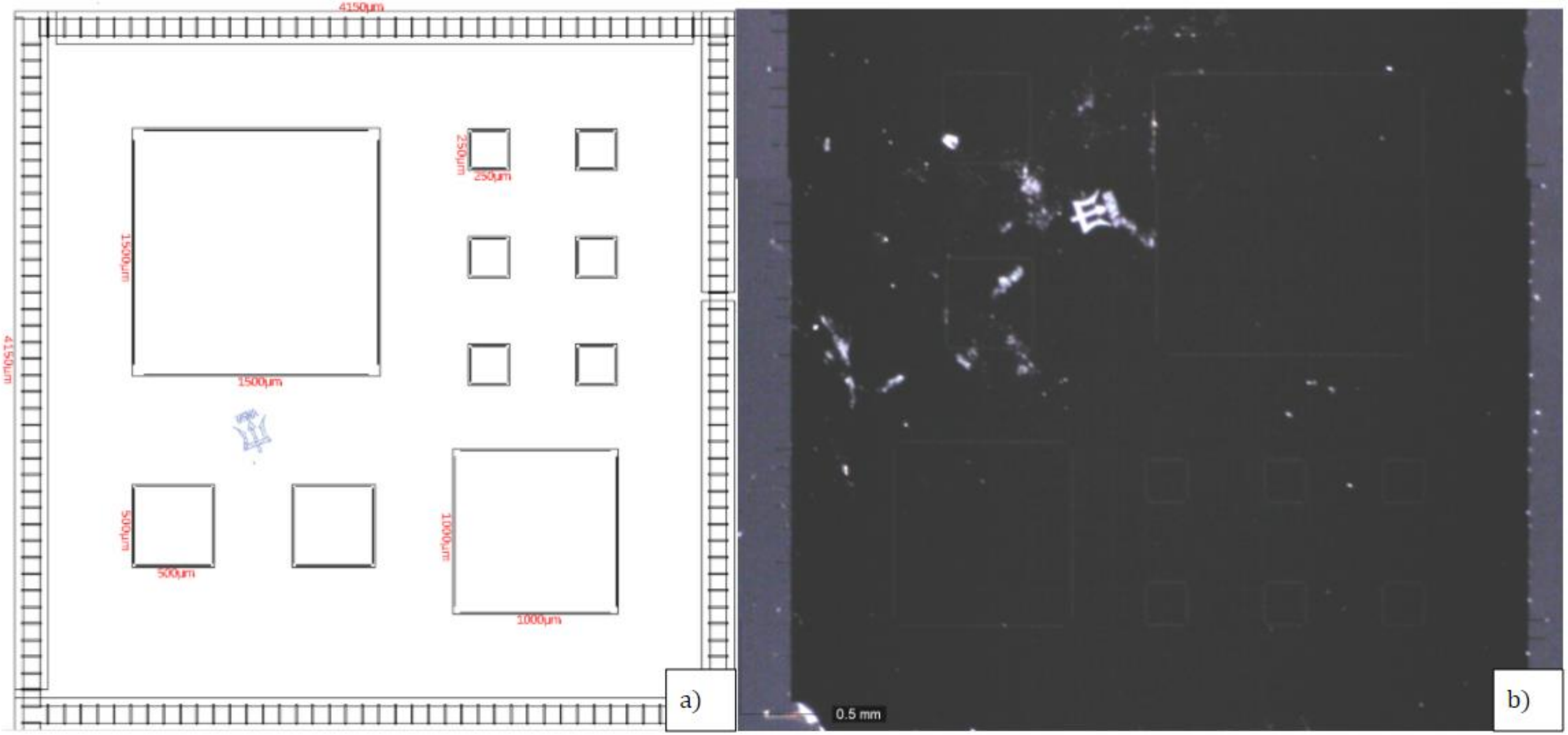

Fig. 17. Trampoline (Unclamped)
a) Layout Editor Design b) Actual Photograph

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1-D Beam (Unclamped and Clamped)

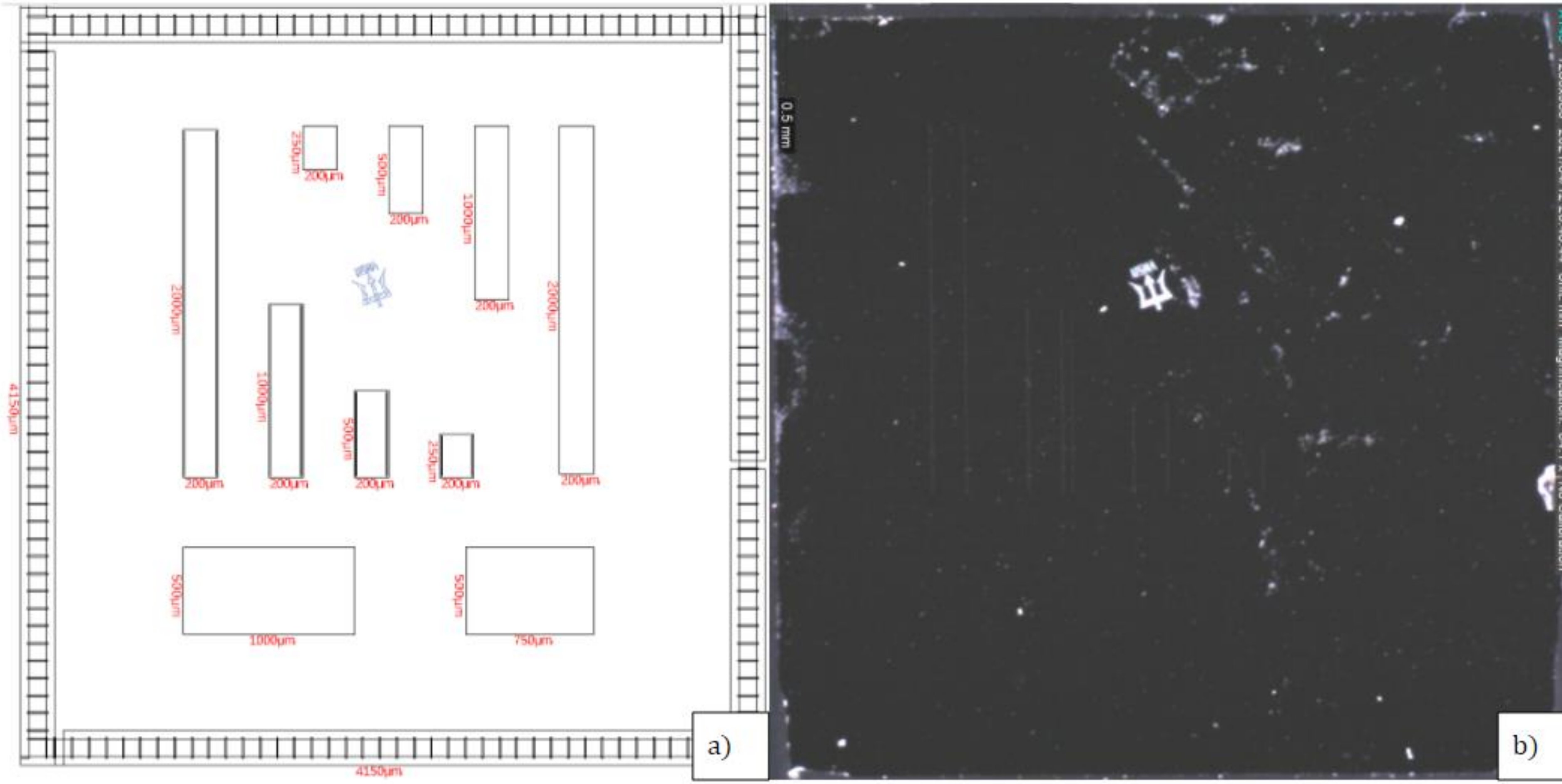

Fig. 18. 1-D Beam (Unclamped and Clamped)
a) Layout Editor Design b) Actual Photograph

Mixture: 2-D Drumhead (Clamped), 2-D Trampoline (Unclamped) and 1-D Beam (Unclamped and Clamped)

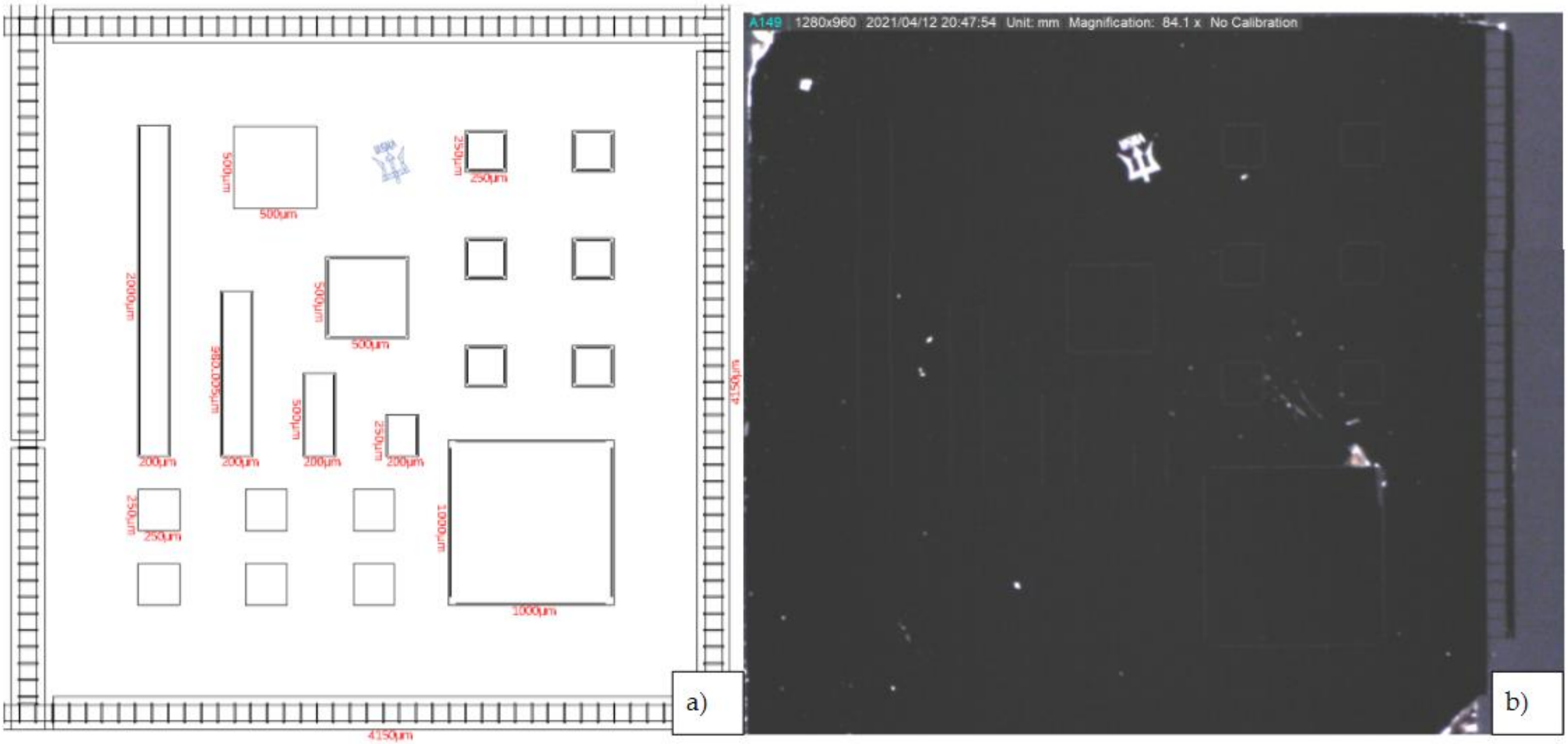

Fig. 19. 2-D Drumhead and 1-D Beam (Unclamped and Clamped)
a) Layout Editor Design b) Actual Photograph

Imaging and Microparticle Detection

- Microparticle detection techniques used on the macroscale are effective on the microscale

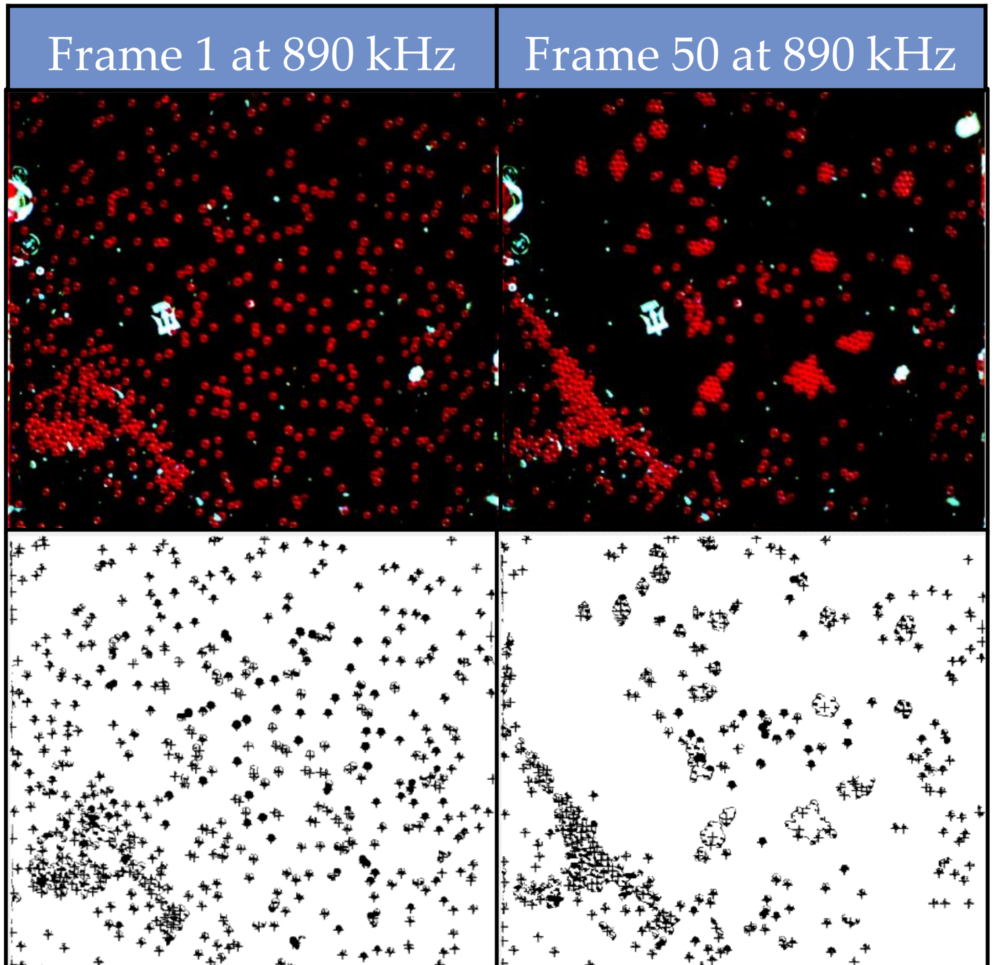

Fig. 20. Microparticles (50 μm) are imaged on the 2-D Drumhead (clamped) chip at 890 kHz

Microparticles (50 μm) identified effectively using post-image processing algorithms

Displacement Maps on the Microscale

- Displacement map algorithim used on the macroscale is effective on the microscale

890 kHz | 440 kHz

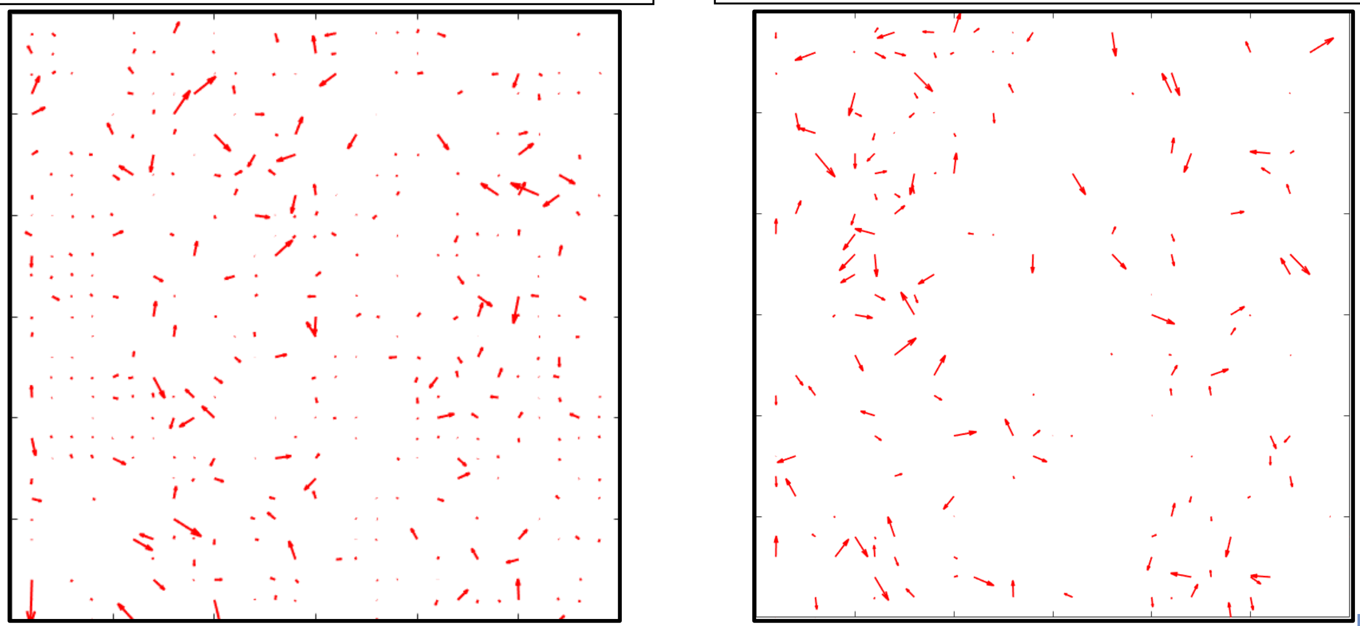

Fig. 21. Displacement maps of particle movement at 890 kHz and 440 kHz

Displacement Maps Overlaid with Original Images on the Microscale

890 kHz | 440 kHz

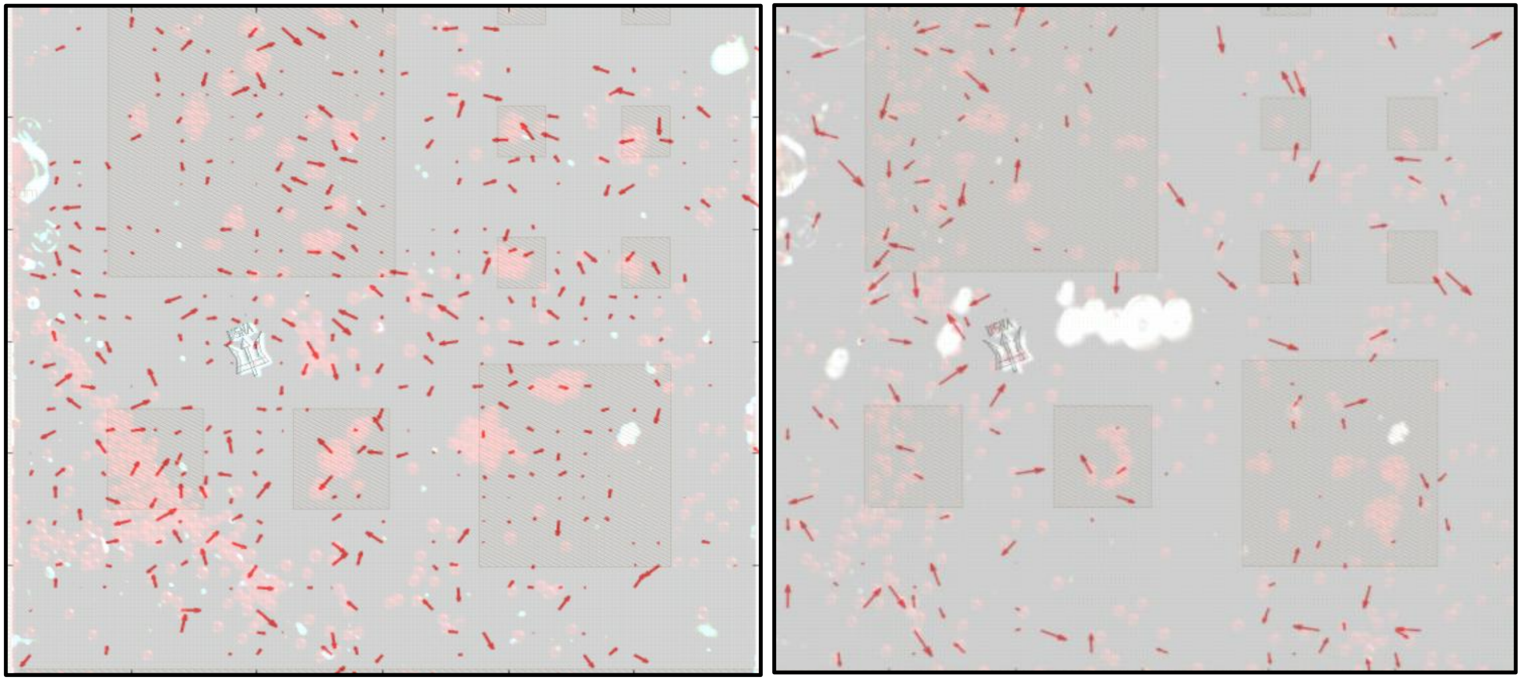

Fig. 22. Microchip Design, original last frame, and displacement maps are overlaid at 890 kHz and 440 kHz

Results and Discussion

- Microscale experiments require new displacement maps due to differing physics and resonators, but the process is similar and informed by the macroscale results.
- On the microscale, the effects of acoustic streaming and effective weight forces severely affect the movement of the particles.

Conclusions

- Further work needs to be done in implementing control algorithim for these displacement maps

Acknowledgments

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