AUTOMATED MARANGONI MONOLAYER TECHNIQUE

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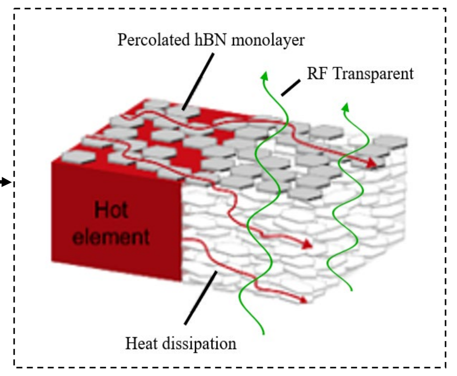
Motivation

- Percolated monolayers of hexagonal boron nitride (hBN) have high thermal conductivity with low radio-frequency interference
- One industrial application is radomes, the protective covering around a radar

KYMETA Radome



Percolated hBN monolayer

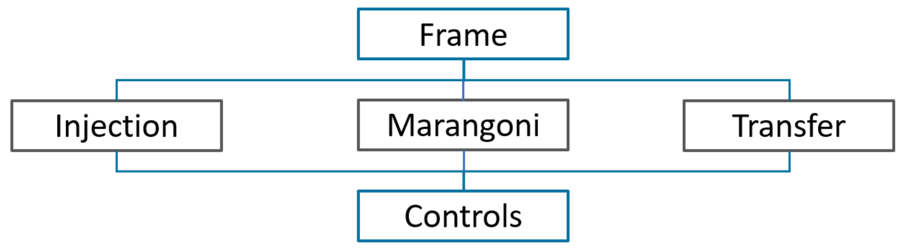
- A small-scale procedure has been developed in the DAPS lab, but there is currently no way to make hBN monolayers on an industrial scale

Problem Statement

The goal of this project is to create an apparatus that autonomously injects a sample of hBN into the trough, uses the Marangoni effect to densify particles into a percolated monolayer, then transfers the monolayer onto a 9in x 9in substrate in a repeatable and precise manner.

Design Overview & Challenges

- Three subsystems: injection, Marangoni, and transfer corresponding to the three-step monolayer creation process



Subsystem Breakdown

(a) Injection (b) Marangoni (c) Transfer

Small Scale Procedure

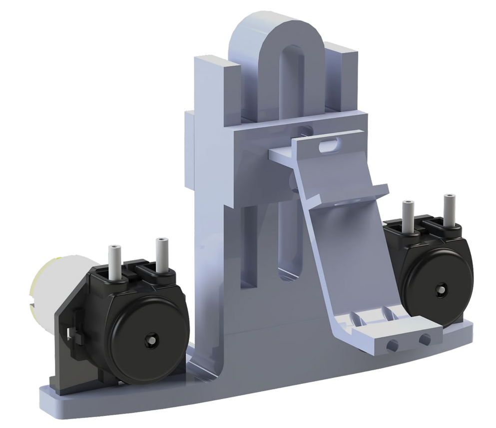
Challenges

- Contamination hinders the Marangoni effect and can be mitigated with disposable troughs and having no mechanical components in contact with the water
- Underlying physics had not been tried at scale

Diversity, Equity, & Inclusion

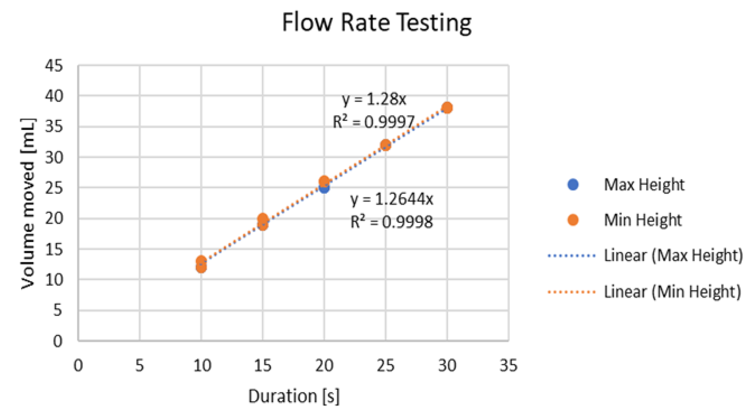
- A diverse user group can operate this product with a user-friendly touchscreen and no high-load or high-precision movements required for proper monolayer creation

Injection Subsystem



Injection Peristaltic Pump Tower

- Purpose is to add a consistent number of particles to the air-water interface
- Homogenizes the solution and injects for a certain time at a known pump flow rate
- Flow rate testing proved consistent pump flow rate
- Maximum flow rate per pump is 1.28 mL/s



Analysis of Sedimentation Concerns

- Reservoir: Use magnetic stirrer to homogenize hBN and ethanol solution
- Tubing: From Stoke's Law, it takes a 45-micron particle 15 seconds to settle in a 2mm ID tube
  - Tubing is cleared after full injection so particles cannot accumulate in the line between runs

Stoke's Law

$$\frac{mg}{6\mu\pi r} = v$$

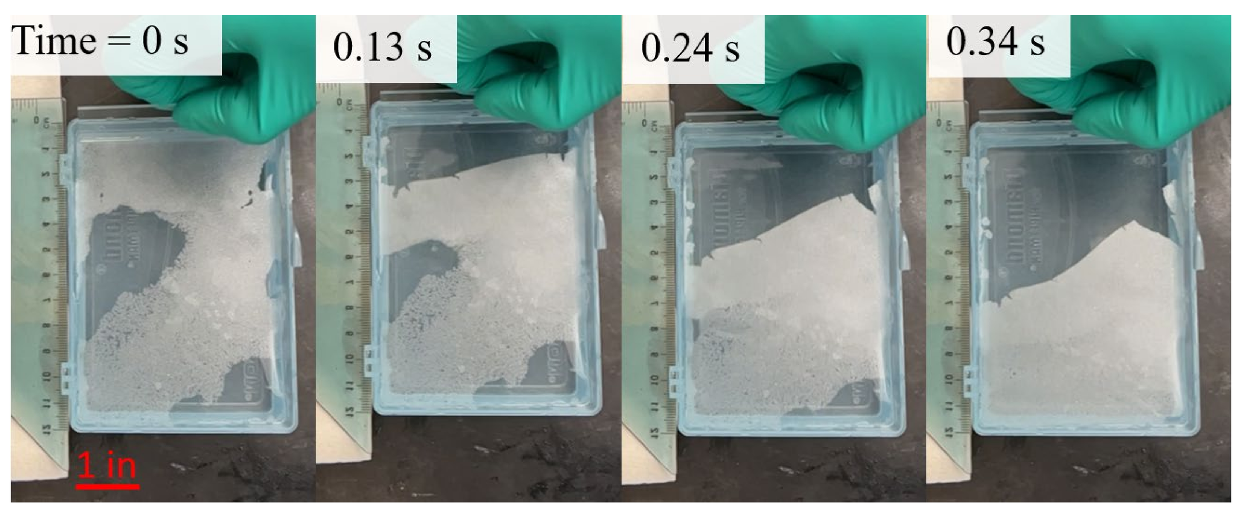
- Trough: To minimize downward momentum of particles, the height of the tower arm is adjustable allowing the exit of the tubing to be placed just above the interface

Marangoni Subsystem

- Marangoni-induced densification is the movement of particles in the monolayer due to a gradient in surface tension caused by adding soap

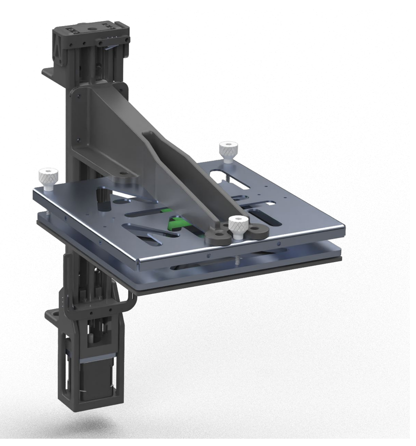
Marangoni Densification Inducer Line

- Densification causes the particles to touch, improving the heat transfer properties of the monolayer
- Any contamination of the air-water interface will decrease the efficacy of the Marangoni densification
- The speed of monolayer densification was analyzed to determine the parallelism tolerance of the inducer line

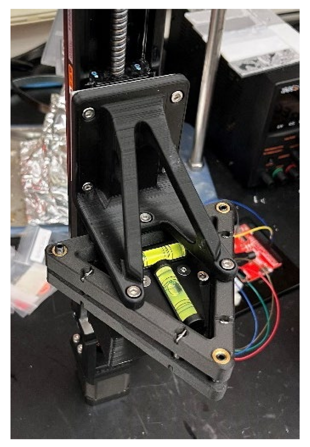


- Speed of densification ≈ 18.7 cm/s
  - If the line of soap moves at a vertical speed of 500 mm/min, the parallelism tolerance is 2.548º which is easily achievable with bubble levels and two-point adjustment

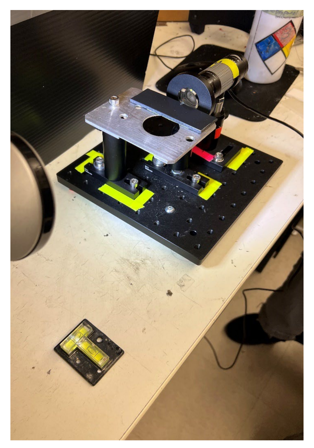
Transfer Subsystem



Transfer Subsystem

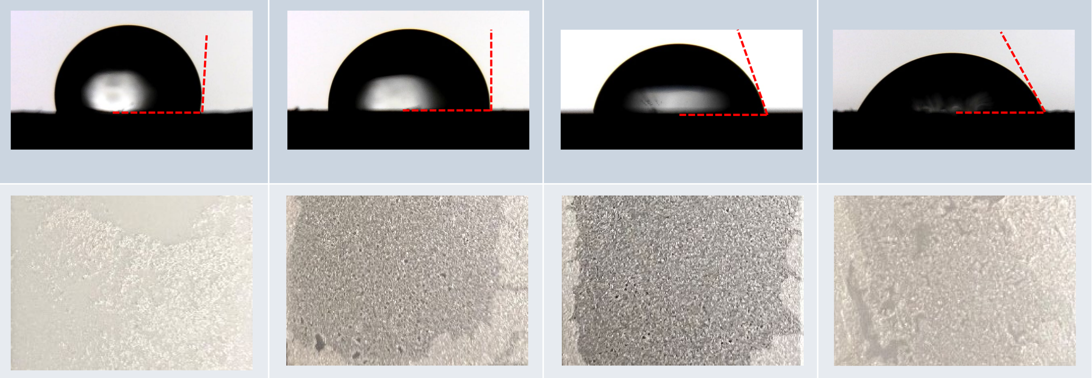


Tilt Testing

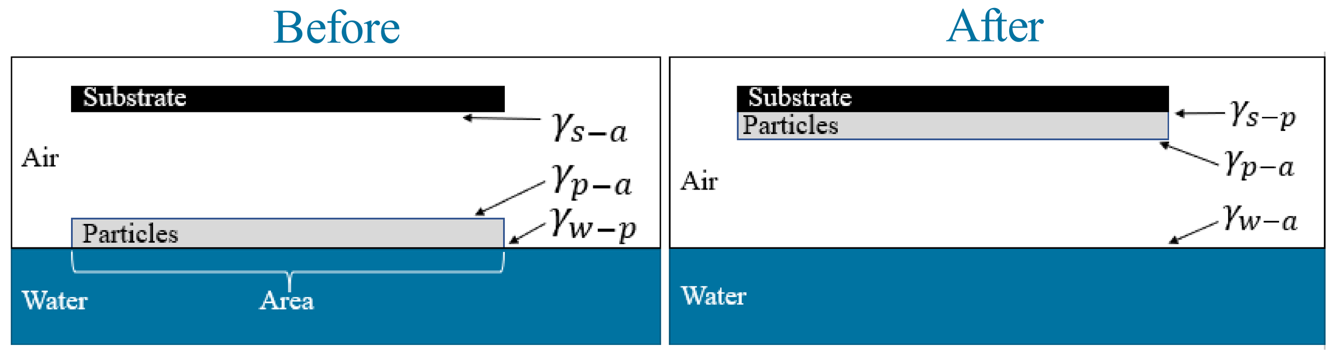


Goniometry

PTFE (95°)	PP (90°)	PVC (77°)	PE (68°)



Contact Angle (Top) and Small-Scale Testing (Bottom)



Helmholtz Energy Argument

$$Area * (\gamma_{w-a} + \gamma_{s-p} - \gamma_{s-a} - \gamma_{w-p}) < 0$$

- Goal is to minimize the surface energy difference between hBN and substrate to make the reaction spontaneous
- Surface energy difference is proportional to the contact angle between the two, which is 83° for hBN
- PVC and PP had the closest contact angle to hBN and best transfer results in small-scale testing
- Optimal tilt angle testing showed that 0.90° offset from parallel limited holes in the monolayer and surface energy impulses

Acknowledgements

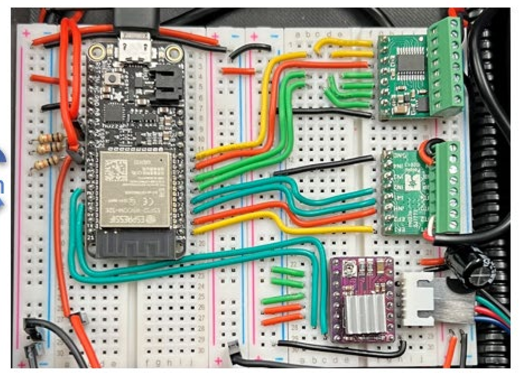
Thank you to our advisor Professor Randall Erb and Northeastern's Directed Assembly of Particles & Suspensions laboratory.

Controls & Electronics

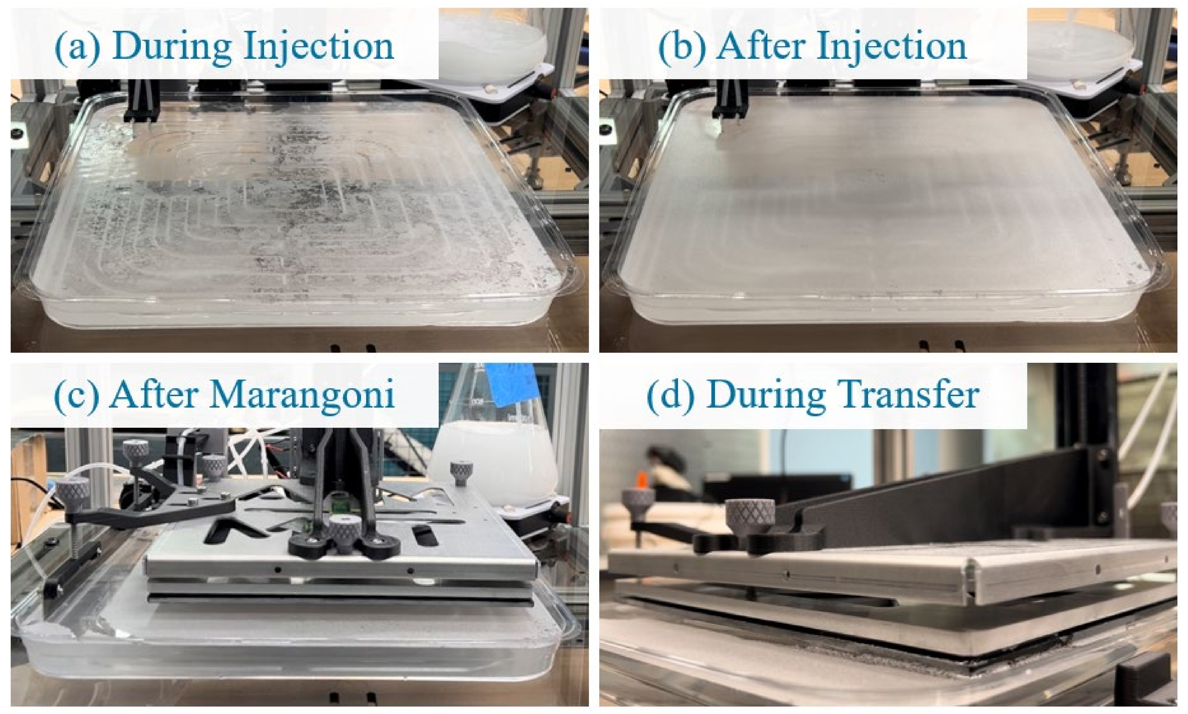
- Python-based GUI running on Raspberry Pi touchscreen for intuitive user experience with ESP32 for motor control

Raspberry Pi GUI

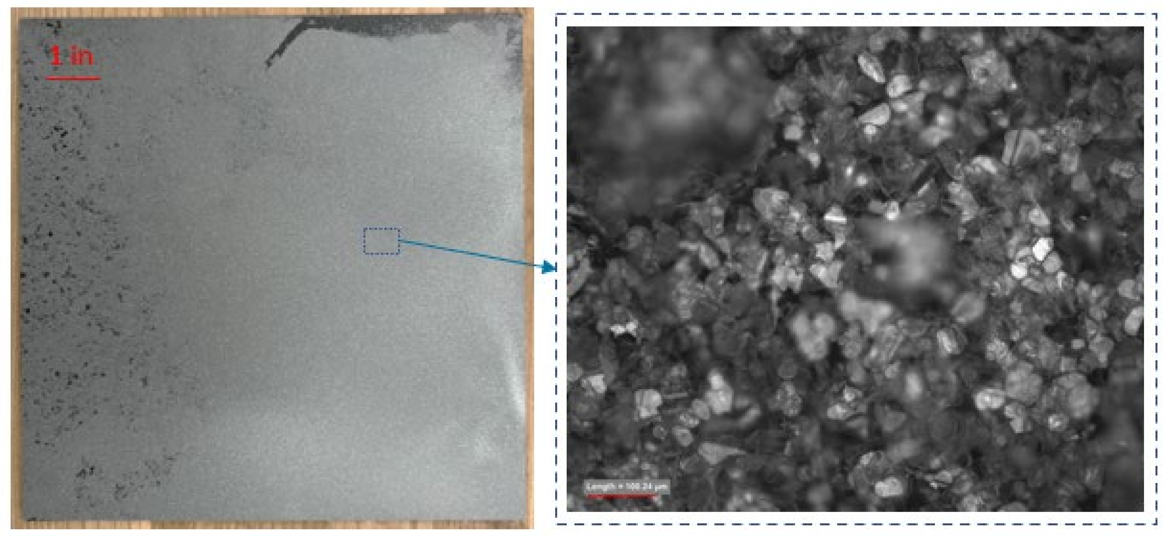
ESP32 and motor drivers



Integration & Validation



Large-Scale Process



Large-Scale Results

- Results prove reliable functioning of all components and high transfer ratios onto the substrates
- Microstructure evaluation showed percolation of the particles, confirming a successfully created monolayer

Future Work & Exit Strategy

- Machine will be handed off to Northeastern's DAPS lab for further research to optimize the process and the thermal and electrical properties of the hBN monolayer
- Process robustness could be improved by adding closed loop-control via a surface tension sensor and vibration dampening to the frame
- Different particles besides hBN that have unique mechanical, electrical, or thermal properties when manufactured into a percolated monolayer could be made with this system