Propulsion of AC-driven Microrobots

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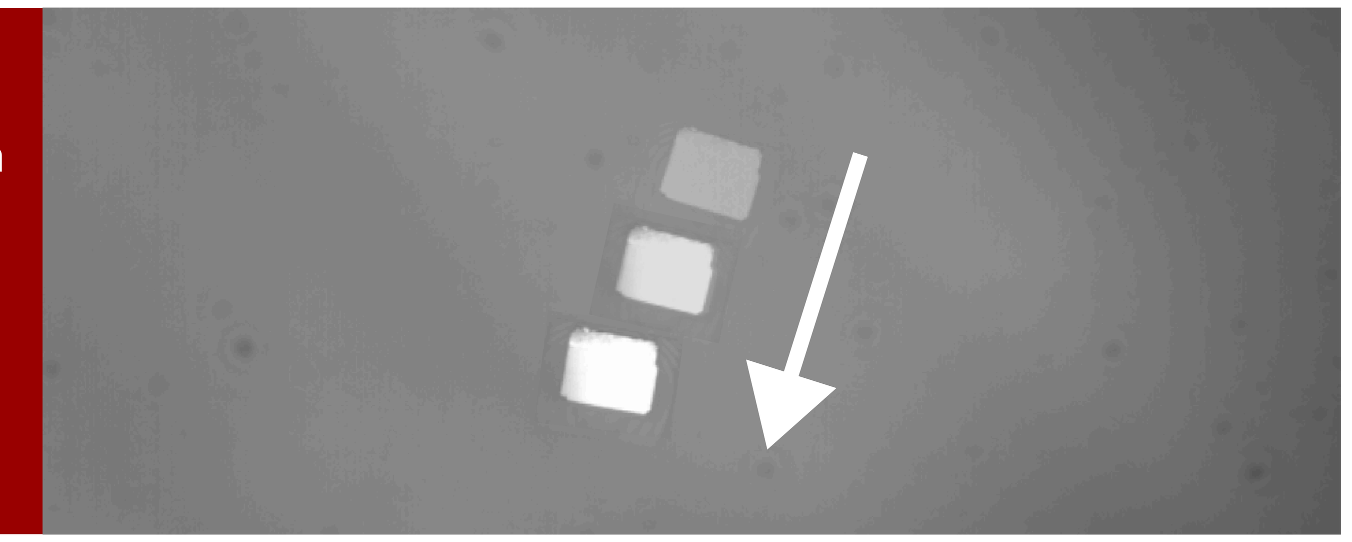


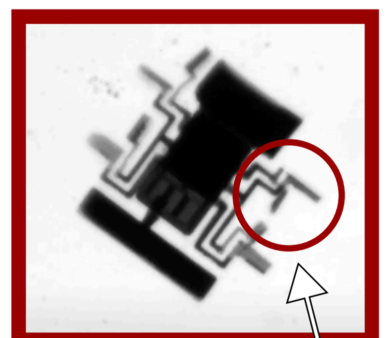
The investigation focused on understanding the propulsion mechanisms of alternating current (AC)-driven microrobots, colloquially termed "rave bots." AC propulsion mechanisms are expected to perform better in higher conductivity solutions over existing DC electro-osmotic mechanisms. The experiments provide evidence that two mechanisms, ACEO and AREF, contribute to rave bot propulsion.

Motivation: Why Alternating Current?

Existing microrobots in the past have
- intricate legs used to walk
  - This makes them very **difficult to fabricate** on such small scales
- Utilize a direct current electro-osmosis implementation that only works in **very low conductivity solutions**

In theory and as seen in literature, **alternating current** electro-osmosis:
- produces fluid flows across electrodes in **higher conductivity** solutions than DC electro-osmosis
- maintains the **mechanical benefits** of electroosmosis (no need to fabricate complex legs)

Higher conductivity environments include biological tissue and fluids, or natural environments. Expanding to these environments is beneficial for biomedical research.



Tiny broken legs

Images of Robots Fabricated by Kyle Skelil (SEAS ESE)

Bending incorrectly, not creating movement

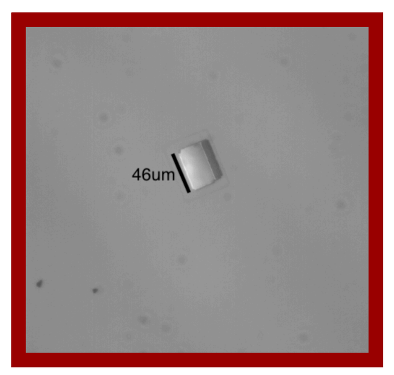


Image of Rave Bot under 10x zoom

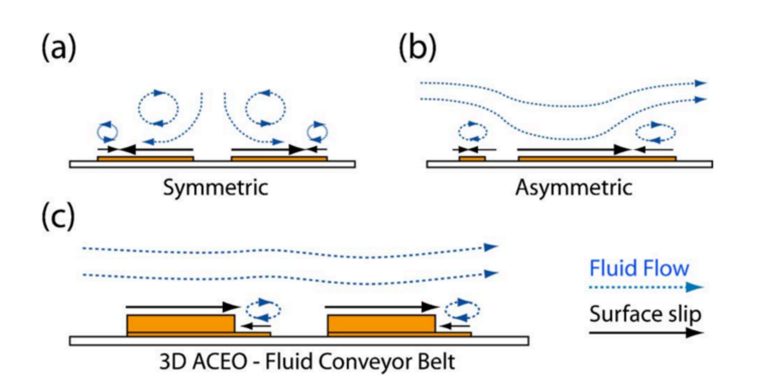
AC fluid flow mechanisms

Initially focus was on understanding what was believed to be the physical principle propelling the robots: AC electroosmosis (see figure on right). There was found to be a significant discrepancy between theoretical models and experimental outcomes, which often resulted in unexpected flow reversals. This led to an exploration of AREF (Alternating Current Reversal Electroosmosis Flow), a newly discovered phenomenon that, while not fully understood, showed promising alignment with the data. By compiling and analyzing an extensive dataset, models were developed that better reflect these complex flow behaviors, ultimately enhancing understanding and control of fluid dynamics in microrobots.

Next Steps

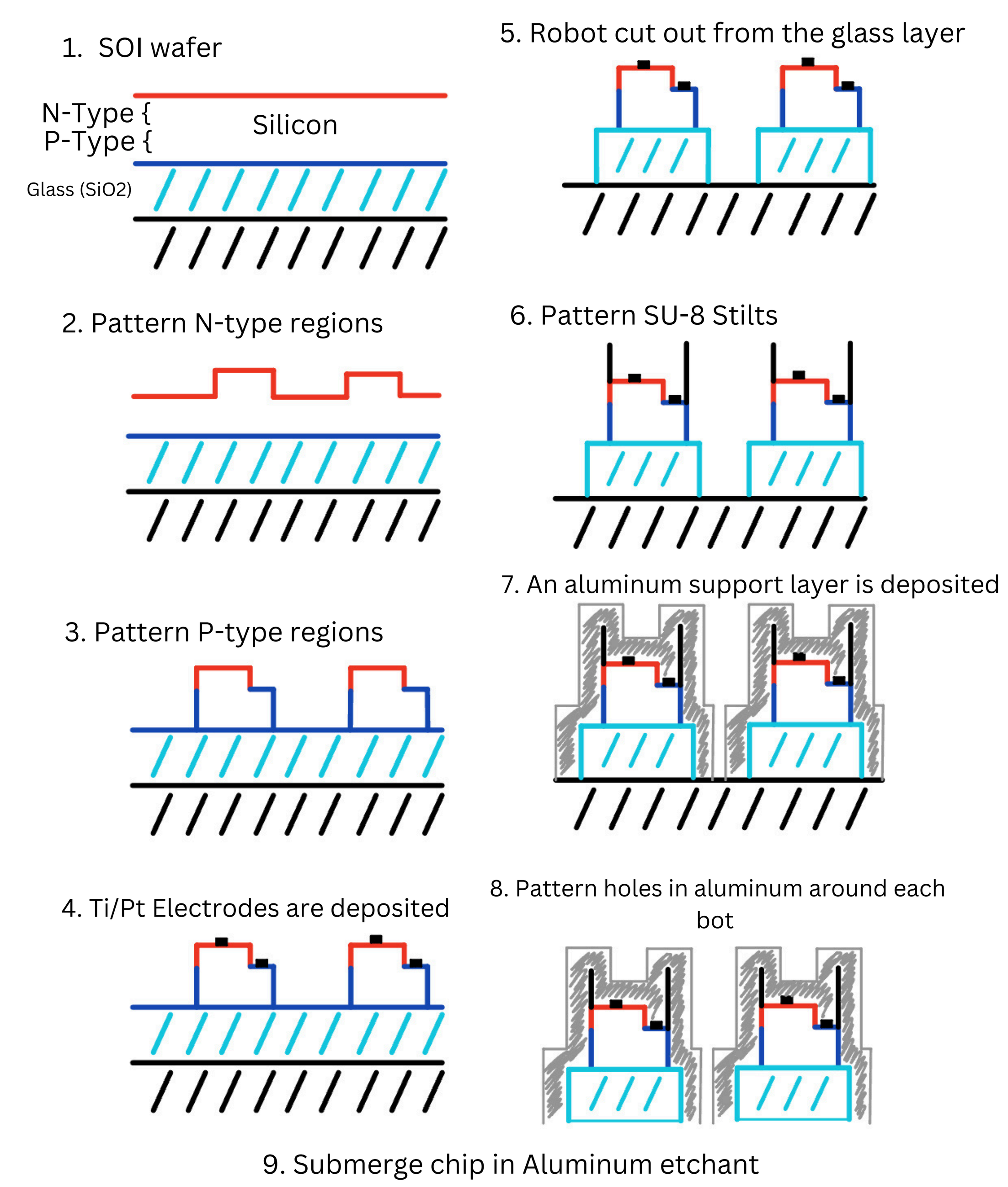
Moving forward, next steps involve
- further refining models to gain deeper insights into the AREF phenomenon and its impact on fluid flow dynamics
- modeling data with analytical and computational models of the electrostatics
- iterating the design to produce faster, more solution-independent robots

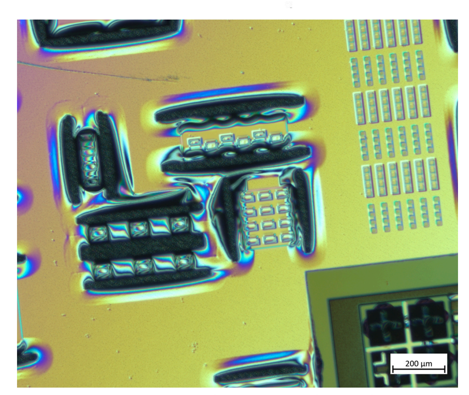
Principles behind ACEO:



Urbanski, J. P., Thorsen, T., Levitan, J. A., & Bazant, M. Z. (2006). Fast ac electro-osmotic micropumps with nonplanar electrodes. Applied Physics Letters, 89(14), 144103. doi: 10.1063/1.2360935

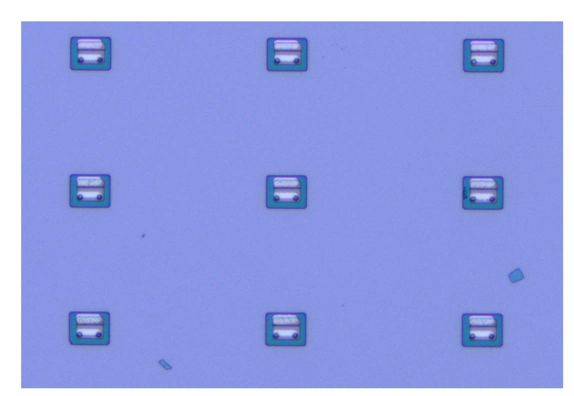
Fabrication of Rave Bots





Rave Bots suspended on aluminum release layer, the last step before they are separated into individual robots

Image from Sophia Handley



fully fabricated rave bots on chip, pre-release

Image from Sophia Handley

Results

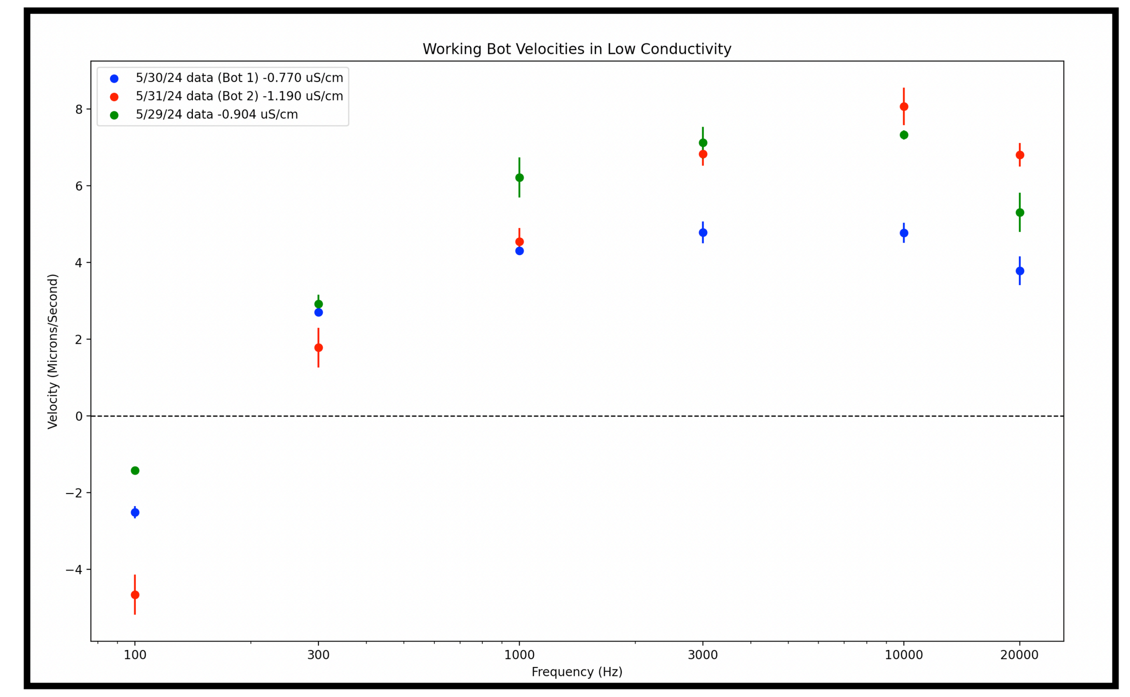


Figure 1: Velocity vs. Frequency Analysis: placed three working robots in deionized water, and graphed their velocity versus frequency on a log scale to assess consistency.

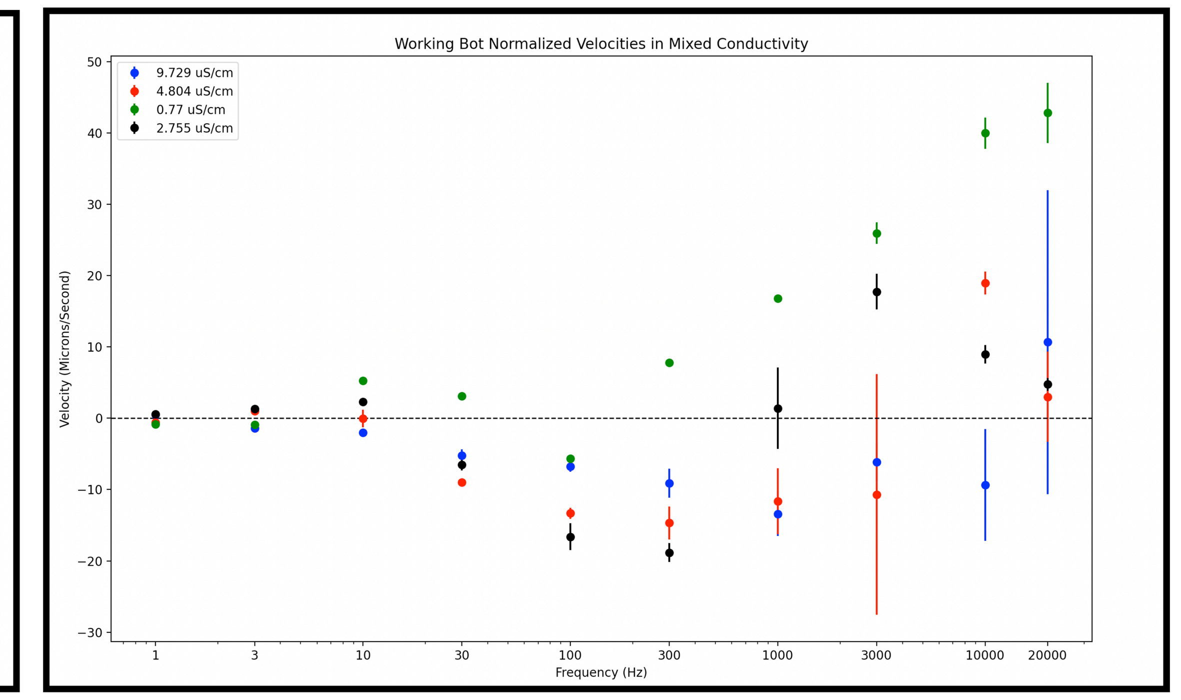


Figure 2: Conductivity Experiments: Focusing on one robot, the water conductivity was increased using NaNO3 up to 30 mM to observe its velocity changes at different frequencies.

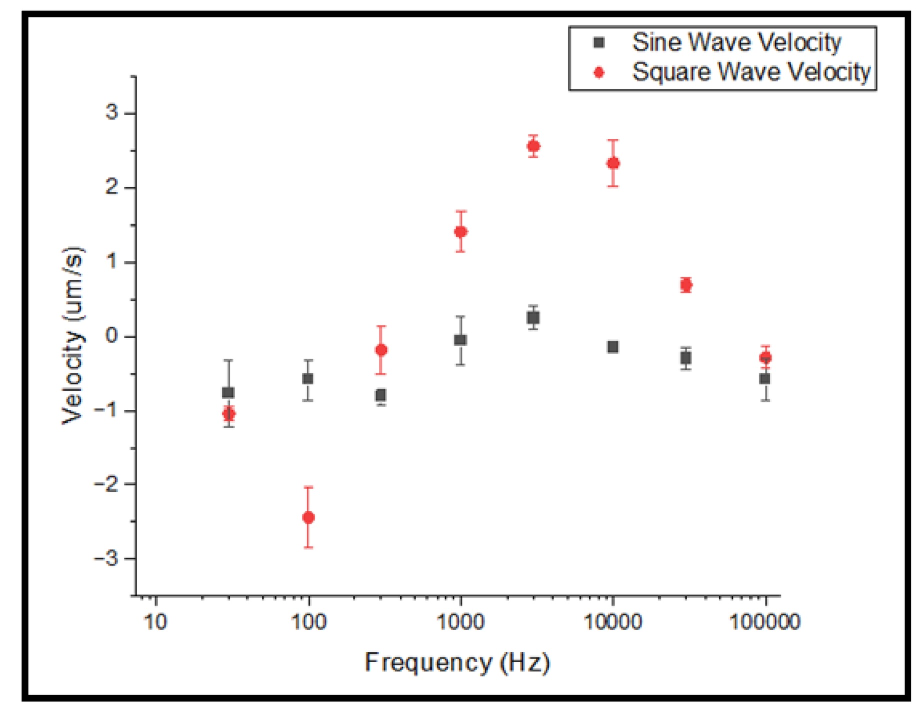


Figure 3: Waveform Testing: different waveforms (sine vs. square waves) were tested on the bots to evaluate their impact on speed.

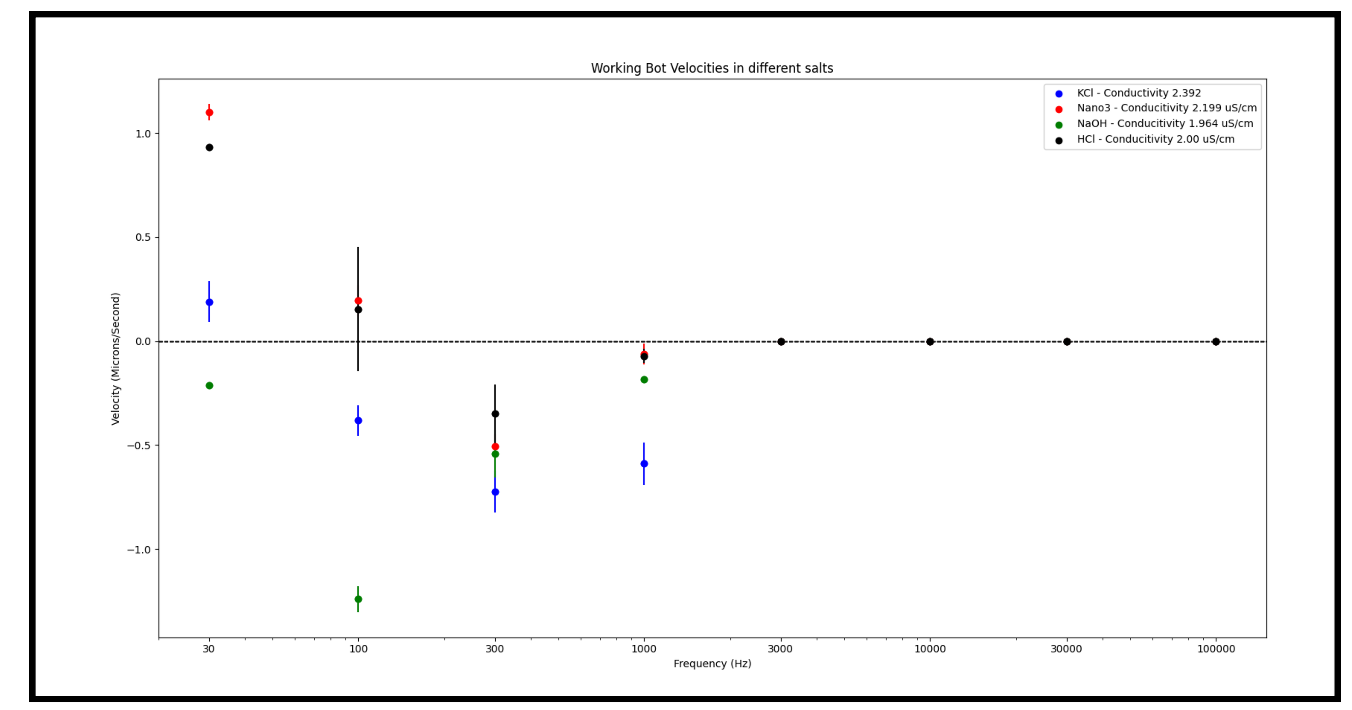


Figure 4: Diffusion Coefficient Testing: one bot was placed in different types of salt to understand how their diffusion coefficients were affecting the speeds.

Experiments and Data Collection

AC-Propulsion was tested by placing a bot in a small petri dish filled with different solutions. Since the bot is a photovoltaic cell, they are powered using light. The "AC" effect is achieved by using a strobe light at various frequencies and recording short videos of the bot moving. Then velocity is measured using ImageJ and video analysis techniques.

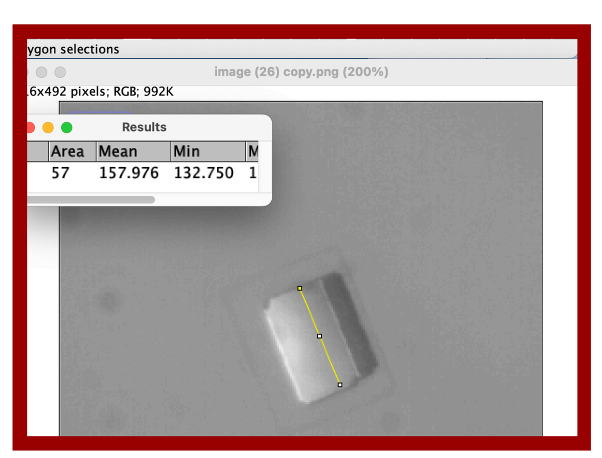
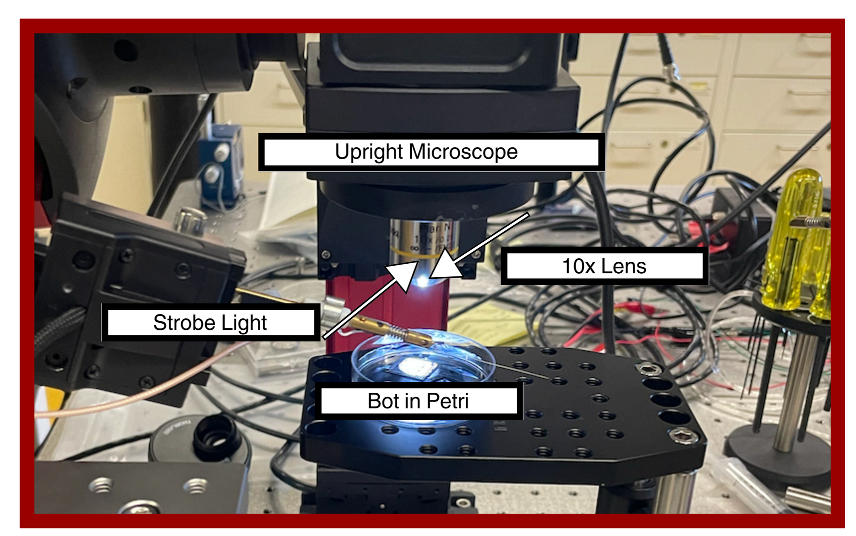


Image Analysis in Image J

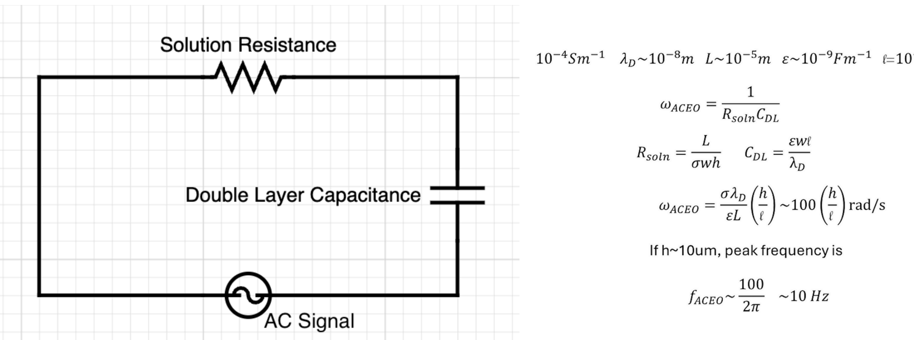


Experimental setup

Discussion

Initially, we attributed motion to AC electro-osmosis (ACEO), but further tests indicated that Alternating Current Electrothermal Flow (AREF) also plays a role. The bot and its solution can be modeled as a series RC circuit (see right) with the solution between electrodes as the resistive element and the electrical double layer as the capacitors. Our RC model predicts a single velocity peak at its resonant frequency. AREF predicts positive and negative electric field peaks for asymmetric waveforms, aligning with our data. Figure 1 shows peak frequencies higher than expected for ACEO. Figure 3 confirmed that asymmetric waveforms produced higher velocities, characteristic of AREF.

Literature on AREF suggests that the field follows the magnitude and sign of the ratio of diffusion coefficients. However, this was not supported by the different-salt experiment data in Figure 4, suggesting that a more tailored approach is needed to model the propulsion of the bots.



Peak Frequency Calcuations by Sophia Handley*