Modeling Robotaxis of Microrobots in Thermal Gradients

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Motivation

Microorganisms rely on sensing and computation at the smallest scales at the boundaries of information and energy.

Their mobility processes are complex, but programmable microrobots can emulate them.

Sub-millimeter robots with sensing, memory, and locomotion offer a controllable testbed for studying microbial behaviors.

This project tests a run-and-tumble model: robots alternate clockwise/counterclockwise motion in response to temperature changes.

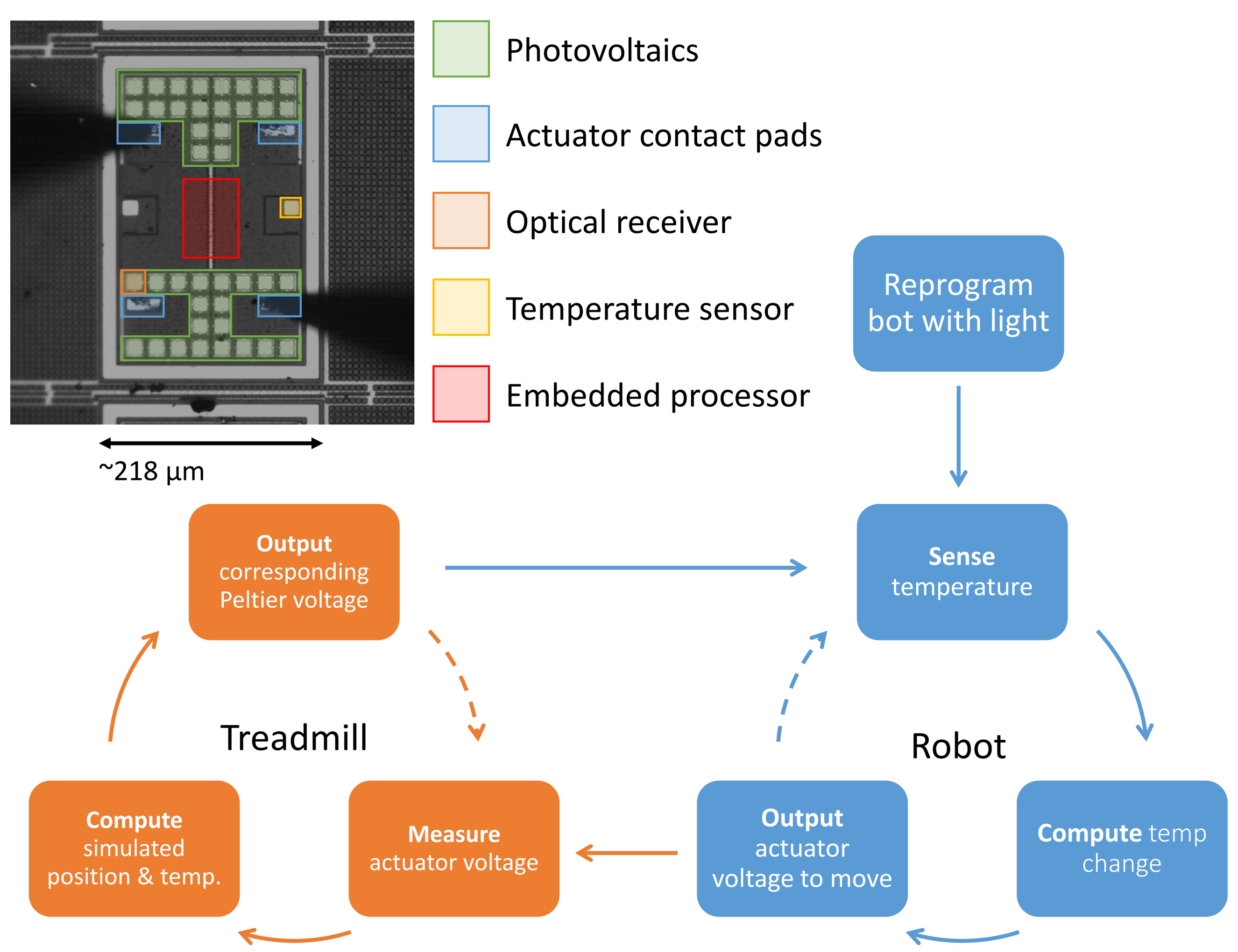
Insights help both:

- Understand microbial mobility
- Define rules for autonomous microrobots to navigate environments

Thermal Treadmill for Rapid Testing

Replaces physical gradients with a simulated temperature field.

Robot is stationary; temperature updates as if it were moving.



Advantages:

Alleviates difficulty of working with released robot:

- Slow, susceptible to fluid flows, get stuck, difficult to track, cannot probe (difficult to automate)

Allows for arbitrary temperature fields and movement rules

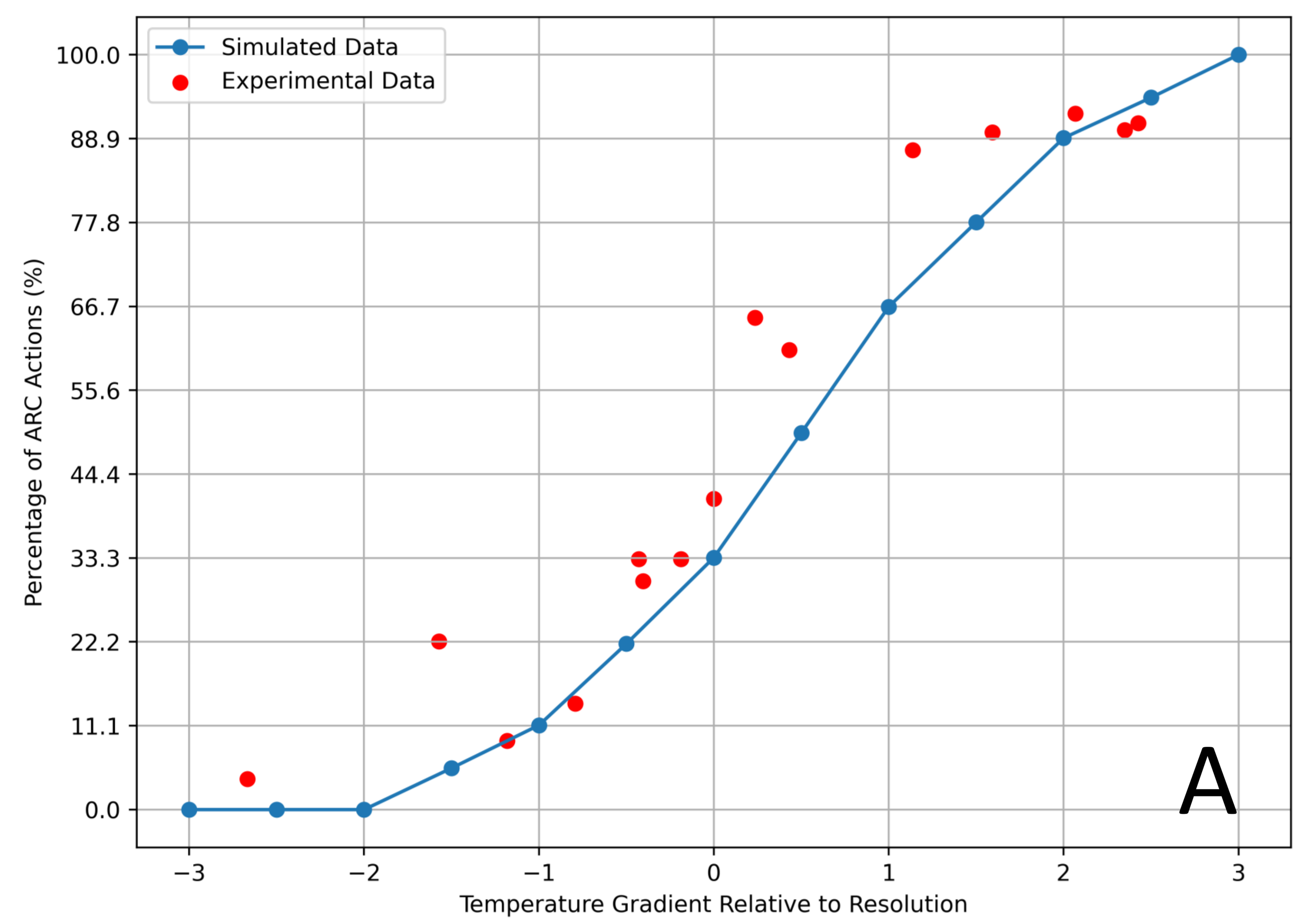
Facilitates direct measurement of robot output via probing

Enables overnight trials, allowing large trajectory datasets

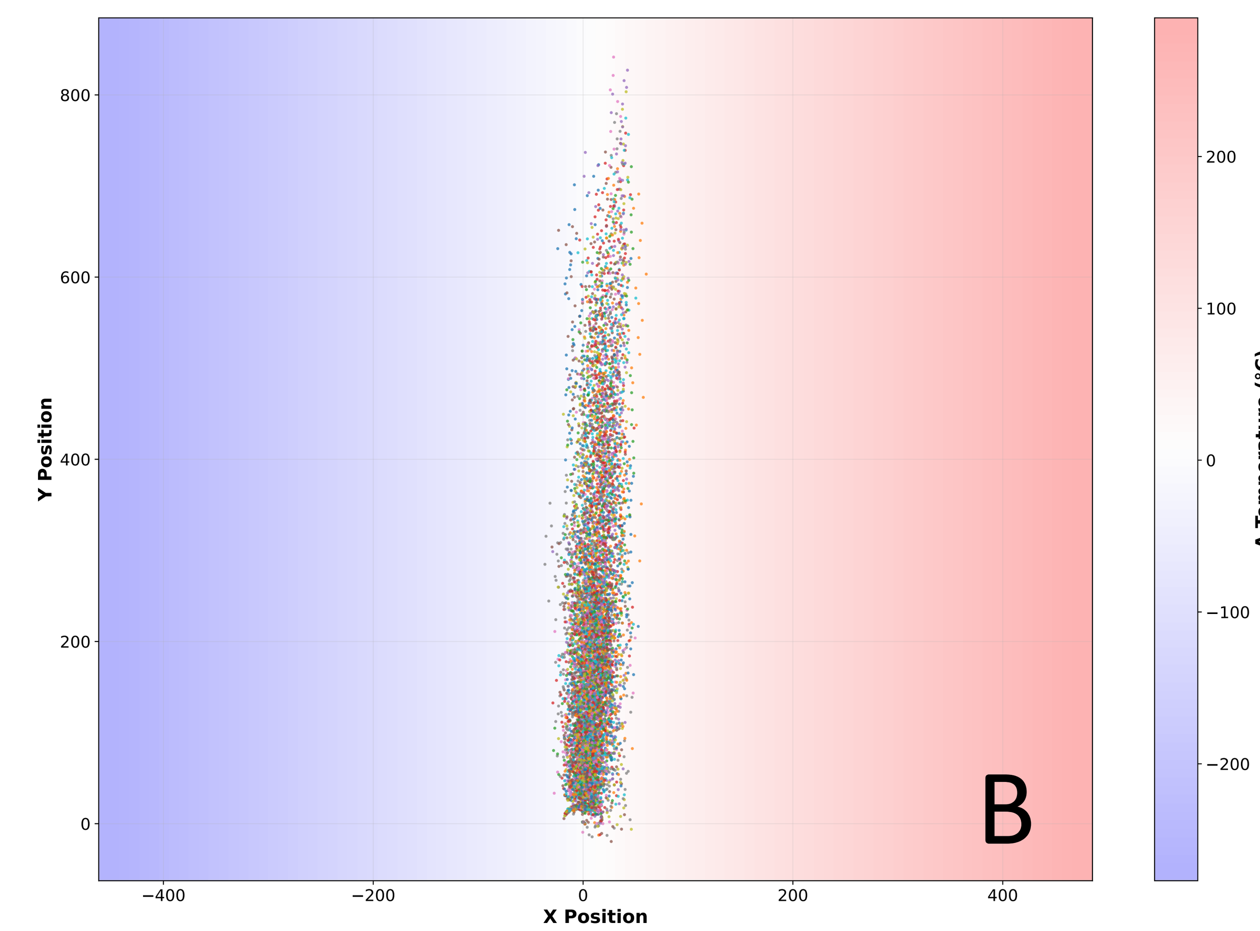
Microrobot Trajectories

Assumptions tested before implementation:

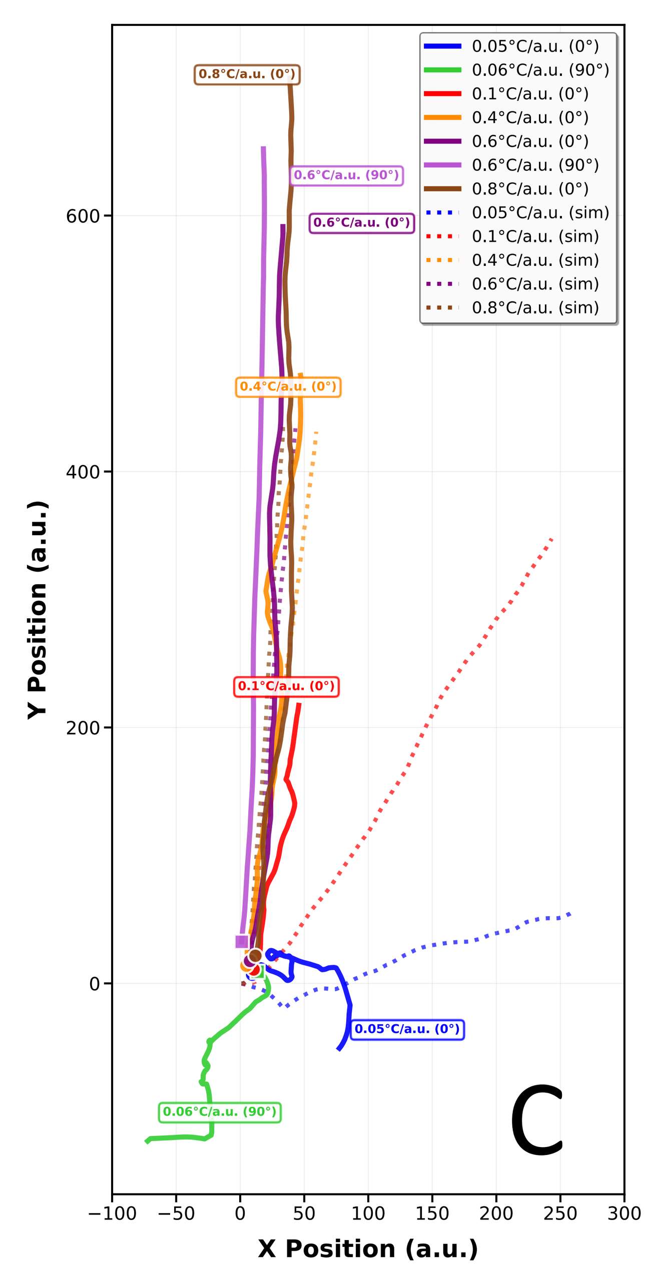
1. Noise modeled as a discrete distribution {-1, 0, +1} of equal probability
2. Robot sensing resolution is 0.1 °C
3. Robots arc counterclockwise if and only if current temperature exceeds previous temperature
4. Robot velocity is 1 a.u./sec



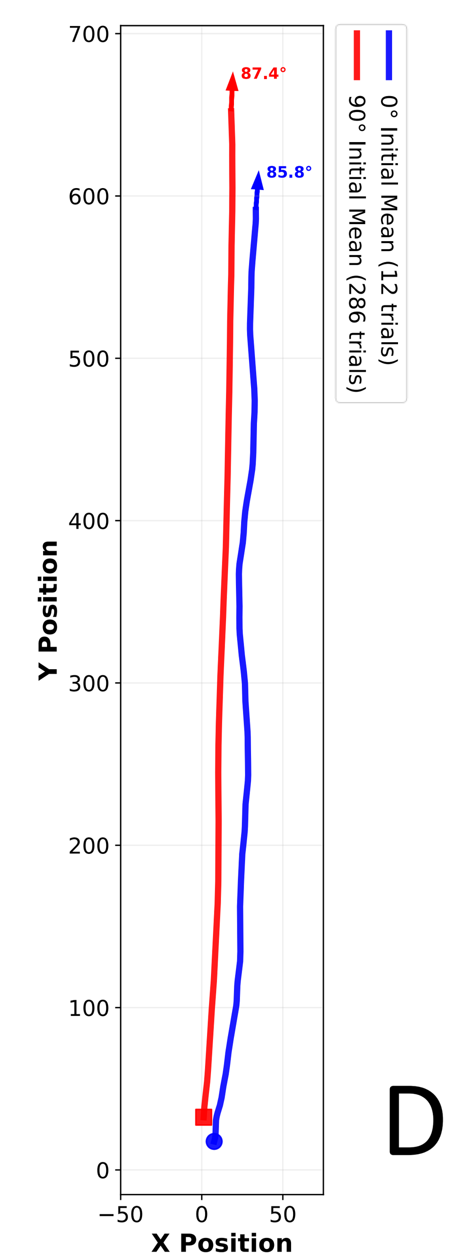
A. Arc action frequency vs. normalized temperature gradient.



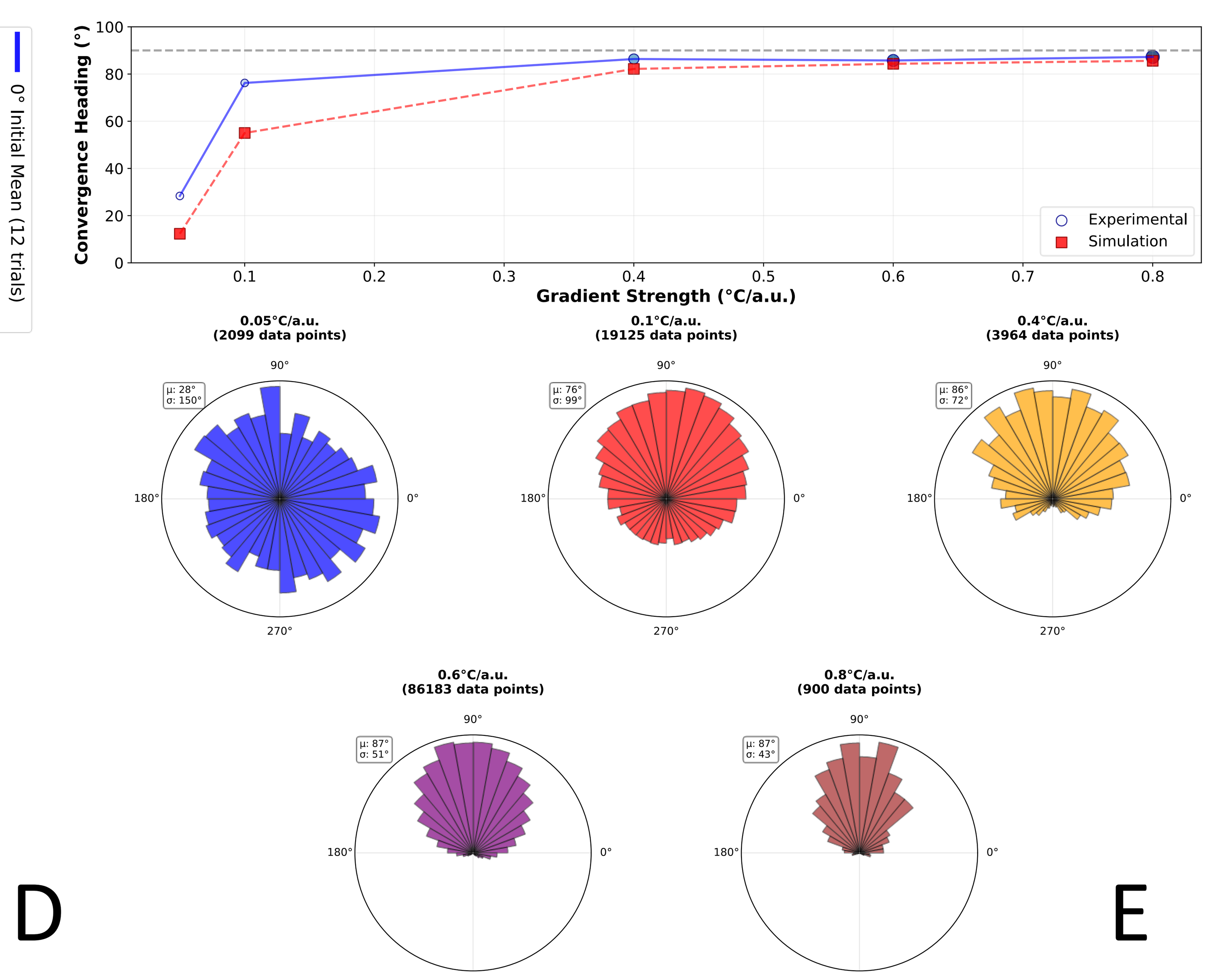
B. Trajectories of microrobot in 0.6 °C/a.u. gradient, 298 trials.



C. Experimental and simulated mean trajectories of robots in various temperature gradients, smoothed with a 20-point moving average.



D. Convergence of trajectories with initial heading of 0° and 90° in a 0.6 °C/a.u. temperature gradient.



E1. Vector-averaged trajectory convergence vs. gradient strength.
E2. Heading distribution by gradient.

Discussion

(A) The experimental data aligns closely with the theoretical probability function, providing confidence in the assumptions.

(C, E) Gradients of 0.05 °C/a.u. and 0.06 °C/a.u. appear to not converge to a heading, with a critical threshold around 0.1 °C/a.u. where trajectories begin to converge.

(D) Different initial headings (0° and 90°) converge to equal headings in the same temperature gradient.

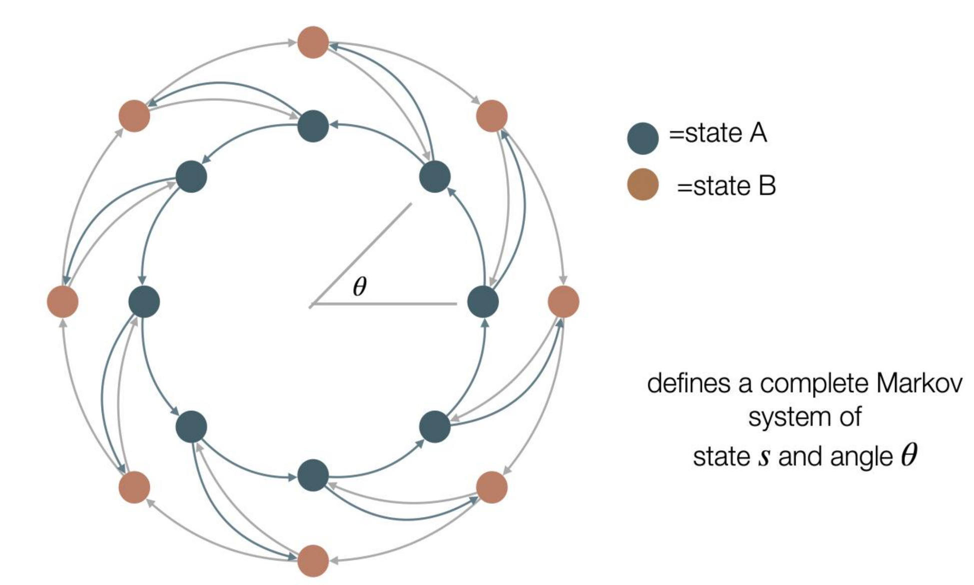
(E) As gradient strength increases, convergence heading asymptotically approaches 90°.

(E2) As gradient strength increase, standard deviation of heading decreases, reflecting stronger convergence.

Overall, there exists a clear model that characterizes the trajectory of these microrobots in varying thermal gradients. These convergence behaviors mirror microbial thermotaxis, suggesting that simple run-and-tumble robots can reproduce biologically relevant navigation strategies. However, convergence angle is sensitive at low temperature gradients, highlighting possible navigational complexity.

Next Steps

A Markov system of clockwise and counterclockwise states and the angle theta may completely describe the steady state of the robot trajectories which may be verified with empirical results.



From dimensionless analysis, since gradient strength and angular velocity is sufficient to characterize the steady state angle, future trials would verify their relations.

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