CAREER: Environmentally-Mediated Coordination in Natural and Robot Swarms

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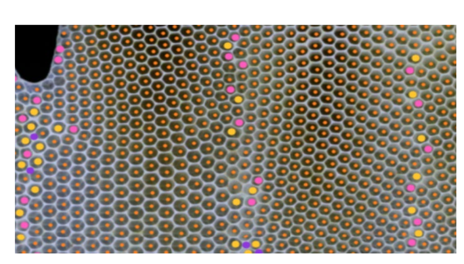
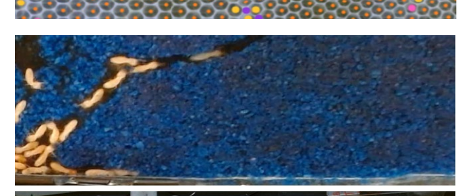
Challenge

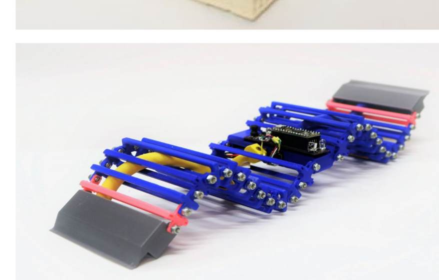
Rooted in experiments with robots and natural swarms, we aim to develop generalizable design methodologies for swarms operating in static *and* dynamic environments that can act to integrate, diffuse, decay, and filter information. These methods may for example be used to estimate practical operating regimes in which the collective size, agent sensor-, motion-, and action abilities, and agent error characteristics are balanced with the specific environment dynamics.

Solution

Static Environments







In robotics today, environmentally-mediated coordination typically exist when robots sense and modify relatively static shared mediums, such as material in a construction task. But how do errors propagate when there is no decay, and how can we mitigate long-term effects?

We study how honeybees use distributed, stigmergic coordination to build honeycomb balancing functionality and material usage, especially in constrained geometries.

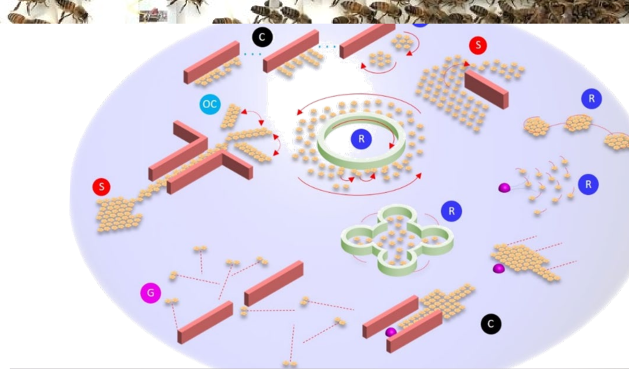
We study the crowding and stigmergic effects that lead to construction of efficient foraging tunnels by termites, leveraging simple robotic models.

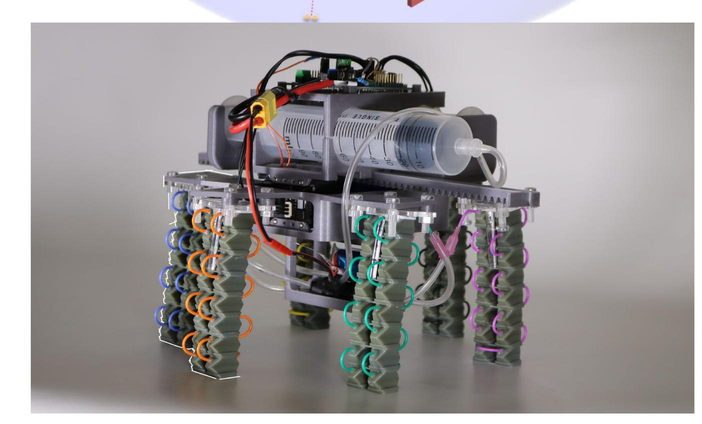
We study how errors propagate (and can be mitigated) in collectives of simple, local robots that coordinate through their shared environment to built blueprint-specific rectilinear structures with custom materials.

We study a minimalistic robot mechanisms and corresponding algorithms for collective construction of functional structures made of amorphous materials.

Smith et al. Imperfect comb construction reveals the architectural abilities of honeybees. PNAS 2022
Smith et al. Convergent architectural solutions in the hexagonal nests of social bees and wasps. [In progress]
Chen et al. Errors in Collective Robotic Construction. Springer Proceedings in Advanced Robotics, vol 22.
Chen et al. Decay-Based Error Correction in Collective Robotic Construction. IROS 2022
Huang et al. Construction and Excavation by Collaborative Double-Tailed SAW Robots. RA-L, vol 7, no 2, 2022.

Dynamic Environments





Many natural swarms are coupled fluidically, but how do they leverage these dynamic environments to coordinate, and can we do the same in robot collectives?

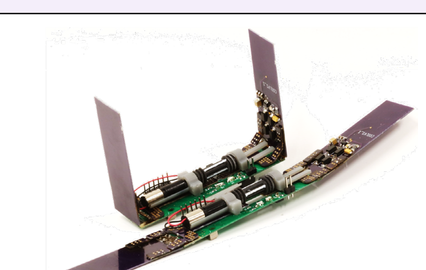
We study how thousands of honeybees coordinate through flow and pheromone in outdoor turbulent environments.

We study microrobots that coordinate through global magnetic fields which alter local hydrodynamic, dipole-dipole, and capillary forces.

We study how connected elastomer bellows can coordinate compression through pressure distributions created by viscous fluids to produce spatially and temporally complex motions.

Defay et al. A customizable, low-cost alternative for distributed 2D flow sensing in swarms. Artificial Life and Robotics. 2022.
Gardi et al. Microrobot collectives with reconfigurable morphologies, behaviors, and functions. Nature Comms. 2022.
Ceron et al. Programmable Self-Organization of Heterogeneous Microrobot Collectives. [In progress]
Matia et al. Harnessing Nonuniform Pressure Distributions in Soft Robotic Actuators. AISYS. 2023.

Programmable (Robotic) Environments



Can we benefit from co-designing the environment dynamics and the robot behaviors?

We study smart entangled matter (Smarticles v2.0).

We study soft robot oscillators that sense, move, and coordinate through strain.

Ma et al. Smarticle 2.0: Design of Scalable, Entangled Smart Matter. DARS 2022
Nilles et al. Strain-Based Consensus in Soft, Inflatable Robots. RoboSoft. 2022
Ceron et al. Soft Robotic Oscillators with Strain-Based Coordination. RA-L. 2021

Scientific Impact

Environmentally-mediated coordination implies thinking of the environment as a medium to which the agents add structure to complement their own limited abilities, and which they leverage to pass, store, and process information pertaining to the collective such that behavior-governing rules become locally checkable. Findings from this research will be fundamental to further state of the art in engineered swarms. Beyond explicitly programmed intelligence and communication, such implicit forms of intelligence in robot collectives may complement existing control architectures, work as a back-up when communication is unstable or slow, or where privacy and security is of concern, and is the only type of distributed coordination feasible for micro-scale robots.

Societal Impact

Autonomous robot collectives are becoming ubiquitous with thousands of robots and drones operating simultaneously in places from warehouses to entertainment light shows, and they may soon be adopted in new sectors like transportation and agriculture.

This technological revolution makes it critical to look beyond good design and control of individual robots, to robust design and coordination of multi-robot systems that complement the particular tasks they are given and the particular environment they operate in.

Educational Impact

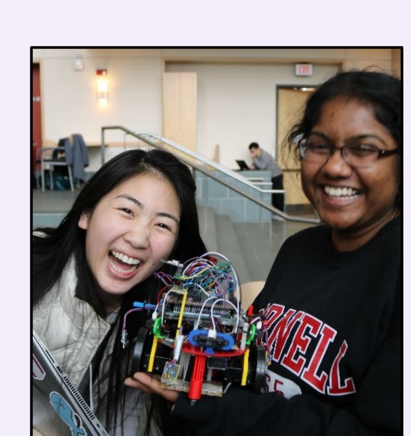
Our goal is to increase and improve retention of a diverse workforce through shared, online curricula and collaborative learning in robotics

- Cornell - ECE4160/5160-MAE4910/5910 Fast Robots (35-55 students)

  Today, kinematic robot design mostly involves software. In dynamic robots, however, any latency or noise is very detrimental. We design a fast autonomous car, explore dynamic behaviors, acting forces, and reactive control on an embedded processor and with partial off-board computation.

- Cornell - ECE3400 Intelligent Physical Systems (90-115 students)

  Students learn to tie the ECE fundamentals across virtual and physical boundaries to create autonomous robots able to perceive, reason about, and act upon their environment. Specifically, in teams of 4-5, students will design and fabricate a robot able to navigate and map out a maze with treasures in the shortest possible time.



- TST Boces New Visions workshops for high school students