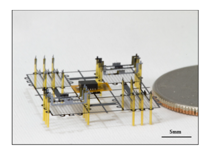
Research Statement --- Daniel S. Drew

In the near future, swarms of millimeter scale robots will be vital and common tools in industrial, commercial, and personal settings. By enabling applications spanning from distributed gas and chemical sensing, to tangible 3D interfaces, to dynamic wearable devices, providing mobility platforms to low-power sensing and actuation nodes will push us that much closer to the dream of ubiquitous computing. My dissertation research focused on development of a novel centimeter-scale flying robot platform; in the future, I want to expand my focus to include research on multi-agent coordination and control, heterogeneous robot systems, and human-swarm interaction. This effort is inherently interdisciplinary and will require pulling from the domains of classical robotics, fundamental device and materials research, human-computer interaction, and machine learning, to name a few. As such, it represents a tremendous opportunity for collaboration, for training a new generation of interdisciplinary investigators, and for forging new ties between the worlds of industry, academia, and design.

a future full of microrobots

Glittering synthetic cockroaches, skittering through the rubble in a search for survivors; a robotic bee hovering above a corn stalk, sending a message back to its colony about the leaf blight it has just spotted; a cloud of glowing gnats, rearranging themselves in front of your eyes to outline the destination of your journey — I believe that insect-scale "microrobots" form the basis for a future set of tools that we will use in our daily lives, across a wide variety of application spaces. Since Kris Pister's "Smart Dust," the tantalizing image of ubiquitous, distributed sensing and actuation has floated just out of reach despite major academic and commercial interest. I believe that one of the greatest barriers to realization of "Smart Dust" was over-reliance on static nodes. A technology that could deploy itself, maintain and reconfigure itself, and add a physical traffic layer to its data transmission may make a huge change in the current economic calculus. A ubiquitous platform will need to be small enough to be placed unobtrusively, inexpensive enough to be purchased in enormous quantities, and both simple and versatile enough to be easily deployed across a large swath of potential scenarios. Luckily, nature has provided a blueprint for such a system; the insects, with their variety of inspirational methods of mobility, sensing, and coordination.

my doctoral work: the ionocraft



The Ionocraft: a 2cm x 2cm flying robot with no moving parts

My dissertation work focused on developing a novel platform for centimeter-scale flight, the "ionocraft". Recent work on flying insect-scale robots has focused primarily on biomimetic propulsion mechanisms, i.e. the motion of flapping wings. Significant progress has been made, but biomimetic fliers remain challenging to design, build, and control. My work shows that although we may still draw on bioinspired methods for sensing and control, we could end up with flying robots that move unlike anything found in nature. The ionocraft is unique in that it uses microfabricated corona discharge-based electrohydrodynamic (EHD) actuators to produce thrust.

Electrohydrodynamic thrust is a propulsion mechanism that is silent, has no mechanical moving parts, is mechanically trivial to design, and theoretically simple to use for controlled flight. It has unparalleled potential for robust construction, high thrust-to-weight ratio, and retaining functionality through a wide range of Reynolds numbers. The thrust itself is scale invariant, indicating a favorable scaling to low-mass systems.

I have been the first to demonstrate thrust and takeoff from a microfabricated EHD propulsion system[1]. My investigations of EHD actuator design sought to maximize beneficial scaling relationships without significant added fabrication complexity, and should help to shed light on some of the major challenges facing sub-millimeter scaling of EHD propulsion systems[2]. Proof-of-concept demonstrations of thrust have been backed up with more rigorous experimental validation so that future researchers will have the foundation in place to make informed design decisions. Ease of assembly is an important metric for a future microrobotic platform, as it may be a key driver of scalability and unit cost. The assembly process has evolved over the course of my dissertation (now a robot per half hour, with nearly a 100% success rate), in a process that could easily be automated thanks to its mechanical simplicity.[3].

Centimeter-scale quadcopters suffer from extremely short flight time and extreme fragility. Simply replacing the rotors with EHD thrusters allows us to sidestep some of the unfavorable

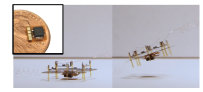
1. Drew, Daniel, Daniel S. Contreras, and Kristofer SJ Pister. "First thrust from a microfabricated atmospheric ion engine." MEMS 2017.

2. Drew, Daniel S., and Kristofer SJ Pister. "Geometric optimization of microfabricated silicon electrodes for corona discharge-based electrohydrodynamic thrusters." Micromachines 8.5 (2017)

3. Drew, Daniel S., and Kristofer SJ Pister. "Takeoff of a Flying Microrobot With COTS Sensor Payload ... " Hilton Head Microsystems Workshop 2018

scaling laws of propellers while maintaining the ability to transfer domain knowledge from the rich world of quadcopter design and control[4]. With the relatively high payload capacity of the ionocraft, it is possible to fly with a commercial 9-axis inertial measurement unit onboard. We have shown controlled hovering and planned flight in simulation, with various experimental measurements made to ground that simulation in the reality of the system. Controlled flight of an ionocraft is now within reach[5].

4. Drew, Daniel S., and Kristofer SJ Pister. "First takeoff of a flying microrobot with no moving parts." MARSS



Tethered takeoff with an onboard 9-axis IMU streaming attitude data

Although my dissertation work is enough to demonstrate that atmospheric ion thrusters are viable for centimeter-scale robots, there is still a large gap between that conclusion and having a functional artificial insect. Ultimately, the remaining work is far beyond what is able to be accomplished by a single graduate student, or even a single research group; it will require parallel effort in further actuator development, sparse computation control, meso-scale fabrication and assembly, power electronics miniaturization, and development of microrobot-specific ASICs, to name a few. There is interest in funding this massive effort. The recently announced multi-year DARPA SHRIMP program aims to demonstrate untethered microrobot platforms in the next three years. I also helped to write a DARPA seedling proposal with Prof. Pister, "Mobility and Power for Micro Robots," which was recently funded.

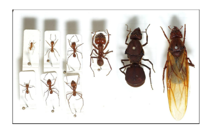
5. Drew, Daniel S., et al. "Toward Controlled Flight of the Ionocraft: A Flying Microrobot Using Electrohydrodynamic Thrust With Onboard Sensing and No Moving Parts." Robotics and Automation Letters 3.4 (2018)

Research Agenda

I aim to continue developing novel insect-scale robotic platforms, but want to guide the work by simultaneously using user-centered design practices to develop proof of concept implementations exploring the future application space. It is clear that future microrobot swarms will have many potential uses, but it is both a design and an engineering challenge to ensure that these resource-constrained systems will actually be useful. Development of functional robot swarms was pronounced as one of the ten "grand challenges" in *Science Robotics* likely to have major breakthroughs and socioeconomic impact in the next decade. There is also growing funding interest along these lines: My proposal for the Intelligence Community Postdoctoral Research Fellowship, "Design and Control of Heterogeneous Microrobot Swarms", was recently funded, and at least three of the 2018 DARPA Young Faculty award research topics are directly related.

greater than the sum of their parts: heterogeneous swarms

While the ionocraft was decidedly *non*-biomimetic, I believe that nature holds great inspiration for functional swarm robotics — just not the same inspiration many others are emulating. One of the major challenges facing useful deployment of microrobots is that a disproportionate amount of robot energy and payload mass is dedicated to locomotion and the minimum sensing capabilities required for control. Researchers have for the most part constructed strictly homogeneous swarms, where every agent is identical. Swarm algorithms attempt to overcome agent limitations through interactions between large numbers of robots, but are fundamentally grounded in an abstract conception of the organization of social insects like ants. In fact, phenotypic diversity among ants allows them to specialize for specific colony tasks; heterogeneous swarms of worker ants (i.e. different "castes") work together to perform complex tasks more effectively than a homogeneous swarm. As outlined in some of my prior published work[6], I plan on combining the best that modern, commercial microelectronics has to offer in sensing and computation with custom actuation and structural components in order to create centimeter-scale robot swarms with distributed intelligence, exploiting specialization to maintain functionality without compromising size or cost. Novel platforms with minimal available resources may require novel low-level control schemes; I plan on continuing my work on data-efficient model based reinforcement learning for control, potentially synthesizing computationally-sparse classical controllers directly from the model so that they can be put on the robots themselves [7].



Phenotypic diversity among the leafcutter ants allows for task specialization

6. Drew, Daniel S., Brian Kilberg, and Kristofer SJ Pister. "Future mesh-networked pico air vehicles." ICUAS 2017

7. Lambert, N. O., Drew, D. S., Calandra, R., Levine, S., & Pister, K. S. "Low Level Control of a Quadrotor with Deep Model-Based Reinforcement Learning." ICRA 2019 Under Review

A first step: Develop a suite of centimeter-scale platforms with specializations in communication, mobility, and actuation using off-the-shelf components. Investigate motion and task planning algorithms using external control and sensing (e.g. OpiTrack) systems before moving to distributed intelligence.
Potential funding: There is a good deal of available funding for robust, autonomous multi-agent systems, including the NSF Smart and Autonomous Systems (S&AS) and Energy, Power, Control, and Networks (EPCN) programs.

collaborators, not operators: human-swarm interaction grounded in robotics

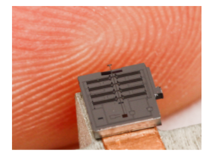
In a world where humans at work and play are significantly outnumbered by the synthetic life around them, it is no longer feasible to imagine directly controlling one or even a few robots. Instead of operators, we must make a shift towards becoming *collaborators* with these autonomous systems. A useful human-swarm interface needs to effectively convey operator intent to the swarm, as well as convey the swarm's status to the operator, without introducing an undue amount of either cognitive load or stress. I envision robotic control algorithms with inferred human emotion, and even real-time physiological signals, in the loop. There is no explicit model for how robot behavior will affect humans in this context, but it is possible to use machine learning techniques to develop one using real data.

Moving beyond audiovisual methods of information transfer, I have shown that it may even be possible to deliver active haptic feedback using insect-scale robots[8]. One of the key challenges is evaluating and designing these interactions without diverging too far from the reality of the robotics implementation; I will use my experience in running multiple formal user studies of hardware systems, as well as my domain knowledge as a designer of robots, to make sure that results can translate back to the design of the platforms themselves.

8. xxx, x, Drew, Daniel S., xxx, x, xxx, x, xxx, x, & xxx, x. "Millimeter-scale Haptics using MEMS Actuators." CHI 2019, under blind review

A first step: Focus on user-centered design of swarm interaction methods: First, an elicitation study to discern "natural" input patterns. Next, an assessment study of the efficacy of some of these candidate inputs with a hardware implementation on 2D wheeled robots. Properly constraining and framing the possible inputs for the elicitation study, and properly specifying control groups and quantitative methods for the assessment, will be a key challenge.

Potential funding: The recent DARPA OFFSET program shows a rising interest in funding investigations in human-swarm collaboration. The NSF NRI program for Ubiquitous Collaborative Robots is a current large, interdisciplinary opportunity.



Microrobot-based tactile interfaces will require fundamental research in micron-scale haptics

ants don't have solar panels: artificial ecosystems to enable autonomy

The pressure pushing researchers towards enabling autonomy of insect-scale systems using methods such as solar energy harvesting neglect an important fact — insects don't have solar panels. The world is in fact connected through an incredibly intricate ecosystem of flora and fauna, working together (or at odds) both explicitly and implicitly, to spread "autonomous" life through all reaches.

Roboticists should not be designing their platforms in a vacuum; without the benefit of waiting for evolution to take its course, we will instead need to intelligently co-design the mobile platforms with the supporting infrastructure they need for shelter, energy, and propagation. I envision implementing control algorithms for centimeter-scale robots that take into account the presence of multifunctional robotic colony structures as well as low-cost, distributed energy accumulators in their environment.

We must design not only the bee, but the plant and colony too [NatGeo]

Proof of concept demonstrations of "artificial ecosystems," with largely off-the-shelf components, may help to more quickly shift the conversation on microrobots beyond enabling long-lifetime operation of a single unit and towards *using* them in long-term deployments.

A first step: Demonstrate a centimeter-scale robot co-designed with its environment: for example, a micro-quadcopter with specialized sensing and actuation components tailored for finding, landing, and charging from a static solar-powered system. We can draw from entomology literature for inspiration — how does a bee find a flower's nectar? How widely, and how often, do insects range from their colonies when searching for resources?

Potential funding: I believe that these systems will be key enablers of the "internet of everything." They may find funding from programs aimed at fundamental research in IoT platforms, such as the current NSF Cyber-Physical Systems (CPS) program.

a massive challenge means wide collaboration

Designing functional centimeter-scale platforms and the algorithms that control them, as well as investigating the interaction methods that make sense for future end users, is a monumental challenge. I look forward to recruiting a diverse group of researchers, and fostering collaborative efforts across departmental boundaries, in order to make this research vision a reality.