Mechanical Engineering Doctoral Defense

Scalable Control Strategies and a Customizable Swarm Robotic Platform for Boundary Coverage and Collective Transport Tasks

School for Engineering of Matter, Transport and Energy

Sean Wilson

Advisor: Spring Berman

abstract

Swarms of low-cost, autonomous robots can potentially be used to collectively perform tasks over large domains and long time scales. The design of decentralized, scalable swarm control strategies will enable the development of robotic systems that can execute such tasks with a high degree of parallelism and redundancy, enabling effective operation even in the presence of unknown environmental factors and individual robot failures. Social insect colonies provide a rich source of inspiration for these types of control approaches, since they can perform complex collective tasks under a range of conditions. To validate swarm robotic control strategies, experimental testbeds with large numbers of robots are required; however, existing low-cost robots are specialized and can lack the necessary sensing, navigation, control, and manipulation capabilities.

To address these challenges, this thesis presents a formal approach to designing biologically-inspired swarm control strategies for spatially-confined coverage and payload transport tasks, as well as a novel low-cost, customizable robotic platform for testing swarm control approaches. Stochastic control strategies are developed that provably allocate a swarm of robots around the boundaries of multiple regions of interest or payloads to be transported. These strategies account for spatially-dependent effects on the robots' physical distribution and are largely robust to environmental variations. In addition, a control approach based on reinforcement learning is presented for collective payload towing that accommodates robots with heterogeneous maximum speeds. For both types of collective transport tasks, rigorous approaches are developed to identify and translate observed group retrieval behaviors in Novomessor cockerelli ants to swarm robotic control strategies. These strategies can replicate features of ant transport and inherit its properties of robustness to different environments and to varying team compositions. The approaches incorporate dynamical models of the swarm that are amenable to analysis and control techniques, and therefore provide theoretical guarantees on the system's performance. Implementation of these strategies on robotic swarms offers a way for biologists to test hypotheses about the individual-level mechanisms that drive collective behaviors. Finally, this thesis describes Pheeno, a new swarm robotic platform with a three degree-of-freedom manipulator arm, and describes its use in validating a variety of swarm control strategies.

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