Mechanical Engineering Doctoral Defense

Exploration, Mapping and Estimation using a Swarm of Resource-Constrained Robots

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abstract

Robotic swarms can potentially perform complicated tasks such as exploration and mapping at large space and time scales in a highly parallel and robust fashion. This thesis presents strategies for mapping environmental features of interest – specifically obstacles, collision-free paths, generating a metric map and estimating scalar density fields in an unknown domain using data obtained by a swarm of resource-constrained robots. First, an approach was developed for mapping a single obstacle using a swarm of point-mass robots with both directed and random motion. The swarm population dynamics are modeled by a set of advection-diffusion-reaction partial differential equations (PDEs) in which a spatially-dependent indicator function marks the presence or absence of the obstacle in the domain. The indicator function is estimated by solving an optimization problem. Second, a methodology for constructing a topological map of an unknown environment was proposed, which indicates collision-free paths for navigation, from data collected by a swarm of finite-sized robots. As an initial step, the number of topological features in the domain was quantified by applying tools from algebraic topology, in particular, the concept of persistent homology, to a probability function over the explored region that indicates the presence of obstacles. A topological map of the domain in the form of an approximate Generalized Voronoi Diagram is then generated using a graph-based wave propagation algorithm. This approach is further extended, enabling the technique to construct a metric map of an unknown domain with obstacles using uncertain position data filtered using noisy measurements of signals received from transmitters located outside the domain by a swarm of resource-constrained robots. Next, a distributed method was developed to construct the occupancy grid map of an unknown environment using a swarm of inexpensive robots or mobile sensors with limited communication. In addition to this, an exploration strategy which combines information theoretic ideas with L´evy walks was also proposed. Finally, the problem of reconstructing a two-dimensional scalar field using observations from a subset of a sensor network in which each node communicates its local measurements to its neighboring nodes was addressed. The effect of network topology on the field reconstruction for grid and chain networks was compared in terms of the trace of the observability Gramian, which provides a quantitative measure of observability, and a performance metric based on the H2-norm of the system, which characterizes a network's robustness to noise.

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