School of Quantum Physics and Matter

PhD Defense

Navigation Strategies of Smart Active Particles in Inhomogeneous Media through Reinforcement Learning

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Active matter—comprising self-propelled particles that consume ambient free energy to generate motion—exhibits rich, nonequilibrium dynamics that give rise to emergent properties such as persistent motion and collective behaviors. Understanding and optimizing navigation of active particles within spatially and temporally heterogeneous environments are important in applications in microfluidics, biophysics, and autonomous microscale robotics. This thesis investigates the integration of reinforcement learning into the navigation policies of smart active Brownian particles (microagents) in both static and dynamically evolving potential landscapes in an otherwise static, viscous fluid background. We first study the optimal navigation of smart active Brownian particles through inhomogeneous static media, employing both tabular methods and deep reinforcement learning techniques. We demonstrate how these methods enable smart active Brownian particles to traverse static potential landscapes subject to ambient noise. The study is extended to time-varying inhomogeneous media, where the surrounding environment dynamically evolves. We specifically analyze how microagents navigate through a rotating, repulsive, Gaussian potential barrier by employing Advantage Actor-Critic and Deep Deterministic Policy Gradient methods. Our results demonstrate that the rotating potential can be utilized for size-based sorting of the microagents, as we show particles of different hydrodynamic radii arrive at a target wall at sufficiently well-separated times, enabling their effective separation. By quantifying the efficiency of this sorting mechanism, we show that training microagents in a noisy background, as opposed to a noise-free one, can improve the precision of their size-based sorting. In addition to single-agent navigation, we examine the collective behavior and emergent flocking of smart active Brownian particles under a multi-agent reinforcement learning framework (that is, the Central Training with Decentralized Execution approach, where the training is performed through a Deep Q-Network method) within different confining geometries.