Persistent Optimal Control of Renewably Powered Vehicle Networks Under Imperfect Information and Constrained Communication

Introduction: Persistent oceanographic observation, search and rescue, and military surveillance are all application domains where persistent and autonomous sensing can be applied. However, for many of these existing applications, the necessary infrastructure for persistent missions does not exist. For example, oceanographic observation using buoys and manned research vessels is limited due to sparsity and/or the short duration of measurements [1]. These limitations can be addressed by fleets of renewably powered robotic vehicles. Sourcing energy from the environment and autonomous control enables persistent missions, while autonomous decision-making can maximize performance of the fleet when given an objective.

Such objectives vary with the application and domain. For example, we may seek to maximize the quantity and quality of salinity measurements collected in an ocean environment over a persistent mission. In prior work, I address the problem of energy-aware control for a *single* renewably powered robotic vehicle [2] [3]. However, when controlling a fleet, multiple individuals must *cooperatively* optimize their performance. As an additional challenge, real-world environments are almost invariably stochastic. As renewably powered robots source energy from the environment, it is necessary to account for environmental stochasticity in an optimal control formulation. Further, the environment typically limits communication among vehicles, impacting their ability to collaboratively make decisions.

Thus, there are three main challenges when addressing the persistent control of a fleet of renewably powered robotic vehicles: 1) the infinite-horizon optimal control problem for the fleet, 2) imperfect knowledge regarding a stochastic energetic resource and environment, and 3) imperfect communication amongst vehicles in the fleet. Cooperative control of a fleet is addressed in existing game theory literature [4]; however, it is done so in the absence of a persistent optimal control problem with imperfect information *and* imperfect communication. Therefore, *the core contribution of this work will be a game-theoretic control solution that addresses an infinite-horizon cooperative game with imperfect knowledge in a stochastic environment*.

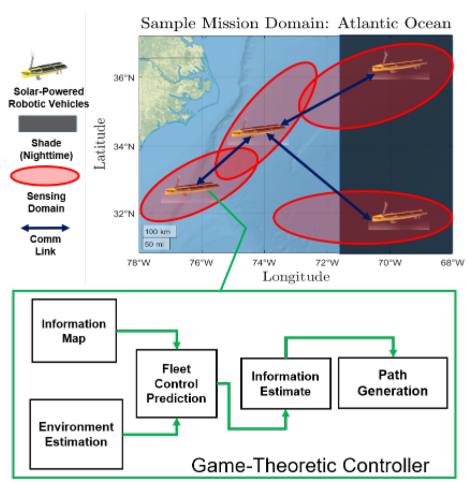

Figure 1: Sample mission with solar-powered robots and block diagram of proposed controller

Research Plan: The proposed research will be conducted in two phases. The first phase will involve developing the mathematical formulation for the proposed game-theoretic controller and providing mathematical guarantees for optimality and stability. The second phase will involve implementation of the controller in a simulation environment as well as on a real-world experimental fleet to validate performance.

Theoretical Work: To address the challenges laid out in the introdcution, I propose the following contributions:

1) For any realistic and nonlinear system, infinite-horizon optimizations are not within the realm of computational feasibility. Thus, to estimate the infinite-horizon performance, we can characterize the energy remaining at the end of a finite-horizon in terms of its utility for future information collection, deemed information value of energy (IVE). In ongoing work, I am applying continuous-time optimal control theory to characterize IVE. This is accomplished by fixing initial and final energetic states to identify a steady-state control solution, and then quantifying the additional information gain with a higher initial energetic state. With this estimate, we can optimize both the finite-horizon performance and IVE estimate, resulting in an optimal infinite-horizon control solution.

2) An objective function for our optimization must incorporate the environment and energetic resource; however, it is impossible to know the exact states of the future environment. While the environment is a

function of random variables, the evolution of those variables can be characterized via statistics (e.g. mean, variance, spatial length scales, temporal length scales, etc), wwhich are not random variables. Thus, I propose an objective formulation that is a function of statistical variables, which will capture the environmental dynamics and enable a deterministic optimization even with imperfect knowledge of the environment.

3) The ideal control of a fleet of vehicles would require that each vehicle constantly communicates its control decisions, energetic state, and performance. However, in sufficiently large mission domains, the environment will limit communication. So each vehicle must make an informed "guess" of the other vehicles' decisions and performance using available information before making its own control decisions. As these guesses must be sufficiently accurate, there exists a limit on the rate of change of decisions made by each individual in the fleet. I propose first characterizing this, resulting in a decision making rate (DMR) term. I hypothesize that a sufficiently high DMR will hinder fleet performance as updated decisions cannot be accounted for by all individuals in a communication constrained environment. Conversely, a sufficiently low DMR will hinder performance as it limits adaptation to the changing environment. Thus, I will identify the optimal DMR for the controller.

Simulations/Experimental Validation: To validate the performance of the controller, a software simulation environment will be developed using MATLAB. This simulation will model each vehicle along with an environmental model. Specifically, I propose modelling a fleet of solar-powered autonomous surface vehicles in an ocean environment (using MAB-SAB-ROM [5] data) with the goal of maximizing information collection over a 2-month simulation period, quantified using clarity [6].

To further validate the performance of the controller, I propose an experiment utilizing a fleet of solar-powered rovers in a laboratory environment. These rovers can built inexpensively, using off-the-shelf components. When testing indoors, the stochastic solar resource can be simulated by controlling the lights in the room. Software can be written to limit communication and impose energetic constraints on the vehicles. Once again, the objective will be to maximize clarity. In both simulation and experimental testing, the proposed controller shall be compared against baseline strategies to both validate the performance of the controller and demonstrate improvement over baseline strategies.

Intellectual Merit: Existing robotics and game theory literature does not address the persistent control of renewably powered robotic fleets with imperfect knowledge *and* imperfect communication. The proposed game-theoretic controller will address these challenges, providing new methods to solve similar problems. The simulation environment and experiments will enable validation of the controller and will demonstrate real-world performance.

Broader Impacts: The creation of energy-optimal information-maximizing controllers for a fleet of renewably powered vehicles will support scientific missions such as persistent ocean monitoring and Mars exploration. It can also bolster economic interests, through applications such as crop monitoring with UAVs, to increase yield and improve food supply.

To disseminate my research to the academic community, I will publish research in journals such as IEEE TCST and present at conferences such as IEEE CDC and ACC. Finally, I will engage in outreach with high school robotics teams, expanding upon my contributions to STEM outreach as highlighted in my personal statement. **Overall, my work will serve to improve STEM engagement and expand the utility of renewably powered robotic vehicles in many applications.**

References [1] He, et al. "Gulf Stream marine hydrokinetic energy resource characterization off Cape Hatteras, North Carolina USA". [2] Govindarajan, et al. "Coverage-maximizing solar-powered autonomous surface vehicle control for persistent gulf stream observation." [3] Govindarajan, et al. "Predictive velocity trajectory control for a persistently operating solar-powered autonomous surface vessel." [4] Branzei, et al. [5] Chen and He. "Numerical investigation of the Middle Atlantic Bight shelfbreak frontal circulation using a high-resolution ocean hindcast model." [6] Agrawal and Panagou. "Sensor-based planning and control for robotic system: Introducing clarity and perceivability"