Collaborative Research: CPS: Medium: Enabling Autonomous, Persistent, and Adaptive Mobile Observational Networks Through Energy-Aware Dynamic Coverage

Pls/Co-Pls: Chris Vermillion (Univ. of Michigan), Dimitra Panagou (Univ. of Michigan), and Ruoying He (NC State)

https://corelab.engin.umich.edu/research/renewably-powered-robotic-systems/, https://websites.umich.edu/~dpanagou/, https://oomg.meas.ncsu.edu

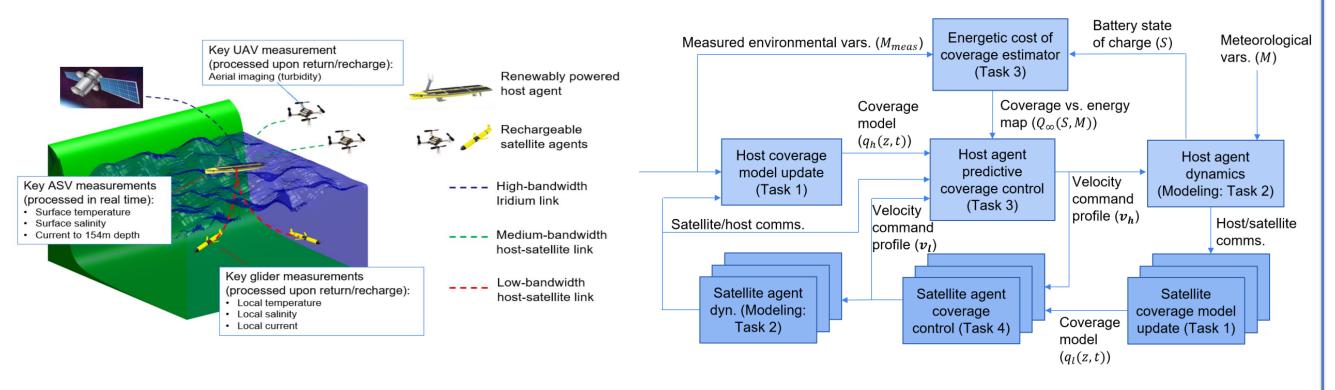
CPS challenge and solution approach:

Goal: Create a *persistent*, *adaptive*, and *autonomous* mission-planning framework that trades off *information (cyber)* and *energy (physical)*.

Key solution components:

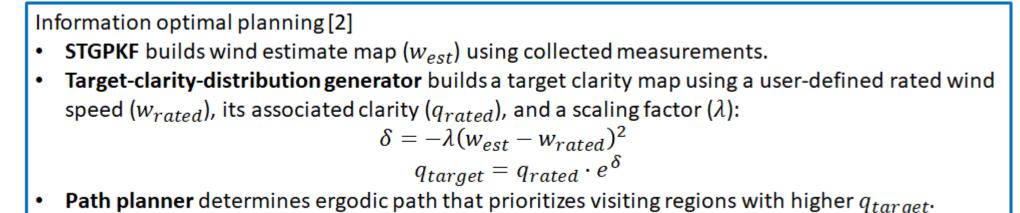
- Predictive, persistent path and velocity control with infinite-horizon information value of energy terminal reward
- Energy-aware coverage for maximally informative observation and safe rendezvous with host agent/charging station

Target application: Persistent surface, aerial, and underwater oceanographic observation in the U.S. Gulf Stream and Outer Banks



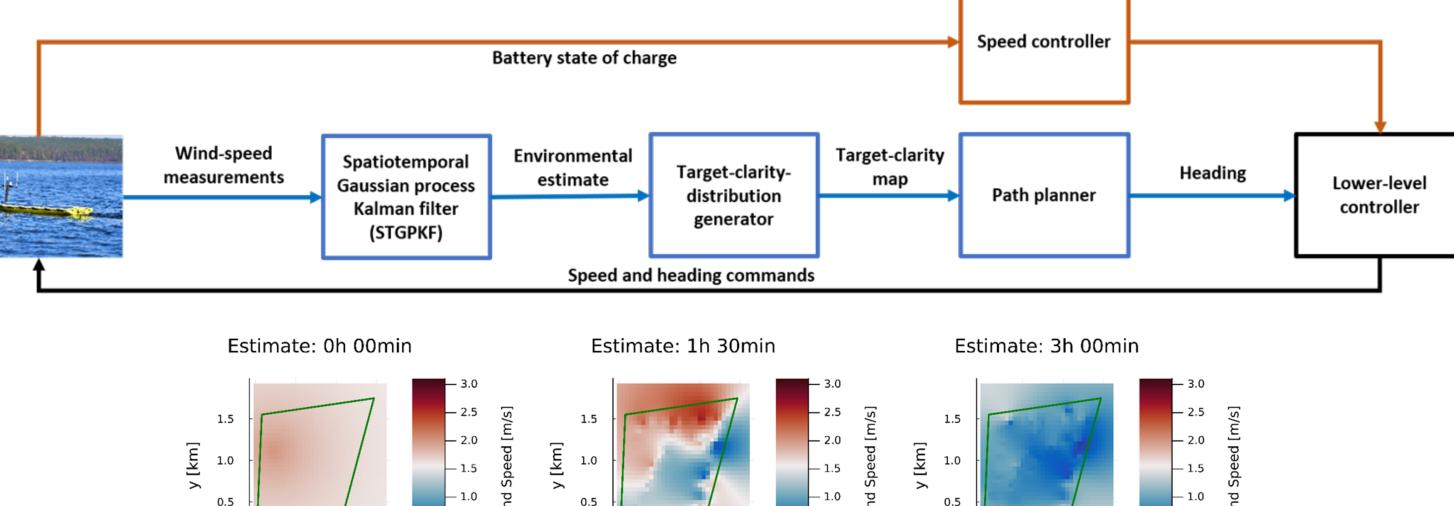
Research progress – exploration of a spatiotemporal environment using a renewably powered host agent [1]:

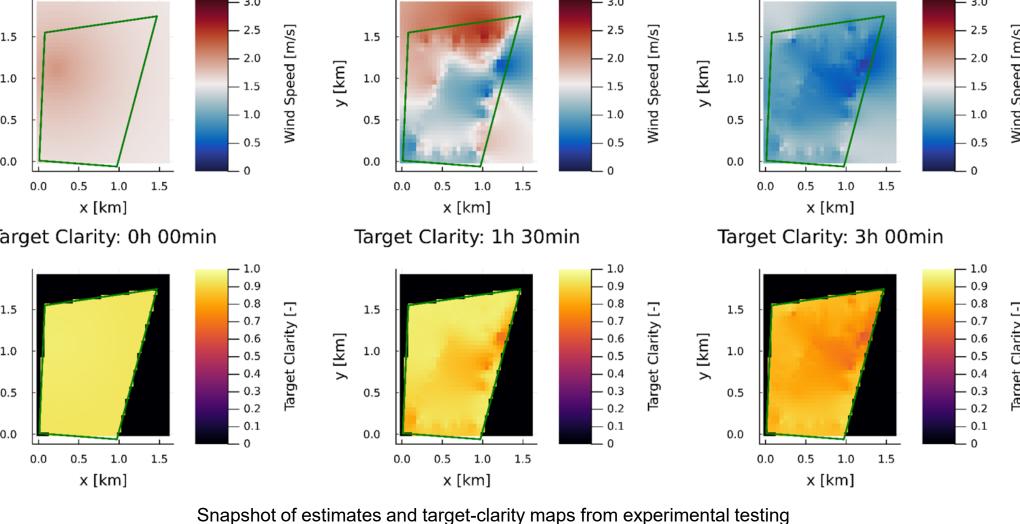
- Goal: Persistently characterize wind speed biasing toward values near a target wind speed.
- Approach: Clarity (bounded between [0,1]) models quality of information about a quantity of interest (e.g., wind speed) considering information decay. This forms the backbone of the proposed algorithm (presented right).
- Experimental testing at Jordan Lake, NC: The proposed algorithm was tested at Jordan Lake, NC using the autonomous surface vessel (ASV).



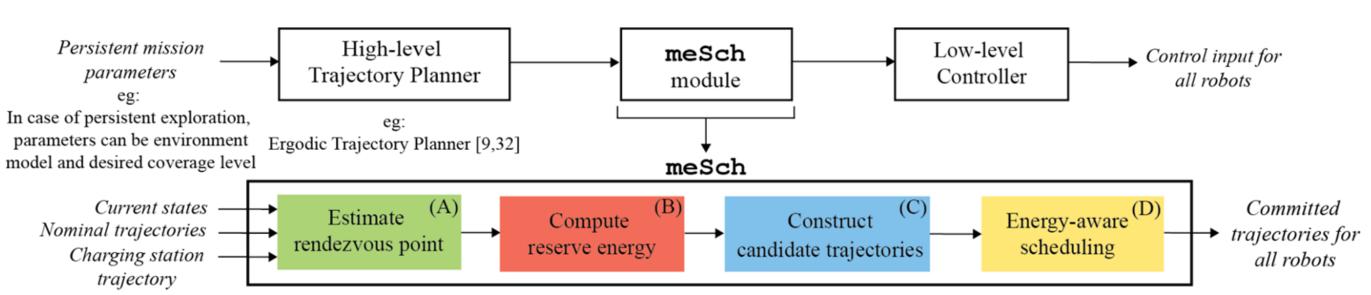
Persistent energy optimal planning Speed controller leverages optimality results derived from indirect methods (in optimal control)

and iterative learning as shown in [3].





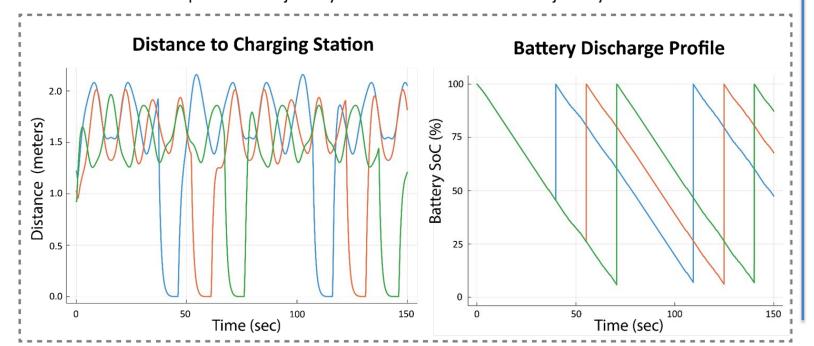
Research progress – energy-aware coordination of satellite agents



meSch (multi-agent energy-aware scheduling for task persistence) [4]

- Objective: Develop an algorithm to track the nominal informative trajectories while ensuring robots never run out of energy and guaranteeing exclusive visits (one at a time) to the possibly mobile charging station.
- Approach: Iteratively generate candidate trajectories and check two conditions:
 - Ensure non-overlapping charging station visits with minimal gaps.
 - Confirm robots have enough energy to continue.
- Contributions:
 - O Handles robots with both uniform and varying discharge rates.
 - \circ Enables scalability with O(NlogN) implementation complexity.
 - Supports online replanning and nonlinear dynamics for adaptive missions.

Sequence of snapshots leading to one quadrotor visiting charging station



Broader impacts & ongoing/future work:

Impact on other application domains:

- The **Eclares** [5] and **meSch** [4] frameworks can be applied to long-horizon, adaptive search-and-rescue operations.
- Quantifying the energy/information tradeoff benefits smart agriculture and transportation networks.

Societal impacts:

 Large deviations in the Gulf Stream, documented with sparse observations, signal potential shifts in atmospheric/oceanic forcing and are crucial for assessing ocean energy-harvesting potential.

Broader Impacts:

- Kaleb Ben Naveed, Outreach Ambassador for Michigan Robotics, partnered with Carnegie Mellon University's Robotics Institute to develop a free robotics education website for high school students.
- Kavin Govindarajan has been working with InspireNC and FIRST Robotics Competition Team 6908 Infuzed to teach high school students robotics, with a focus on autonomous controls.



Ongoing/future work:

value of energy

Ocean-resource

at Outer Banks, NC

Characterizing information

optimal rendezvous planning

characterization experiments

of host and satellite agents

Information-and-energy







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[3] K. Govindarajan, D. Agrawal, D. Panagou, C. Vermillion, "Fusion of Indirect Methods and Iterative Learning for Persistent Velocity **Trajectory Optimization of a Sustainably-Powered Autonomous Surface Vessel,**" IEEE CCTA 2025 (Under Review)

[4] K.B. Naveed, A. Dang, R. Kumar, D. Panagou, "meSch: Multi-Agent Energy-Aware Scheduling for Task Persistence," IEEE IROS 2025 (Under

Tracking Approach", JGR-Oceans, Volume 129, Issue 9, 2024 [7] Wu. T. and R. He, "Gulf Stream Mesoscale Variabilities Drive Bottom Marine Heatwaves in Northwest Atlantic Continental Margin

Methane Seeps", Communications Earth & Environment, 5, 574 (2024) [8]] Mao, S., He, R. and M. Andres, "Modes of North Atlantic Western boundary current variability at 36° N", Scientific Reports 13, 18773, 2023 [9] Mao, S., R. He, J. Bane, G. Gawarkiewicz, and R. E. Todd, "A data-assimilative modeling investigation of Gulf Stream variability", Deep Sea Research Part II: Topical Studies in Oceanography 211:105319, 2023

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