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

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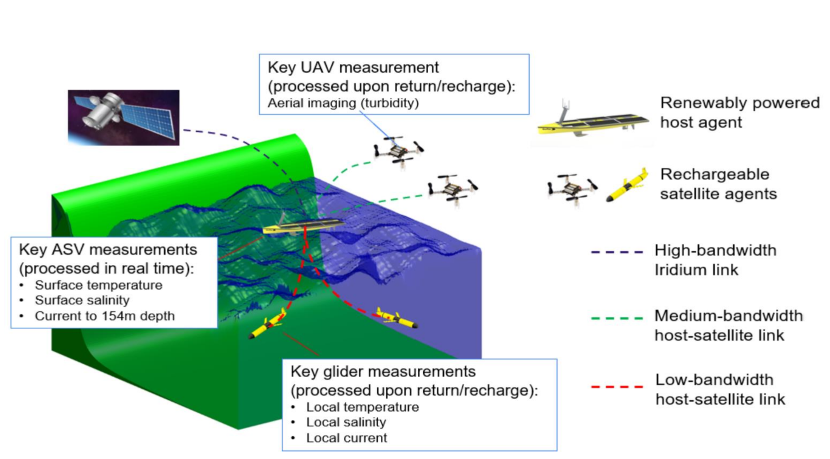
https://corelab.engin.umich.edu/research/renewably-powered-robotic-systems/, https://websites.umich.edu/~dpanagou/, https://oomg.meas.ncsu.edu

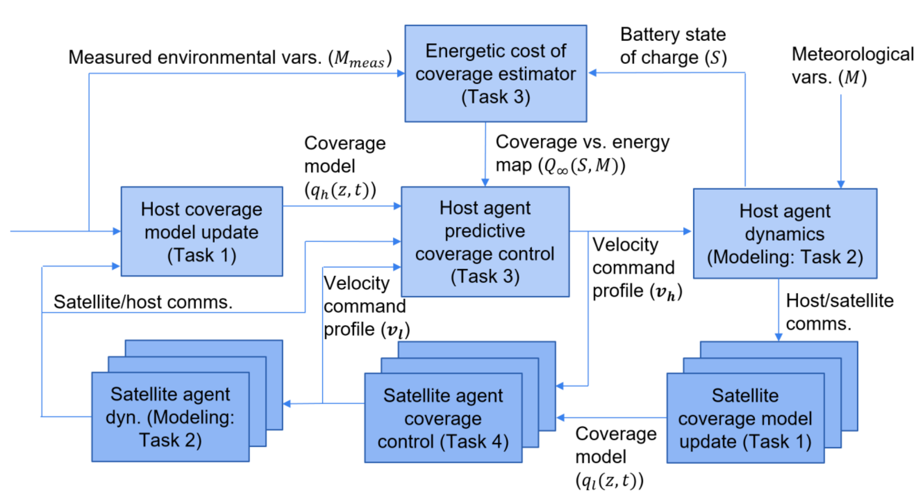
CPS challenge and solution approach:

Goal: Create a ***persistent***, ***adaptive***, ***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 – Velocity optimization [1]:

- Dist. traveled = surrogate for information
- ***Indirect methods*** show that the unconstrained optimal velocity is ***piecewise constant***; value of this constant is estimated using iterative learning ctrl. (ILC).
- ***Barrier functions*** used to ensure feasibility of future battery limits

Optimization formulation:

$$\text{Maximize } J = \int_0^{t_f} u(t)dt$$

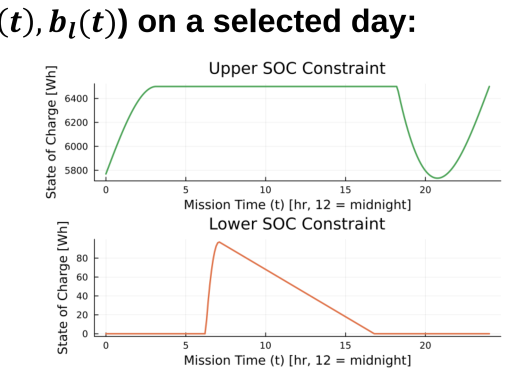
Subject to:

$$\dot{b}(t) = P_{in}(t) - k_h - k_m u(t)^3$$
$$b(t_f) = b(0)$$
$$0 \le b(t) \le b_{max}, 0 \le t \le t_f$$
$$u_{min} \le u(t) \le u_{max}, 0 \le t \le t_f$$

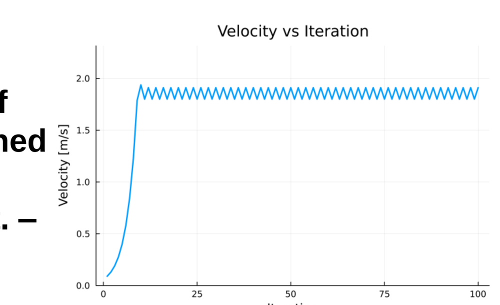
Result:

$$u^*(t) = \begin{cases} u_{max}, b(t) \ge b_u(t) \\ u_{min}, b(t) \le b_l(t) \\ \text{undetermined p. w. constant, o. w.} \end{cases}$$

Evolution of barrier functions ($b_u(t), b_l(t)$) on a selected day:

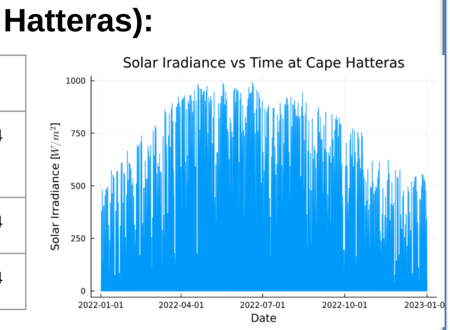


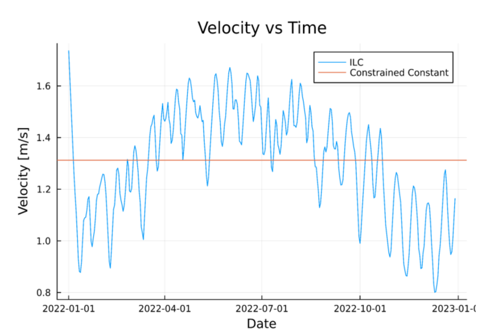
ILC-driven evolution of unconstrained optimal velocity est. – idealized conditions:

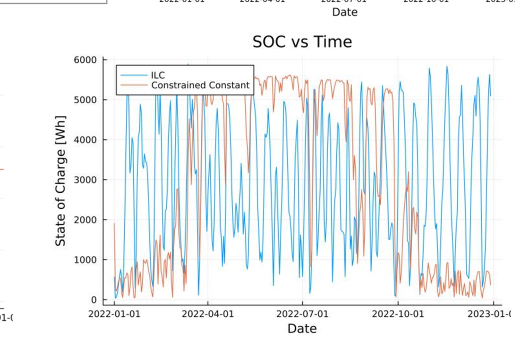


Year-long simulation results (Cape Hatteras):

Strategy	Dist. (km)
Unconstrained Constant Velocity (Non-Tight Upper Bound)	4.116 x 10⁴
Indirect Optimal Control + ILC	3.871 x 10⁴
Constrained Constant Velocity	3.711 x 10⁴

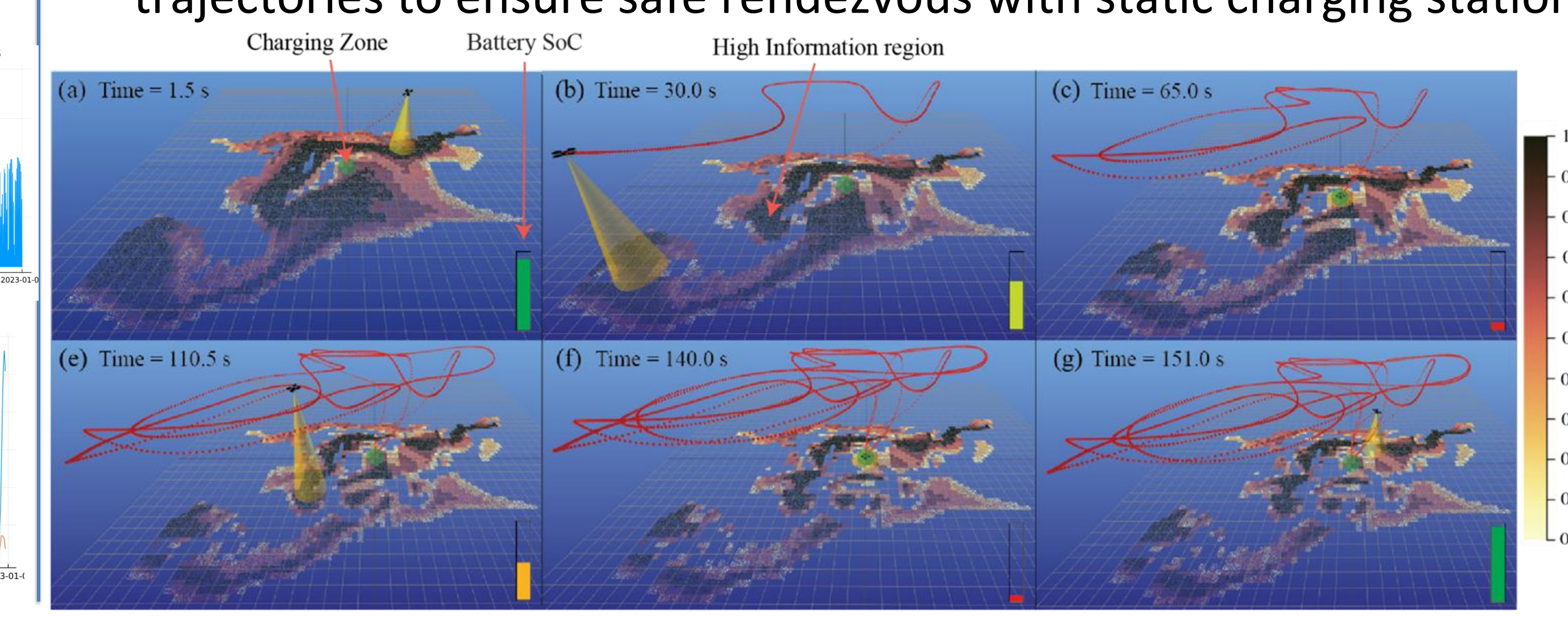






Research progress – Energy-aware, clarity-driven dynamic coverage [2]:

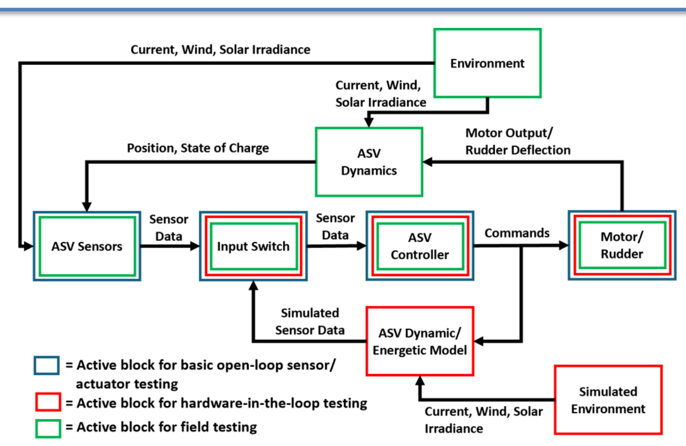
Proposed Solution: Eclares (Energy-aware, clarity-driven ergotic search):
- ***Clarity*** (bounded between [0,1]) models quality of information about a quantity (e.g. salinity), considering information decay.
- ***Clarity-driven ergodic search*** iteratively generates informative trajectories to acquire desired clarity level.
- Online ***energy-aware (`eware`)*** add-on iteratively filters ergodic trajectories to ensure safe rendezvous with static charging station.

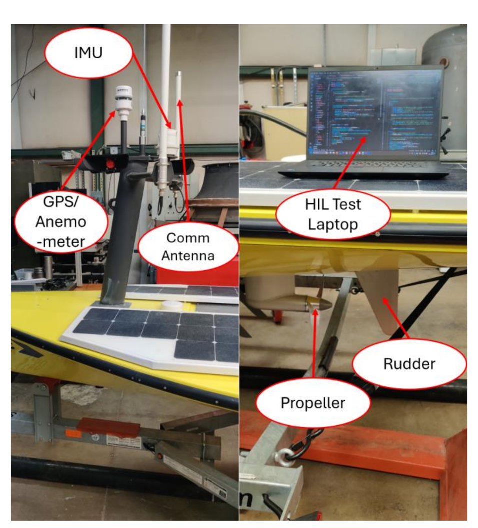


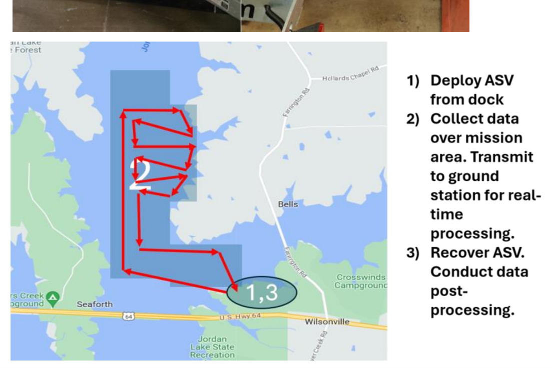
Research progress – Experimental evaluation:

Autonomous Surface Vessel (ASV) Experiments:
- ***Hardware-in-the-Loop (HIL) Tests (top and middle images)***: Test controller on vehicle hardware in a simulated environment. This validates the operation of the boat and the controller without needing to put the ASV in the water.
- ***Open-Water Testing (bottom image)***: We will test the persistent planning algorithms with the ASV at Jordan Lake, NC, with the goal of characterizing the wind resource in the lake (with future characterizations of salinity offshore at Cape Hatteras).

Quadrotor and Rover Experiments (MAir):
- ***Indoor testing using crazyflies:*** Test `Eclares` framework and the extended multi-agent version in the indoor facility for initial validation
- ***MAir testing using rovers*** : We will perform wind profile characterization in the outdoor MAir facility using `Eclares`.







Broader impacts:

Impact on other application domains:
- `Eclares` framework can applied to long time horizon search and rescue operations
- Energy/information tradeoff also useful for smart agriculture and intelligent transportation networks

Societal impacts:
- Large deviations in the Gulf Stream have been documented, but only with sparse observations
- Such deviations are warnings of larger shifts in atmospheric/oceanic forcing
- High-resolution Gulf Stream monitoring is also relevant to assessing ocean energy-harvesting potential

Broadening participation in engineering and computing:
- Kaleb Ben Naveed partnered with Carnegie Mellon Univ.'s Robotics Institute to organize the "*Math behind Robotics*" for STEM educators in Venano County, PA.
- Kavin Govindarajan has been working with the InspireNC nonprofit organization and FIRST Robotics Competition Team 6908 Infuzed to teach high school students concepts in robotics, particularly focusing on autonomous controls.
- Devansh Agrawal hosted a workshop on building gliders for female high school students with WISE (Women in Science and Engineering).

NC STATE UNIVERSITY

UNIVERSITY OF MICHIGAN

[1] 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," Submitted to *IEEE Conference on Decision and Control*, 2024.

[2] K. Naveed, D. Agrawal, C. Vermillion, D. Panagou, "Eclares: Energy-Aware Clarity-Driven Ergotic Search," Accepted to ICRA 2024.

Award ID#: 2223844, 2223845