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Maximizing Seaweed Growth on Autonomous Farms: A Dynamic Programming Approach for Underactuated Systems Operating in Uncertain Ocean Currents

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Abstract— **Seaweed biomass presents a substantial opportunity for climate mitigation, yet to realize its potential, farming must be expanded to the expansive open oceans. However, in the open ocean neither anchored farming nor floating farms operating with powerful engines are economically viable. Recent studies have shown that vessels can navigate with low-power engines by *going with the flow*, utilizing minimal propulsion to strategically leverage beneficial ocean currents. In this work, we focus on low-power autonomous seaweed farms and design controllers that maximize seaweed growth by taking advantage of ocean currents. We first introduce a Dynamic Programming (DP) formulation to solve for the growth-optimal value function when the true currents are known. However, in reality only short-term imperfect forecasts with increasing uncertainty are available. Hence, we present three additional extensions. Firstly, we use frequent replanning to mitigate forecast errors. For that we compute the value function daily as new forecasts arrive, which also provides a feedback policy that is equivalent to replanning on the forecast at every time step. Second, to optimize for long-term growth, we extend the value function beyond the forecast horizon by estimating the expected future growth based on seasonal average currents. Lastly, we introduce a discounted finite-time DP formulation to account for the increasing uncertainty in future ocean current estimates. We empirically evaluate our approach with 30-day simulations of farms in realistic ocean conditions. Our method achieves 95.8% of the best possible growth using only 5-day forecasts. This confirms the feasibility of using low-power propulsion to operate autonomous farms in real-world conditions.**

I. Introduction

Recent research has shown promising applications of seaweed biomass for climate mitigation. It can be used as human food, as cattle feed that reduces methane emissions [1], for biofuel and plastic [2], and for carbon capture i.e. when the biomass is sunk to the ocean floor, it removes carbon dioxide from the atmosphere [3]. To deliver on this promise, production must scale by expanding seaweed farming from labor-intensive operations near shore to automated solutions utilizing the vast expanse of the open oceans [4]. But conventional farming becomes economically infeasible in deeper waters as anchoring costs increase with depth [5].

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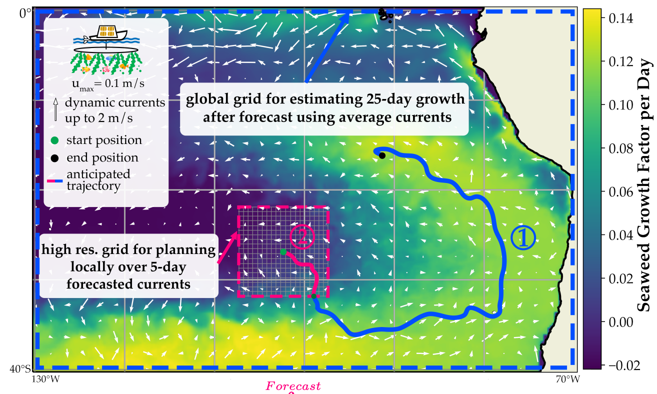

Solve for: $J^*_{Forecast}(\boldsymbol{x}, t) = \int^{Forecast} growth(s)ds \; + \; \mathbb{E}\left[growth_{afterForecast}\right]$

Apply: $\pi_{Forecast}(\boldsymbol{x}, t) = \arg\max_{\boldsymbol{u} \in \mathbb{U}} f(\boldsymbol{x}, \boldsymbol{u}, t) \cdot \nabla_x J^*_{Forecast}(\boldsymbol{x}, t)$

Fig. 1: Our method maximizes long-term growth on autonomous seaweed farm that operate by harnessing ocean currents. We solve for the value function $J^*_{Forecast}$ that is long-term growth-optimal under the forecast with dynamic programming. We first compute the expected 25-day growth after the forecast based on historical average currents (**1**) and then use it to regularly solve for the value function over the next 5 days using daily current forecasts (**2**). Applying the induced policy $\pi_{Forecast}$ as feedback controller ensures high growth despite imperfect short-term forecasts.

A promising solution could be non-tethered, autonomous seaweed farms that roam the oceans while growing seaweed [6], [7]. These floating farms needs to be able to control their position to prevent stranding, colliding with ships, or drifting to nutrient-depleted waters. While they could be steered with powerful ship engines, the power and hence energy costs are prohibitively high due to the drag force scaling quadratically with the relative velocity of the farm. In our recent work, we demonstrated that an Autonomous Surface Vehicle (ASV) can navigate reliably by *going with the flow*, using its minimal propulsion ($0.1\frac{m}{s}$) strategically to nudge itself into ocean currents ($[0-2\frac{m}{s}]$) that drift towards its destination [8], [9]. This work has been extended to reduce the risk of stranding [10] and to fleets of vessels that navigate while staying connected in a local communication network [11]. In this paper, we use this low-power steering paradigm for operating seaweed farms. Our objective is to maximize seaweed growth along the trajectory of the farms building upon prior research on optimal deterministic autonomous sea farming [12], [13]. From the control perspective, there are four key challenges that we need to tackle. First, the currents are non-linear and time-varying. Second, in realistic settings, only coarse uncertain forecasts are available [14]–