Navigating Underactuated Agents by Hitchhiking Forecast Flows

Marius Wiggert1, Manan Doshi2, Pierre F.J. Lermusiaux 2 and Claire J. Tomlin1

Abstract—Underactuated agents can achieve energy-efficient navigation in the air and oceans by hitchhiking complex flows. However, in real flows the forecast error can be larger than the actuation of the agent which poses a challenge for reliable navigation. In this paper, we propose a closed-loop control schema in the spirit of Model Predictive Control (MPC) which allows time-optimal replanning at every step with one computation per forecast. We use the recent Multi-Time Hamilton-Jacobi Reachability formulation to obtain a value function which is used for closed-loop control. We evaluate the reliability of our method empirically over a large set of multi-day start-target missions in the ocean currents of the Gulf of Mexico with realistic forecast errors. Our method outperforms the baselines significantly and achieves high reliability, measured as the success rate of navigating from start to target within a maximum allowed time, at low computational cost.

I. INTRODUCTION

We increasingly see autonomous systems operating in the air and oceans. Beyond airplanes and ships, there are emerging applications such as balloons in the stratosphere for delivering internet access [1], airships, ocean gliders, and active drifters for collecting data in situ [2]–[5], floating solar farms storing energy in methanol [6], and floating seaweed farms for biomass and carbon sequestration [7], [8]. The overactuated navigation approaches used in ships and planes require significant energy to overcome the drag forces inherent in navigating through fluids. This is even more challenging for slower environmental monitoring systems with large cross-sectional areas, such as floating seaweed farms, as it makes steering them prohibitively expensive and limits their operating times and structures. This motivates our investigation of an energy-efficient steering paradigm based on the winds and ocean currents around these systems: navigating agents by hitchhiking complex flows. By leveraging these non-linear, time-varying flows for propulsion, only a minimal amount of energy is required to nudge the agents into beneficial flows, e.g., balloons going up and down or small horizontal propulsion in the oceans. Because the power required to counter drag forces scales cubically with the relative velocity of the system, navigating with $\frac{1}{1000}$th of the speed means only $\frac{1}{1000}$th of the power is required. This enables a host of new applications.

1M.W., and C.J.T. are with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, USA. For inquiries contact: mariuswiggert@berkeley.edu.
2 M.D. and P.F.J.L. are with the Department of Mechanical Engineering at the Massachusetts Institute of Technology, USA.

The authors gratefully acknowledge the support of the C3.ai Digital Transformation Institute, the NASA ULI Grant on Safe Aviation Autonomy, the DARPA Assured Autonomy Program, the SRC CONIX Center, and the ONR BRC program.

Fig. 1: Our method for reliable navigation in flows is based on frequent replanning. For that the Time-to-reach map $J^*(x,t)$ is computed daily as new flow forecasts $\hat{v}(x,t)$ become available. Then for closed loop operation, the time-optimal control $u^*_t$ is calculated from $J^*(x,t)$ which is equivalent to replanning at every step. The systems is simulated using the true flow $v(x,t)$ which differs from the forecast by the forecast error $\delta(x,t)$.

From a control perspective, there are three core challenges with navigating by hitchhiking these flows. First, the dynamics of the wind and ocean flows are non-linear and time-varying. Second, in realistic scenarios only coarse forecasts of the flows are available and these differ from the true currents [9]–[12]. Third, because agents are underactuated they cannot easily compensate for these forecast errors with classical methods such as robust control. There is a rich literature on planning time- and energy-optimal paths in flows both in the oceans [13]–[32] and the air [33]–[36]. For planning in known flows researchers have proposed level-set methods for Hamilton-Jacobi (HJ) reachability [13]–[15], non-linear programming [16], [17], evolutionary algorithms [18], and graph-based techniques such as A* [19], [20], [35], RRT [21], [34], and time-varying Dijkstra [22]. Non-linear programming, evolutionary algorithms, and graph-based methods suffer from discretization error and the non-convexity of the problem which can cause solvers to get stuck in local minima and infeasible solutions. In contrast, the level-set method for HJ reachability is guaranteed to obtain time-optimal paths when the flows are known, as it solves...