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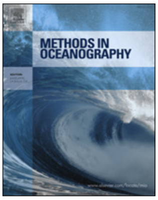

Full length article

Oceanographic pursuit: Networked control of multiple vehicles tracking dynamic ocean features

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ABSTRACT

We present an integrated framework for joint estimation and pursuit of dynamic features in the ocean, over large spatial scales and with multiple collaborating vehicles relying on limited communications. Our approach uses ocean model predictions to design closed-loop networked control at short time scales, and the primary innovation is to represent model uncertainty via a projection of ensemble forecasts into local linearized vehicle coordinates. Based on this projection, we identify a stochastic linear time-invariant model for estimation and control design. The methodology accurately decomposes spatial and temporal variations, exploits coupling between sites along the feature, and allows for advanced methods in communication-constrained control. Simulations with three example datasets successfully demonstrate the proof-of-concept.

1. Introduction

The behavior of ocean fronts and similar structures such as plumes and filaments has long been of interest to oceanographers (Gangopadhyay and Robinson, 2002; Ferrari, 2011). Recent measurements in a front off Japan have revealed sub-mesoscale structure that figures unexpectedly large in the

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energy balance (D'Asaro et al., 2011). Fronts and plumes are implicated in foundational work on Lagrangian coherent structures (Olascoaga and Haller, 2012), and can show dramatic physical, chemical, and biological variability that is critical to understanding ocean–atmospheric coupling, ecological systems, and pollution (Camilli et al., 2010; Farrell et al., 2005).

Despite continual advances in modeling of complex natural processes, ocean features at the mesoscale and smaller remain challenging (Canuto and Dubovikov, 2005; Hanna and Yang, 2001), and hence have emerged as a primary focus area for mobile sensing systems. Here, progress has been rapid, e.g. Fiorelli et al. (2006) and Wang et al. (2009). Zhang et al. (2012b,a) carried out at-sea experiments where measurements both drove trajectory decisions and triggered collection of large samples. A single vehicle has successfully tracked a plankton bloom (Godin et al., 2011), while a coordinated approach for a similar problem using a drifter and vehicle has been studied in Das et al. (2012) and Graham et al. (2013). A collaborative control technique for tracking Lagrangian coherent structures is presented in Michini et al. (2014), and a distributed approach for plume and thermocline tracking is considered in Petillo et al. (2012). Supporting all these developments, basic water properties are routinely measured today from mobile robots, while sophisticated chemical and biological analyses *in situ* are becoming mature technologies, for example DNA probes (Scholin et al., 2006) and mass spectrometers (Camilli et al., 2010). In turn, ocean modeling is becoming integrated with real-time sampling systems, e.g., Willcox et al. (2001), Haley et al. (2009) and Smith et al. (2010), and is increasingly taking on multi-disciplinary aspects (Stow et al., 2009). Non-cooperative path-planning based on current forecasts has been studied extensively, for example by Smith et al. (2010) and Lolla et al. (2012). Ocean model uncertainty predictions and communication constraints, however, have not been a central focus in these works.

Already exploited regularly in the terrestrial and air domains, networks of mobile agents are an attractive means for tracking and pursuit of dynamic processes over mixed spatial scales (Dunbabin and Marques, 2012), although wireless communication inevitably brings fundamental challenges in control (Baillieul and Antsaklis, 2007). Underwater, wireless communication over distances beyond about one hundred meters is made almost exclusively via acoustics, which suffer packet losses caused by ambient noise, multipath, and other environmental conditions (Heidemann et al., 2012). This packet loss, combined with low data rates and long delays, has limited the use of acoustic communications in high-performance, real-time tasks. Our own experience with acoustic modems (Reed et al., 2013) strongly suggests that control system design should encompass communication limits from the beginning. To this end, there has been considerable recent work in the field of control under communication constraints. Constructive results exist for lossy estimation (Sinopoli et al., 2004; Gupta et al., 2007), lossy commands (Quevedo et al., 2011) and H_∞ sampled-data control (Lall and Dullerud, 2001). We extended the work of Imer et al. (2006) to the case of independent multi-channel packet losses (Reed and Hover, 2013); Imer's dynamic programming approach results in a highly tractable recursion. These principled methods for networked control design, however, usually require linear time-invariant (LTI) system representations.

In this paper, we combine the themes above to focus on tracking and pursuit of dynamic ocean fronts by multiple unmanned vehicles, posing the problem in such a way as to accommodate the most promising developments in communication-constrained feedback control. As diagrammed in Fig. 1, our approach fits as an intermediary between high-bandwidth vehicle flight control (at the seconds time scale) and lower-frequency procedures in numerical ocean modeling, assimilation, and adaptive sampling. Notably, we are using linearization for a completely different purpose here than the norm in physical oceanography, where it has helped characterize instability and maximum sensitivity directions through adjoint models (Moore et al., 2004). As described in full below, our approach explicitly leverages *ocean forecast ensembles, a projection onto vehicle coordinates, and stochastic system identification*, yielding a dynamics description that is directly suitable for control system design. These elements enable a *reactive control methodology for dynamically sampling the ocean*, that may surpass approaches used today. Looking forward, we hope that our framework may provide a basis for tradeoff studies in designing complex deployments.

We describe the overall technical framework in Section 2, with some additional background comments on forecasting and linearization. Projection is detailed in Section 3, and the integration of projection, system identification, estimation and control in Section 4. Projection and identification

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