Decentralized Navigation for Multiple Underwater Vehicles using Acoustic Communication

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I. Introduction

This poster reports the theory and current implementation of a decentralized navigation system that enables simultaneous single-beacon navigation of multiple underwater vehicles.We summarize the architecture and design of the acoustic communications (Acomms) system consisting of an underwater acoustic modem, synchronous clock, and the software necessary to run them; the salient results from the validation of the decentralized information filter using a simulated data set; and on-going research to incorporate inter-vehicle range measurements in the decentralized solution without creating overconfident navigation solutions.

II. One-Way Travel-Time Navigation

The goal of this work is to enable high-precision absolute navigation of multiple underwater vehicles over length scales of $\mathcal{O}$(1-100km). Using underwater modems to combine acoustic communication and navigation, the vehicles employ one-way-travel-time (OWTT) navigation to estimate their own position using ranges from a single georeferenced beacon [1], [4], [5]. The ranges are measured from the one-way travel-time of acoustic broadcasts from the reference beacon and require no centralized processing. The acoustic messages are broadcast from a single reference beacon that has knowledge of its position in the world frame, e.g. a vehicle or ship that is equipped with a GPS receiver. The acoustic broadcasts encode both information about the position of the sender and the time at which the message was transmitted. Each receiving vehicle can then measure the time-of-flight of the acoustic signal using the time-of-launch encoded in the broadcast and the time-of-arrival measured by its own clock. Note that the reference beacon does not need to be stationary as information about the current location of the beacon is included in each broadcast. Between range measurements the vehicle performs dead-reckoning navigation.

III. Acoustic Communications System

The Acoustic Communications (Acomms) system is a platform-independent system for combined communication and navigation of multiple underwater vehicles that integrates Woods Hole Oceanographic Institution (WHOI) Micro-Modems [2], a stand-alone software interface [3], and subsea precision clocks [1].

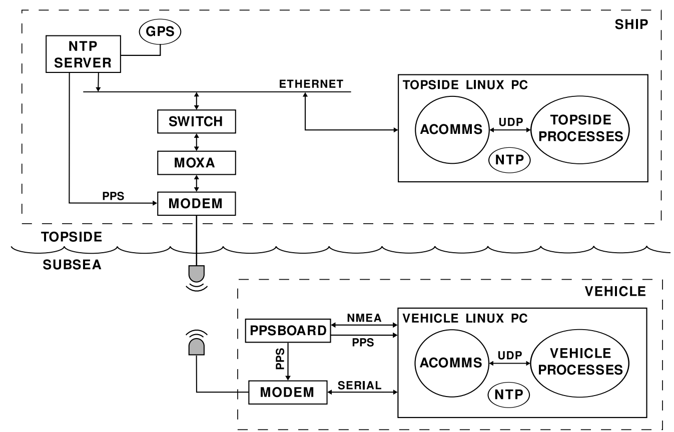

Fig. 1. Typical sea-going architecture for a two-node deployment of the Acomms system.

The Acomms system enables both asynchronous communication between multiple underwater and surface vehicles and, when used in conjunction with precision clocks, synchronous communication and navigation. The Acomms software, designed to operate symmetrically on all nodes, initializes the modem and issues a sequence of modem commands, defined by the user, to initiate data transmissions between nodes, transmit ranging pings, and interrogate acoustic navigation beacons. In addition, the Acomms software enables the user to specify modem configurations and ensures that the modem stays properly configured in the event of a vehicle or modem reboot.

IV. Decentralized Extended Information Filter

Decentralized estimation in the context of underwater communication and navigation faces unique constraints in terms of low bandwidth and high latency, which renders many of the decentralized estimation solutions from land-based applications unsuitable. The decentralized extended information filter (DEIF) is designed for one-way-travel-time navigation and recreates the results of a centralized extended Kalman filter (CEKF) that has real-time access to measurements from both the vehicle and the beacon's navigation sensors.

The implementation of the DEIF relies on two separate filters, both of which process sensor data causally and asynchronously. The information filter on the ship has access to ship sensor data but not range measurements (we will use the term ship to refer to the reference beacon for the remainder of this derivation). The ship-based filter is used to calculate the change in the ship's information vector and information matrix between acoustic broadcasts, and this delta information is acoustically transmitted to the vehicle. The DEIF on the vehicle is designed to run locally on a submerged vehicle with real-time access to the vehicle's navigation sensors and infrequent, asynchronous access to acoustic broadcasts from a moving reference beacon. The DEIF does *not* have access to real-time global positioning system (GPS) measurements from the reference beacon or any other information except information that is received acoustically. Figure 2 shows a schematic of the delta ship information transmitted from the ship to the vehicle, where TOL refers to the time-of-launch of an acoustic data packet, and TOA refers to the time-of-arrival.

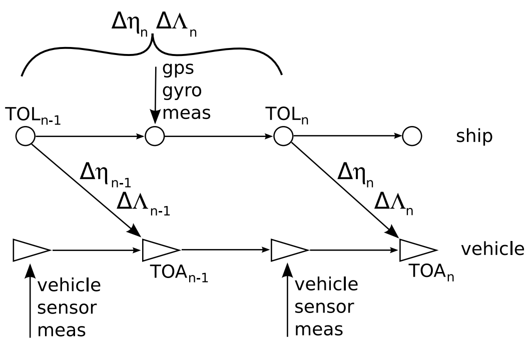

Fig. 2. A schematic of the information contained in the range packet acoustically transmitted from the ship to the vehicle.

V. Simulation Results

The DEIF is tested using a simulated 6 hours survey at 3800m depth. For comparison purposes this simulation is designed to mimic the experimental setup of the deep water survey [4]. In the simulated mission presented here, the vehicle drives ten 700 m tracklines spaced 80 m apart at a velocity of 0.35 m/s. During the 6 hours is takes the vehicle to complete the survey, the ship drives around the vehicle's survey area in a diamond pattern at 0.5 m/s, broadcasting acoustic data packets every 2.5 minutes. To test the validity of the filter, we compare the DEIF estimation results to those obtained with a CEKF, reported in [4] with experimental validation, at every time step.

Comparing the mean of the vehicle's 12 degree-of-freedom (DOF) state vector as estimated by the DEIF versus the CEKF, Figure 3 shows the norm of the difference over the course of the simulation. The lower plot highlights the norm of the difference immediately after a range measurement, as marked by the asterisks. Note that the y-axis on the lower plot has been scaled down by two orders of magnitude to show the precision with which the DEIF is able to reproduce the results of the CEKF. The average difference between the filters across the entire dive is 5.68e-3 (5.7 mm) in x-y position and 3.35e-8 in the other state elements. The average difference immediately after a range measurement is 8.27e-5 m in x-y position and

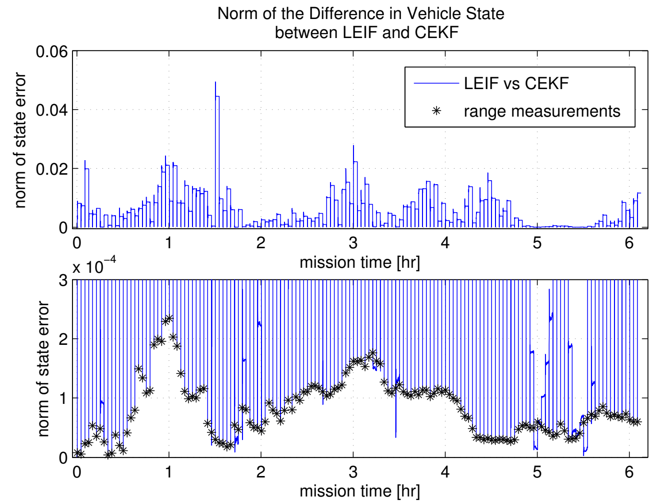

Fig. 3. The sum of the squared error between the mean vehicle position as estimated by the DEIF versus the CEKF. Note that the y-axis on the lower plot has been scaled down by two orders of magnitude.

1.70e-10 in the other vehicle states. These results support the prediction based on the theory that the DEIF produces state estimates that are comparable to the CEKF: *immediately after* each range update the results should be identical within the tolerance of numerical precision; *between* range updates, the results should differ only due to linearization errors.

VI. Extension to Inter-Vehicle Ranges

In the future, the natural expansion of this algorithm is to incorporate acoustic broadcasts from *other vehicles* in addition to broadcasts from the reference beacon. The addition of vehicle-based acoustic broadcasts would generate inter-vehicle range information that could be used to further constrain each receiving vehicle's navigation solution. Incorporating inter-vehicle ranges presents a number of challenges for continued research, including the nonlinearity of the process models of the vehicles initiating the acoustic broadcast, and the problem of over confidence associated with double counting information passed between the vehicles.

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