FINAL REPORT
Maneuvering Performance of Autonomous Underwater Vehicles

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LONG-TERM GOALS AND OBJECTIVES

The long-term goal is to develop strategies and tools for effective maneuvering and flight control of autonomous underwater vehicles. Vehicles capable of advanced maneuvering performance would be appropriate for aggressive maneuvers, such as tight cornering at high speed, high-precision tasks, such as synthetic aperture sonar imaging, and operations off the typical design condition, such as very low or very high speed, high angles of attack, or in turbulent conditions. The hovering condition is also of high practical significance, since vehicles capable of hovering are increasingly attractive for detailed inspection tasks.

The scientific objectives are to understand the dynamic behavior of autonomous underwater vehicles, and to develop robust control systems for them that meet mission-specific levels of performance.

APPROACH

We focus on the family of Bluefin survey vehicles and on the ONR Hovering AUV (HAUV) for ship hull inspection. A number of the survey vehicles are in use today throughout the underwater community, e.g., the Bluefin21, and several others are in development. The HAUV has performed surveys under ship hulls and is in prototype stage today.

Our overall strategy is to first study the dynamic response of the vehicles so as to construct and validate low-order models. From these models, we develop first linear controllers for operation reasonably near the design point; these are the PID-type controllers in most common use today. We bring the algorithms into field operation as soon as is feasible. In the survey vehicles, we developed low-order models and an adaptive control scheme, so as to adjust gains automatically, given different geometry,

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trim, or speed conditions; this was delivered to Bluefin in FY2004. In the hovering vehicle, we partition the control into low-level and mid-level algorithms, using respectively the inertial measurement unit (IMU) and depth, and the navigation package, currently an RDI Doppler velocity logger. This separation of control into several levels allows us to handle the sporadic and non-stationary data from the DVL, with minimal impact on the flight stability. Gains for all controllers are deduced from simple vehicle models, and then tuned if necessary in the field.

The vehicles work is supported by extensive testing, especially for the hovering vehicle.

We have also performed theoretical and numerical work in broader control system design, using linearization and tools from stochastic simulation, wherein the benefits of a Monte-Carlo technique are captured with significantly less computational effort, hence enabling completely new ways of looking at control design.

WORK COMPLETED

Streamlined Vehicles
1) We performed a detailed dynamic analysis of the Bluefin vehicle *Caribou*, operated by MIT Sea Grant's Autonomous Underwater Vehicles Laboratory. This included quantifying latencies of the operating system and software, characterizing noise on various sensor channels, and documenting the dynamic response of the tail-cone, which actuates the rudder and elevator of the vehicle. The tail-cone proved to be the dominant dynamic element in the vehicle system.
2) We developed a complete hydrodynamic model of *Caribou* based on available data for streamlined AUV's, and then performed at-sea confirmation and tuning of the vehicle dynamic model, taking into account the characteristics of the tail-cone. We conducted a single cycle of model-based control tuning, and documented the improvements.
3) The tool for tuning of the Bluefin survey vehicles has been verified in a total of four vehicles. This tool has been provided directly to Bluefin for use in the field.
4) An adaptive PID routine has been fully implemented in real-time code and delivered to Bluefin. The gains are developed to satisfy maximum sensitivity conditions at a selected bandwidth, based on Yaniv & Nagurka (2004) extended to discrete-time systems. For parameter estimation, we employ the essential recursive least-squares method (e.g., Ljung, 1987), with the stabilized Kalman equation for long-term numerical stability.
5) A small number of tests were performed with Bluefin survey vehicles, to understand wave-induced motions at shallow depth, and to study response of the vehicles to random rudder input, for the purpose of gain adaptation.

Hovering Vehicle
6) A basic simulation capability for the hovering vehicle was developed and integrated into Bluefin's Huxley operating system.

7) Real-time estimation and control code was written and implemented so as to achieve the core vehicle stability at high bandwidth. We employ a high-rate Kalman filter to incorporate measurements from the inertial measurement unit and the depth sensor, and to close PID loops on depth, pitch, roll, and several linear accelerations.
8) A multivariable approach to relative navigation, for the HAUV using a Doppler velocimetry logger, was developed and implemented.
9) The HAUV has been successfully demonstrated to ONR and EOD representatives. We achieved controlled surveys on walls from ten to ninety degrees inclination, and demonstrated 100% coverage with the DIDSON imaging sonar. Five vessels have been surveyed, including a large cruiser, a barge, two small oceanographic vessels (one with a flat bottom), and a small submarine.

General
10) A method for controller design under saturating control channels was identified and studied in simulation (Huang and Lam, 2002).
11) A sequential linearization scheme was developed for vehicles having rotating thrusters, i.e., thrusters that rotate about an axis normal to the spin axis. This has been studied in simulation, and applies to underwater vehicles as well as surface vessels, e.g., performing dynamic positioning with podded propulsors.
12) We developed three new capabilities with stochastic simulation relating to general control problems. These are relevant to vehicle maneuvering when nonlinear effects play a significant role.

MAJOR RESULTS

1) The Matlab-based code for tuning of PID controllers for Bluefin's streamlined vehicles was tested on four 21" vehicles, generally achieving heading performance of 0.5 degrees and 5 cm depth. Figure 1 shows representative data (*Unicorn; MIT Ocean Engineering*).
2) The pitch/depth plane dynamic response in the Bluefin 21" vehicles has a slow, lightly-damped mode, whereas the yaw modes are exponential. In verifying the models, we relied mainly on step responses, which revealed two major areas of uncertainty in coefficient-based modeling. The first of these pertains to the cross-coupling terms – for example, the sway force induced by yaw rate and the yaw moment induced by sway velocity (sideslip) – which are notoriously hard to predict since they depend strongly on geometric balance and separated flow conditions. The cross terms in our preliminary model were modified by about thirty percent, based on our at-sea data. The second point of uncertainty is the total gain of the rudder and elevator. The vehicles carry a unique thrust-vectored nozzle, such that the moments and forces generated are a combination of lift on the duct, and the various components of thrust. There is very little information available in the open literature about nozzles, and as a result, we were in error about fifteen percent on these model terms.

3) The wave and random-rudder data from the survey vehicle tests were inconclusive. We learned that the vehicle operating at 2m depth in a following sea of approx. 0.7m wave height, has pitch and depth variations greater than three times the levels seen at other bearings. This finding illustrates the sensitivity of the current closed-loop system to periodic disturbances; once the phenomenon is better understood for a range of operating conditions, it can be attenuated through a careful controller design.

4) The hovering vehicle has been successful in four major demonstrations through April 2006. We confirmed that the DVL is a suitable sensor for these inspections relative to the hull, with update rates as high as 10Hz that allow us to control the vehicle very well. Through the use of several new control schemes, we established a fundamental capability of transitioning smoothly from a near-vertical wall to a near-horizontal one, with no loss of vehicle control or orientation to the surface (see Figure 2). We have also performed surveys under flat bottoms, and have made quantitative maps of features and targets, based on sonar imagery data. In a flat-bottom mission length of about ten minutes, the drift due to the DVL is on the order of one meter.

5) The process of sequential linearization takes the two degrees of freedom in an azimuthing thruster (the thrust level and the azimuth angle) and reduces it to one, by assigning to the azimuth angle a specified, cyclic trajectory. This step allows a fully linearized but time-varying description of the system. Once in this form, the system is amenable to the very powerful techniques of linear multivariable control design, which carry specific robustness and performance guarantees; nonlinear controllers that are in common use carry few, if any, *a priori* assurances of robustness or performance.

6) We showed that the stability of a given dynamical system (with some restrictions) can be assessed practically through the evolution of probabilistic modes, specifically using the Hermite Polynomial Chaos. This is an important result for nonlinear systems, where traditional stability checks can fail, leaving only Monte Carlo simulation. We are able to consider random parameter variations and random initial conditions. As a variation on this approach, we found that the actual control gains for a feedback system can be parameterized in random variables; the polynomial chaos then allows one to efficiently search the space of gains for an optimal one, without resorting to repeated simulations. Finally, we discovered that path optimization problems can also be solved with the polynomial chaos, allowing one to generate a complete family of optimal paths parameterized with random variables; these can represent variations in the plant model or in the cost function.

IMPACT/APPLICATIONS AND TRANSITIONS

We have assisted Bluefin to meet flight performance specifications in their survey vehicles. Level flight with varying vehicle geometry is required for virtually all applications, especially synthetic aperture sonar. Algorithms were provided to assist manual gain selection and to perform automatic identification and controller design.

Following demonstrations of the hovering vehicle, ONR is now supporting work in map-based navigation, and the creation of a second prototype vehicle. Bluefin is in a strong position to design and build the first production versions (BAA expected later in 2006).

The azimuthing thruster control approach may find application in hovering underwater vehicles and station-keeping surface vessels. The polynomial chaos approach in control problems appears to be completely new. It is especially well-suited to systems with polynomial nonlinearities, which are common in both the inertial and hydrodynamic or aerodynamic terms of vehicle models.

RELATED PROJECTS

Hovering vehicle work was conducted in conjunction with the ONR/EOD project "Small Autonomous Vehicle for Precision Maneuvering in Survey and R-I-N Missions," N00014-02-1-0946 (T.F. Swean and R. Simmons). Control work has been also supported by the Office of Naval Research's Electric Ship Research and Development Consortium (K. Drew). Under NOAA support, through the MIT Sea Grant program, the PI is leading the development of a new deepwater, hybrid AUV having azimuthing thrusters. The PI has developed through Sea Grant and DARPA support, with M. Triantafyllou of MIT, a biomimetic vehicle having four flapping foils for enhanced propulsion and maneuvering in energetic waters. We worked also on the application of artificial muscles to variable pitch propellers and control surfaces of AUV's, through an ONR STTR with Molecular Mechanisms, LLC.

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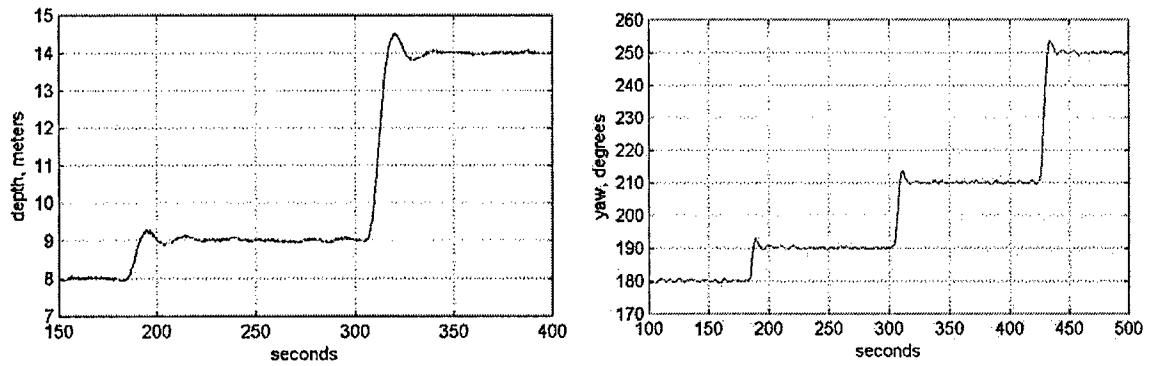
Figure 1: Typical performance in depth (top) and heading (bottom) for the Bluefin21 vehicle Unicorn, with a nose-mounted SAS array. Depth performance is plus or minus four centimeters, and heading is plus or minus one-half degree.
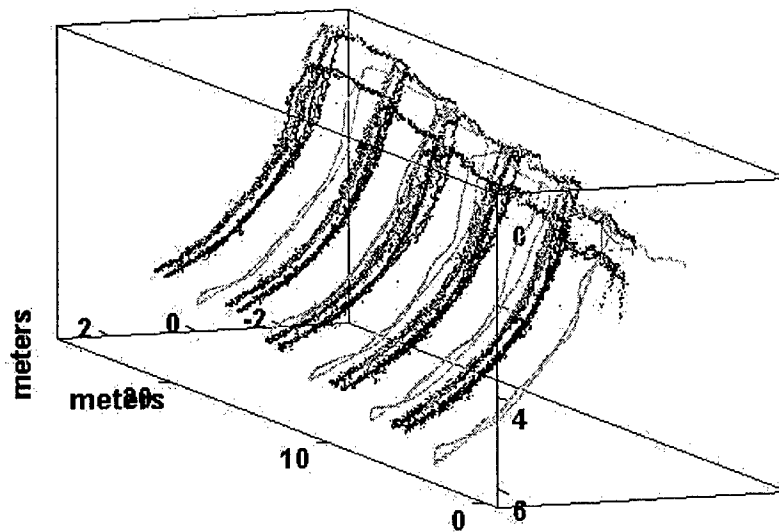

Figure 2: Hull shape reconstruction as inferred from HAUV trajectory. This run has five vertical slices down to an inclination angle of sixty degrees, separated by short horizontal slices. The blue lines indicate vehicle position, whereas the colored dots show the hull position.

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14. ABSTRACT

High-fidelity linear pitch and yaw dynamic models were developed for a class of autonomous underwater vehicles manufactured by Bluefin Robotics Corporation, based on analysis and field data. Classical control design was then carried out and successfully tested. An algorithm for automatic identification of these models, followed by automatic specification of gains, was developed and delivered to Bluefin. We also created modeling and control schemes for the ONR hovering autonomous underwater vehicle (HAUV), that was developed jointly by MIT and Bluefin; this vehicle has now successfully performed hull surveys on five vessels. Finally, we have applied stochastic simulation techniques to general control problems (which include vehicle maneuvering), illustrating new methods for assessing basic stability and for performing control gain selection in nonlinear systems.

15. SUBJECT TERMS

autonomous underwater vehicle, system identification, control system design

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