Modeling and Control of an Autonomous Underwater Vehicle with Combined Foil/Thruster Actuators

by

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Abstract

The Sentry AUV represents a radical departure from conventional AUV design, particularly with respect to actuation. The vehicle's combined foil/thruster actuators have the potential to produce a vehicle both maneuverable in the veritcal plane and efficient in forward flight, well suited to survey work over rough topography. Capitalizing on this; however, requires an understanding of the vehicles dynamics.

In this work, we present the development and analysis of an analytic model of the Sentry AUV. Our goals were to develop a model sufficiently accurate in terms of the mission profile to identify critical vehicle behaviors influencing successful mission completion. The analytical vehicle model was developed with structural accuracy in mind, and under the requirement that it handle a large range of vertical plane velocities.

Our primary methodology for analysis was through the design of a linear controller, whose behavior was investigated in simulation and as implemented on a $\frac{1}{4}$-scale physical model. Based on decoupled linearized models for near-horizontal flight derived from the full non-linear model, classical linear controllers were designed and validated by simulation and implementation on the physical model. Closed loop simulations conducted at high angle of attack verified the vehicle's predicted maneuverability in the vertical plane. Ultimately we determined the vehicle's input structure limited the achievable performance of a classical linear controller.

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To my parents to whom I owe everything, thank you, yet again. And finally, thank Rachel for your unfailing confidence in me.

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Chapter 1

Introduction

Over the last half decade, interest in autonomous underwater vehicles (AUVs) as tools for oceanographic science has grown. The Woods Hole Oceanographic's (WHOI) Autonomous Benthic Explorer (ABE) has been used with success to survey and collect data from deep ocean rift and hydrothermal vent sites. The data provided by an AUV for geological work represents a cost effective use of ship time. The data resolution is unmatched because of the vehicle's proximity to the seafloor, and the surface ship is free to perform other work while the AUV completes its survey. Ultimately, AUVs like ABE may be left entirely unattended awaiting ocean events or conducting repeated surveys.

ABE was originally designed to remain on the ocean floor for extended periods of time, periodically leaving a fixed mooring to collect data over the same region of the ocean. To date, ABE has not been used in that capacity, and has instead been deployed in conjunction with remotely operated vehicles and manned submersibles, generally surveying an area to locate features of interest before these other vehicles.

The time saved using ABE-generated maps to navigate along the seafloor results in a much more productive use of remotely operated and manned assets. In response to the pervasive use of ABE as a complementary vehicle, a new AUV, Sentry, has been designed at WHOI, and is slated for sea trials in Spring 2003.

Sentry is radically different from all currently operational AUVs. It has been designed to incorporate the features of ABE that have made it well suited to scientific work, but its design is tailored to the particular mission that it will carry out [26]. Like ABE, Sentry will be highly maneuverable; capable of purely vertical motion and hover, and more hydrodynamically efficient than ABE. A larger battery capacity will allow longer mission times. Finally, experience with the ABE vehicle and particular attention to maintenance and operational considerations in the design ensures a quick deck turnaround to support daily operations.

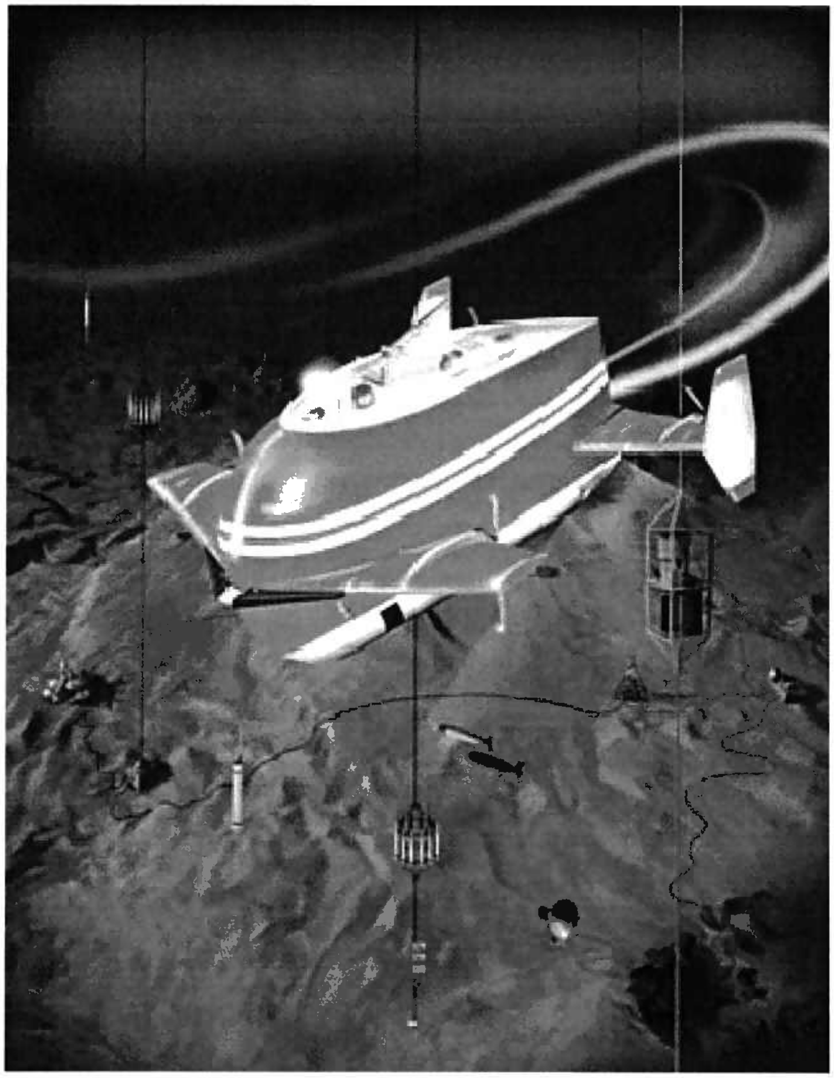

Figure 1-1: An artist's rendering of the Sentry vehicle. Both the fore and aft set of foils (and attached thrusters) are capable of swivelling 270°. Sentry will be both maneuverable and efficient in the vertical plane.

The proposed design shown in Figure 1-1 represents a departure from other AUV designs in three significant ways:

1. Unlike more standard AUV designs actuated by a single main propeller and aft control foils, Sentry will be maneuverable even at zero forward speed.

2. Sentry's swivelling thruster/foil actuators allow vehicle control uncompromised by thruster performance degradation in crossflows [22].

3. Sentry's aerodynamically shaped monolithic hull will provide the same degree of static stability in pitch and roll as possessed by the ABE vehicle, but at lower drag.

These design features represent hold considerable promise, but their realization will require a careful study of the proposed vehicle's dynamics and a control system design motivated by an understanding of the opportunities and constraints imposed by the vehicle dynamics. This analysis is the subject of this work.

The first part of this work (Chapters 3 & 4), is devoted to the development of a six–degree of freedom vehicle dynamics model. The model developed herein is based on theoretical and existing empirical hydrodynamics work. It is expected that parameters within the model will require tuning once the full scale vehicle is operational in Spring 2003; our focus herein is on model structure. A sufficiently accurate model structure and understanding of the resultant dynamics through analysis and simulation enables intelligent model-based control design, and ensures that once the full-scale vehicle becomes available, its dynamic behavior will be understood.

In the second part (Chapters 5 & 6), we present an analysis of near equilibrium flight conditions for nominally horizontal flight and a linear control design based upon this simplified model. Simulation results are presented using the full non-linear six–degree of freedom model. Results are also given from the implementation of this control design on a $\frac{1}{4}$-scale physical model. We close by considering the limitations of linear control design in fully exploiting the capabilities of the Sentry vehicle and suggest directions for further work.