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

by
Michael V. Jakuba

Submitted to the Joint Program in Applied Ocean Science and Engineering

in partial fulfillment of the requirements for the degree of
Master of Science in Mechanical Engineering

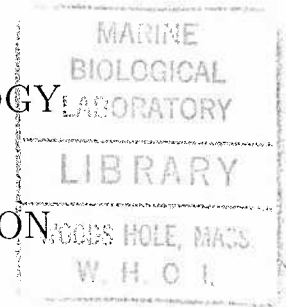
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water

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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 vertical 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.

Thesis Supervisor: Dana R. Yoerger
Title: Associate Scientist, WHOI

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Contents

1	Introduction	15
2	The Sentry Autonomous Underwater Vehicle	19
2.1	Vehicle Geometry	19
2.2	Vehicle Mass Properties	21
2.3	Mission Profile	23
3	Equations of Motion	25
3.1	Coordinate Frames	25
3.2	Kinematics	25
3.3	Rigid Body Dynamics	28
3.4	Complete Equations of Motion	30
4	Hydrodynamics	33
4.1	Added Mass	34
4.1.1	Body Added Mass	35
4.1.2	Foil Added Mass	37
4.1.3	Combined Added Mass	38
4.2	Strip-Theory Lift and Drag	40
4.2.1	Basic Results from Dimensional Analysis	41
4.2.2	Lift and Drag Coefficient Approximation	42
4.2.3	Differential Lift and Drag of an Aerodynamic Section	45
4.3	Quadratic Hydrodynamic Moments	48
4.3.1	Center of Pressure Locations	49
4.3.2	Differential Moment of an Aerodynamic Section	49
4.3.3	Combined Lift and Drag	50
4.3.4	Expanded Expressions for Quadratic Lift and Drag	51
4.4	Longitudinal Hull Lift Coefficients	53

4.4.1	Linear Damping	56
4.5	Hydrostatic Forces	57
4.6	Thruster and Control Foil Interaction	58
5	Simplified Models	63
5.1	General Linearization Procedure	63
5.2	Near Horizontal Flight	65
5.2.1	Decoupled Models	68
5.3	Nonlinearity Considerations	72
5.3.1	Flow Separation: Foil Stall	72
5.3.2	Input Mapping Nonlinearity	72
6	Controller Design	75
6.1	Control Objective	76
6.2	Decoupled Control Design	76
6.2.1	Speed Control	77
6.2.2	Pitch-Depth Control	77
6.2.3	Heading Control	86
6.3	Controller Evaluation: Simulation and Experimental Results	88
6.3.1	Controller Performance at Nominal Operating Conditions	88
6.3.2	Speed Dependence	92
6.3.3	Controller Performance at High Angles of Attack	94
6.4	Non-Linear Approaches	97
7	Conclusions	101
7.1	Further Work	102
7.1.1	Model Verification	102
7.1.2	Control Design	103
A	Expressions for Arbitrary Control Foil Angles	105
A.1	Rigid Body Inertia	105
A.2	Combined Added Mass	106
A.3	Gravitational Restoring Moment	107
B	Physical Model	109
B.1	Similitude	109
B.2	Design	110

List of Figures

1-1	The Sentry vehicle	16
2-1	Sentry: top view.	20
2-2	Sentry: side view.	20
2-3	Multibeam Sonar Bathymetry Collected by ABE	24
3-1	Sentry AUV Body-Fixed, Aft Foil, and Inertial Coordinate Frames	26
4-1	Aerodynamic Section Definition	45
4-2	Classical Actuator Disk Analysis of a Propeller	59
4-3	Thruster and Control Foil Interaction	60
4-4	Lift Gain vs. Thrust	62
6-1	Pitch-depth Eigenvalues vs. Nominal Forward Speed	78
6-2	Vehicle Response (Linear Model) vs. Control Foil Angle Ratio	81
6-3	Zeros of the Depth Transfer Function (Linear Model) vs. Control Foil Angle Ratio	82
6-4	Zero of the Pitch Transfer Function (Linear Model) vs. Control Foil Angle Ratio	83
6-5	Vehicle Response to a Ramp-Smoothed Transition in Desired Depths.	89
6-6	Controller Performance: Physical Model	91
6-7	Closed Loop Vehicle Response to Step Change in Desired Depth	93
6-8	Simulated Vehicle Response with Pitch Disturbance.	95
6-9	Simulated Vehicle Response with Yaw Disturbance.	96
6-10	A Foils-Fixed Configuration Suitable for Low Speed Maneuvering.	98
B-1	$\frac{1}{4}$ -Scale Physical Model of Sentry	110
B-2	Physical Model: Midplane	111
B-3	Physical Model: Electronics Housing	112
B-4	Physical Model: Interface	113

List of Tables

2.1	Sentry Hull Geometric Parameters	21
2.2	Sentry Foil Geometric Parameters	21
2.3	Sentry Hull/Roots Mass Properties	22
2.4	Sentry Foil Mass Properties	22
2.5	Combined Mass Properties (Foils Flat)	22
4.1	Body Added Mass Coefficients	37
4.2	Foil Added Mass Coefficients	38
4.3	Combined Added Mass Coefficients ($\phi_f = 0$)	40
4.4	Geometry Relevant to Strip-Theory	41
4.5	2D Section Lift and Drag Leading Coefficients	42
4.6	Section CP Location (% Chord)	49
4.7	Longitudinal Hull Lift Coefficients	56
5.1	Near Horizontal Flight: Combined and Mass Coefficients	69
5.2	Near Horizontal Flight: Foil and Thruster Coefficients	69

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.

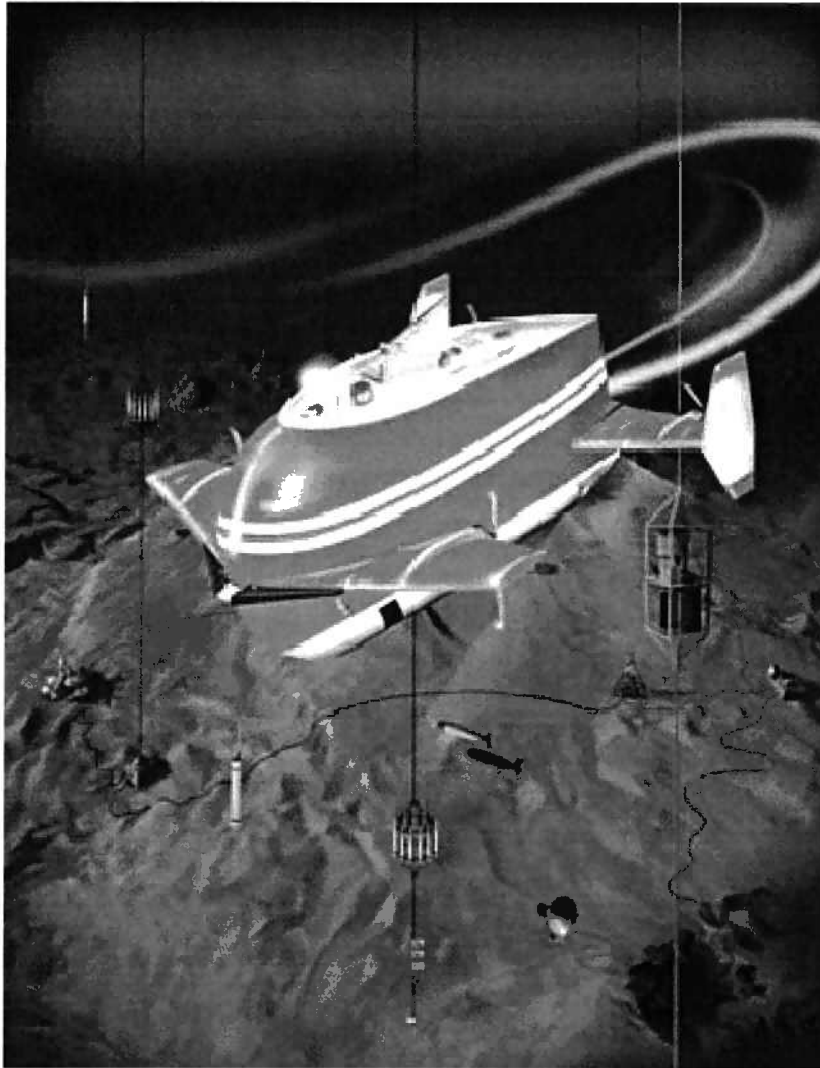


Figure 1-1: An artist's rendering of the Sentry vehicle. Both the fore and aft set of foils (and attached thrusters) are capable of swivelling 270° . Sentry will be both maneuverable and efficient in the vertical plane.

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.

