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14. ABSTRACT

Advanced Mobility is a critical research area under the Naval S&T Focus Area of Platform Design and Survivability. Enhanced mobility is a key objective in the design of new platforms, but one may also enhance mobility of existing platforms through advanced modeling and control, enabling current assets to operate within larger environmental envelopes. This final report concerns accomplishments by a Virginia Tech research team – in collaboration with the Australian Defence Science & Technology (DS&T) Group under the auspices of The Technical Cooperation Program (TTCP) – concerning submarine maneuvering in elevated sea states. In this scenario, advanced modeling and control can improve disturbance rejection and maneuvering performance, enabling new mission capabilities for operations at or near the surface.

15. SUBJECT TERMS

maneuvering, seakeeping, submarine, underwater vehicle

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					19b. TELEPHONE NUMBER *(Include area code)*
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Report Information

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Contract Information
Contract Numbers: N00014-14-1-0651
Contract Title: Motion Prediction and Control for Submarines in High Sea States
Program Officer: Deborah Nalchajian
CO-PI Information: Eric Paterson (Virginia Tech, egp@vt.edu)

Abstract

Advanced Mobility is a critical research area under the Naval S&T Focus Area of *Platform Design and Survivability*. Enhanced mobility is a key objective in the design of new platforms, but one may also enhance mobility of existing platforms through advanced modeling and control, enabling current assets to operate within larger environmental envelopes. This effort -- a collaboration with the Australian Defence Science & Technology (DS&T) Group, organized under the auspices of The Technical Cooperation Program (TTCP) – concerns submarine maneuvering in elevated sea states. In this scenario, advanced modeling and control can improve disturbance rejection and maneuvering performance, enabling new mission capabilities for operations at or near the surface.

The goal of this effort is to critically assess the effectiveness of energy-based nonlinear control approaches for motion control of a submarine in high sea states. More specifically, the team will work to develop a parametric model structure that faithfully represents the motion of a submarine maneuvering in a seaway but is amenable to nonlinear control design, to design a model-based predictive motion control law, and to assess the performance of this autopilot design by comparing its performance to conventional designs. The specific objectives of the collaboration are:

- To develop theory and methods to obtain energy-based parametric models for submarine maneuvering in high sea states for use in motion prediction and control.
- To validate the proposed models with experimental data.
- To demonstrate the use of these parametric models for motion prediction.
- To develop robust, predictive, energy-based motion control algorithms.
- To compare the performance of these nonlinear controllers with the performance of controllers developed using linear methods.

The Virginia Tech team is focusing development of a suitable parametric motion model and on the development of motion prediction strategies to support control design and implementation.

Technical Section

Following is a summary of the originally proposed research tasks and the technical approach.

Task 1: Control-Oriented Modeling

- Review of prior efforts to unify maneuvering and seakeeping models for model-based motion control of a vessel in a seaway.
- Development of a reduced order model (ROM) amenable to energy-based nonlinear control design.

Task 2: Hydrodynamic Analysis

- Development of a strip-theory model of the vessel using widely available computational tools and comparison to experimental data to identify gaps in modeling.
- RANS/URANS modeling of the vessel with validation to experimental data. Emphasis shall be placed on conditions and physics not captured by reduced order, strip-theory modeling.

Task 3: Motion Prediction

- Development of a motion prediction scheme to aid feedforward disturbance rejection.

As proposed, the effort requires the use of CFD to identify parameter values in a low-order mathematical model that can be used to predict vessel motion in waves. To enable validation, the effort focuses on a well-studied geometry: The Joubert (BB2 variant), shown below. Captive model experiments at the Australian Maritime College will be used to assess the adequacy and improve the quality of the model.

Figure 1. The Joubert (BB2 Variant), fully appended

Final Report Statement

During the project period of performance (6/1/2014 through 5/31/2018, including a one-year no-cost extension), the team:

- Developed a Lagrangian mechanics (potential flow) model for the maneuvering dynamics of a submerged rigid body operating near a free surface, including memory effects using a nonlinear extension of the Cummins equation.
- Incorporated ambient wave effects (Froude-Krylov forcing) to obtain a nonlinear maneuvering and seakeeping model. Incorporating a conventional filter to approximate memory effects, this model is a low-dimensional mechanical system model – a "control-oriented" model that is amenable to the design of nonlinear estimation and control methods based on the mechanical system structure.
- Began developing a parameter computation approach for this control-oriented motion model using a time-domain panel method. (That effort continued under follow-on support.)
- Supported efforts by Dr. F. Valentinis, with Australia's Defence Science and Technology (DST) Group to adapt the Lagrangian nonlinear maneuvering (LNM) model to the Joubert BB2 and to obtain experimental validation of the Lagrangian nonlinear maneuvering and seakeeping (LNMS) model.
- Presented the results in 5 international conference presentations, with 2 more to appear, and 1 doctoral dissertation. No journal publications appeared during the period of performance, but 1 was in review and 2 were in preparation based on T. Battista's dissertation at the end of the period.

Refereed Journal Articles

- None [Note: A paper by Valentinis and Woolsey on energy-based submarine control was in review for *Ocean Engineering* and a 2-paper series based on T. Battista's dissertation was in preparation for the *IEEE J. Oceanic Engineering* at the end of the period of performance.]

Books And Chapters

- "Model-Based Path Planning," A. Wolek and C. A. Woolsey. In *Sensing and Control for Autonomous Vehicles: Applications to Land, Water and Air Vehicles*, T. I. Fossen, K. Y. Pettersen, and H. Nijmeijer, Editors. [In press.]

Technical Reports

- *Lagrangian Mechanics Modeling of Free Surface-Affected Marine Craft*, T. Battista, Doctoral Dissertation, Virginia Tech, March 2018.

Contributed Presentations

- "An immersed spheroidal pendulum oscillating near a free surface," B. Andersen*, C. Beardsley*, M. Gates*, J. Schlafman*, T. Battista*, S. Jung*, and C. A. Woolsey, *Proc. MTS/IEEE OCEANS*, Charleston, SC, October 2018. (To appear.)
- "An analytical approximation of a force prediction model for a prolate spheroid moving at a constant forward speed parallel to a calm free surface," S. Jung*, T. Battista*, F. Valentinis, S. Brizzolara, E. Paterson, and C. Woolsey, *Proc. 13th Int. Conf. on Hydrodynamics*, Incheon, Korea, September 2018. (To appear.)
- "Effects of depth on added mass obtained from virtual PMM tests of a submerged prolate spheroid," S. Jung*, T. Battista*, E. Paterson, and C. Woolsey, *Proc. MTS/IEEE OCEANS*, September 2017, Anchorage, AK.
- "An energy-Casimir approach to underwater vehicle depth and heading regulation in short crested waves," T. Battista*, S. Jung*, C. Woolsey, and E. Paterson, *Proc. Conference on Control Technology and Applications*, Kohala Coast, HI, August 2017. (Invited, Peer-reviewed)
- "A dynamic model for underwater vehicle maneuvering near a free surface," T. Battista, C. A. Woolsey, T. Perez, and F. Valentinis, *Proc. 10th IFAC Conf. on Control Applications in Marine Systems*, Trondheim, Norway, September 2016. [Best Student Paper Award]
- "Underwater vehicle depth and attitude regulation in plane progressive waves," T. Battista*, C. A. Woolsey, L. McCue-Weil, E. Paterson, and F. Valentinis, *Proc. Conference on Decision and Control*, Kyoto, Japan, December 2015. (Peer-reviewed)
- "Control of an underwater vehicle in irregular waves," T. Battista, C. A. Woolsey, L. McCue-Weil, and E. Paterson. *Proc. MTS/IEEE OCEANS 2015*, Washington, DC, October 2015.

* denotes a graduate or undergraduate student researcher.

Patents

- None

Honors

- Best Student Paper Award: Battista*, Woolsey, McCue-Weil, Paterson, and Valentinis, *IFAC CAMS*, 2016.

Related Sponsored Work

- NSF Grant No. CMMI-1435484: Biolocomotion Analysis and Design Using Geometric Control and Averaging Methods (Woolsey, PI) focuses on the use of nonlinear control design and analysis methods for simultaneous design optimization of the morphology and gait of biomimetic systems. The dynamic model used to incorporate unsteady, nonuniform flow effects on submarine motion in waves may also be applied to biomimetic systems.
- NSF Grant No. CMMI-1635143: Collaborative Research: Unsteady Hydrodynamics and Geometric Control of Pisciform Locomotion (Woolsey, PI) builds on efforts begun under the preceding grant, but with a focus on experimental validation of low-order motion models for aquatic (e.g., pisciform) locomotion systems.

ONR Statistics

Grad Students(total):	3
PI/Co-PI Women:	1
PI/Co-PI Minority:	0
Grad Students Women:	0
Grad Students Minority:	0
Post Docs Students:	0
Post Doc Women:	0
Post Doc Minority:	0
Under Grad Students(total):	4
Under Grad Students Women:	0
Under Grad Students Minority:	0
Degrees Granted:	1
Invention disclosures citing ONR support:	0
Other funding sources:	0