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Model Based Adaptive Control of Underwater Vehicles for Improved Ocean Science

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1. Progress statement

Motivation for research

Recent advances in unmanned underwater vehicle (UUV) capabilities have enabled oceanographic scientists to consider addressing research topics previously thought impractical or impossible. One such topic is the validation of high resolution computer models; long term deployments of coordinated UUV survey teams have been proposed to collect the density of measurements required. Another topic is the study of biological diversity in volatile areas; UUV intervention/sampling deployments have been proposed because of the inherent risks.

In general, providing a high density of high accuracy measurements requires passing many targets as quickly and closely as possible. Similarly, efficacy for intervention/sampling deployments requires agile and accurate vehicle operation. Thus full utilization of UUV capabilities for ocean sensing, and therefore ocean science, requires accurate trajectory tracking. Currently UUVs use linear controllers which do not model or compensate for nonlinearities such as drag, buoyancy, inertia and hydrodynamic forces. In experimental evaluations of UUV Model Based Controllers (MBC), compensating for such nonlinearities provided significant performance gains over linear controllers [5]. Since the system identification necessary for MBC is rarely available, I feel Model Based Adaptive Controllers (MBAC) will be required to realize these performance gains because MBACs are able to learn the correct model parameters as part of the control process.

Results

MBAC are evaluated in two ways: trajectory tracking error and the capacity of the parameter estimates to model UUV performance. Trajectory tracking error is the difference between the reference trajectory provided to the controller and the actual trajectory followed by the UUV. When modeling UUVs for control and simulation, the goal is to find a set of parameters which, when multiplied by the UUV's position and velocity, accurately predict the UUV's behavior over time.

Typically four types of parameters are used to model UUV dynamics: hydrodynamic mass, drag, gravitational and buoyancy [4]. Hydrodynamic mass terms represent the inertial effects of the UUV and the surrounding water. Drag terms represent the force resisting UUV motion exerted by the surrounding water. The gravitational term summarizes the force of gravity. The buoyancy terms characterize the restoring torque occurring when the center of buoyancy is not on top of the center of gravity. An important conclusion from [5] was that parameterizations which include the coupling effects between the different degrees-of-freedom (DOF) provide good predictive capacity during simultaneous dynamic motion in all six DOF.

MBAC development

I spent the fall of 2012 developing a novel MBAC. This controller simultaneously tracks any speci_ed trajectory while continually improving its estimates of the 241 independent parameters required to model the coupling effects between all DOF. As part of the development process, we created an analytic proof of stability which mathematically guarantees asymptotic convergence to perfect trajectory tracking. This result will be reported in [2].

MBAC performance degradation due to thruster stiction

In addition to developing a UUV MBAC, I have also performed an experimental evaluation of MBAC during simultaneous dynamic motion in all DOF. This comparison of MBAC and linear PD control was performed in full scale trials using the Johns Hopkins University Hydrodynamic Test Facility (see Figure 1). Through the 8 month process of implementing and debugging the novel MBAC I discovered a previously unreported UUV MBAC failure mode caused by thruster stiction. When a thruster reverses direction, the thruster must overcome the stiction (i.e. static friction) in its bearings before beginning to turn in the opposite direction. In the pitch and roll DOF, the combined effects of the buoyancy-driven restoring torque and thruster stiction caused the mass estimation process to fail. Over a multi-hour experiment the mass estimates in these DOF would evolve to negative values. Negative mass is physically impossible and can produce unpredictable, erratic behavior. [1] will present our experimental analysis of how thruster stiction causes UUV MBAC failure.

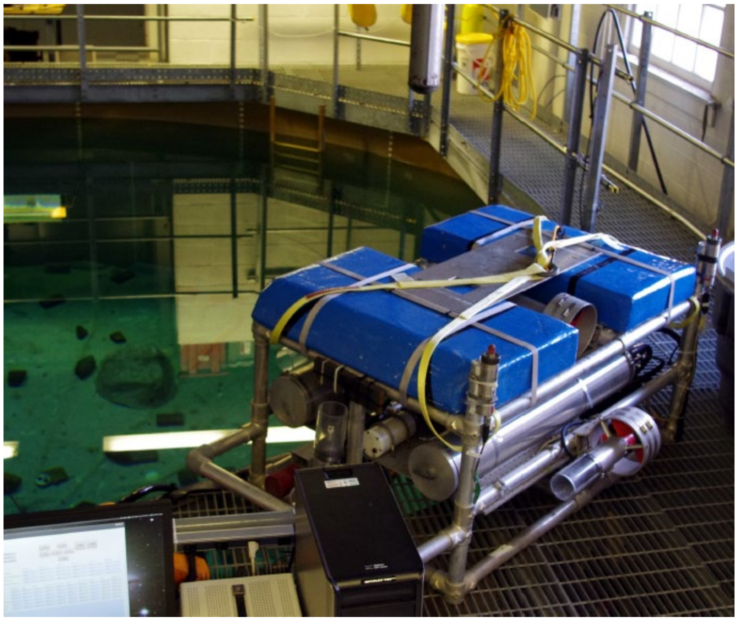

Figure 1: JHU ROV inside the Johns Hopkins Hydrodynamic Test Facility. This Facility allows full scale experimental evaluation of UUV controller performance. It includes a fully instrumented vehicle, a 50,000 gallon tank, and a full suite of state-of-the-art sensors [6].

Two-step model identification

During my experimental evaluation of MBAC failure due to thruster stiction, I discovered that MBACs which only identify mass and drag parameters do not fail due to thruster stiction. [1] will report a method where the buoyancy and gravity terms are independently identified and used in conjunction with a modified UUV MBAC algorithm. This second MBAC only estimates mass and drag parameters. An experimental evaluation of Mass-Drag-Adaptation-Only MBAC was preformed showing:

- Parameter estimates converged to physically realistic values (i.e. mass and drag terms converge to positive and negative values respectively).
- Trajectory Tracking improved as parameter adaptation progressed.
- After parameter estimate convergence, the AMTC provided 30% better position tracking over traditional linear PD control.

To simplify the comparison of Mass-Drag-Adaptation-Only MBAC to Full-Parameter MBAC, this experimental evaluation identified only the uncoupled mass and drag terms (12 parameters were identified instead of 237). Table 1 and Figure 2 summarize the Mass-Drag-Adaptation-Only MBAC experimental evaluation from [1].

Table 1: Parameters identified during an experimental evaluation of the Mass-Drag-Adaptation-Only MBAC. In this experiment, all 12 mass and drag parameter estimates were initialized to zero and converged to physically realistic values.

	$m_i(t_o)$	$m_i(t_f)$	$d_i(t_o)$	$d_i(t_f)$
Trans X DOF	0.0	628	0.0	-1259
Trans Y DOF	0.0	791	0.0	-1429
Trans Z DOF	0.0	1043	0.0	-3083
Angular X DOF	0.0	95.7	0.0	-727.1
Angular Y DOF	0.0	145.3	0.0	-783.4
Angular Z DOF	0.0	110.2	0.0	-465.6

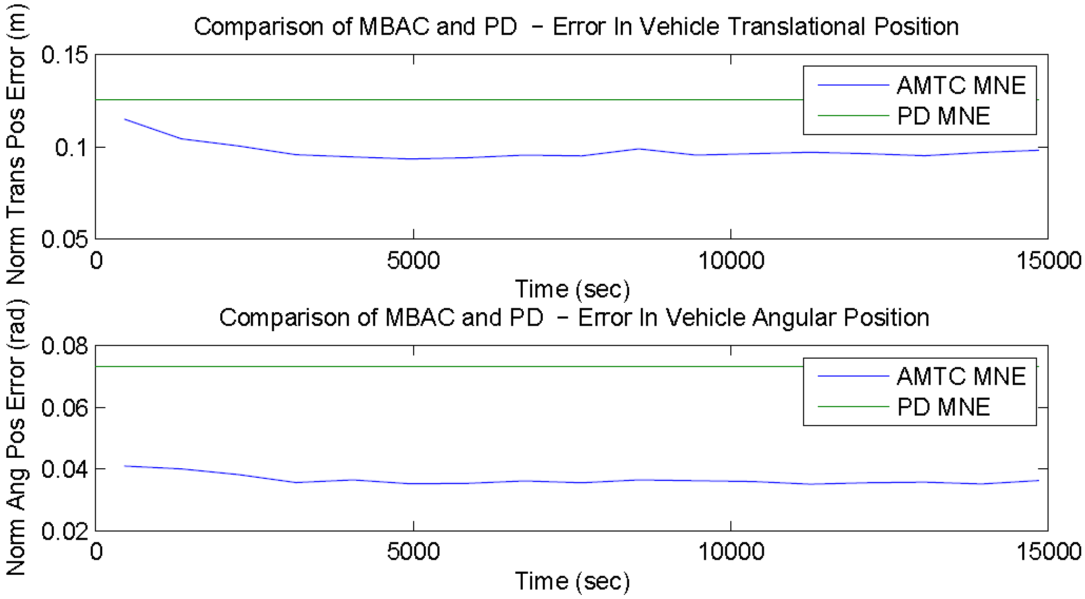

Figure 2: Translational and angular position data for two experimental evaluations. The green line is the mean of the average error over a 10 minute PD controller experiment. The blue line is the mean of average error over 15 minute windows of the Mass-Drag-Adaptation-Only MBAC experiment.

Significance and impact

The National Deep Submergence Facility (NDSF) operates the fleet of U.S. deep-sea oceanographic research vehicles; the NDSF UUV control software is the control architecture used in the JHU Hydrodynamic Test Facility. By integrating a suite of C++ functions for adaptive methods into the NDSF control software, I have enabled these vehicles to utilize the MBAC reported herein as well as adaptive methods developed previously by me, my advisor and other researchers.

Future Plans

Over the final months of my thesis work this fall, Professor Whitcomb and myself hope to find a way to test the full MBAC discussed in Section 1.2.1. We are currently developing a novel MBAC which allows for small amounts of thruster stiction. We hope to include an experimental evaluation in [2].

Over the coming years I am interesting using adaptive identification (AID) and MBAC techniques for UUV fault detection and recovery. AID uses the difference between anticipated and measured UUV performance to identify plant parameters. I hope to use the mechanics of AID to characterize unanticipated changes in vehicle performance indicative of UUV component failures. Further, since MBAC algorithms can adapt during the control process, there is the possibility that they can allow recovery from detected failures. Developing a suite of AID algorithms to switch between a collection of MBAC could enable novel UUV autonomous and semi-autonomous operations.

2. Bibliography and anticipated publications

Publications anticipated to acknowledge Link Foundation support

[1] C. J. McFarland and L. L. Whitcomb. Experimental Analysis of the Effects of Thruster Stiction on Underwater Vehicle Model Based Adaptive Control. IEEE International Conference on Robotics and Automation, Hong Kong, China, (*In Preparation*)

[2] C. J. McFarland and L. L. Whitcomb. A New Model Based Adaptive Controller for Underwater Vehicles: Theory and Experimental Implementation. IEEE International Conference on Robotics and Automation, Hong Kong, China, (*In Preparation*)

[3] C. J. McFarland and L. L. Whitcomb. Comparative Experimental Evaluation of Model Based Adaptive Control for Underwater Vehicles. Journal of Field Robotics, (*In Preparation*)

Other citations from this report

[4] T. I. Fossen. Guidance and Control of Ocean Vehicles. New York: John Wiley and Sons, 1994.

[5] S. C. Martin. Advances in Six-Degree-Of-Freedom Dynamics and Control of Underwater Vehicles. PhD thesis, The Johns Hopkins University, Baltimore, MD USA, September 2008.

[6] J. C. Kinsey, D. A. Smallwood, and L. L. Whitcomb. A new hydrodynamics test facility for UUV dynamics and control research. In Proceedings of IEEE/MTS Oceans, pages 356-361, San Diego, CA, September 2003.

[7] C. J. McFarland and L. L. Whitcomb. Adaptive Methods for Model Identification of Underwater Vehicles: Theory and Experiment. In Proceedings of Sixteenth Yale Workshop on Adaptive and Learning Systems, New Haven, CT, USA, June 2013.

3. Statement of how discretionary funds were spent

The majority of the funds provided by the Link Fellowship were spent on stipend support. My advisor and I were invited to present our work on Adaptive Identification algorithms for Underwater Vehicles at the Sixteenth Yale Workshop on Adaptive and Learning Systems. I used the remainder of my Link Fellowship Support (1000$) to cover my transportation, hotel and registration expenses for this event. By attending, I was able to present our work from [7] at the workshop.

4. How did the fellowship make a difference?

I have been pursuing a Ph.D. at Johns Hopkins University with Professor Whitcomb since 2007. The majority of my first five years were focused in two directions:

- developing novel state and parameter estimation algorithms which could only be tested in simulation,
- supporting UUV deployments in the open ocean through experimental sensor evaluations and vehicle hardware/software development.

Through my work on novel state and parameter estimation algorithms, I became aware of the long history of theoreticians developing UUV MBACs. I also became aware that operationally relevant experiential evaluations of MBAC during simultaneous dynamic motion in 6 DOF is a lacuna in the literature. In my final year I wanted utilize my theoretical and operational expertise to fill this lacuna. My advisor did not have the funding to support this work, thus without the support of the Link Foundation an additional year of PhD research tackling this important topic would not have been possible. I am so grateful that the Link Foundation recognized the importance of the contribution which was proposed, and trusted in my capacity to complete a research topic which required so many different skill sets.