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Intelligent Supervisory Switching Control of an Unmanned Surface Vehicle

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1. Narrative

Introduction

The project originally proposed for this fellowship focused on developing a framework for multimodal control of an unmanned surface vehicle (USV) – transitioning it from an underactuated system to an overactuated one. This would assist in two main functions USVs are typically tasked with: transiting and station-keeping. This project has since expanded to encompass novel territory in control theory, robotics, and computer science. The author is hopeful that the work reported here will assist in the transition of USVs from an academic pursuit into a valuable, pervasive tool for the oceanic sciences and the ocean industry.

For the continued expansion USVs play in day-to-day maritime operations, they will need to exhibit a variety of behaviors that manned vessels exhibit in the same environment (e.g., transiting, berthing, docking, etc.), which most likely will be determined by different controllers with varying system models [1]. So far, the literature has been mostly focused on developing controllers suitable for a particular task with certain performance requirements, dictating the type of controller, gains, and parameters used. However, this approach does not translate well to the breadth of operations USVs will need to exhibit in the near future. Although some research has been conducted on incorporating different behaviors through motion planning [2], this leads to difficulties in computationally expensive control space searches and forces the system to go through a replanning cycle when perturbed under the presence of unmodeled disturbances (e.g. environmental disturbances). There lies an advantage in redistributing this behavior "switch" (and thus, controller "switch") to the low-level control system, , as in [3], rather than a high-level motion planner.

An approach to do this exists in supervisory switching control (SSC) [4], [5]. Under an SSC structure, multiple controllers are switched into and out of the closed loop system depending on an estimation or performance metric. Three controllers were tied to three behaviors, defined as:

- **Transiting** - the behavior exemplified by a vehicle navigating from one destination to another. An example would be a container ship navigating between ports, following a given trajectory closely. A nonlinear backstepping controller, as proposed in [6], is used.
- **Station-keeping** – regulating the kinematic states of a vehicle to a desired position and orientation. This is demonstrated in a research vessel collecting acoustic data in a general direction at specific geographic location. A nonlinear backstepping controller, as proposed in [7], is employed for this behavior.
- **Reversing** – sternward motion of a vehicle for short durations. Due to the low dynamic range of this behavior, a Proportional-Integral (PI) controller with an anti-windup extension is proposed for surge velocity control, while a Proportional (P) controller is used to regulate vehicle orientation. A nested loop structure is constructed with a Line-of-Sight (LOS) guidance system providing reference outputs to the inner P/PI control loop [8].


(a) (b)

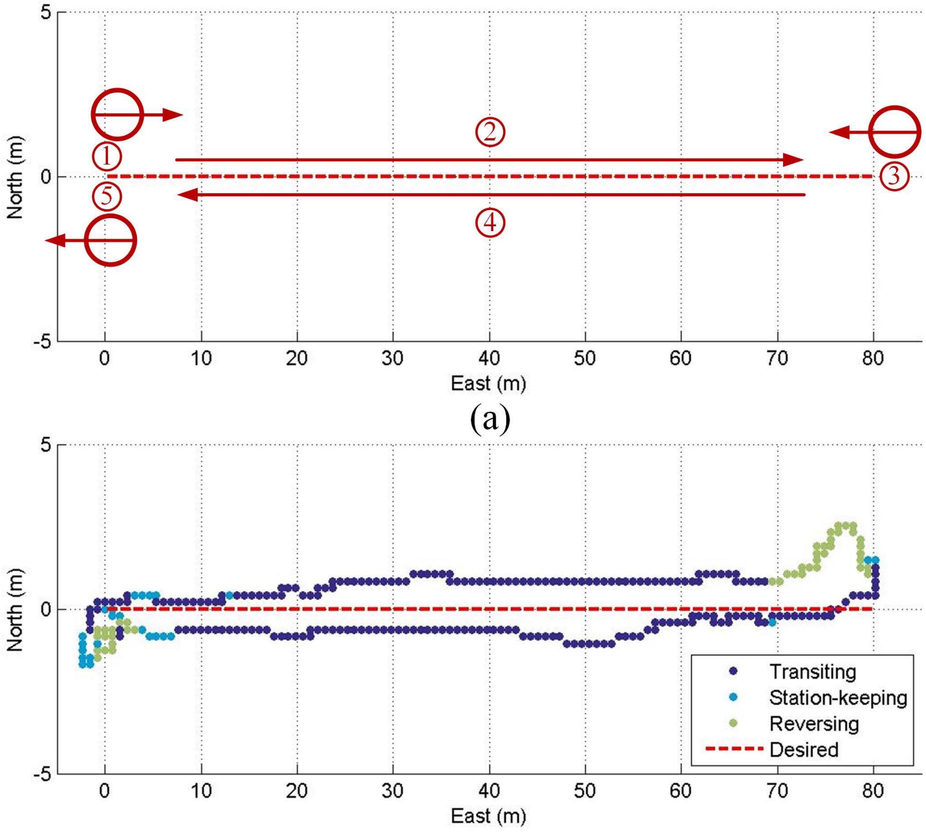
Figure 1 - The USV16 CAD model featuring the novel propulsion system (a). The USV16 in transit in Marina Bay, Singapore during the Maritime RobotX Competition

An SSC was employed on a 4.9m (16’) Wave Adaptive Modular-Vessel available at FAU’s SeaTech campus, the USV16 (Figure 1). The USV16 possesses a custom-built propulsion system capable of independently pivoting each propeller at its transom within $\pm 45^o$ of the vehicle’s longitudinal axis. This lead to an overactuated system with more control inputs than controllable degrees of freedom. This configuration was especially effective in station-keeping the vehicle [7], but due to the actuator limitations, was less effective during transiting operations. The total thrust of each propeller was directed towards a lateral direction, causing less thrust dedicated towards forward motion. Improvements could be made through combining the transiting, station-keeping, and reversing cases in a SSC system.

A performance-based supervisory switching control system (PBSSC) was used to determine which controller to insert into the loop at each time step. A performance metric was created through a Lyapunov value based on the errors in the system (which each controller is tasked to mitigate). Simultaneous, real-time simulations were used to judge the future performance of each controller, and select the corresponding one that gives the best performance over a given time window.

Results

Experiments were conducted with the PBSSC described above on the USV16 vehicle. First, a trajectory was created that all three controllers could accomplish, to varying degrees (Figure 2a). Initially, the trajectory required the vehicle to remain in the same location while pointing East for 30s, constituting a station-keeping maneuver (1). It was then tasked with moving due East, slowly accelerating to 1m/s, for 80m (2), immediately followed by holding that position while facing West for another 30s (3). It was then desired to transit back to the starting location at 1m/s (4), subsequently holding the concluding pose for a final 30 seconds (5).



(a)

(b)

Figure 2 – The desired path for the USV16 to follow, broken into 5 segments (a). Results of the PBSSC system proposed as part of the Link Foundation Ocean Engineering and Instrumentation Fellowship (b). The USV16 was able to switch between three controllers tied to three behaviors, ultimately improving the performance of the entire system.

This trajectory was run multiple times under a varying environmental conditions. A sample result representative of all runs is displayed in Figure 2b. For segment (1) of the trajectory, the vehicle used a combination of the transiting, station-keeping, and reversing controller to hold at the initial location for the full 30s. Since the vehicle was under some environmental disturbances, it would slowly drift from the desired position, using the reversing controller to back into the location, and the transiting controller to pull into it. The station-keeping controller was employed when there was a lateral error, since this controller enabled the azimuthing of the thrusters. Once at the location, all three controllers were used to maintain the desired heading. After the initial 30s, the vehicle progressed to segment (2), where the PBSSC switched to the transiting controller exclusively, bringing the vehicle up to the nominal 1m/s desired velocity. Once it transited approximately 70m in segment (2), the reversing controller was selected to “brake” the vehicle for the “hold and point” maneuver in segment (3). Since the desired heading in segment (3) was opposite of that in segment (2), the reversing controller was used to align the vehicle in the proper orientation and reverse to the desired point. For segment (3), the vehicle utilized the station-keeping controller to hold that pose, along with the reversing controller when differential thrust was sufficient in orienting the vehicle correctly. The PBSSC once again selected the transiting controller for the return to the initial location in segment (4). The final hold maneuver in segment (5) used a combination of the three controllers to maintain the desired pose, as in segment (1).

The same trajectory was run with each controller individually to determine the system response and compare it to the PBSSC. Two metrics were created for comparison – one corresponding to the integral of the square of the error in position, and the other comprising to the integral of the square of the error in heading. These results are displayed in Table 1. It is apparent that the system with the PBSSC employed was superior in regulating both position and heading when compared against any of the controllers individually.

Table 1 – Comparison of the PBSSC against each controller individually

	Integral of Square of Position Error (m^2s)	Integral of Square of Orientation Error (deg^2s)
PBSSC	1142.0	98663.02
Transiting	1254.5	951679.39
Station-keeping	5899.8	242036.43
Reversing	51206.6	6210014.39

Significance and impact

The PBSSC was able to accurately change the controller depending on the current and future situation of the vehicle. It is important to note that the trajectory given to the vehicle did not explicitly state what controller to use – the vehicle was able to autonomously decide which controller to insert into the closed-loop system at each time step. This can be particularly useful to the end-user using a commercial system, since all he or she would need to provide would be a series of reference trajectories for the vehicle to follow. The controller selection to improve the performance would happen in the background. Likewise, in vehicle in motion planning, the search in the control space to determine what controller to use while deciding a reference trajectory can be avoided.

To the author's knowledge, this is the first time a SSC system was tested on a marine vehicle in the field. This is doubly significant since it has been well known in the USV research field that there is a lack of publications involving full-sized physical platforms employing advanced control techniques (such as nonlinear backstepping control) [9].

Potential Future Research Paths

Although a successful PBSSC system was designed and validated on a physical platform, future work can extend these results even further. The question remains - though the vehicle was able to accurately switch controllers for a given trajectory, is it possible to learn from these decisions in this trajectory to improve the future performance for all given trajectories? In this author's opinion, the solution to this question resides in reinforcement learning [10] and integrating such an algorithm in the PBSSC system. This future work is planned for the remainder of the author's current tenure at FAU.

References

[1] J. E. Manley, "Unmanned Surface Vehicles, 15 Years of Developmen," in *IEEE Oceans*, Quebec City, Canada, 2008.

[2] T. Wongpiromsarn, U. Topcu and R. M. Murray, "Synthesis of control protocols for autonomous

systems," *Unmanned Systems,* vol. 1, no. 1, pp. 21-39, 2013.

[3] T. D. Nguyen, A. J. Sorenson and S. T. Quek, "Multi-operational controller structure for station keeping and transit operations of marine vessels," *Control Systems Technology, IEEE Transactions on,* vol. 16, no. 3, pp. 491-498, 2008.

[4] D. Liberzon, Switching in Systems and Control, Boston, Massachusetts, USA: Birkhauser, 2003.

[5] J. P. Hespanha, "Tutorial on supervisory control," in *Lecture Notes for the workshop Control using Logic and Switching for the 40th Conf. on Decision and Contr.*, Orlando, Florida, USA, 2001.

[6] A. P. Aguiar, L. Cremean and J. P. Hespanha, "Position Tracking for a nonlinear underactuated hovercraft: controller design and experiment results," in *42nd IEEE Conference on Decsion and Control (2003)*, 2003.

[7] E. I. Sarda, I. R. Bertaska and K. D. von Ellenrieder, "Development of a USV station-keeping controller," in *IEEE/MTS International Oceans Conference*, Genoa, Italy, 2015.

[8] T. I. Fossen, Marine Control Systems, Trondheim, Norway: Tapir Trykkeri, 2002.

[9] H. Ashrafiuon, K. R. Muske and L. C. McNinch, "Review of nonlinear tracking and setpoint control approaches for autonomous underactuated marine vehicles," in *American Control Conference*, Baltimore, MD, 2010.

[10] R. S. Sutton and A. G. Barto, "Reinforcement Learning: An Introduction," MIT Press, Cambridge, Massachusetts, USA, 1998.

2. Publications, Presentations, and Other Outputs.

The Link Foundation Ocean Engineering and Instrumentation Fellowship has helped support the following publications and presentations:

Publications

Title	Publication Institution	Publication Date
Experimental evaluation of automatically-generated behaviors for USV operations	Journal of Ocean Engineering	July 2015
Development of a USV station-keeping controller	IEEE/MTS OCEANS '15 (Genoa, Italy)	May 2015
Supervisory switching control of an unmanned surface vehicle	IEEE/MTS OCEANS '15 (Washington DC, USA)	October 2015
Control of an unmanned surface vehicle with	Journal of Oceanic	TBD (Under

uncertain displacement and drag	Engineering	review)
Station-keeping position and heading control of an unmanned surface vehicle exposed to wind and current disturbance	Journal of Mechatronics	TBD

Presentations

Title	**Presentation Location**	**Date**
Intelligent supervisory switching control of an unmanned surface vehicle	FAU SeaTech Campus (Dissertation Proposal)	April 2015
Development of a USV station-keeping controller	IEEE/MTS OCEANS '15 (Genoa, Italy)	May 2015
Supervisory switching control of an unmanned surface vehicle	IEEE/MTS OCEANS '15 (Washington DC, USA)	October 2015

3. Future Plans and How did the fellowship make a difference?

On the conclusion of the Link Foundation Ocean Engineering and Instrumentation Fellowship, I plan on finishing my Doctor in Philosophy at Florida Atlantic University, then transitioning into a position at NASA's Marshall Space Flight Center in Huntsville, Alabama. I am fortunate enough to be part of NASA's Pathways Internship program, where I spend a certain amount of time each year working at a NASA center. I plan to continue my research in controls and artificial intelligence for small, unmanned spacecraft.

The Link Foundation Ocean Engineering and Instrumentation Fellowship was vital in providing me the resources necessary to complete the second year of my degree. This fellowship gave me the flexibility to focus exclusively on my research rather than teaching classes or conducting research under a grant that was only tangentially related to my research interests. I frequently recommend this fellowship to my colleagues as it is directly applicable to the Ocean Engineering graduate program at FAU, and has "spawned" successful researchers that are currently making a difference in their respective fields.