A Naval Hydrodynamics Undergraduate Curriculum for the Midwestern United States

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Introduction

The development and retention of a competent Navy workforce with a broad range of skills and knowledge concerning modern naval science and technology is critical to efficiently sustaining strong national defense capabilities on the nation's coastlines and overseas [3,5]. However, there are limited programs in the United States that concentrate directly on naval engineering [3]. There is therefore a demand for quality educational programs that contribute to the national objective by introducing students to naval science and technology challenges, providing a strong educational foundation accompanied by a comprehensive set of skills, and helping students to identify career paths.

To support this objective, a naval hydrodynamics curriculum was developed within the mechanical engineering undergraduate program at the University of Iowa. The curriculum leverages a long history of naval hydrodynamics research and graduate education to provide students with a comprehensive set of skills in computation, experimentation, and analysis centered on naval hydrodynamics. The constituent courses are organized into a certificate program designed to enhance students' understanding of naval science and technology challenges, to inform students of potential engineering career paths in or in support of the U.S. Navy, and to provide students with a firm foundation in basic concepts of naval hydrodynamics, fluid dynamics, and related experimental and computational techniques.

Development of the program is inherently subject to multiple constraints. To be attractive to undergraduate students at the University of Iowa, the knowledge and skills acquired through this curriculum must be sufficiently broad to satisfy the Navy's technical requirements for bachelor's level graduates and to ensure flexibility for students not committed to a career in the Navy or its contactors. Due to the geographic location, the university has not historically been an institution sought by prospective undergraduates interested in studying naval and marine engineering, nor have those industries actively recruited bachelors degree graduates. Therefore, it is particularly important to the vitality of the certificate that students achieve depth in the fundamentals to ensure transferability and thus mitigate risk in students' career planning. It is also necessary to provide students with this comprehensive background through existing and new elective courses using limited faculty resources. We leverage faculty effort by designing new project-intensive courses, that naturally support learning communities, and provide an online bulletin board to facilitate student communication.

The positive impact of learning-community participation on student success in higher education is well supported by multiple researchers and educators (e.g., [2,7,8]. A learning community increases student involvement, builds connections through the curriculum and extracurricular activities, enhances student-student and student-faculty intellectual interactions and collaborations, and expands learning beyond the classroom [1]. As students participate in a learning community that purposely structures the curriculum to link courses or coursework, they spend a substantial amount of time engaged in common intellectual activities where they

develop meaningful friendships and experience a great sense of belonging, which is vital for student retention [1].

In this paper, we discuss the structure, interactions between, and effectiveness of three new courses introduced into the mechanical engineering elective curriculum, providing a foundation in naval hydrodynamics education for the certificate program.

Program structure and facilities

The naval hydrodynamics certificate is an official University of Iowa certificate and is therefore available to students of all disciplines; however, due to the subject nature and introductory fluid mechanics prerequisite, the program has, so far, exclusively attracted undergraduates and junior graduate students in the mechanical engineering program. A certificate consists of 18 credits (6 courses); whereas the mechanical engineering program requires 21 credits of technical electives, so that students can typically complete the certificate without taking extra courses. The certificate is summarized in Table 1. Students completing the certificate will take elective courses that are broadly related to naval hydrodynamics (e.g. fluid mechanics, numerical methods, dynamics, etc.) as well as two new courses on naval hydrodynamics: ME:4175 Computational Naval Hydrodynamics (CNH) and ME:4176 Experimental Naval Hydrodynamics (ENH). Students earning the certificate must also complete a capstone experience involving naval hydrodynamics, which can be either a full-year design course or a one-semester independent study. The two naval hydrodynamics courses and the capstone course thus form the subject-specific core of the naval hydrodynamics curriculum, which we will focus on in this paper.

Table 1: Naval Hydrodynamics Certificate overview

Required courses • ME:5160 Intermediate fluid mechanics • ME:4175 Computational naval hydrodynamics • ME:4176 Experimental naval hydrodynamics
Limited electives (students must complete one from each of the following categories): • Full-year capstone design elective (one semester is required for all students) OR one semester of supervised independent study, each focused on an approved Naval Hydrodynamics project • An approved introductory numerical methods course
General electives • Students must complete one additional course from a selection of related courses including topics such as linear systems and dynamics, control systems and theory, and additional continuum mechanics and fluids courses.

Whereas the capstone design course is offered every year, the availability of faculty resources dictates that CNH and ENH are offered in alternating years such that one course is offered each spring. Undergraduate students therefore typically complete one of the courses in their junior year and the other in their senior year. Consequently, neither course can be a prerequisite of the other, and therefore the courses cannot assume any prior background in naval hydrodynamics. To make the course content within reach of the junior students while not excessively redundant

for senior students, we therefore heavily emphasize fundamental concepts of experimental and computational methods and tools in their application to the study of naval hydrodynamics. This also provides students with a broad set of skills for a career in naval engineering that and transferable skills for students not *a priori* be committed to pursuing a career in naval hydrodynamics. Similarly, students completing a capstone design course in naval hydrodynamics would typically have an opportunity to complete at most one of the computational or experimental naval hydrodynamics courses, and we do not depend on students having any background in naval hydrodynamics when taking the capstone design course.

Central to our approach in this program is the use of complex, open-ended projects employing either a proprietary naval hydrodynamics flow solver or advanced measurements in a small towing tank designed for the curriculum. In CNH and ENH, a substantial portion of student effort (>50%) was focused on projects that leveraged these resources. The proprietary computational fluid dynamics (CFD) flow solver, REX [4] – developed through our graduate research program and used for research purposes in academia, Navy labs, and industry – was adapted to student use, and a small educational towing tank was constructed to be physically accessible by students. The CNH course relied heavily on REX for organized class activities and open-ended projects; whereas ENH utilized the towing tank. Both facilities are available to support the capstone (design or independent study) experiences.

REX is a general purpose CFD code with a vast array of capabilities and specific inputs and outputs to analyze naval hydrodynamics problems, including the classic surface and underwater craft areas of resistance, propulsion, seakeeping and maneuvering. REX and preceding codes have been used for decades for research at the graduate student level, so a challenge was to enable use by undergraduate students in the context of a junior and senior level course. Since REX is an overset code with extensive moving body capabilities, and complex features fundamental to simulating naval hydrodynamics problems, the difficulty of teaching students is higher. To achieve the goal a set of simplified inputs to solve the classical naval hydrodynamic problems was implemented, an extensive manual was written, and, most importantly, tutorials were developed to introduce students to basics of the Linux operating system and high-performance computing, overset technology and grid generation, simulation setup with motions and prediction of forces, moments and motions.

The educational towing tank is shown in Figure 1. The test section is 0.61 m wide, and typically contains water levels up to 0.61 m deep. Carriage travel is approximately 10 m, and is programmatically limited to a maximum speed of 2 m. Typical ship and underwater vehicle models used in the facility are approximately 1 m in length, which is a compromise between blockage effects, boundary development time, and Reynolds number effects. A LabVIEW control interface is used directly by students, and provides basic speed control as well as display of system status (carriage speed, limit and home switch states, etc.), and leads the operator through a safety checklist which must be completed before each run begins. Resistance and thrust data are acquired from a single-axis load cell, and data acquisition is controlled from a separate LabVIEW program that is typically generated by the students as part of their course deliverables.

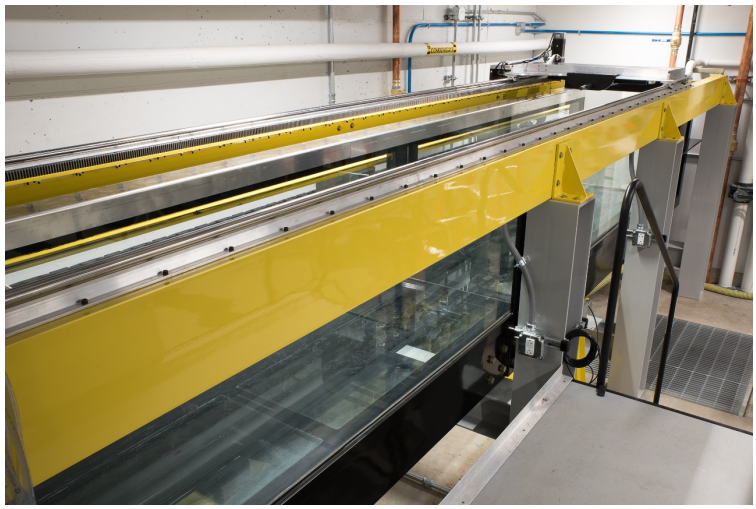

Figure 1: The educational towing tank. The tank is elevated with glass walls, permitting visualization and optical instrumentation access from the sides and floor of the tank. Rails mounted on beams detached from the tank for a stable and precise track for the carriage to traverse.

Curriculum

In CNH, simulations based on relevant vessels (DTMB 5512) and propellers (KP505) are used to introduce the use of computational fluid dynamics for the analysis of surface and underwater marine craft performance, while also introducing naval hydrodynamics concepts related to resistance, propulsion, maneuvering and seakeeping. The propulsion section includes simulations of a propeller open water curve and description of how a self-propulsion computation produces propulsion factors (thrust deduction, Taylor wake fraction, rotative and propulsive efficiency, etc.) Seakeeping response is studied performing pitch and heave simulations in head waves, while maneuvering includes a static (pure drift) simulation and computation of maneuvering derivatives. A complete example is worked in class using the generic submarine DARPA SUBOFF advancing in irregular waves.

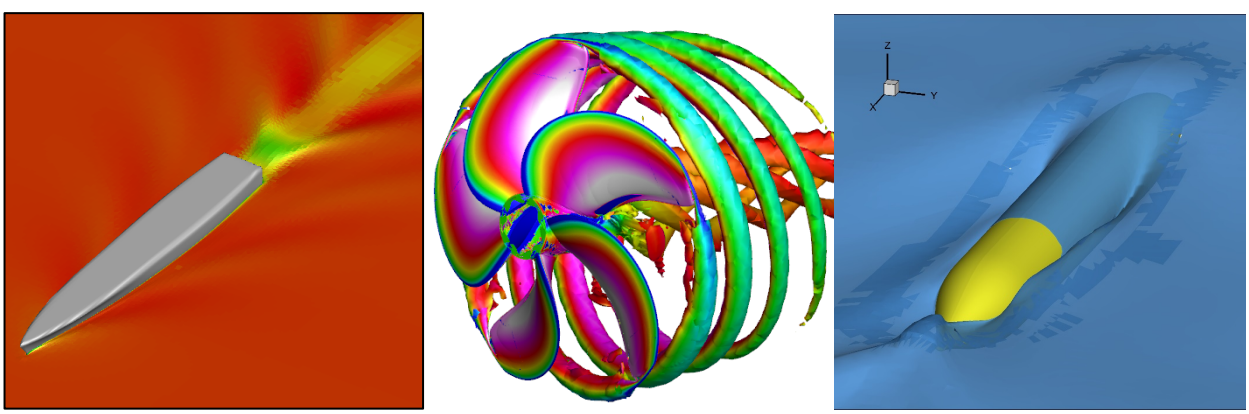

Figure 2: Simulation results from CNH: Athena Research Vessel resistance free to sink and trim (left), KP505 propeller at J=0.5 (center), DARPA Suboff near the surface in sea state 5 waves (right).

ENH focuses on conducting experiments on benchmark underwater vehicles (DARPA SUBOFF) and surface vessels (KRISO Container Ship; KCS), and a propeller, to introduce experimental methods for measuring marine craft performance. Figure 3 shows some of the models used in the class. Commensurate with the capabilities of the towing tank facility, ENH addresses primarily resistance and propulsion, though planned enhancements to the towing tank (wave generation and increased degrees of freedom) will expand the possibilities. Due to the necessity of using scaled models to conduct experiments, Froude and Reynolds number scaling is addressed in detail, and considerable time is spent discussing laboratory safety, instrumentation, data acquisition systems, and uncertainty analysis. Students complete several homework assignments individually, and three standard projects, completed in teams, involving a) measurement of resistance on an underwater vehicle, b) measurement of resistance on a surface vessel, and generation of open water curves on a propeller.

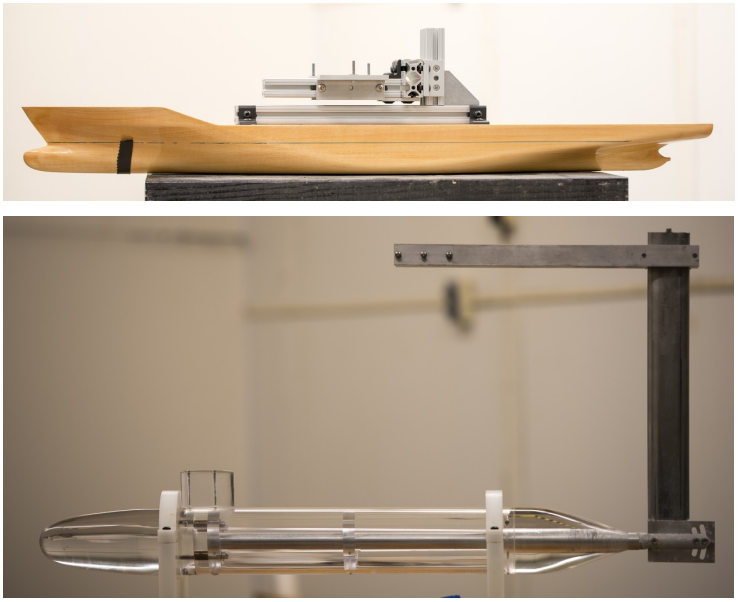

Figure 3: Towing tank models used in ENH. Top: KRISO container ship (KCS) with Hama strips mounted near the bow to force transition; bottom: DARPA SUBOFF.

Content in CNH and ENH is delivered using a range of resources, including lecture notes, supplementary texts, and ITTC (International Towing Tank Conference) guidelines that define specific tests related to naval hydrodynamics, and best practices for computations and experiments.

The capstone design course shares a limited curriculum (the design process, project management, and basic tools for design development, analysis, and decision-making) with students working on projects unrelated to naval hydrodynamics. Despite that the students completing naval hydrodynamics projects are in a distinct section from other project teams, the instructor, deliverables (proposal, progress reports, design review meetings, and final presentation) and grading scheme are shared. Figure 4 contains simulation results from an ongoing project in which students are designing a ducted propeller for use on an autonomous boat that will compete

in the annual RoboBoat competition sponsored by the Office of Naval Research and the Association of Unmanned Vehicle Systems International (AUVSI). A prototype has been built and tested in the educational towing tank. The naval hydrodynamics faculty and Navy professionals serve as advisors to the naval hydrodynamics project teams. Given the lack of a prerequisite sequence, providing students with sufficient background on naval hydrodynamics concepts and operation of applicable tools (e.g. CFD software and towing tank) can be onerous, but not necessarily atypical of capstone design courses where students often encounter new industries and their associated tools. In the two offerings of the naval hydrodynamics capstone design section, it is typical to have students who have completed at least one of CNH or ENH such that there is initially some knowledge of naval hydrodynamics fundamentals and skill in using the specialized tools.

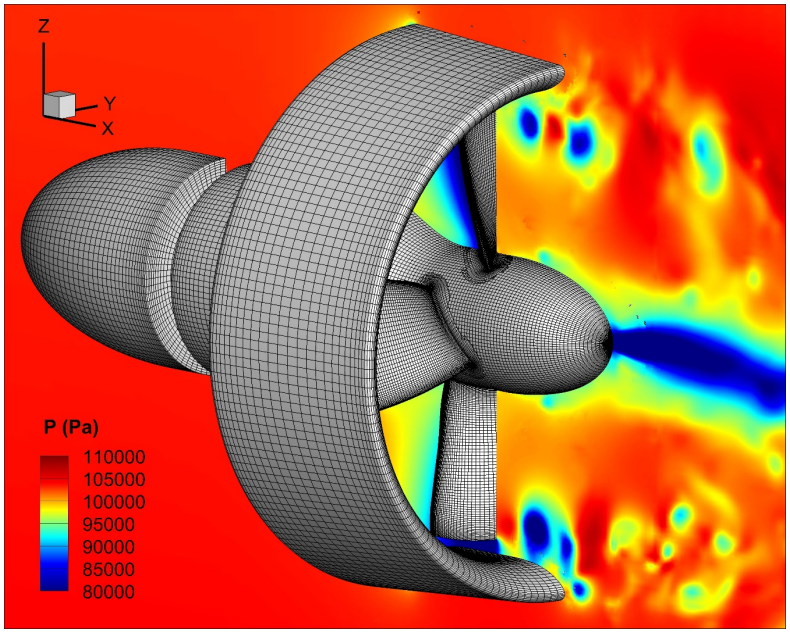

Figure 4: Simulation of a ducted propeller conducted in a capstone design project. The surface overset computational grid and a slice with absolute pressure are shown.

Instructional Strategies

The CNH and ENH courses both included lectures and problem-solving, written homework assignments; whereas CNH also required students to complete tutorials to convey basic principles of high-performance computing facility usage, grid generation, and setup and analyze resistance, seakeeping and propulsion simulations using REX. Both classes relied heavily on project work in teams, during which time the teams would have meetings with course instructors in lieu of lectures. Out of the 45 hours of contact time in each course, each course involved approximately 30 hours of lectures and 15 hours of class time devoted to project work and instructor meetings. One faculty instructor and one quarter-time (10 hours/week) teaching assistant administered each course.

Projects were designed to be open-ended and structured such that students wrestle with complicated tasks that included computational model and grid generation, setup of simulations, data interpretation, uncertainty analysis, and application of advanced experimental measurement techniques such as particle image velocimetry, in order to help them develop maturity and independence in their analysis of naval hydrodynamics (and other engineering) problems.

The tutorials in CNH are designed to cover topics necessary to design and perform naval hydrodynamics simulations and obtain results of engineering interest. The topics covered are a) Linux and system tools in a high performance computing environment, b) grid design and gridding methodologies for model and full scale Naval craft, c) overset grid technology and associated tools Suggar++ and Gviz [6], d) use of the CFD software, REX, and associated tools for postprocessing, e) principles of Resistance, Seakeeping, Propulsion and Maneuvering, related simulation techniques, and interpretation of results.

The three projects in ENH are assigned such that the basic measurements are common to all teams, and distinct supplementary variations are assigned to each team (e.g. for an underwater vehicle, vary distance from the free surface, towing speed, or yaw angle). Presentation of the baseline comparisons allows teams to compare their results, implicitly identifying best practices; while the variations provide deeper insight into the physics and often provide a segue into future topics.

Both courses make use of an open-ended final project to emphasize topics discussed in the course, introduce new naval hydrodynamics concepts, and/or learn new methods (e.g. new experimental techniques such as particle image velocity may be used to better understand the physics governing features observed in experimentally-measured resistance curves). Each project team is assigned a unique project in consultation with Navy laboratory staff, and often receives feedback from the professionals, though this interaction has been somewhat limited in past offerings.

To help support the learning communities within each of the Computational and Experimental Naval Hydrodynamics classes, a bulletin board was established as a class forum to facilitate semi-real-time communication between students, which instructors could monitor, mediate, and otherwise contribute to. Past experience has indicated that students are not naturally inclined to use the bulletin board, so a small percentage of the final grade was devoted to student participation (asking or answering questions) on the forum. The content of the bulletin boards will also be used to generate a knowledge base such as a list of frequently asked questions that will be available to future students and users of the facilities.

A wiki was also established in which students were asked to create their final project deliverables (tutorials in CNH, and comprehensive reports in ENH). Students had the option of not putting their work on the wiki, and provided written permission to display their work in this way. The objective is to support the learning community by making these online documents available to future students as a growing, student-generated knowledge base.

Finally, Navy staff were invited to engage our students to expose them to possible career paths and naval science and technology challenges. Visitors included a nuclear propulsion officer,

multiple Navy lab research staff, and industry professionals, many of whom are alumni. The visitors either gave presentations to the class in person or remotely.

Assessment

The first offering of CNH was delivered in the spring of 2016, followed by the first offering of ENH in the spring of 2017. In the fall of 2015, sophomore students were surveyed to assess their perceptions of their competencies as well as their interest in the certificate program and its constituents. Out of 52 respondents, 37% (19 students) expressed interest in taking the first offering of Computational Naval Hydrodynamics, 29% (15 students) expressed interest in completing the certificate, and 46% (24 students) expressed interest in participating in Navy-sponsored projects through existing courses. Fourteen students registered for Computational Naval Hydrodynamics in spring 2016, and eight students registered for Experimental Naval Hydrodynamics in spring 2017. Four students (one project team) completed the naval hydrodynamics capstone design project in the 2016-17 academic year, and an additional team of four students is pursuing a project in the 2017-18 academic year.

Surveys were conducted at the conclusion of each of the three courses to obtain students' perceptions of their achieved technical competencies and the effectiveness of the instructional strategies used in the courses. Results for the Computational and Experimental Naval Hydrodynamics courses are given in Tables 2 through 4.

Table 2. Participants

Male	Under Represented Minority	First Generation Students	Avg. Cumulative GPA before taking this class	Avg. Course grade
19 students	4 students	3 students	3.15	3.76

Only one student in Computational Naval Hydrodynamics also completed Experimental Naval Hydrodynamics. This is because the vast majority of students that completed the first offering of Computational Naval Hydrodynamics was either senior undergraduate students or graduate students, and were not enrolled in the following spring. The demographics of the students completing both courses is given in Table 1. All students were male; however, the classes included under-represented minorities and first-generation students. The average grade was higher than the average cumulative GPA of the students completing the course.

The perceived technical competencies were aligned with the learning objectives of the classes, as listed in Table 3. Students were asked to indicate their competencies on a 7-point scale, where 1 indicates very weak and 7 indicates very strong. Students' perceptions of achieved technical competencies were solid; their assessments of learning in the areas of fluid mechanics fundamentals, experimental, and computational methods were generally above 6 on a 7-point scale. However, they indicated slightly lower perceived competencies in the areas of career planning. While this is an area to focus on for future improvement, anecdotal evidence (e.g. through academic advising) suggests that students in the mechanical engineering program may

regard their understanding of career paths to be somewhat weaker than that of their technical competencies.

Students' perceptions of the effectiveness of the instructional strategies is summarized in Table 4 for the Computational and Experimental Naval Hydrodynamics courses. Lectures and homework provide opportunities for students to learn basic technical knowledge, whereas teamwork, projects (which are always conducted in teams), and the bulletin board are designed to support learning communities within the classes, and Navy personnel were asked specifically to address naval science and technology challenges as well as career paths (though not the only source of this information). The effectiveness of lectures was rated moderately high by students; whereas homework was rated moderately to very high for the classes. The tutorials, used in the computational class only, were deemed to be the most effective instructional component. Projects and working in teams were rated consistently very high.

Interestingly, use of the bulletin board was rated somewhat lower, and especially so for the experimental class. The slight decrease in effectiveness in the computational class is presumably influenced by students' reluctance to post their questions and answers in a public setting (which is why a grade was assigned for its use). However, the drastic difference between its effectiveness in the two classes stems from differences in the nature of the work. Since students performing computations could access required computational resources remotely, the bulletin board provided a means for near real-time discussions as students wrestled with challenges in physical isolation. On the other hand, conducting experiments required students to be physically co-located with each other and with an instructor (a safety requirement when operating the towing tank) so that there was seldom a need for communicating on the bulletin board, and students used and monitored it infrequently.

Students were visibly interested in presentations by Navy personnel and readily engaged with them. In a few cases, students remained in contact with the visitors for advice on Navy career strategies (e.g. internships or Navy-sponsored educational programs) that they were pursuing as a result of the class interactions. Yet, the reported effectiveness of these interactions was neutral. More data needs to be acquired to better understand this result; however, we hypothesize that the lack of effectiveness was due to the limited role of the visitors in the curriculum. There were at most, a few visits from Navy personnel in each course, and while they participated in defining the scope of final projects and provided some feedback on the student work, they were typically not actively involved with the students during their daily work. Geographical location undoubtedly presents a challenge in this regard.

Discussion and Conclusions

An elective undergraduate curriculum in naval hydrodynamics was developed within the mechanical engineering curriculum at The University of Iowa, to support a national need for quality naval science and technology education. Whereas a graduate research program was well-established in this area, the undergraduate program did not have an established pipeline of incoming students nor employers providing jobs to graduates. To mitigate the investment risks to both institution and students, a certificate program was established with the development of

Table 3. Students' Perceptions of Competencies

Computational naval hydrodynamics (14 students)	Mean
Employ CFD and principles of Naval Hydrodynamics to assess vessel performance in resistance, seakeeping and propulsion.	6.64
Apply fluid mechanics principles to problems in Naval Hydrodynamics (Dimensional Analysis and Similarity, Boundary Layers, etc.).	5.57
Adopt the workflow process for Naval Hydrodynamics CFD, including problem definition, grid generation, case setup, perform simulations and post process the results.	6.50
Identify areas of computational hydrodynamics of importance to the Navy.	6.14
Recognize Navy science and technology challenges in the area of hydrodynamics.	6.21
Understand what a career in or in support of the Navy would look like.	5.00
Experimental naval hydrodynamics (8 students)	
Employ principles of Naval Hydrodynamics to assess vessel performance in resistance and propulsion.	6.38
Apply fluid mechanics principles to problems in Naval Hydrodynamics (Dimensional Analysis and Similarity, Boundary Layers, etc.).	6.38
Apply ITTC recommended procedures in uncertainty analysis to assess uncertainties in naval hydrodynamics measurement data.	5.75
Conduct measurements of hull resistance and propulsion.	6.25
Extrapolate measurements made at model scale to full-scale, and design model-scale experiments based on full-scale applications.	6.50
Identify areas of experimental hydrodynamics of importance to the Navy.	5.25
Recognize Navy science and technology challenges in the area of hydrodynamics.	5.63
Understand what a career in or in support of the Navy would look like.	5.50

Note. 7-point scale

Table 4. Students' perceptions of instructional components in Computational Naval Hydrodynamics (CNH) and Experimental Naval Hydrodynamics (ENH)

Instructional component	**CNH**	**ENH**
Lecture notes	5.6	5.6
Homework problems	6.5	5.5
Projects	6.7	6.6
Working in teams	6.4	6.1
The use of the bulletin board	5.6	3.4
Interaction with Navy personnel	4.4	4.8
The use of tutorials	6.8	N/A

Note. 7-point scale

only two new technical courses and a subject-focused capstone experience, that provided a broad education in fundamental principles of fluid dynamics, and computational and experimental methods, focused on naval hydrodynamics applications. For students completing the full certificate, the program culminated in a capstone experience in naval hydrodynamics.

To provide a quality learning experience for students while leveraging faculty resources, learning communities were facilitated in the new courses by including a significant component of team projects designed to emphasize course concepts and promote sharing of outcomes between teams. Class bulletin boards were also established to facilitate communication. Students learned about naval science and technology challenges and career path options through interactions with Navy professionals who gave class presentations and served as project advisors.

At the ends of the courses, student perceptions of their technical competencies were generally very high, and they generally rated their knowledge on naval science and technology challenges and career opportunities moderately high. Among the instructional strategies contributing to these successes, students highly valued working on projects in teams and, for CNH, the use of tutorials. Use of the course bulletin board was moderately effective in CNH, but relatively ineffective in ENH, presumably due to the increased level of face-to-face contact with students and instructors required in the experimental course.

Efficiency in the delivery of future offerings of the courses will be an important factor in ensuring the vitality of such a small program with extensive hands-on activities. The intricacies of using high-performance facilities, generating grids, and setting up simulations are far from formulaic for novice practitioners of computational fluid dynamics. Similarly, safe and proper use of experimental facilities to conduct naval hydrodynamics measurements requires supervision and hands-on guidance. In this regard, future improvements in the knowledge base supporting student work will be available as additional student-authored project reports and tutorials are made available on the wiki, and future students can use the existing examples as a baseline to improve the quality of their own work.

Other opportunities to improve the efficiency and effectiveness of the program also exist. Expanding the learning community to include members outside the course (e.g. graduate students) can further leverage instructor efforts. To facilitate this, we are in the process of consolidating the experimental facilities along with computational resources in a novel fluids laboratory and “maker space” accessible to all students in the College of Engineering. We have also established a student organization dedicated to designing and building a competitive autonomous boat as a means to attract enthusiasts and maintain a robust community of scholars that can persist outside of the confines of a single course. The organization and efficacy of such a community will be the subject of a future paper.

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