MIT 2.680
Unmanned Marine Vehicle Autonomy, Sensing and Communications
Spring 2023

Lectures:	T-R 130-230pm, NE45-202
Labs:	T-R 930-1230pm, NE45-202
Lab Material:	`http://oceanai.mit.edu/ivpman/labs`
Class Website*:	`http://oceanai.mit.edu/2.680`
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Office Hours:	Wednesday 230-430pm, 5-214, or by appointment
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About This Course

This course covers basic topics in autonomous marine vehicles, focusing mainly on software and algorithms for autonomous decision making (autonomy) by underwater vehicles operating in the ocean environments, autonomously adapting to the environment for improved sensing performance. It will introduce students to underwater acoustic communication environment, as well as the various options for undersea navigation, both crucial to the operation of collaborative undersea networks for environmental sensing. Sensors for acoustic, biological and chemical sensing by underwater vehicles and their integration with the autonomy system for environmentally adaptive undersea mapping and observation will be covered. The subject will have a significant lab component, involving the use of the MOOS-IvP autonomy software infrastructure for developing integrated sensing, modeling and control solutions for a variety of ocean observation problems, using simulation environments and a field test-bed with small autonomous surface craft and underwater vehicles operated on the Charles River.

Teaching Approach

A primary objective of this course is to introduce students to a wide set of theoretical and practical issues involved in designing autonomy algorithms in fielding unmanned marine vehicles for ocean sensing problems. A key insight we hope to convey in this course is the relationship between effective autonomous decision-making, sensor processing, and communications. Often the strengths in one aspect may compensate for the shortcomings in others, in effect creating an interesting design space of vehicle properties, where certain points in that space are more appropriate than others for certain design goals and constraints on vehicle size, cost, reliability and duration.

In this class students will be introduced to robot architectures at four different levels - the robotic middleware level for managing software packages at the process level, a behavior-based architecture for autonomous decision-making, a field-control or nested autonomy level for organizing a sensing system across multiple platforms, and finally the payload-platform interface that allows us

to design our solutions in a vehicle agnostic manner. Students will be introduced to the fundamental properties of ocean acoustics to better understand the limits on inter-vehicle communications at different relative depths and environmental conditions.

The class has a strong lab component with the goal of providing every student the end-to-end skills needed to field actual marine robotic equipment during the second half of the semester. These skills include an understanding of the robot architectures, the effects of band-width and range limited communications on autonomy algorithms, basic C++ programming skills, cooperative software development and the use of version control services, and mastery of the command-line.

Class Mechanics

This class will be taught as a combination of two weekly one hour lectures and two weekly three hours labs. We will meet Mondays and Wednesdays each week for three hours in the morning and a one hour in the afternoon. In the first part of the semester, lectures will take place in the first hour of the morning session to introduce new material covered in that day's lab. The remaining two hours in the morning are for beginning the lab, with an additional hour in the afternoon for completing the lab.

In the second part of the semester, the morning sessions will be spent at the MechE Marine Autonomy Lab at the MIT Sailing Pavilion. We have chosen this arrangement to coordinate with the other activity at the Pavilion. Generally there is a lot of sailing activity with higher winds in the afternoon, and there is less sailing and calmer water in the mornings to suit our lab work. In the second part of the semester, lectures will be held in the one hour meeting back on campus in Building 5.

Prerequisites

There are no formal prerequisites for this class. This class involves a good deal of programming however, and students should either have some programming background (C++ preferably), or a willingness and expectation to work harder to build their skills in this area. In the past we have had students finish at the top of the class with no prior C++ or command-line background, but it will be extra work without this prior experience. Because the class is in the Spring term, several students in the past have used the IAP period to take an informal C++ class we offer.

Grading

Grading is based entirely on lab performance and attendance. Attendance for all lectures and labs is mandatory. On a case-by-case basis, arrangements may be made with the instructors to accommodate scheduling conflicts. There will be no final exam. Although there are presently no scheduled tests or quizzes, we reserve the right to have them and include them in the final grade.

Textbook

There are no formally required textbooks for this class, but we will be drawing from the following sources during the class.

- F.B. Jensen, W.A. Kuperman, M.B. Porter, H. Schmidt, "Computational Ocean Acoustics", Springer, New York, 2011.
- R.J. Urick, principles of Underwater Sound,3rd Ed., McGraw-Hill, New York, 1983.
- M. Seto, ed., Marine Vehicle Autonomy, Springer, December 2012
- M. Benjamin, H. Schmidt, P. Newman, J. Leonard, "Unmanned Marine Vehicle Autonomy with MOOS-IvP", book in preparation, http://oceanai.mit.edu/ivpman.
- Steve Oualline, "Practical C++ Programming", O'Reilly Publishers, 2003.
- B. Collins-Sussman, B.W. Fitzpatrick, C.M. Pilato, Version Control with Subversion, For Subversion 1.7, 2012. http://svnbook.red-bean.com

Additional required and recommended reading assignments will be posted on the course wiki page during the semester.

Schedule

- *Week 1*: The first meeting and lab will offer an overview of the course and we'll discuss expectations you may have and we have for the course. We will give an overview of marine robotics, marine vehicles and marine autonomy. The goal of our first lab will be to ensure that all students have a suitable lab computer, able to build and run the course software. We have a number of course lab computers to lend to students who need them. We will identify who needs what and make sure that the course computing environment is resolved for all students at the end of the first lab.
- *Week 2*: In our next two meetings we will provide an overview of the ocean environment and marine robotics applications, from mine counter-measures, sea-bed mapping, side-scan sonar imaging, mammal sonar characteristics, navigation in the ocean, target tracking with sonar, environment adaptation, depth-dependent acoustic sensing and deep ocean communication connectivity.

  In the second meeting we will introduce the MOOS robotic middleware used in this class. Three of the key robotic architectures covered in this class are introduced - the backseat-frontseat payload autonomy architecture, the MOOS publish-subscribe middleware architecture and the IvP Helm behavior-based architecture. The focus in this meeting will on MOOS, inter-process communication, data logging, analysis and scoping. The topics of inter-robot communication via the middleware will be discussed, and the basic structure of a MOOS application from a programmer's perspective will be covered.

  The first lab will provide a condensed course on C++ for those students without the background. Included are discussions on working in the command-line environment and using a text editor for code development. The second lab will introduce the MOOS middleware environment, publish-subscribe architectures and how to interact with MOOS applications from the command-line.

- *Week 3*: In the first meeting MOOS programming will be introduced. Topics include the MOOS application structure in terms of user overloadable functions, the MOOS message structure, registering for and publishing mail, serializing and de-serializing messages, and time warping for simulating faster than real-time. We will also discuss Appcasting, a means for organizing MOOS over multiple deployed vehicles. Finally we discuss unwritten development conventions that make for good programming practice in the community of MOOS developers at MIT and elsewhere.

  In the second meeting in week 3, the topic is marine autonomy. We will discuss evolving perspectives of what is considered to be artificial intelligence in the context of marine vehicles. We explore the tradeoffs between scripted and adaptive autonomy, and the corresponding tolerance for risk of mission failure or vehicle loss. We review the evolution of action selection methods from early Rodney Brooks behavior based architectures to present day methods including multi-objective optimization action selection. The IvP Helm architecture is introduced, with its approach to action selection, and an overview of existing helm behaviors is presented.

  The first lab in week 3 will ask students to build their first substantial applications, introducing the basic structures of MOOS applications. The second lab introduces the IvP Helm through example missions, and introduces basic tools for launching, monitoring and analyzing missions.

- *Week 4*: In the first meeting in week 4 the focus is on methods of constructing autonomy missions through collections of individual vehicle behaviors. Common vehicle behaviors are introduced, and methods for grouping and executing sequences of behaviors and plans are described. The concept of hierarchical mode structures for organizing behaviors is introduced. The notion of multi-vehicle operations coordinated with a single human shoreside operator is described, with attention to the uField Toolbox distributed with the course software. Students will begin to address the technical issues of arranging inter-vehicle communication and vehicle to operator communications.

  In the second meeting this week, the topic switches to applications of underwater sound. Topics covered include passive vs. active sonar, underwater acoustic bottom mapping, ocean acoustic tomography, underwater acoustic communications, the deep ocean sound speed structure, Snells law, geometric spreading, the Llyod mirror effect, deep sound channel propagation, surface duct propagation, convergence zone propagation, arctic propagation, reflectivity and shallow water propagation, and constructive interference modal propagation

  In the first lab this week, students will become familiar with constructing and controlling multi-vehicle missions in simulation. A single vehicle mission from an earlier lab will be converted to a multi-vehicle version and students will construct a simple distributed Traveling Salesman Problem across two vehicles.

  In the second lab, we will develop an underwater vehicle autonomy/mobility algorithm to allow a vehicle to communicate using directed acoustic communications. The simultaneous consideration of relative vehicle position, the ocean environment, and communication using a directional conical beam of fixed width may allow vehicles to communicate at much longer

distances using a fraction of the energy compared to transmitting sound from all directions using a point source. The assignment in this lab to develop an algorithm capable of predicting how a particular directional beam of sound is propagating through the environment, and more importantly solve the inverse problem of determining the vertical transmission angle that will make the sound beam reach the collaborator or the target of interest. The creation of a MOOS process that performs this task is the goal of this Lab assignment.

- *Week 5*:

  In the first meeting of week 4 we will introduce the *nested autonomy* approach for environmentally adaptive undersea sensing. The communication constrained nature of undersea networks will be discussed and its influence on the nested autonomy approach. The IvP Helm nested autonomy system architecture will be discussed with the example of harbor surveillance. Data driven and model driven approaches to autonomous adaptation and collaboration will be discussed.

  In the second class this week, the problem of autonomous search using marine vehicles is introduced in the context of the classic mine countermeasures problem. We describe components of the search process from detections, verifications and acting on objects of interest and discuss the role that autonomy may have in reducing the unreliability and time-line of the search. Since our lab emphasis is on *collaborative* search, we introduce the mechanics of inter-vehicle messaging use in our simulation and in-water experiments. Students will begin to contemplate strategies for overcoming range-limited, band-width limited communications by using adaptive mobility and autonomy in their overall approach.

  In the first week 5 lab, students will push further in building multi-vehicle simulations in preparation for the next lab on collaborative search. In this lab, students will set up multi-vehicle missions and simulations across multiple laptops, with an instructor's machine acting as the shoreside or mission-control computer.

  In the second lab students will begin the Hazard Search lab, which is a three-session lab spanning this week and both labs of the following week, culminating with an in-class competition in simulation. In this first lab students will explore the baseline example mission provided by instructors, and explore the competition rules and properties of sensors and inter-vehicle communications allowed to them.

- *Week 6*: In week 6 the first meeting will focus on radiation and scattering of sound, and sonars.

  In the second meeting this week, contact-related vehicle behaviors is introduced. Contact-related behaviors reason about other vehicles or contacts in its vicinity. We discuss how contacts may come to be known to one another through either AIS systems, on-board sensors, or directed communications, and how the issues of latency and uncertainty are handled. Approaches to contact management are introduced and the relationship to event driven decision-making. We conclude by discussing the contact-related behaviors in the IvP Helm.

  The first week 6 lab will be dedicated to further completion of the autonomous hazard search lab. The second lab will be used to hold an in-class competition on the hazard search problem. Each competition entry consists of two vehicles working collaboration with the two lab

partners each using their laptop to simulate one of the vehicles. The instructors will run the shoreside, mission-control, community on their machine with the operation area and display projected on the classroom screen. Each team will have at least two runs to demonstrate their solutions.

- *Week 7*: The two lectures and two labs this week will be dedicated to acoustic communications, with the lectures and labs by Dr. Toby Schneider.

- *Week 8*: In our first meeting after break, we begin the topic of behavior authoring. Up to this point the focus has been on using existing MOOS applications and Helm behaviors, augmented with student-written MOOS applications, to comprise student autonomy solutions. The goal of this meeting is to prepare students for upcoming lab work involving student-authored behaviors. The basic behavior mechanics including key overloadable functions, retaining information local to the helm and local to the behavior, the notion of behavior run-states, behavior spawning and completion and behavior parameter handling is discussed.

  In the second meeting in week 8, the discussion focuses on optimization and the role of optimization in marine autonomy. In particular single objective vs multi-objective optimization is discussed. Linear Programming is introduced as the classic form of single-objective optimization. Multi-objective optimization and Pareto optimality are covered in the context of evolution of marine autonomy missions from single vehicle scripted missions to multi-vehicle, long-duration collaborative missions.

  The labs during week 8 cover the second round of the autonomous hazard search lab, with migration to the in-water competition vs. the simulation competition. Students will begin to prepare vehicles at the MIT Sailing Pavilion for their lab work.

- *Week 9*: In week 9, we will have our first guest lecturer, Dr. Mae Seto from Defence Research and Development Canada (DRDC). Dr. Seto will present joint research at DRDC and Dalhousie University on arctic exploration with unmanned underwater vehicles.

  The second meeting in this week will be dedicated to student presentations of their autonomous hazard search lab solutions, and results from the in-class competition held during the first lab of this week. The second lab of this week is at the MIT Sailing pavilion preparing students for an in-water run of their autonomous hazard search solutions.

- *Week 10*: In the first week 8 meeting, the topic returns to behavior creation and in particular the elements of the IvP tool for creating objective function output of behaviors. We discuss the characteristics of the decision space used on autonomous vehicles and how it is configured by the user and handled by the helm. We describe the notion of piecewise linear approximation of smooth objective functions, and general strategies for creating these approximations quickly. We then tie these concepts to the actual hooks in the helm software used in this class.

  In the second meeting, the primary focus is on parameter estimation in preparation for the final "front-estimation" lab in the course. Topics covered are least square approximation, parameter estimation, curve fitting, simulated annealing and genetic algorithms.

  In the first lab of this week students will complete their in-water demonstration of their hazard search solution on the autonomous surface craft at the Pavilion. The goal is not to

compete on the solution metrics, but rather to accustom the students to operating vehicles in the water using a problem they are well familiar with.

In the second lab of this week, the front-estimation challenge will be introduced to the students. In this lab the objective is to estimate a time-varying thermal front using a vehicle equipped with a single point sensor measuring the temperature in the water at that position in time. Students will be provided with a simulated annealer to aid in the estimation of the front characteristics, but will be challenged to develop an autonomous search algorithm that results in the best possible estimation of the front characteristics.

- *Week 11*: We will only have one meeting this week due to the Patriots Day holiday. The focus of this meeting is on *adaptive acoustic sensing* and its relationship to intelligent autonomy. Passive sensing and the problem of passive acoustic tracking with a towed array is present, with discussions of related field-trial results. Other topics include model-based environmental adaptation, depth-dependent acoustic sensing, and deep ocean communication connectivity. Active sensing and results from related field trials will also be presented.

  Our lab work this week will continue with in-water vehicle preparation for the parameter estimation lab at the MIT Sailing Pavilion.

- *Week 12*:

  In our first meeting this week, we will have our second guest lecture on AUV Navigation, by Prof. John Leonard. Topics include a review of AUV navigation, underwater SLAM, feature based navigation, moving long baseline navigation.

  The first lab of this week is the simulation competition on the front estimation lab. Students will present their results in the second lecture time slot. The second lab this week will be at the Pavilion preparing for the in-water version of the front-estimation lab.

- *Week 13*: The first meeting this week will be dedicated to covering basic safety operations related to multi-vehicle operating at the pavilion. This includes how to configure standard mission components for recovering and emergency station-keeping of the vehicles.

  In the second meeting this week we will have our third guest lecture, Dr. Lee Freitag from the Woods Hole Oceanographic Institution.

- *Week 14*: In our last week, our last lecture will include a discussion of active research in COLREGS autonomy, or collision avoidance in accordance to the Coast Guard Collision Regulations. This will include open components of this research for those considering topics for their research studies.

  Our last class will be used for student presentations of their in-water front-detection competition.