Accelerated Marine Vehicle Autonomy, Sensing, and Communications

Spring Semester 2019
2.014 Autonomy Mini-course

Introduction

We are driven by the desire to use marine robotic systems to better understand our oceans, our coastal regions and inland waters.

Our focus is on the relationship between autonomy, sensing and communications to maximize the performance of marine robotic systems.
Lab Overview

MIT Laboratory for Autonomous Marine Sensing Systems

Thank You!!
MIT Marine Robotic Platforms
The Bluefin SandShark One-Person Portable UUV

Two Bluefin 21-inch UUVs
(Macura and Unicorn)
Lab Overview

MIT Marine Robotic Platforms
The Clearpath Robotics Heron USV

Lab Overview

MIT Marine Robotic Platforms
The WAM-V Unmanned Surface Vehicle
MIT Marine Robotic Platforms
The WAM-V Unmanned Surface Vehicle
From RobotX 2014 – International Competition in Singapore

MOOS-IvP Open Source Marine Robotics Community
(MOOS-DAWG’15)
moos-dawg.org
MOOS-IvP Open Source Marine Robotics Community
(MOOS-DAWG’17)
moos-dawg.org

Lab Overview
Autonomy Trends
Autonomy Education
Three Architectures
MOOS-IvP
Projects
Course Objectives

Michael Benjamin, Henrik Schmidt

MIT Dept of Mechanical Engineering

Marine Autonomy Trends
Marine Autonomy Trends

- Recent Past and Present. (And future?)

2006 2016 2026?

- The Role of Open Source Software

Monterey Bay 2006

PLUSNet Field Trials on the R/V New Horizon

Monterey Bay 2006 (PLUSNet)
• Payload Autonomy supported on virtually all commercial platforms.
• The MIT MOOS-IvP Project Launched. (35+ work-years, 130,000+ lines of code, 40+ applications)
Marine Autonomy

2006

2016

2026?

Trends in Component Technologies

Platforms

Launch & Recovery

Acoustic Comms

Sensors

Computation Power

Autonomy
Trends in Component Technologies

Critical maturity level

Components:

Platforms
Launch & Recovery
Sensors
Acoustic
Comm's
Autonomy

Computation
Power

Time:

1995
2006
2018
2025 ??

Autonomy:

Deterministic/Canned
Adaptive/Dynamic
Collaborative

Marine Autonomy

2006
2016
2026?

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Trends in Component Technologies

Prediction: Human Robot Interaction will grow in importance 2017-2017

Human Robot Interaction

Platforms
- reliability
- endurance
- cost, size

Launch & Recovery

Sensors

Acoustic Comms

Computation Power

Autonomy

Components:
- Launch & Recovery
- Sensors
- Compute
- Power
- ACOMMS
- MOOS

Time:
- 1995
- 2006
- 2017
- 2027 ??

Autonomy:
- Deterministic/Canned
- Adaptive/Dynamic
- Collaborative
- Cyborg

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Autonomy Education
Robot Software is an Ecosystem
The MOOS-IvP Ecosystem

Example Missions

Documentation

Tools
• Device/Sensor interfaces
• Vehicle Simulation
• Environmental Simulation
• Comms Simulation
• Debugging Tools
• Mission Planning Tools
• Mission Operation Tools

Autonomy Behaviors

Math and Utility Libraries

Autonomy Architecture

Robot Middleware

• 35+ workyears
• 140,000+ lines of code
• 20+ vehicle types
• 40+ projects
• 9+ countries

MIT 2.680 Marine Autonomy, Sensing and Communications

MIT MECH. Dr. Michael Benjamin, Prof. Henrik Schmidt

APPROACH

• Undergraduate and Graduate students.
• The principles and skills needed to field a fully autonomous marine vehicle capable of long-duration missions with little or no human intervention.
• The relationship between the ocean environment and limits in underwater communication, and the opportunity to overcome some limits with intelligent and coordinated mobility between platforms.
• The potential for intelligent autonomous mobility to overcome sensing limits faced by non-adaptive single vehicles or single-vehicle systems without communications.

SPONSOR/STATUS

• Funded by Battelle since 2011 – support for course development, robot and computing equipment and lab space. $1.2M since 2011.
• Average course eval since 2011: 6.3 / 7.0.
• Average instructor eval since 2011: 6.8 / 7.0.
• Next offered Spring Term 2018.
Evolution of the Ecosystem, Education and Research

- MOOS written
- IvP written
- IvP Integrated with MOOS
- Payload autonomy introduced
- First MOOS-DAGG Users workshop
- First offering of MIT 2.680

- Build 100% of the ecosystem yourself
- Build 40% of ecosystem
- Build 20% of ecosystem
- Build 5% of ecosystem
- Learn from apprenticing
- Learn from documentation
- Learn from apprenticing
- Learn from coursework
- Learn from documentation
- Learn from apprenticing

- Faculty
  - Post-docs
- Faculty
  - Post-docs
  - PhD students
- Faculty
  - Post-docs
  - PhD students
  - Masters students
- Faculty
  - Post-docs
  - PhD students
  - Masters students
  - Undergrads

MIT 2.680 Students (2015)
Architectures
Robot Architectures: Ground, Air and Sea

Robot Software
(What's Inside?)

Proprietary Autonomy
(50 work years)
Robot Architectures: Ground, Air and Sea

Proprietary Autonomy
(30 work years)

GNU/Linux

Proprietary Autonomy
(10 work years)

Component Software
Robot Middleware
GNU/Linux

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Robot Architectures: Ground, Air and Sea

- Proprietary Autonomy (~0 Work Years)
- MOOS-IvP
  Open Robot Autonomy
  (35 Work Years)
  (www.moos-ivp.org)
- GNU/Linux

Robot Architectures: Ground, Air and Sea

- Proprietary Autonomy (~0 Work Years)
- Component Autonomy
- Robot Autonomyware
- Component Software
- Robot Middleware
- GNU/Linux

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MOOS-IvP Open Source Marine Autonomy Software
MIT MECHE. Dr. Michael Benjamin, Prof. Henrik Schmidt

• Used on dozens of distinct vehicle types: marine, ground, air. Predominantly marine.

APPROACH
• Key idea: Multi-objective optimization to balance competing autonomy goals on each decision, several times per second.
• New Autonomy behaviors easily integrated by simply requiring each behavior to produce an objective function over a common decision space.
• The Helm, and behaviors, are part of a larger ecosystem of software including simulation modules, mission monitoring, post-mission analysis, and visualization tools.
• 130,000+ lines of code. 35+ work years. All MIT.

SPONSOR/STATUS
• Funded by ONR (Code 311) since 2004.
• Funded by Battelle since 2011.
• MOOS-IvP software is the basis for MIT 2.680 student labs and in-water exercises.
• Latest release was July 2017.
• Autonomous COLREGS algorithms included in the July 2017 release.
• Next release planned for January 2018.
• Industry impact: Riptide Autonomous Solutions, and Sea Machines: two recent start-ups based their autonomy on MIT/MOOS-IvP software.

Payload UUV Autonomy
(Architecture Principle #1: Payload Autonomy)

UUV
Payload Computer
Main Vehicle Computer
• ROS, DOS, Windows...
• Bluefin, Hydroid, Gavia, Ocean Server, Clearpath, ...

Autonomy commands ➞ Navigation Info

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2/21/19
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Platforms Field-Deployed with MOOS-iP Payload Autonomy

Payload Autonomy

(Architecture Principle #1: Payload Autonomy)
Payload Autonomy
(Architecture Principle #1: Payload Autonomy)

Main Vehicle Computer
- ROS, DOS, Windows...
- Bluefin, Hydroid, Gavia, Ocean Server, Clearpath, ...

Payload Computer

• ROS, DOS, Windows…
• Bluefin, Hydroid, Gavia, Ocean Server, Clearpath, …

Payload Autonomy
(Architecture Principle #2: Publish-Subscribe Middleware)

Main Vehicle Computer

Architecture Principle #2
Autonomy System Middleware
De-couple Software Procurements
Sensing, Autonomy, Simulation, Comms...

Simulation
MOOS Application
MOOS Application

Contact Management

MOOS Helm
Autonomy
Payload Autonomy (Architecture Principle #3: Behavior-Based Helm)

MOOS Middleware
MOOS Applications

Main Vehicle Computer
- ROS, DOS, Windows...
- Bluefin, Hydroid, Gavia,
  Ocean Server, Clearpath, ...

Payload Computer

Simulation

Sensing

MOOS Application

Contact Management

Comm.

MOOS Application

Autonomy

Payload Computer

IvP Helm

Behavior-Based Modular HELM

UUV

MOOS-IPv
What is MOOS? MOOS-IvP?

- MOOS is Open Source Robot Middleware from Oxford
- MOOS is application communications architecture

- IvP is Open Source Autonomyware from MIT
- IvP is an autonomous decision-making architecture.

- Both are Open Source
- Both support layering of commercial, proprietary, even classified components built upon the Open Source libraries.

Overview of the IvP Helm
Behavior Output and Action Selection

- The objective functions are called IvP functions – functions of a certain format.
- The Solver is called the IvP Solver – they exploit the IvP function structure.

- Typical Decision Space: Heading, Speed, Depth
IvP Functions
The IvP Function vs. Underlying Function

An **IvP function** is a piecewise linear approximation of an objective function, over a discrete decision space (domain).

\[ f(x,y) = \left(1 - \frac{\sqrt{(x-250)^2 + (y-250)^2} - 100}{250}\right)^8 \times 200 - 100 + \left(1 - \frac{\sqrt{(x-50)^2 + (y-50)^2} - 100}{250}\right)^8 \times 200 - 100 \]

**Piecewise Linear Approximation**
525 Pieces

---

Overview of the IvP Helm
Example IvP Functions for Collision Avoidance
Interval Programming Solution Algorithms

Overview

An IvP problem consists of a set of $k$ functions, each with a priority weighting. The solution is given by:

$$\hat{x}^* = \arg\max_x \sum_{i=1}^{k} w_i f_i(x)$$

The Search Tree:
- 1 level for each function
- $n^k$ leaf nodes ($n$ pieces per function).

The Solution algorithm:
- Branch and bound
- Pruning based on intersection look-ahead.

Example:
Waypoint Traversal
Behavior
Overview of the IvP Helm
Behavior Output and Action Selection

Objective Functions

Example:
Collision Avoidance Behavior

\[
\begin{align*}
& \text{Behavior 1: } \mathbf{x}_1(x_1, x_2, \ldots, x_n) \\
& \text{Behavior 2: } \mathbf{x}_2(x_1, x_2, \ldots, x_n) \\
& \text{Behavior 3: } \mathbf{x}_3(x_1, x_2, \ldots, x_n)
\end{align*}
\]

Solver

\[
\bar{x}^* = \arg \max_x \sum_{i=1}^{k-1} w_i f_i(\bar{x})
\]

Action

\[
\mathbf{w}_i f_i(\mathbf{x}) = 0
\]
COLREGS Autonomy

- **Funded by:** Office of Naval Research (ONR)
- **Idea:**
  - Enable autonomous surface vehicles to obey the “Rules of the Road” COLREGS.
  - Establish a road test for validating the autonomous collision avoidance.

Humans are very good at improvising

[link to PortOfAmsterdam.mov]
COLREGS Autonomy

• Funded by: Office of Naval Research (ONR)
  • Enable autonomous surface vehicles to obey the “Rules of the Road” COLREGS.
  • Establish a road test for validating

• Research Focus:
  • Map the protocols written for humans into algorithms.
  • Find minimal set of field tests that validate widest set of scenario permutations.

• Technical Approach:
  • Collision avoidance protocols mapped to set of modes, and submodes.
  • Modes map to a unique form of objective function. Multi-objective optimization with IvP to solve.

• Impact:
  • Autonomous long-duration coastal sampling with autonomous platforms.
  • Multi-vehicle/swarm capabilities can be built on COLREGS foundation.
COLREGS Collision Avoidance

(sponsored by ONR)

- The objective is to avoid collisions with other autonomous and non-autonomous vehicles.
- COLREGS are the rules of the road for seagoing vessels.
- They provide a protocol of roles and required actions between vessels.
- They were written for humans, not autonomous systems.

Collision Avoidance without COLREGS

What’s Wrong with Non Protocol Based Collision Avoidance?

- Consider the head-on situation
- If ownship rates candidate maneuvers based on closest point of approach, a maneuver to port or starboard looks equally good.
What's Wrong with Non Protocol Based Collision Avoidance

- Consider the head-on situation
- If ownship rates candidate maneuvers based on closest point of approach, a maneuver to port or starboard looks equally good.

- And the same is true for the contact, so
- It's possible one turns to port and the other to starboard, or vice versa.

![Contact vs Ownship Diagram]

COLREGS Collision Avoidance

- The head-on situation is referenced in Rule 14 of the COLREGS.

  When two power-driven vessels are meeting on a reciprocal or nearly reciprocal courses so as to involve a risk of collision each shall alter her course to the starboard so that each shall pass on the port side of the other

- The COLREGS IvP Behavior on ownship heavily penalizes the "wrong" kind of turn.

![COLREGS Diagram]
COLREGS Collision Avoidance

• The head-on situation is referenced in Rule 14 of the COLREGS.

When two power-driven vessels are meeting on a reciprocal or nearly reciprocal courses so as to involve a risk of collision each shall alter her course to the starboard so that each shall pass on the port side of the other.

• The COLREGS IvP Behavior on ownship heavily penalizes the "wrong" kind of turn.

![Heatmap of COLREGS Collision Avoidance](image)

COLREGS Collision Avoidance

• The give-way (crossing) situation is referenced in Rule 15 of the COLREGS.

When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

• The give-way vehicle may cross ahead of the other vessel if it clearly makes more sense.

![Heatmap of COLREGS Collision Avoidance](image)
COLREGS Collision Avoidance

- The objective is to avoid collisions with other autonomous and non-autonomous vehicles.
- COLREGS are the rules of the road for seagoing vessels.
- They provide a protocol of roles and required actions between vessels.

Collision Avoidance with COLREGS

COLREGS - Testing / Validation

In-Water Tests

Simulation
COLREGS
Testing / Validation

Simulation
Data

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Michael Benjamin, Henrik Schmidt
MIT Dept of Mechanical Engineering
How do we learn from the data?

The Challenge:
- 12 hours of simulation
- 4 vehicles
- 1009 encounters

When did something interesting happen?

RESULTS
- 1009 encounters
- 2 collisions
  - one 0.95m
  - one 7.5m
- 9 near misses (8-12m range)
### Auto Generated Encounter Plots

**Encounter Plots**
- Part of the alogview tool
- Open Source
- Works on any mission log file
- Developed Nov '15 to present.
- In latest Release 17.7 of MOOS-IvP

### Aquaticus  Human-Robot Cooperative Teaming Test-bed

**MIT MECHE. Dr. Michael Benjamin, Dr. Michael Novitzky, Prof. Henrik Schmidt**

#### APPROACH
- Mixed Human-robot teaming with humans in the field of play with robotic teammates.
- Unique factor: full in-field integration of human teammates. Multiple communication modes.
- Field is ~160x80m on Charles River at MIT.
- Choice of robot autonomy configurations, modes, strategies, contingencies, protocols must consider what is most useful and digestible to humans.
- Humans are in motorized kayaks with voice-to-text for comms to robots.

#### SPONSOR/STATUS
- Funded by DARPA TTO through ONR. Seedling.
- Full competitions (4 on 4) planned for summer 2018.
- Operated in conjunction with Marine Autonomy Summer High School Program (Year 3, 2018).
- Human-Use Approval (MIT, DoD) March 2017.
- Goals, operating environment, team structure may be changed mid-competition, per requests of model developers.
Hypotheses:

The most effective Human-Robot systems are where the robot **augments** the human. An effective robot is one that has high **autonomous capability**, high **operator trust**, and low **operator load**.

This is a tradeoff space – the right mix is not immediately obvious for a given application or set of humans. Part of Aquaticus is to discover the basic relationships – to find that mix for any human-robot application.
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Boston Harbor RoboChallenge - Autonomous Inland Transiting

MIT MECHE, Dr. Michael Benjamin, Dr. Paul Robinette, Dr. Michael Novitzky, Prof. Henrik Schmidt

APPROACH

• Fully autonomous deployment of an unmanned surface vehicle launched from MIT transiting to Mass Bay.
• Collision free path with static obstacles, lock walls, bridge pylons, buoys.
• Collision free path with moving vessels, ensuring safety and COLREGS compliance
• Accurate detection of contact bearing, range and heading relative to the robot.
• Autonomous voice interaction with Lock operators and Drawbridge operators.
• Navigation in GPS-denied areas.

SPONSOR/STATUS

• Funded by Lockheed Martin and Battelle
• Mercury Marine support in the form of a donated Boston Whaler support vessel.
• 2017 Partial autonomy transits, sensor development, robot–marine radio interface development.
• 2018 goals: autonomous transit through bridges, radar and LIDAR integration for collision avoidance, migration of COLREGS code, testing for voice interface over marine radio.

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Boston Harbor Robo-Challenge

• Remote Ocean Sensing Launched from MIT
• Entering Year 2 of Lockheed support

Lockheed Martin

Boston Harbor Robo-Challenge
Sep 12th 2013

Battelle
Summer Marine Robotics Internship Program
MIT MECH. Dr. Michael Benjamin, Dr. Michael Novitzky, Dr. Paul Robinette, Prof. Henrik Schmidt

**APPROACH**
- 10 Week program from late June to mid August
- Learn to program marine robot software
- Robot "pit crew" support research experiments involving up to 8 simultaneous deployed robots.

- High School students mentored by
- Undergraduates mentored by
- Graduate students mentored by
- Faculty and Research Staff
- 2017: 6 HS students, 4 Undergrads, 4 Grad students.

**SPONSOR/STATUS**
- Funded by Battelle, DARPA and MIT UROP Office
- Began in 2016 with 5 students
- 2017 program had 14 students
- 50-60 applicants each year, applications open in January, acceptances sent March 31st.
- Skills learned: Programming (C++), Robot autonomy architecture (MOOS-IvP), command line operation of robots, networking, version control software, boat handling/safety, video editing and social media communications.

RobotX International Autonomous USV Competition
MIT MECH. Dr. Michael Benjamin, Dr. Paul Robinette, Prof. Henrik Schmidt

**APPROACH**
- Competition using a 16-foot unmanned surface vehicle (USV). Identical vehicle for all teams.
- All teams are university based.
- Focus is on sensing and autonomy.
- Tasks include:
  - obstacle detection and avoidance,
  - path planning throug a buoy field, autonomous docking,
  - underwater inspection and others.
- MIT team will leverage MOOS-IvP autonomy codebase, and the WAM-V platform used in the Boston Harbor RoboChallenge project.

**SPONSOR/STATUS**
- MIT Team will compete in Hawaii, December 2018.
- Student team needs to raise funds – sensor and computing equipment, shipping, travel and lodging.
- MIT team seeks corporate sponsorship. Existing Battelle grant covers some research staff time for mentoring.
- The 2014 Team won the Grand Prize, roughly $6K of 2014 prize funds to be used in 2018.
END