Accelerated Marine Vehicle Autonomy,
Sensing, and Communications

May, 2017
國立台灣大學
National Taiwan University - Taiwan

Introduction

Web http://oceanai.mit.edu/ivpman

Email:
Mike Benjamin mikerb@mit.edu
Henrik Schmidt, henrik@mit.edu

Schedule

Day 1 (Saturday, May 20th):
- Lecture 1: *Introduction to Marine Autonomy at MIT*
- Lab 1: Getting Started with the MIT MOOS-IvP Software

Afternoon
- Lecture 2: *Introduction to MOOS*
- Lab 2: Working with MOOS

Day 2 (Monday May 22nd):
- Lecture 3: *Introduction to the IvP Helm*
- Lab 3: Getting Started with the Helm

Afternoon
- Lecture 4: *A Deep Dive into Behaviors*
- Lab 4: Working with Behaviors

Day 3 (Tuesday May 22nd):
- Lecture 5: *Multi-Vehicle Operations*
- Lab 5: Simulating Multi-Vehicle Operations on Multiple Machines

Afternoon
- Lecture 6: *Inter-Vehicle Communications*
- Lab 6: Simulated Multi-Vehicle Missions with Communications

Day 4 (Wednesday May 23rd): Pool Tests

Today's Material

From your Browser:

- http://oceanai.mit.edu/ntu/lecture01.pdf
- http://oceanai.mit.edu/ntu/lab01.pdf
- http://oceanai.mit.edu/ntu/lecture02.pdf
- http://oceanai.mit.edu/ntu/lab02.pdf

Or using wget:

```
$ wget http://oceanai.mit.edu/ntu/lecture01.pdf
$ wget http://oceanai.mit.edu/ntu/lab01.pdf
$ wget http://oceanai.mit.edu/ntu/lecture02.pdf
$ wget http://oceanai.mit.edu/ntu/lab02.pdf
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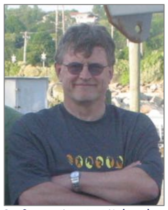
Lab Overview

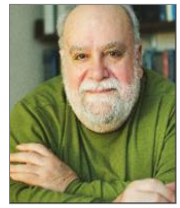
MIT Laboratory for Autonomous Marine Sensing Systems

Collaborators


Prof. Henrik Schmidt (MIT)

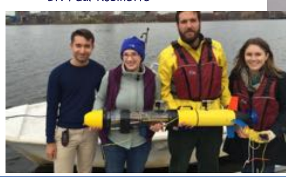

Prof. John Leonard (MIT)


Prof. Paul Newman (Oxford)

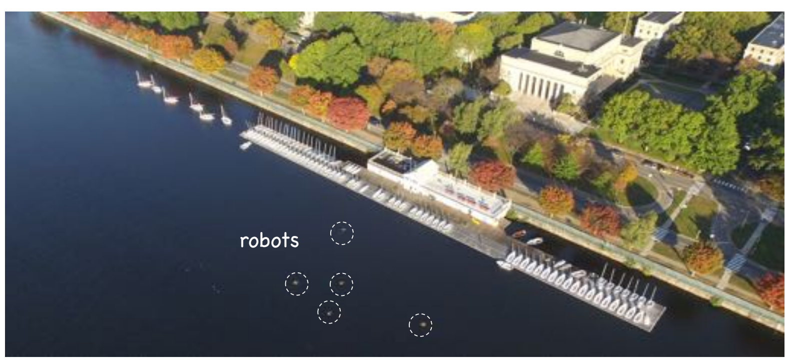

Prof. Chryssostomidis (MIT)


Dr. Michael Novitzky


Dr. Paul Robinette



The MIT Marine Autonomy Bay



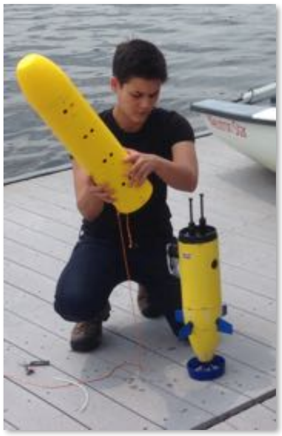
- Laboratory for Autonomous Marine Sensing Systems (MECHE)
  henrik@mit.edu

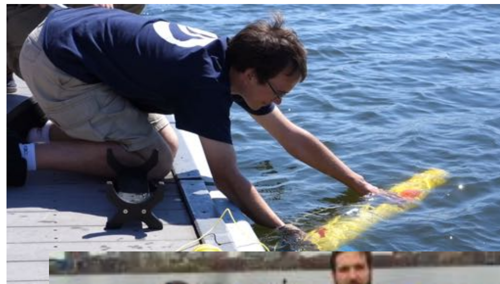
- Marine Robotics Group (CSAIL)
  jleonard@mit.edu

- The AUV Laboratory (MIT Sea Grant)
  chrys@mit.edu

MIT Marine Robotic Platforms

The Bluefin SandShark One-Person Portable UUV



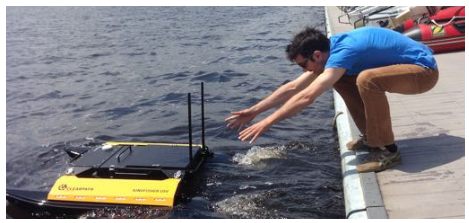


MIT Marine Robotic Platforms

Two Bluefin 21-inch UUVs (Macrura and Unicorn)

MIT Marine Robotic Platforms

The Clearpath Robotics Heron USV



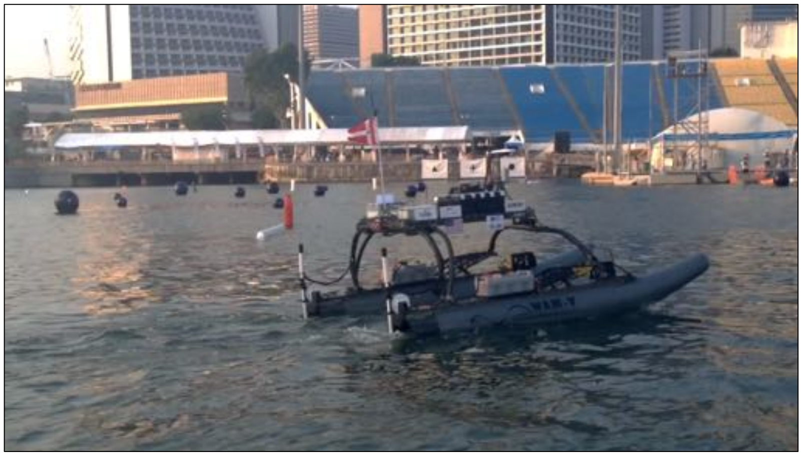
MIT Marine Robotic Platforms

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)

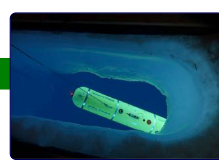
moos-dawg.org

Marine Autonomy Trends

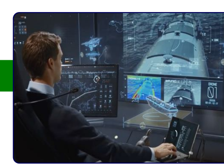
Marine Autonomy Trends

- Recent Past and Present. (And future?)

2006



2016



2026?

- The Role of Open Source Software

Lab Overview | Autonomy Trends | Autonomy Education | Three Architectures | MOOS-IvP | Projects | END

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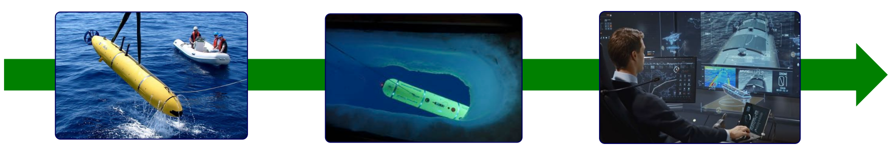
Monterey Bay 2006

PLUSNet Field Trials on the R/V New Horizon

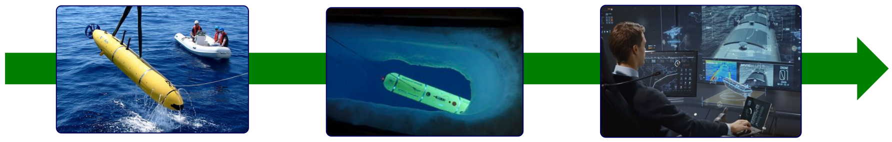
Marine Autonomy



2006 2016 2026?

- Payload Autonomy supported on virtually all commercial platforms.
- The MIT MOOS-IvP Project Launched. (35 work-years, 130,000 lines of code, 30+ applications)

Marine Autonomy



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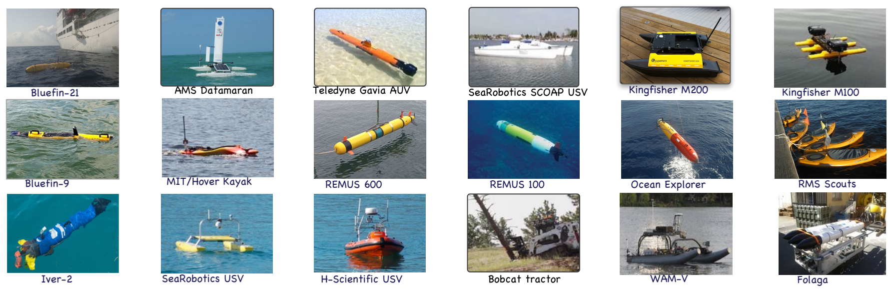

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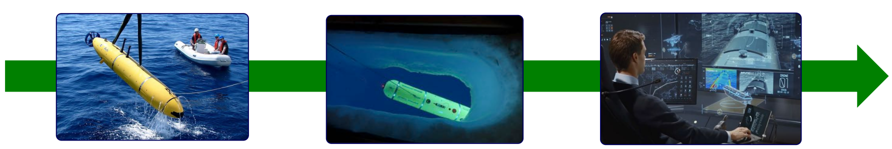
Marine Autonomy



2006 2016 2026?

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ICEX 2016

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Marine Autonomy

2006 2016 2026?

?

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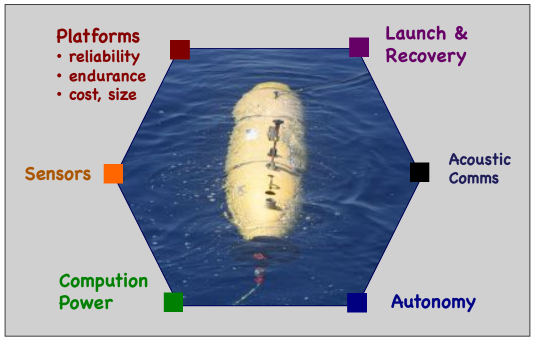
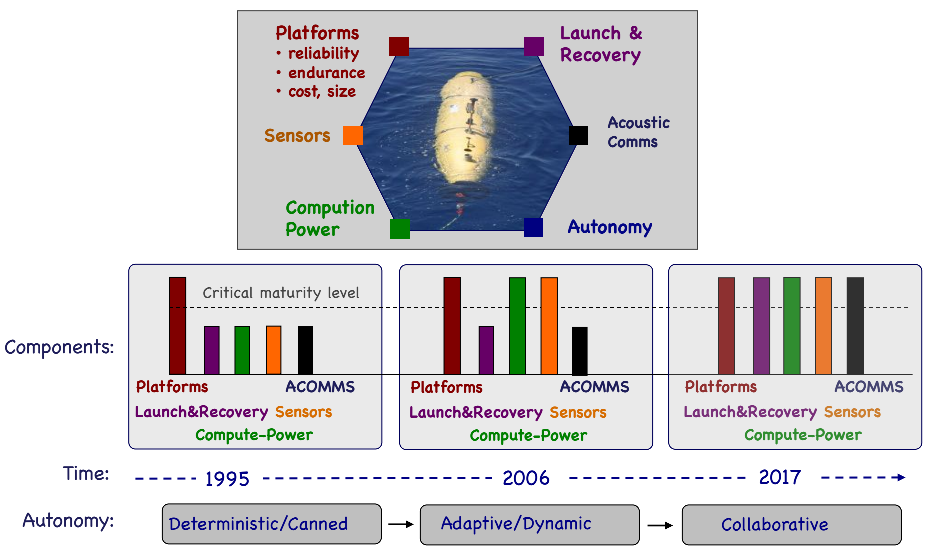
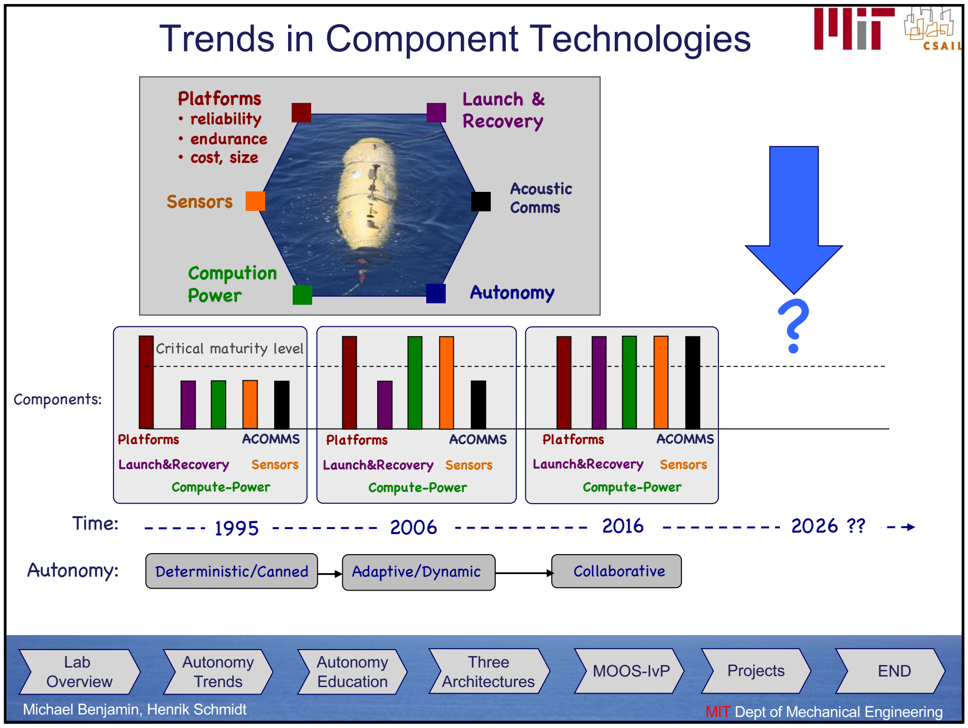
Trends in Component Technologies



Trends in Component Technologies




Trends in Component Technologies
Platforms
• reliability
• endurance
• cost, size
Launch & Recovery
Acoustic Comms
Sensors
Compution Power
Autonomy
Critical maturity level
Components:
Platforms ACOMMS
Launch&Recovery Sensors
Compute-Power
Platforms ACOMMS
Launch&Recovery Sensors
Compute-Power
Platforms ACOMMS
Launch&Recovery Sensors
Compute-Power
?
Time: ----- 1995 -------- 2006 ---------- 2016 --------- 2026 ??
Autonomy: Deterministic/Canned Adaptive/Dynamic Collaborative
Lab Overview
Autonomy Trends
Autonomy Education
Three Architectures
MOOS-IvP
Projects
END
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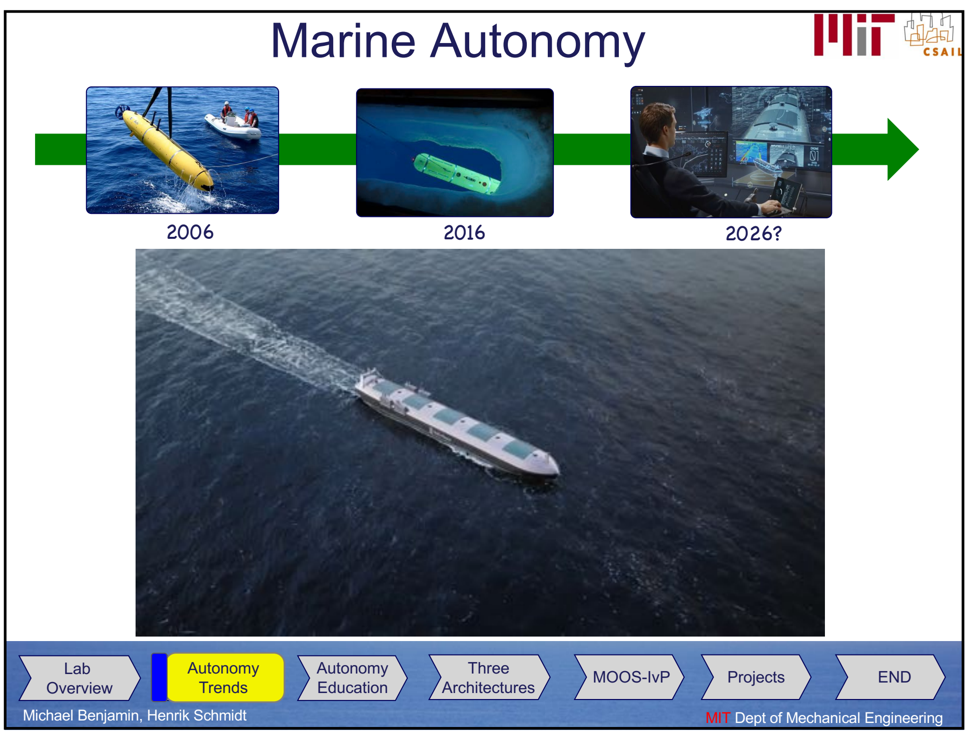
Marine Autonomy
2006
2016
2026?
Lab Overview
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END
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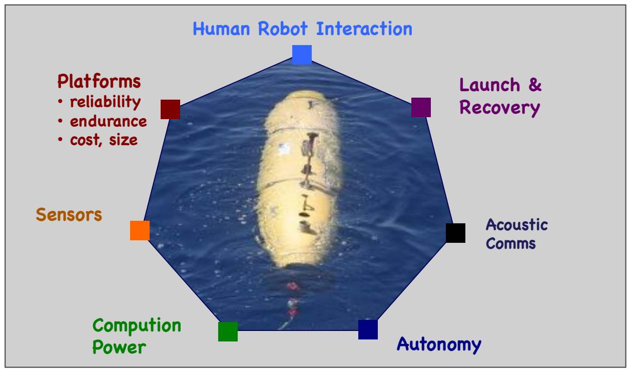
Trends in Component Technologies

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



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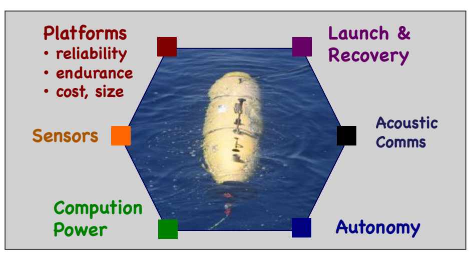
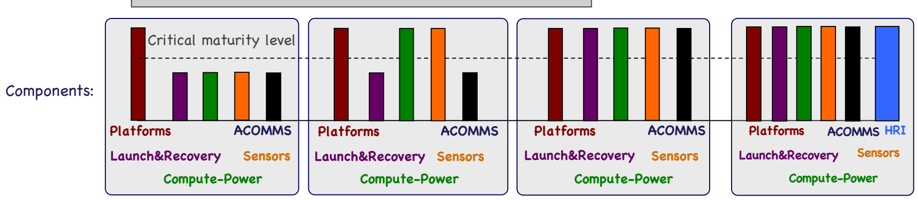
Trends in Component Technologies





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

Autonomy: Deterministic/Canned → Adaptive/Dynamic → Collaborative

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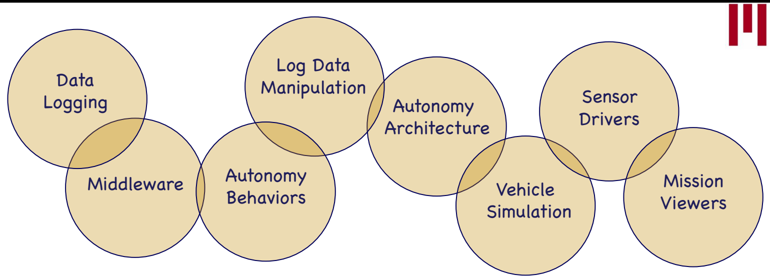
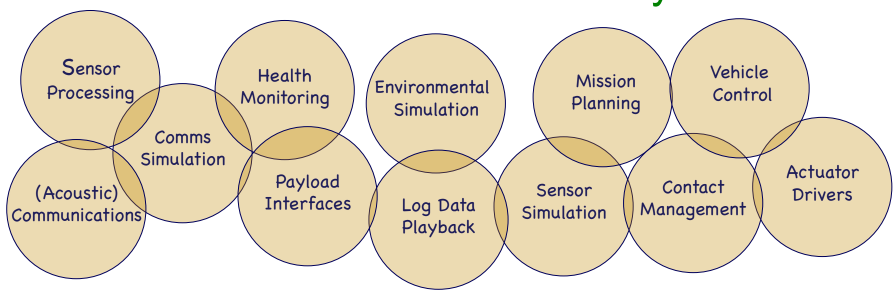
Autonomy Education

Autonomy Education

Robot Software is an Ecosystem



Robot Software is an Ecosystem



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The MOOS-IvP Ecosystem

- 800+ pages of text
- Many Working examples
- Agreement w/ Cambridge Univ. Press
- 35 workyears
- 120,000 lines of code
- 20 vehicle types
- 40+ projects
- 9+ countries

Example Missions

Documentation

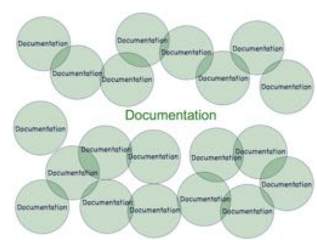
Tools
- Device/Sensor interfaces
- Vehicle Simulation
- Environmental Simulation
- Comms Simulation
- Debugging Tools
- Mission Planning Tools
- Mission Operation Tools

Autonomy Behaviors

Math and Utility Libraries

Autonomy Architecture

Robot Middleware



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Evolution of the Ecosystem, Education and Research

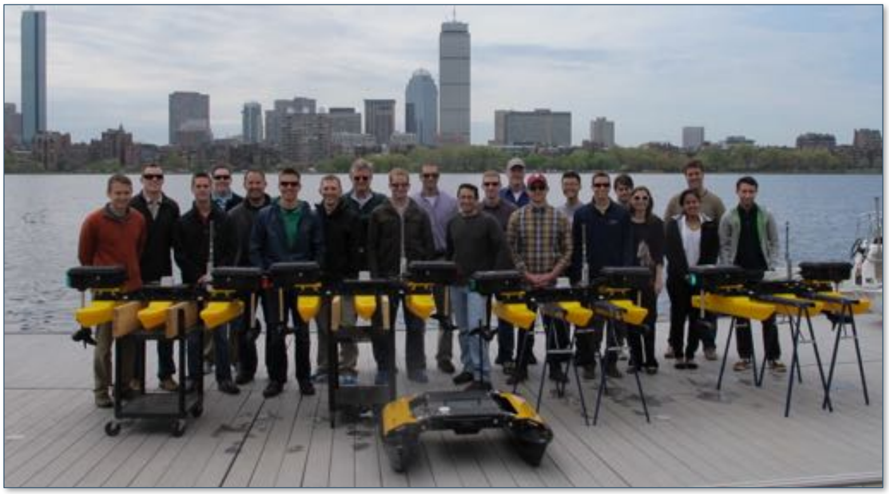
2000	2005	2010	2017
MOOS written	IvP Integrated with MOOS; Payload autonomy introduced	First MOOS-DAWG Users workshop	First offering of MIT 2.680
• Build 100% of the ecosystem yourself	• Build 40% of ecosystem	• Build 20% of ecosystem	• Build 5% of ecosystem
	• Learn from apprenticing	• Learn from documentation • 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

Class Structure

1. Overview of Marine Vehicles – Technologies, Commercial Platforms, Common Missions
2. Fundamentals of the marine robotics software environment
   - Command-line environment, text editing, use of the shell, scripts etc.
   - Introduction to C++
   - Version control software
3. Introduction to MOOS Middleware and Common MOOS applications
   - Using existing MOOS application
   - Writing your own simple MOOS applications
4. Introduction to Marine Autonomy, IvP Helm

5. First Marine Autonomy Lab sequence on the Hazard Search Problem
6. A Lab sequence on Acoustic Communications
7. Second lab sequence continuing Hazard Search – in-water experiments
8. Third Lab on Autonomous Thermal Front Detection

MIT 2.680 Students



MIT 2.680 Students

(May 16th 2017)

Lab Overview | Autonomy Trends | Autonomy Education | Three Architectures | MOOS-IvP | Projects | END

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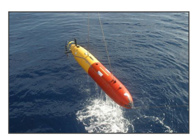
Architectures

Robot Architectures: Ground, Air and Sea

Robot Software

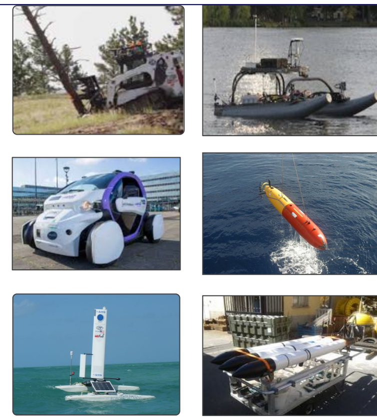
(What's Inside?)



Robot Architectures: Ground, Air and Sea

Proprietary Autonomy

(50 work years)



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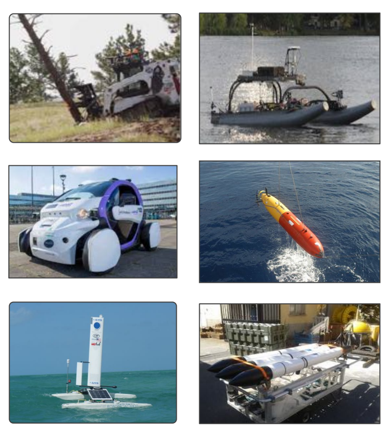
Robot Architectures: Ground, Air and Sea

Proprietary Autonomy

(30 work years)

GNU/Linux



Lab Overview | Autonomy Trends | Autonomy Education | Architectures | MOOS-IvP | Projects | END

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Robot Architectures: Ground, Air and Sea

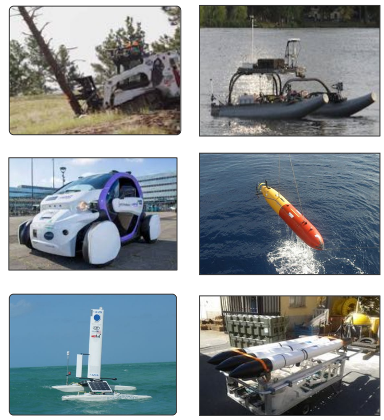
Proprietary Autonomy

(10 work years)

Component Software

Robot Middleware

GNU/Linux



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Robot Architectures: Ground, Air and Sea

Proprietary Autonomy
(~0 Work Years)

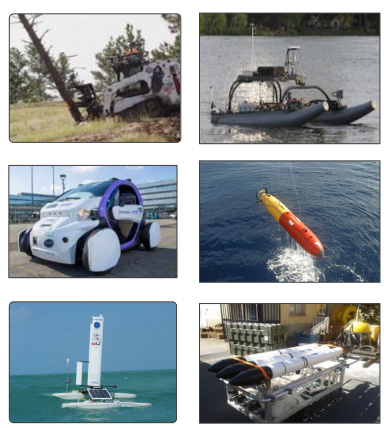
Component Autonomy

Robot Autonomyware

Component Software

Robot Middleware

GNU/Linux



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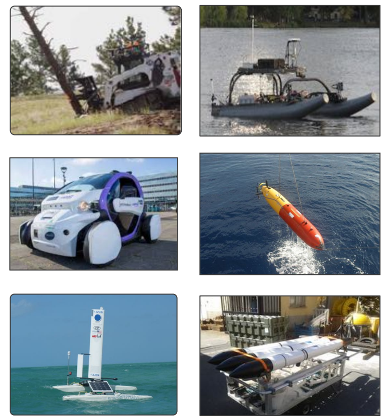
Robot Architectures: Ground, Air and Sea

Proprietary Autonomy
(~0 Work Years)

MOOS-IvP
Open Robot Autonomy

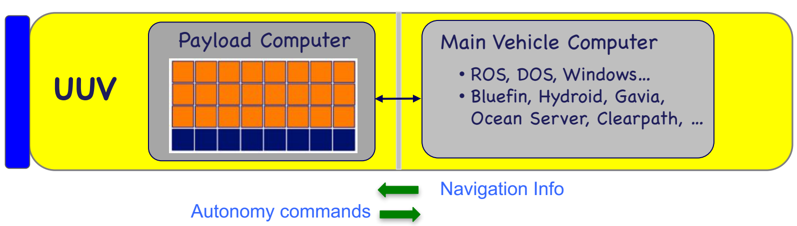
(35 Work Years)
(www.moos-ivp.org)

GNU/Linux

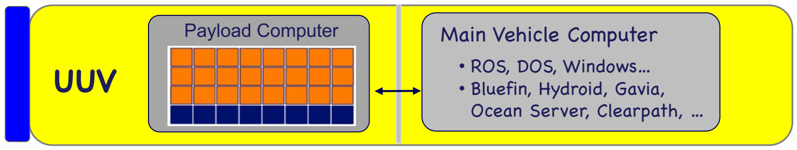


Payload UUV Autonomy

(Architecture Principle #1: Payload Autonomy)



Payload Autonomy
(Architecture Principle #1: Payload Autonomy)



Payload Autonomy
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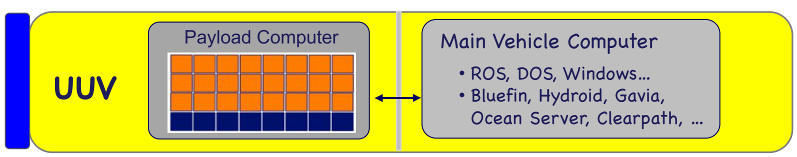
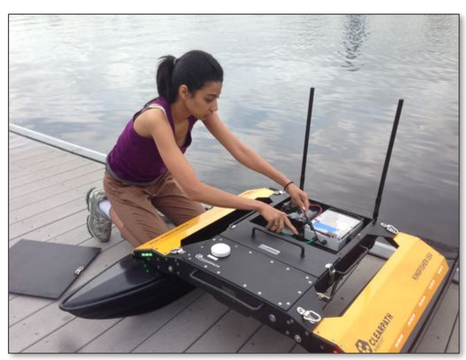
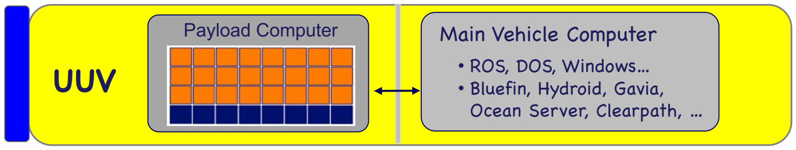
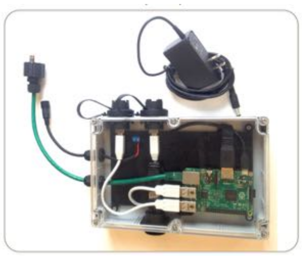


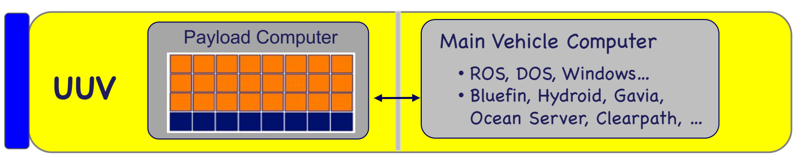


Payload Autonomy
(Architecture Principle #1: Payload Autonomy)

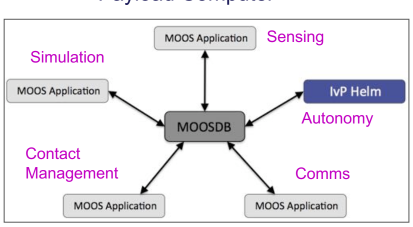




Payload Autonomy
(Architecture #2: Publish-Subscribe Middleware)



Payload Computer



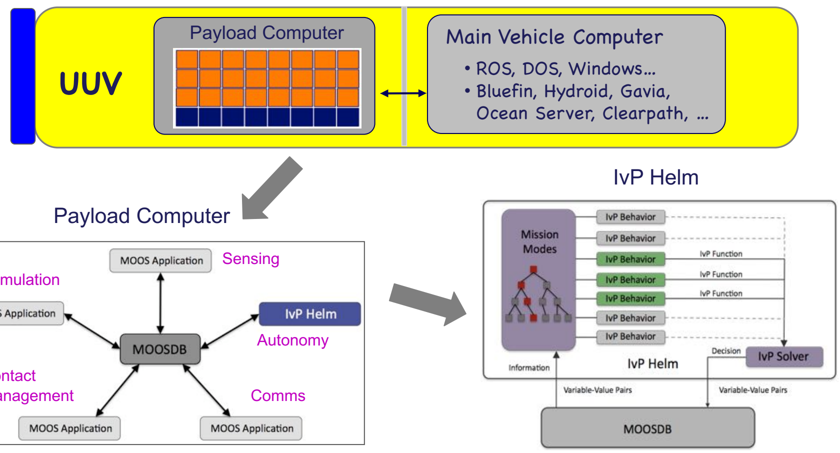
MOOS Middleware
MOOS Applications

Architecture Principle #2
Autonomy System Middleware

De-couple Software Procurements
Sensing, Autonomy, Simulation, Comms…

Payload Autonomy

(Architecture #2: Publish-Subscribe Middleware)



MOOS Middleware
MOOS Applications

Behavior-Based
Modular HELM

MOOS-IvP

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

Behavior 1 → $f_1(x_1, x_2, \ldots, x_n)$
Behavior 2 → $f_2(x_1, x_2, \ldots, x_n)$
Behavior 3 → $f_3(x_1, x_2, \ldots, x_n)$

Objective Functions

$$\vec{x}^* = \underset{\vec{x}}{\operatorname{argmax}} \sum_{i=0}^{k-1} w_i f_i(\vec{x})$$

Solver

Action

- 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

Lab Overview | Autonomy Trends | Autonomy Education | Three Architectures | MOOS-IvP | Projects | END
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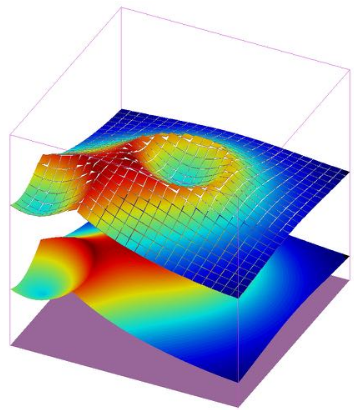
IvP Functions

The IvP Function vs. Underlying Function

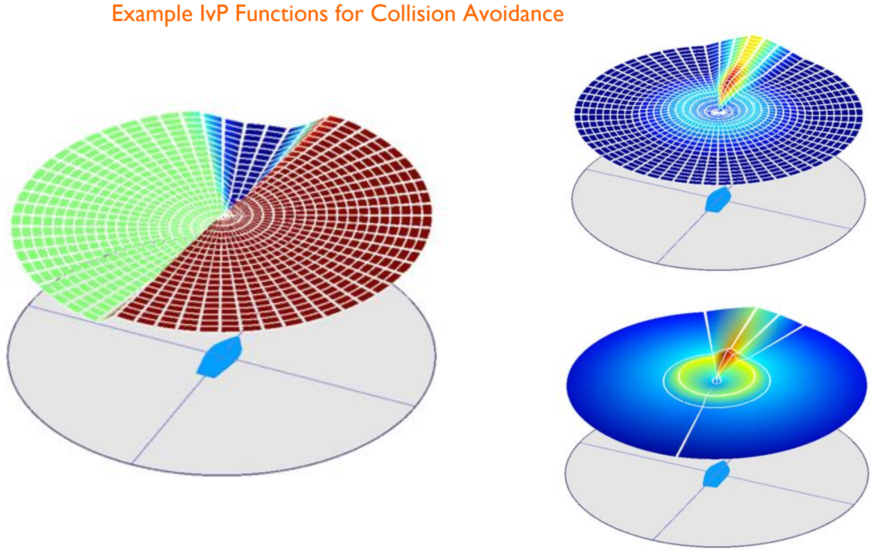
An *IvP function* is a piecewise linear approximation of an objective function, over a discrete decision space (domain).



$$f_i(x,y) = ((1 - \frac{|\sqrt{(x-250)^2 + (y-250)^2} - 100|}{2500})^8 * 200) - 100, + ((1 - \frac{|\sqrt{(x-50)^2 + (y-50)^2} - 100|}{2500})^8 * 200) - 100$$

Overview of the IvP Helm

Example IvP Functions for Collision Avoidance



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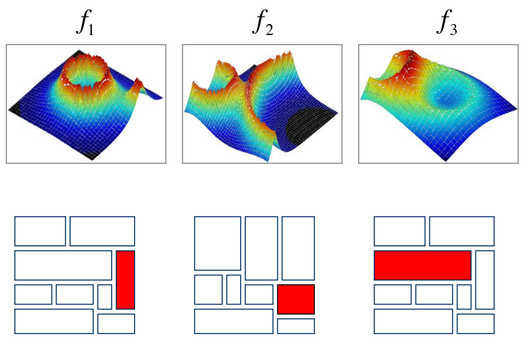
Interval Programming Solution Algorithms
Overview

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

$$\vec{x}^{*} = \underset{\vec{x}}{\operatorname{argmax}} \sum_{i=0}^{k-1} w_i f_i(\vec{x})$$

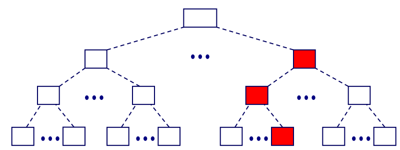


The Search Tree:

- 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.



Overview of the IvP Helm
Behavior Output and Action Selection

Behavior 1 → $f_1(x_1, x_2, \ldots, x_n)$
Behavior 2 → $f_2(x_1, x_2, \ldots, x_n)$
Behavior 3 → $f_3(x_1, x_2, \ldots, x_n)$

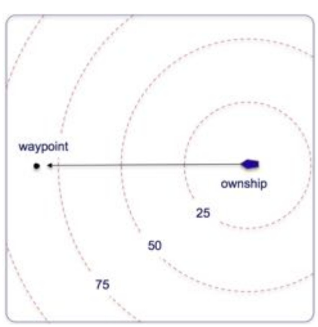
$$\vec{x}^{*} = \underset{\vec{x}}{\operatorname{argmax}} \sum_{i=0}^{k-1} w_i f_i(\vec{x})$$

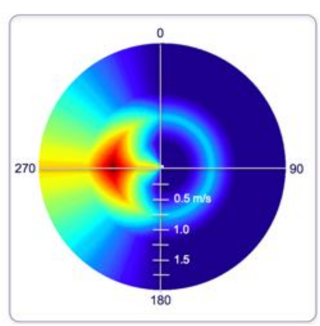
Action

Objective Functions

Solver

Example:
Waypoint Traversal
Behavior





Overview of the IvP Helm

Behavior Output and Action Selection

Behavior 1 → $f_1(x_1, x_2, \ldots, x_n)$

Behavior 2 → $f_2(x_1, x_2, \ldots, x_n)$

Behavior 3 → $f_3(x_1, x_2, \ldots, x_n)$

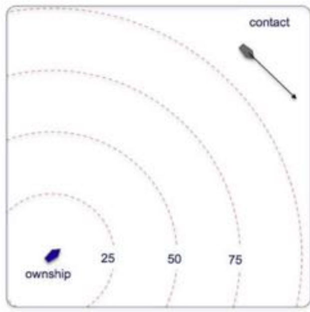
Objective Functions

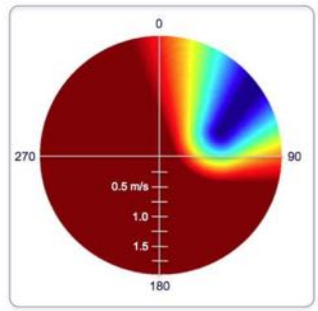
$$\vec{x}^* = \underset{\vec{x}}{\operatorname{argmax}} \sum_{i=0}^{k-1} w_i f_i(\vec{x})$$

Solver

Action

Example:
Collision Avoidance
Behavior





Overview of the IvP Helm

A Simple Collision Avoidance Example

Behavior 1 → $f_1(x_1, x_2, \ldots, x_n)$

Behavior 2 → $f_2(x_1, x_2, \ldots, x_n)$

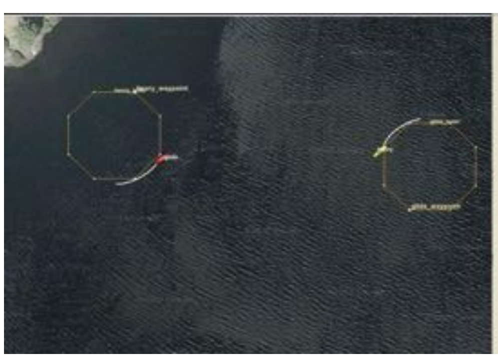
Behavior 3 → $f_3(x_1, x_2, \ldots, x_n)$

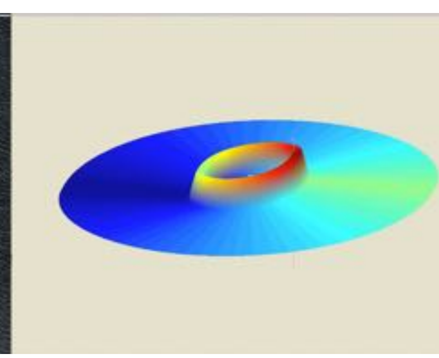
Objective Functions

$$\vec{x}^* = \underset{\vec{x}}{\operatorname{argmax}} \sum_{i=0}^{k-1} w_i f_i(\vec{x})$$

Solver

Action





Projects

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.

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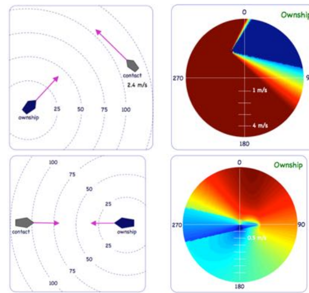
COLREGS Autonomy

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



Crossing Situation

Head-on Situation

- 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)

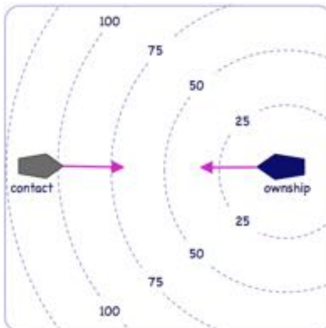
- The objective is to avoid collisions with other autonomous and non-autonomous vehicles.
- COLREGS are the rules of the road for seagoing vessels.
- They provide a protocol of roles and required actions between vessels.
- They were written for humans, not autonomous systems.

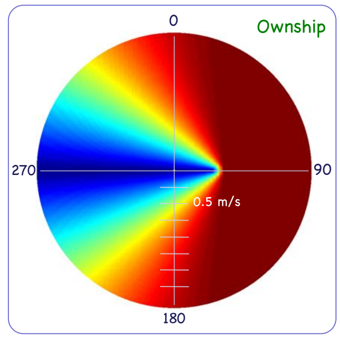
Collision Avoidance WITHOUT COLREGS

藍色是不建議的方向，紅色是可以的，但這有個問題
，就是他是對稱的，因此相遇時有可能走左或走右，就有可能相撞

What’s Wrong with Non Protocol Based Collision Avoidance

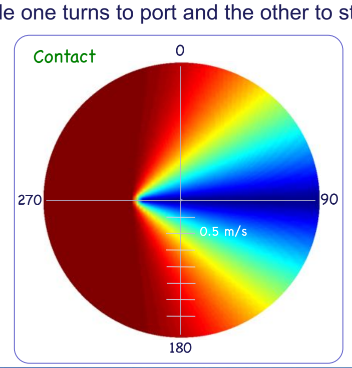
- Consider the head-on situation
- If ownship rates candidate maneuvers based on closest point of approach, a maneuver to port or starboard looks equally good.

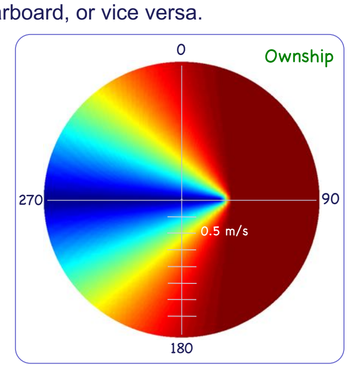




What’s Wrong with Non Protocol Based Collision Avoidance

- 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.





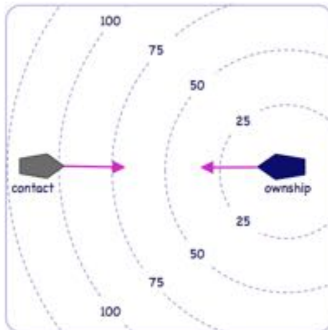
所以訂了一個守則，相遇時要轉port右舷向

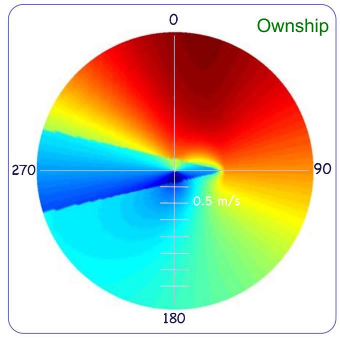
COLREGS Collision Avoidance

- 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.





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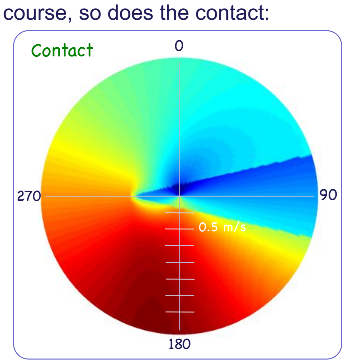
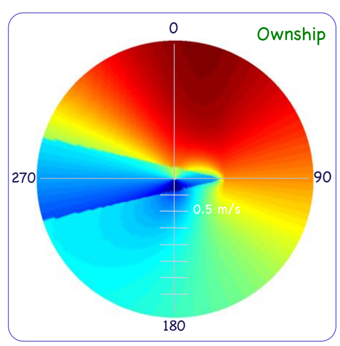
- The COLREGS IvP Behavior on ownship heavily penalizes the “wrong” kind of turn.
- And, of course, so does the contact:





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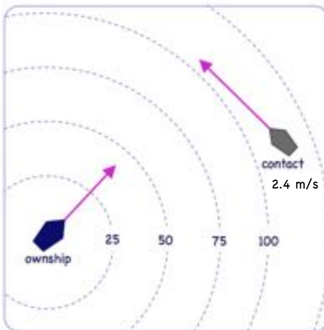
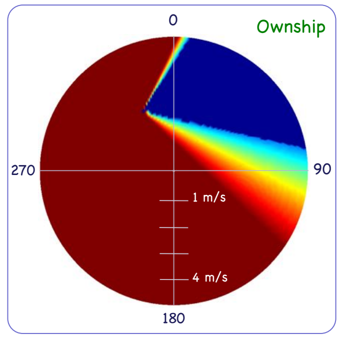
COLREGS Collision Avoidance

- 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.





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Collision Avoidance
WITH COLREGS

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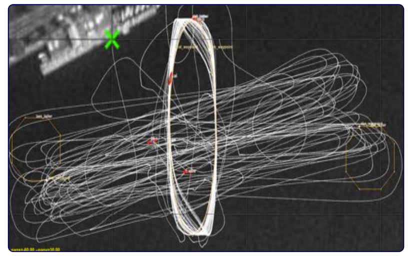
COLREGS
Testing / Validation

- Simulation
- In-Water Tests



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COLREGS
Testing / Validation

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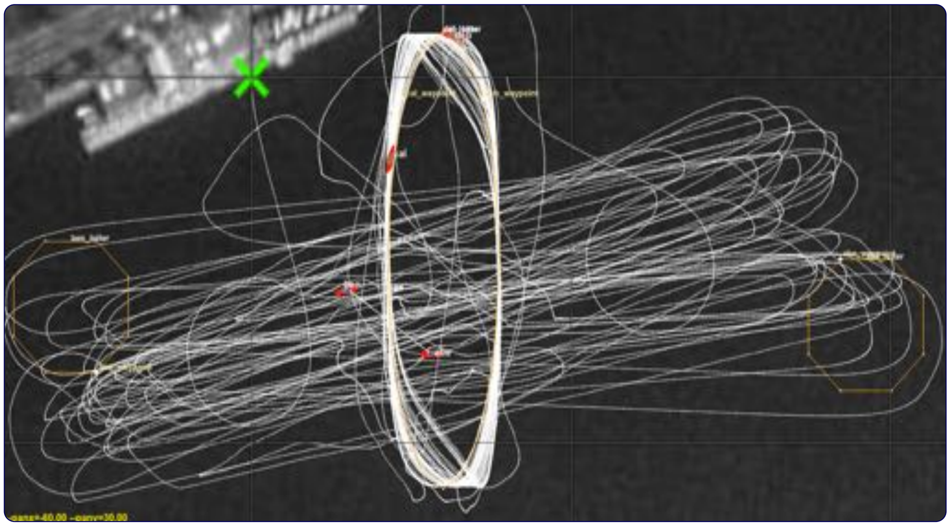
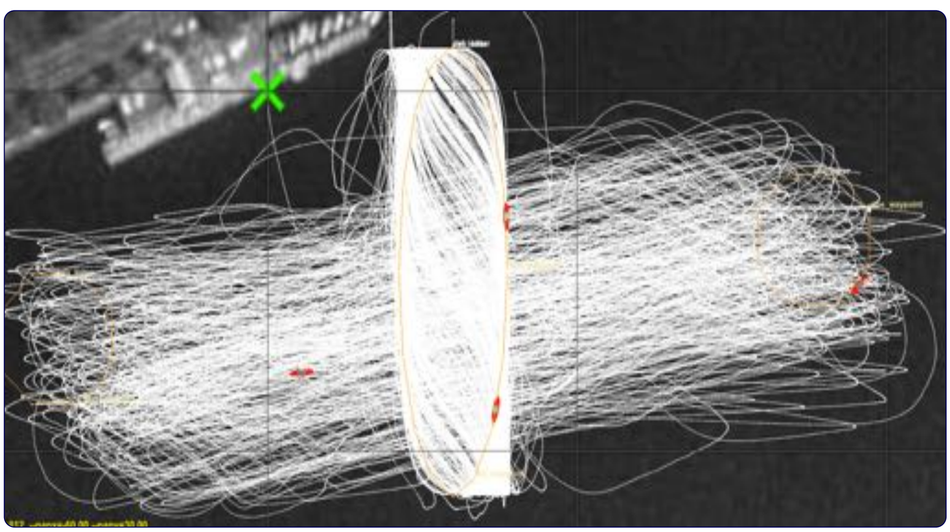
Testing / Validation



Testing / Validation



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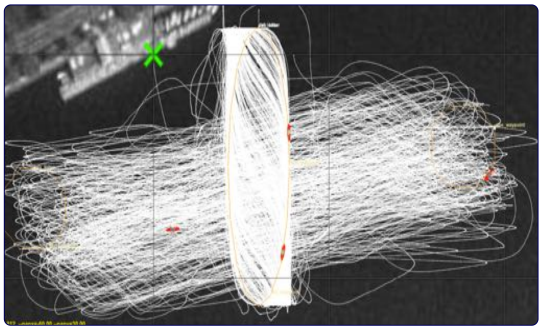
How do we learn from the data?

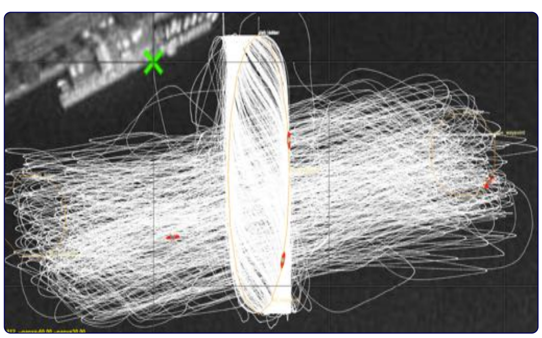


The Challenge:

- 12 hours of simulation
- 4 vehicles
- 1009 encounters

When did something interesting happen?

How do we learn from the data?



The Challenge:

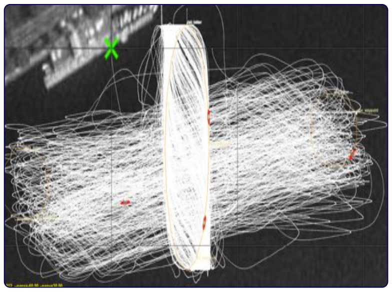
- 12 hours of simulation
- 4 vehicles
- 1009 encounters

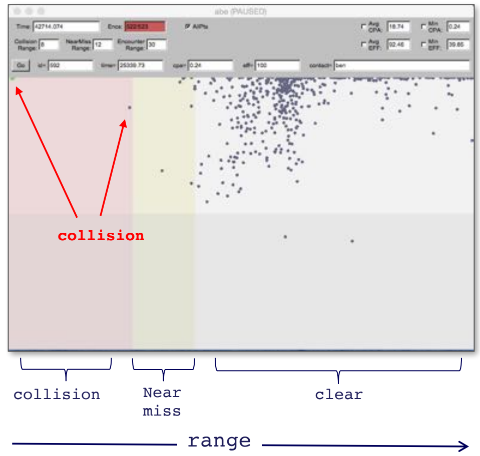
RESULTS

- 1009 encounters
- 2 collisions
  - one 0.95m
  - one 7.5m
- 9 near misses (8-12m range)

模擬了很多次後發向有兩次相撞，
一個是程式的問題（好像撞到岸上
一個是三艘相遇的時候

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 next release of MOOS-IvP

Aquaticus

A Mixed Human Machine Robotic Competition

vs

DARPA TTO

Michael R. Benjamin
Michael Novitzky
Paul Robinette
Henrik Schmidt
John Leonard

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Computer Science and AI Lab
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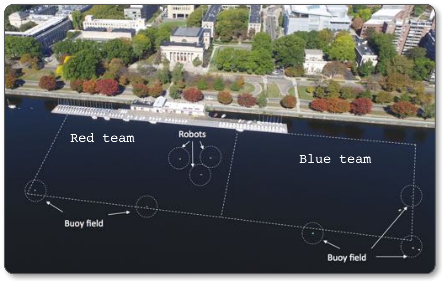
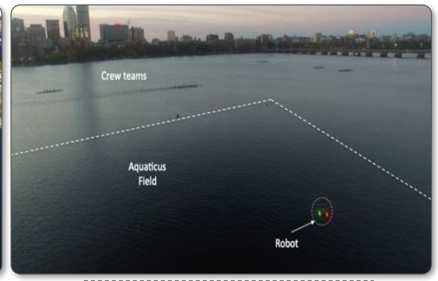
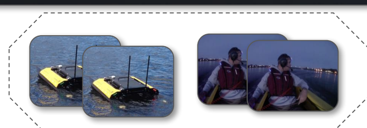
What is Aquaticus

- Aquaticus is a human-robot competition developed at MIT on the Charles River.
- It pits teams of humans and robots against other teams of humans and robots.
- It explores advanced marine *autonomy*, *human-robot trust*, *operator load* and the interface between robots and humans embedded in the field with robots.







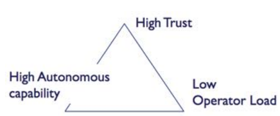
vs.

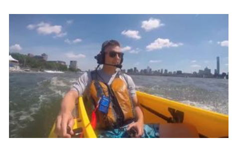
Aquaticus

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*.

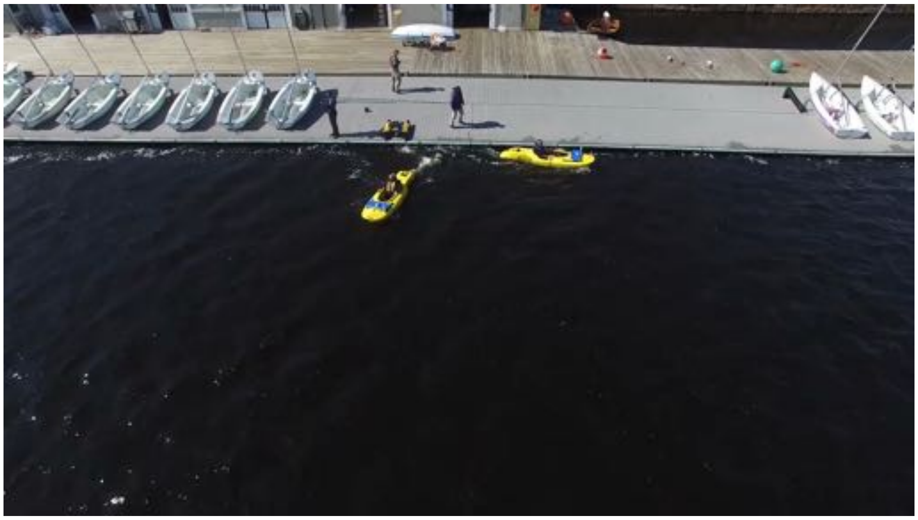




This is a tradeoff space – the right mix is not immediately obvious for a given application or set of humans.

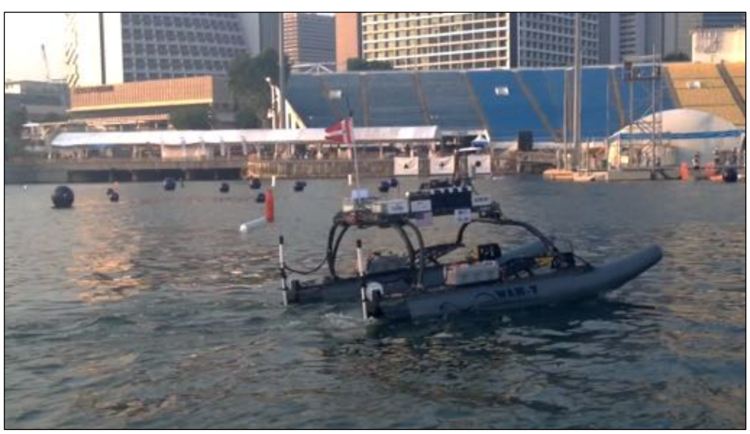
Part of Aquaticus is to discover the basic relationships – to find that mix for *any* human-robot application.

Aquaticus

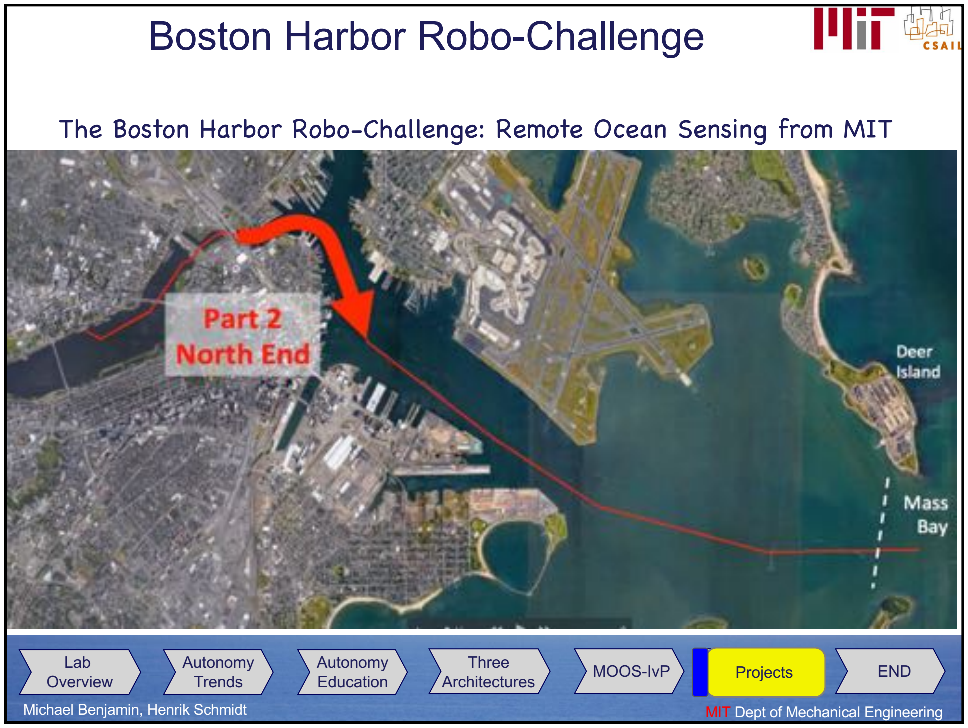


Boston Harbor Robo-Challenge

- Remote Ocean Sensing Launched from MIT
- Currently a seed project



海洋的檢測很耗時耗人力，因此自動化導航過去把sensor插到水裡，完成任務



另一件值得思考的事情是，當今天交通工具沒有人在上面的時候，
有人的交通工具或警察該怎麼跟他溝通？或許要建立一套系統，讓機器人有respose
說他自己在幹麻

可以下達指令給他，同時也會知道他確實執行出來的pattern

middware 幫助 所有程式間互相溝通