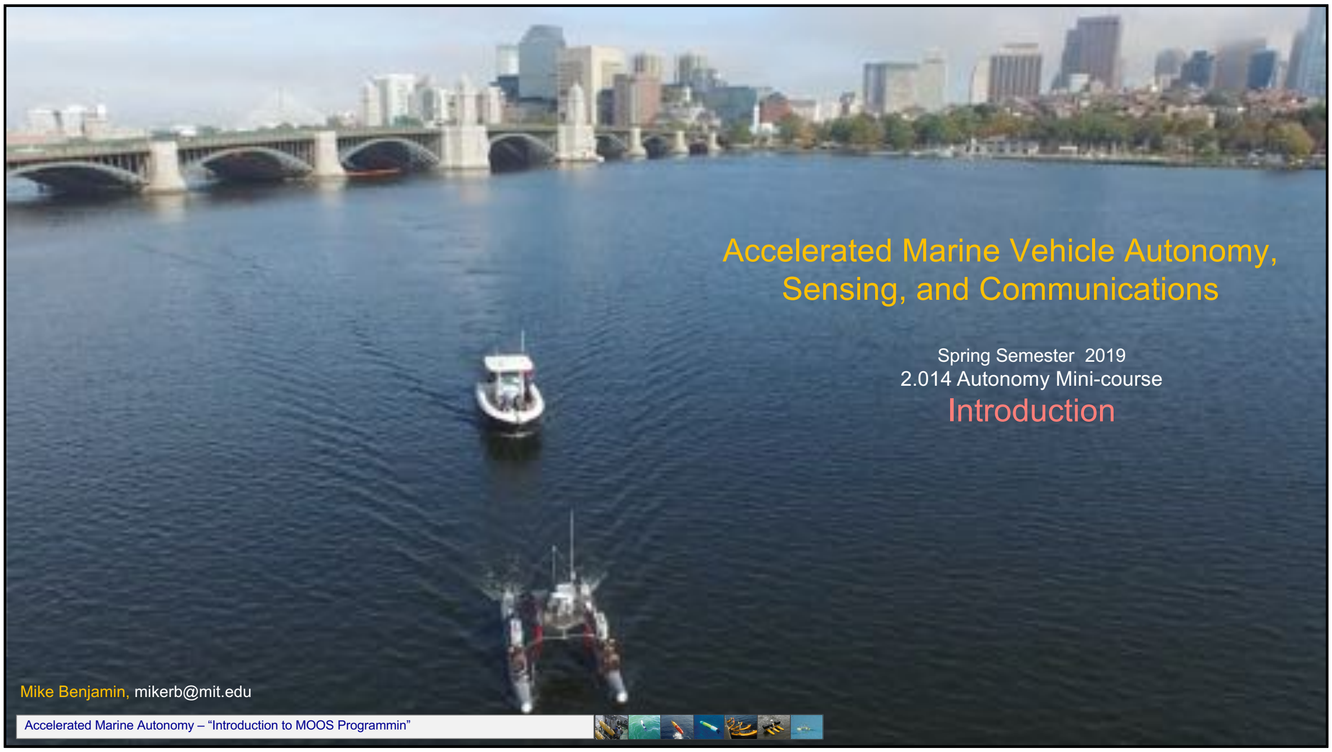


Accelerated Marine Vehicle Autonomy, Sensing, and Communications

Spring Semester 2019
2.014 Autonomy Mini-course

Introduction

Mike Benjamin, mikerb@mit.edu

Accelerated Marine Autonomy – "Introduction to MOOS Programmin"

2.680 *Marine Autonomy, Sensing and Communications*

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.

Michael Benjamin, Henrik Schmidt

MIT Dept of Mechanical Engineering

Lab Overview

MIT Laboratory for Autonomous Marine Sensing Systems

Thank You!!

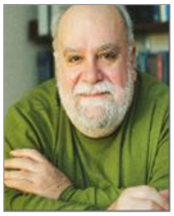
UK

Collaborators


Prof. Henrik Schmidt (MIT)


Prof. John Leonard (MIT)

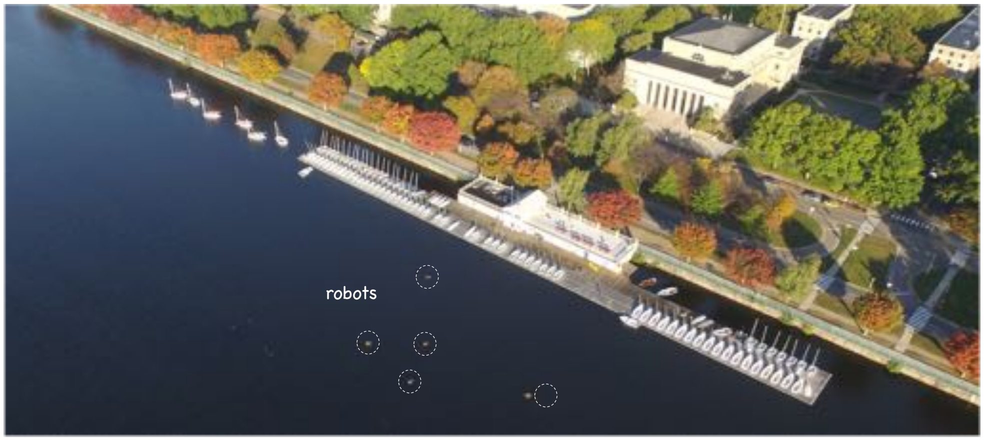

Prof. Paul Newman (Oxford)


Prof. Chryssostomidis


Dr. Paul Robinette


Dr. Michael Novitzky

The MIT Marine Autonomy Bay




henrik@mit.edu

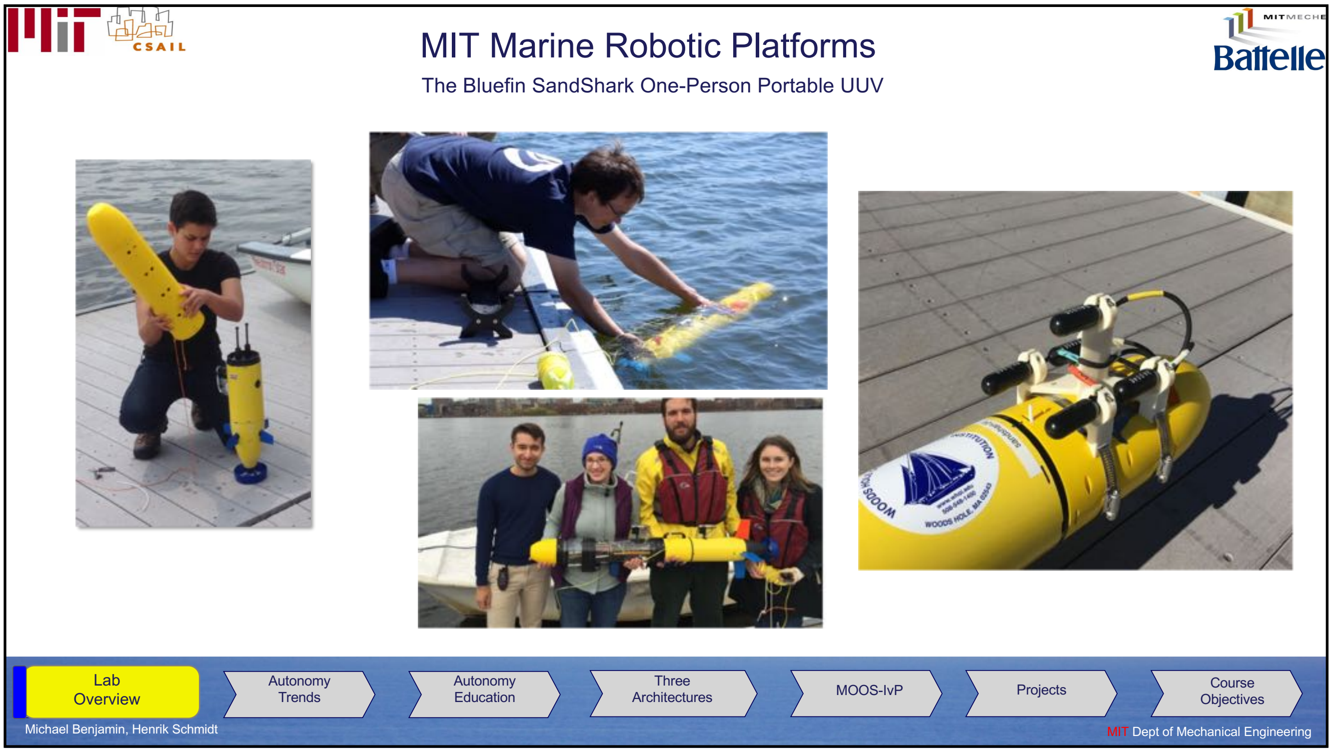
Laboratory for Autonomous Marine Sensing Systems (MECHE)


jleonard@mit.edu

Marine Robotics Group (CSAIL)


mistetri@mit.edu

The AUV Laboratory (MIT Sea Grant)



MIT Marine Robotic Platforms

The Bluefin SandShark One-Person Portable UUV

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

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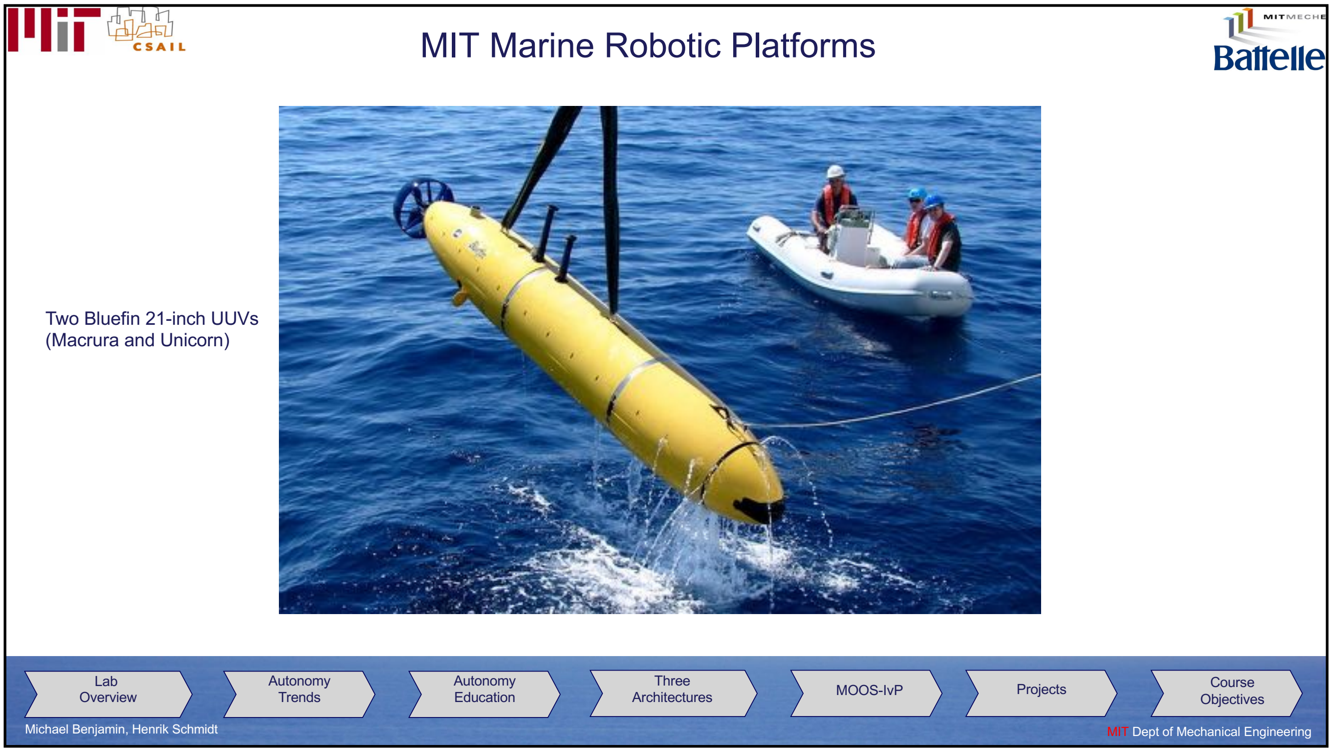

MIT Marine Robotic Platforms

Two Bluefin 21-inch UUVs (Macrura and Unicorn)

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MIT Marine Robotic Platforms

The Clearpath Robotics Heron USV

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MIT Marine Robotic Platforms

The WAM-V Unmanned Surface Vehicle

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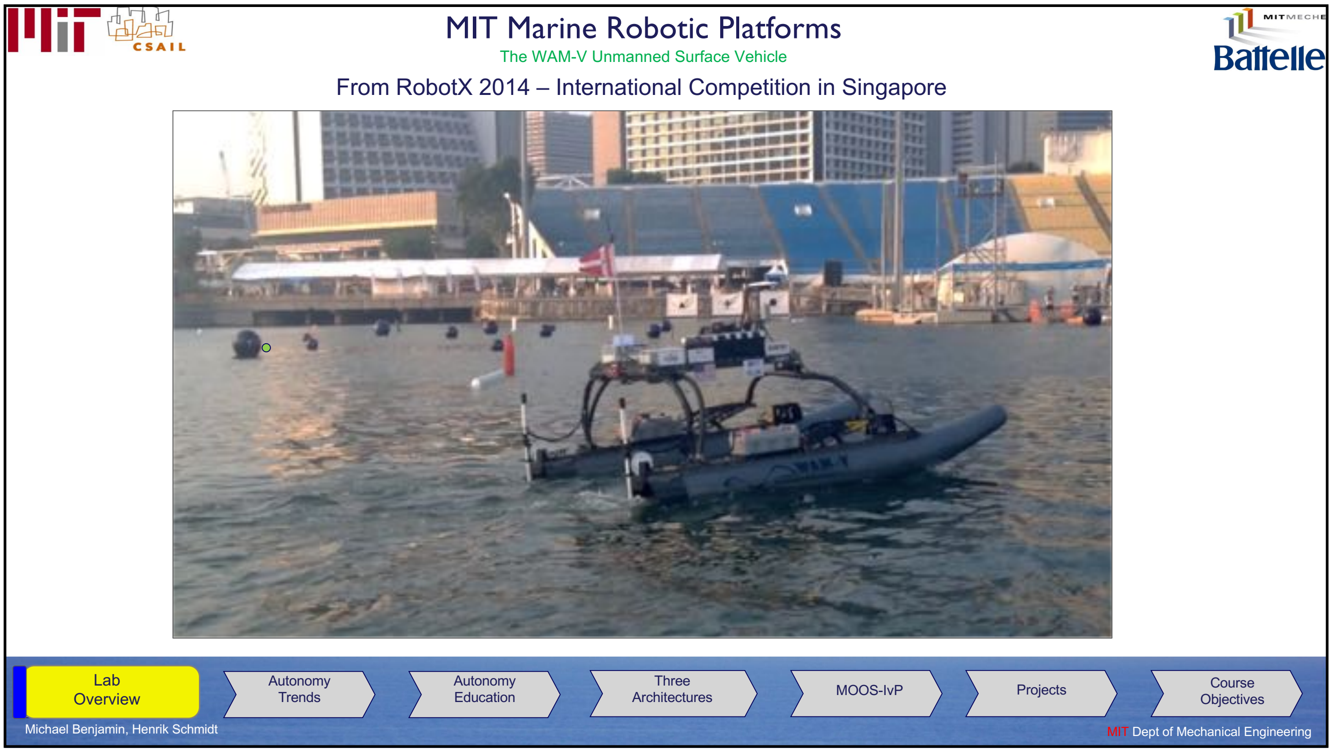

MIT Marine Robotic Platforms

The WAM-V Unmanned Surface Vehicle

From RobotX 2014 – International Competition in Singapore

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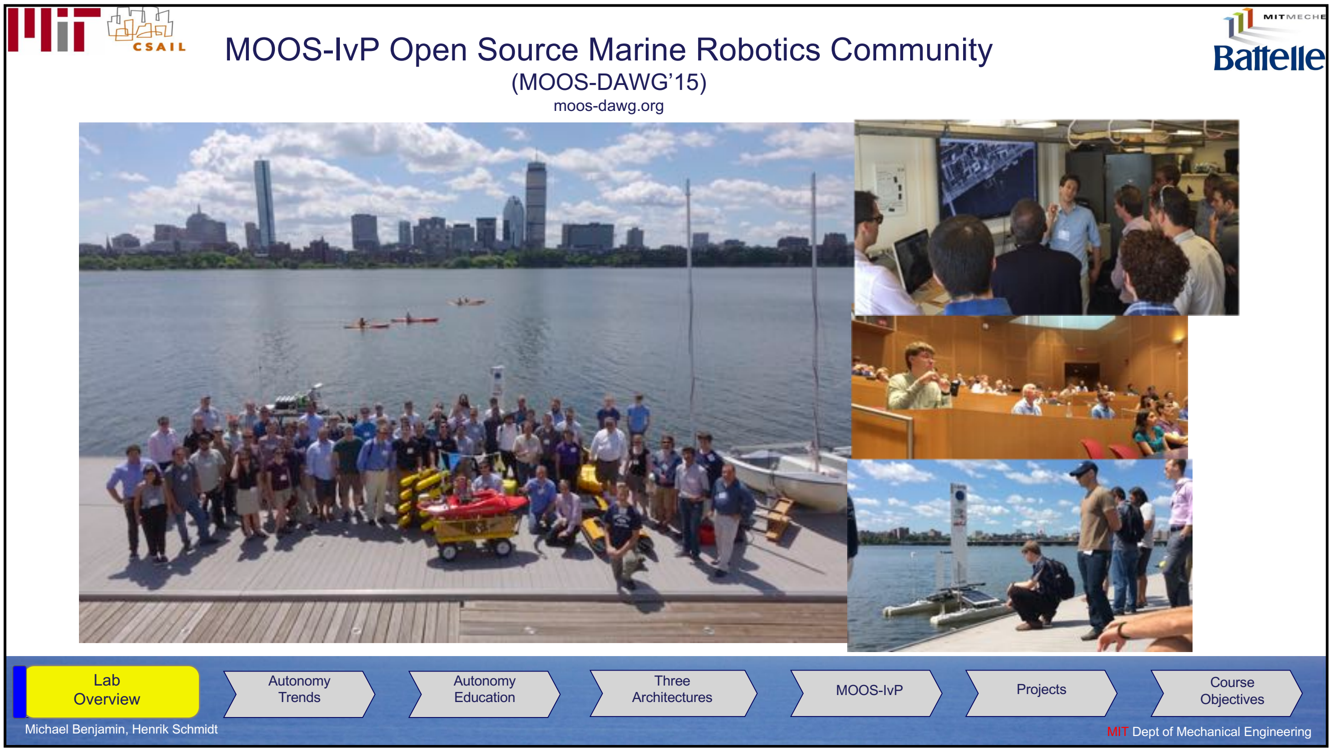

MOOS-IvP Open Source Marine Robotics Community

(MOOS-DAWG'15)

moos-dawg.org

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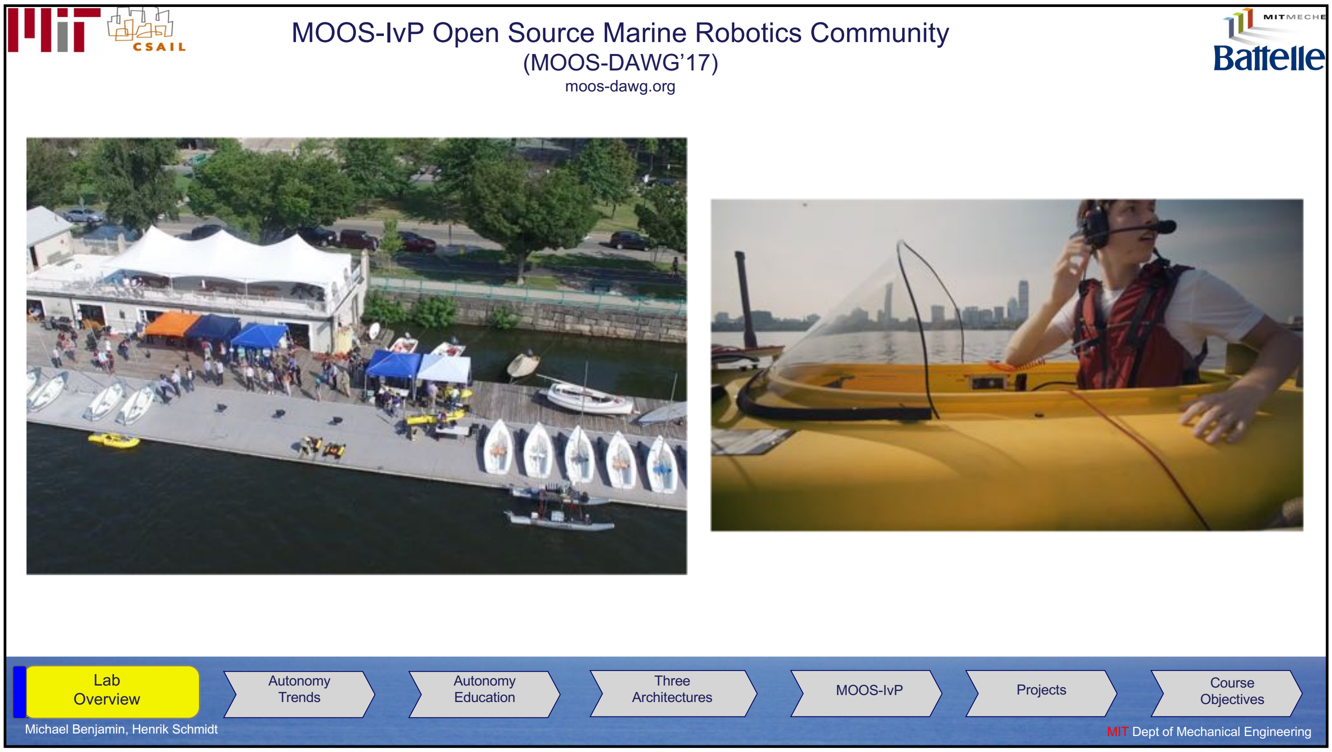
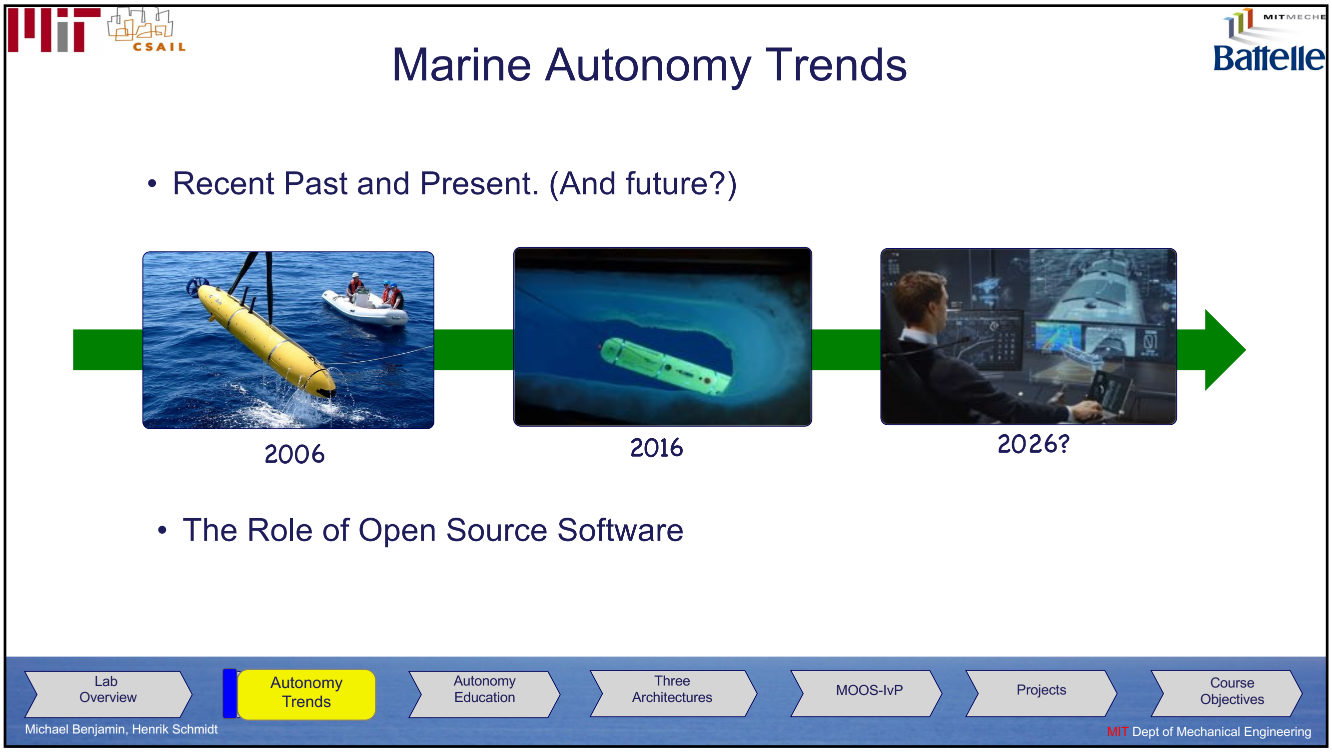


MOOS-IvP Open Source Marine Robotics Community

(MOOS-DAWG'17)

moos-dawg.org

Marine AutonomyTrends



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
Course Objectives

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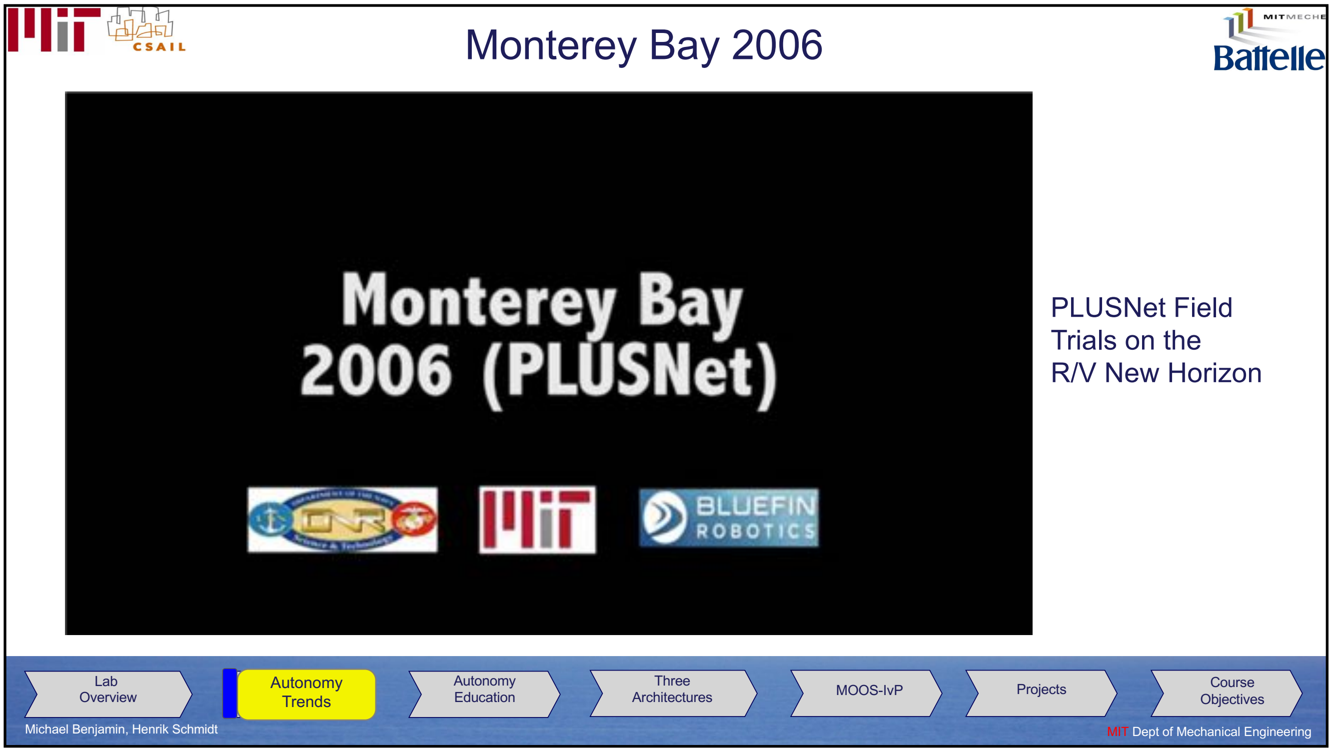

Monterey Bay 2006

PLUSNet Field Trials on the R/V New Horizon

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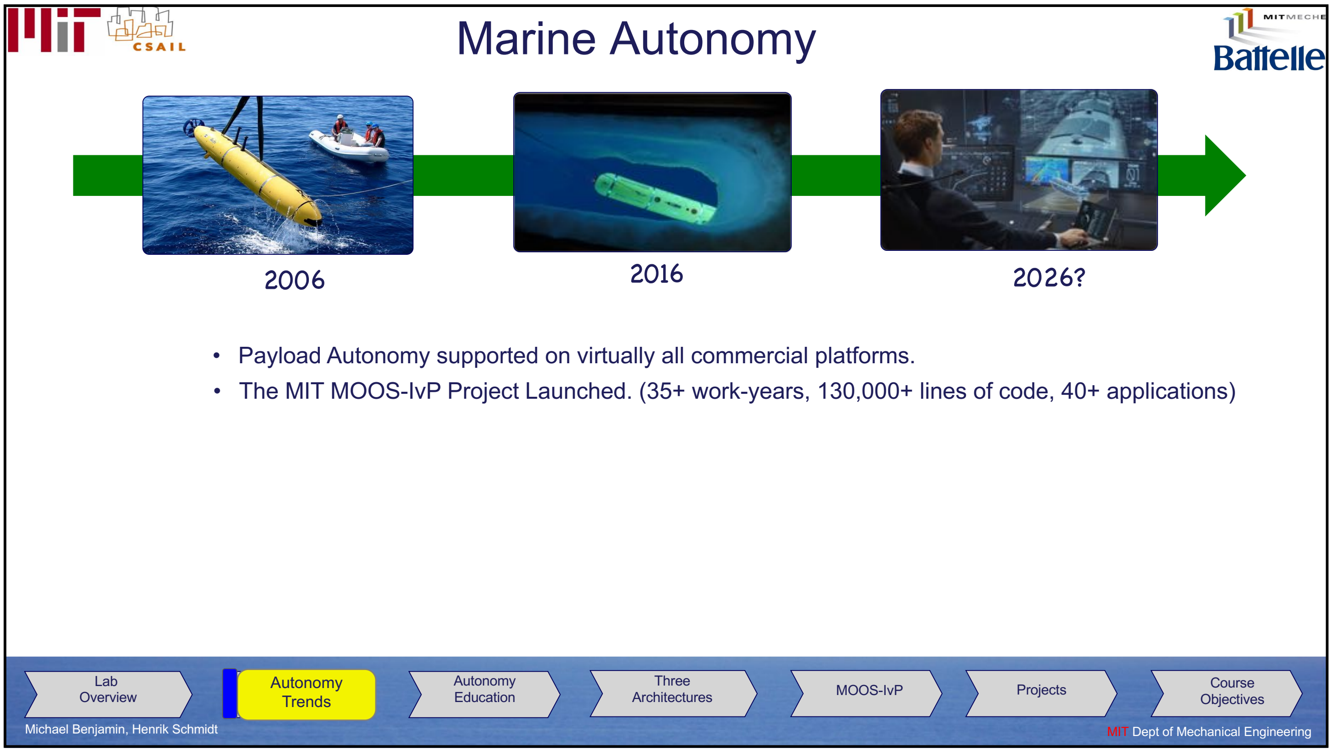

Marine Autonomy

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, 40+ applications)

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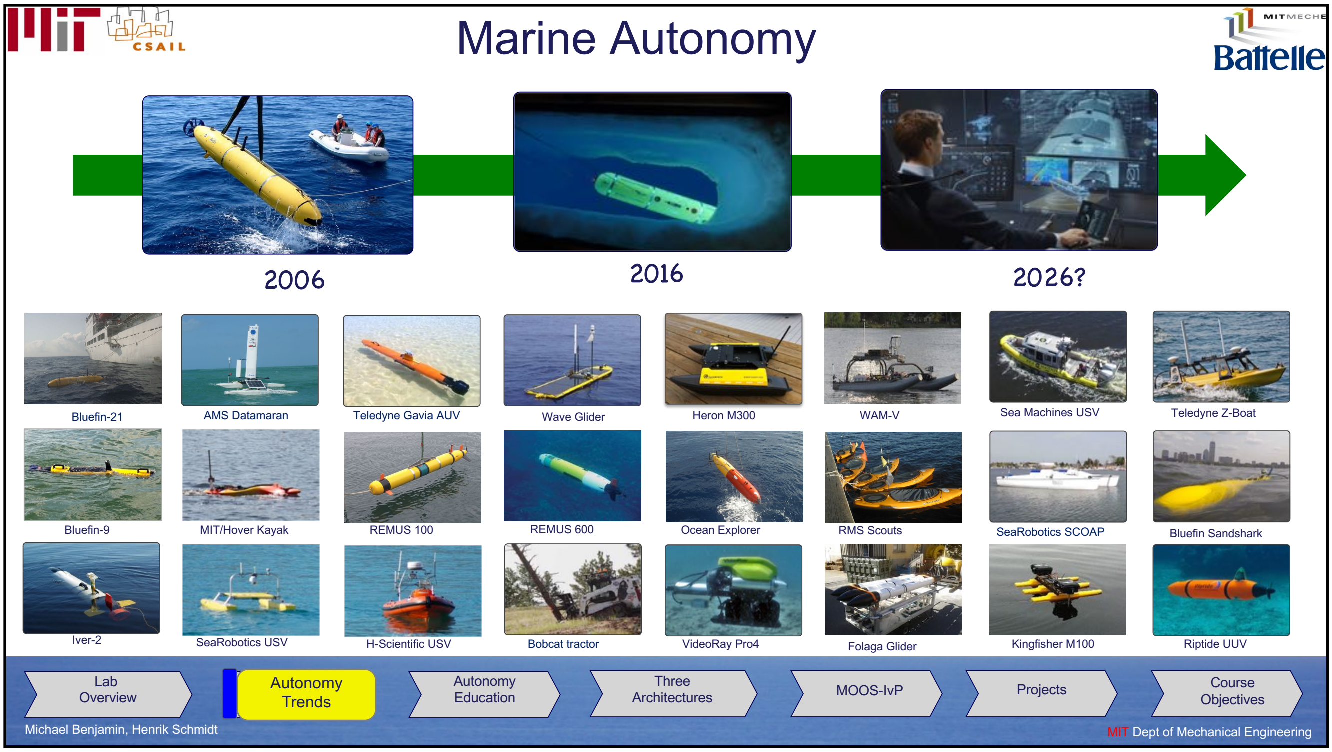

Marine Autonomy

2006

2016

2026?

Bluefin-21
AMS Datamaran
Teledyne Gavia AUV
Wave Glider
Heron M300
WAM-V
Sea Machines USV
Teledyne Z-Boat
Bluefin-9
MIT/Hover Kayak
REMUS 100
REMUS 600
Ocean Explorer
RMS Scouts
SeaRobotics SCOAP
Bluefin Sandshark
Iver-2
SeaRobotics USV
H-Scientific USV
Bobcat tractor
VideoRay Pro4
Folaga Glider
Kingfisher M100
Riptide UUV

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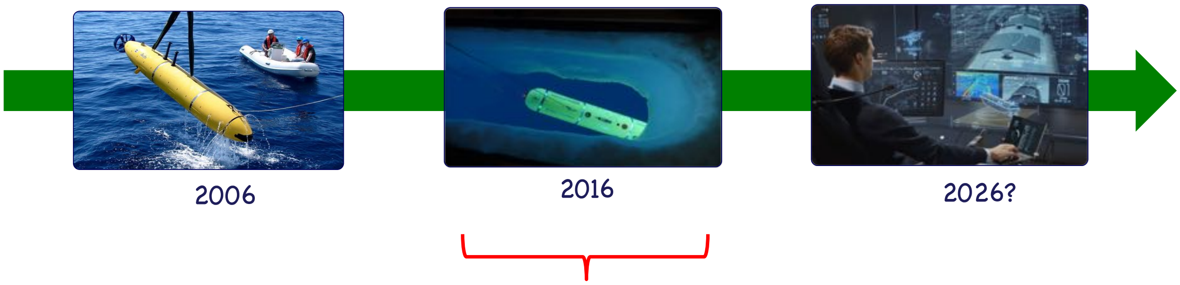
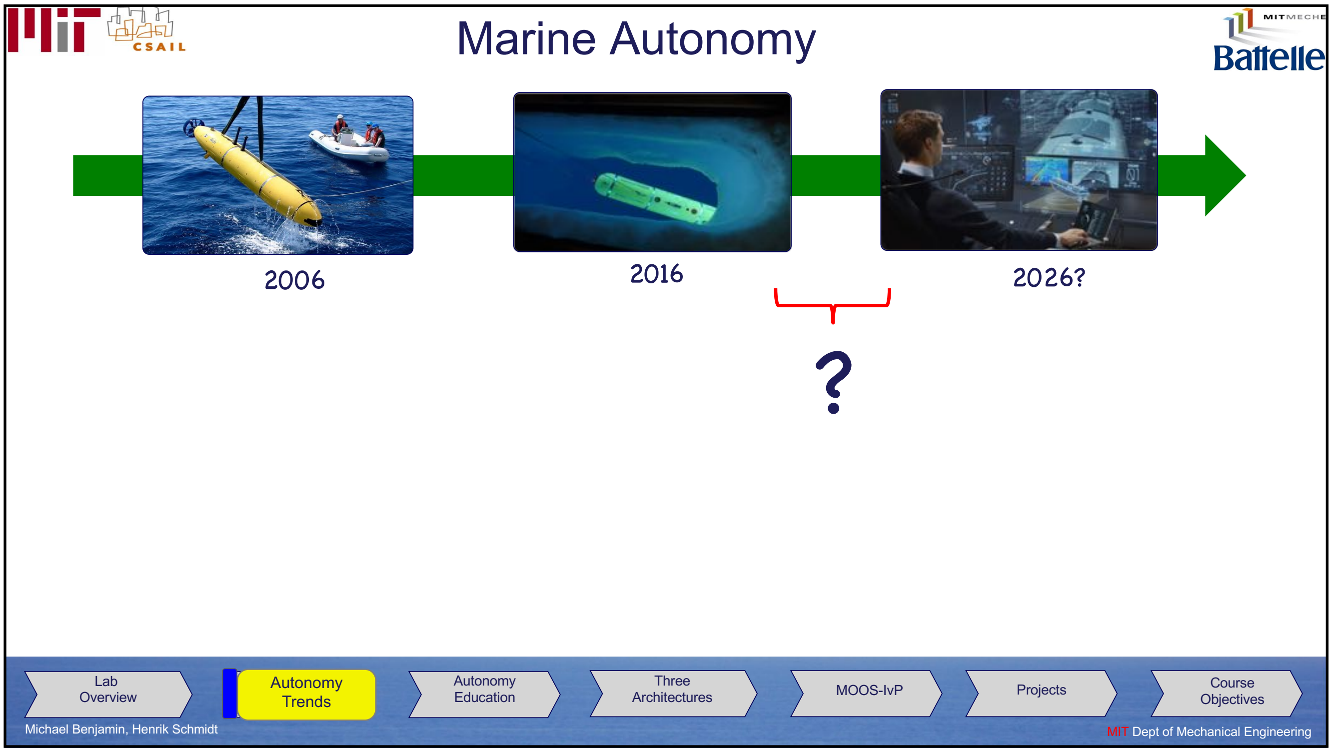
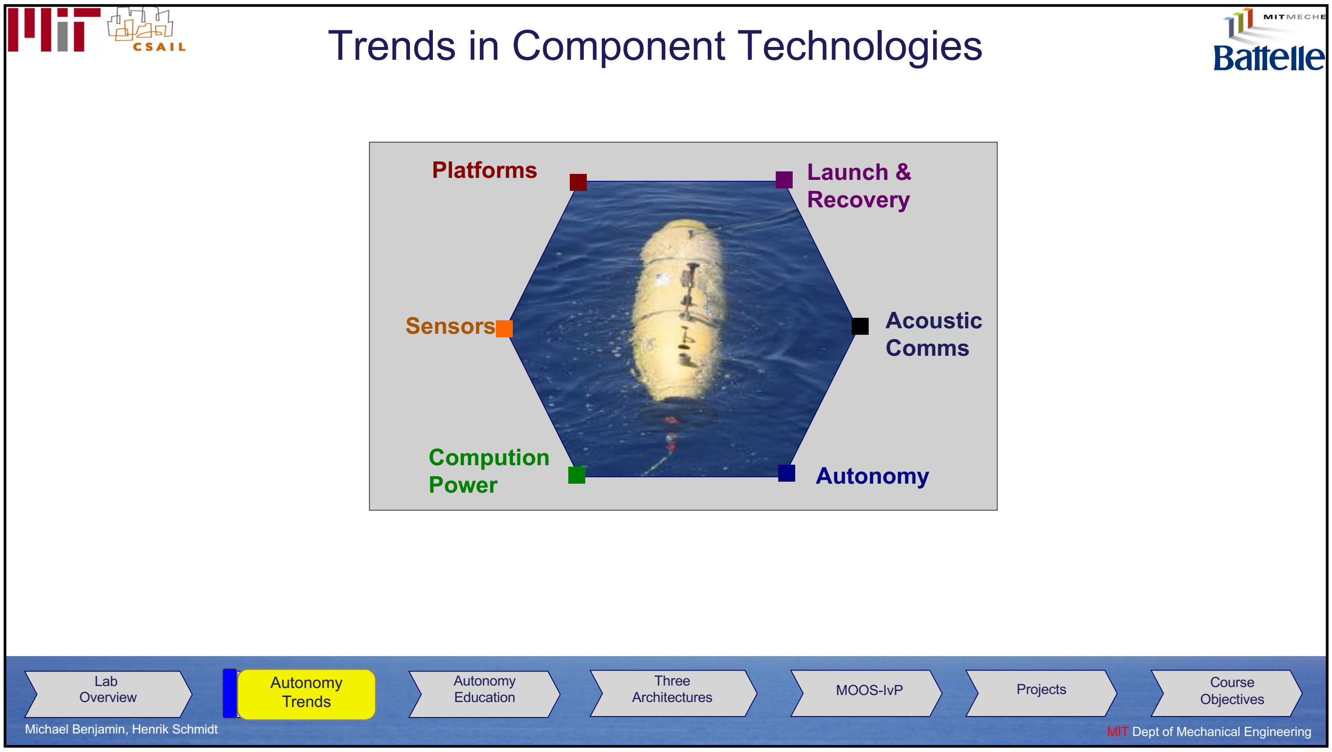
Marine Autonomy



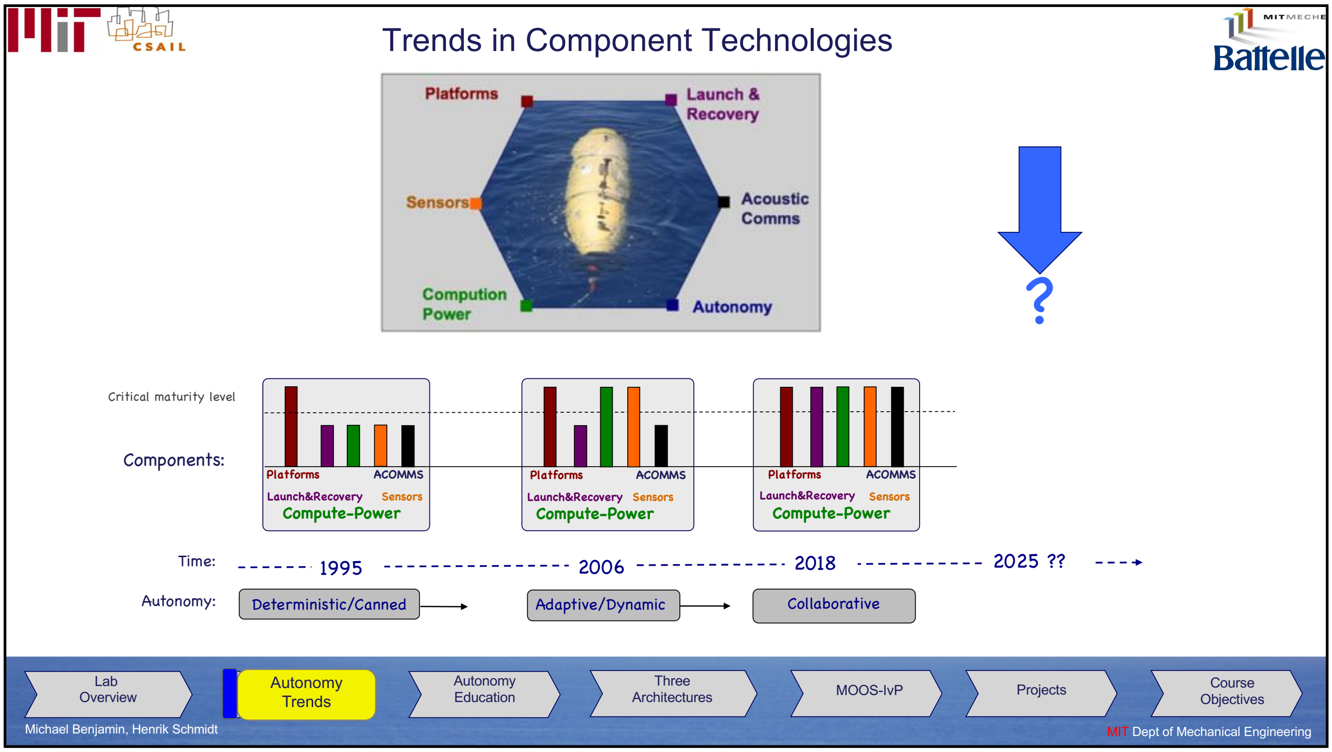
ICEX 2016



Marine Autonomy



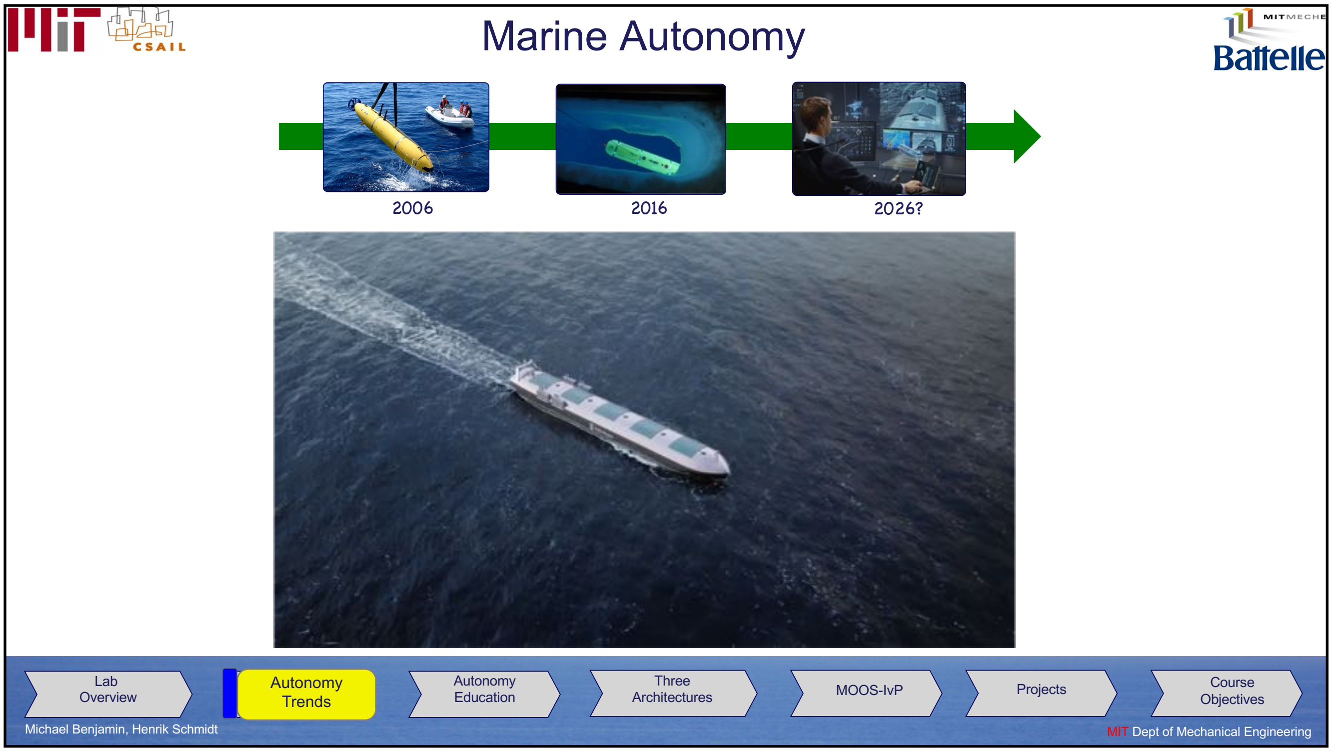
Trends in Component Technologies



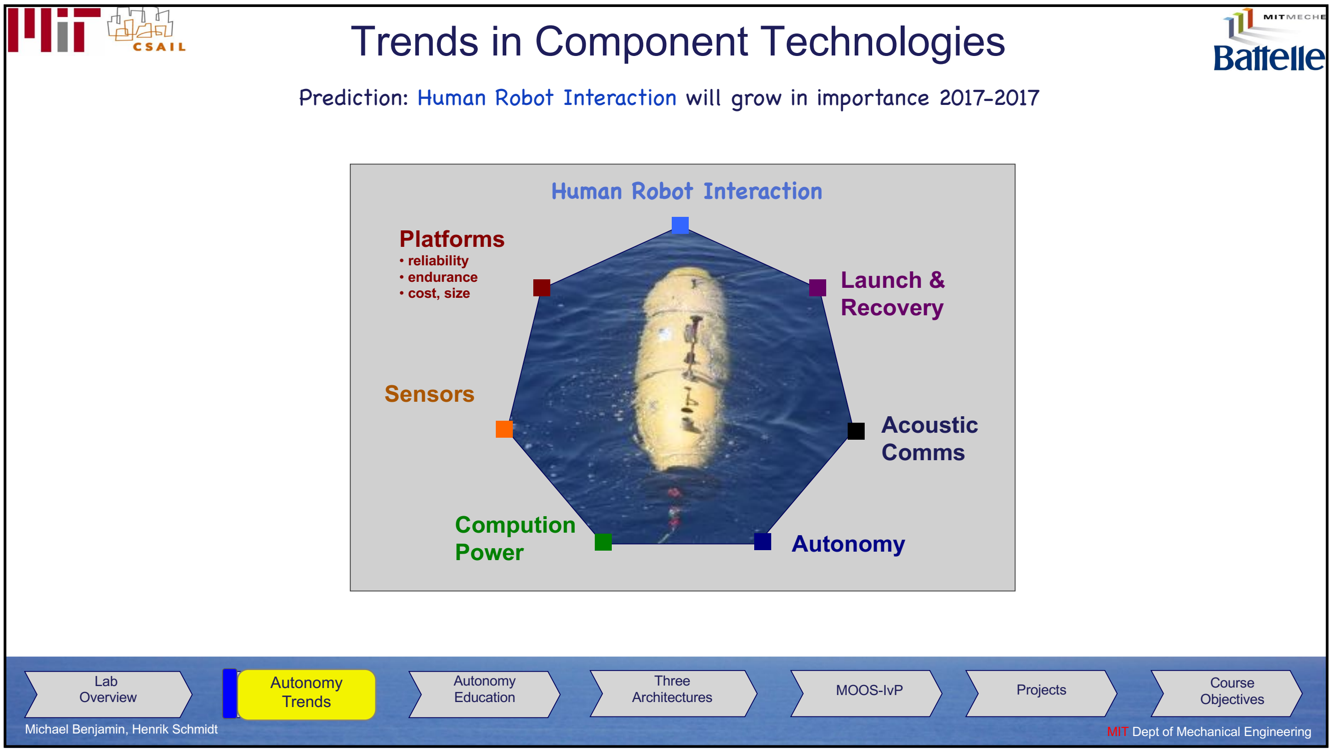
Trends in Component Technologies

Time: ------ 1995 ---------------- 2006 ------------- 2018 ----------- 2025 ?? ---→

Autonomy: Deterministic/Canned → Adaptive/Dynamic → Collaborative

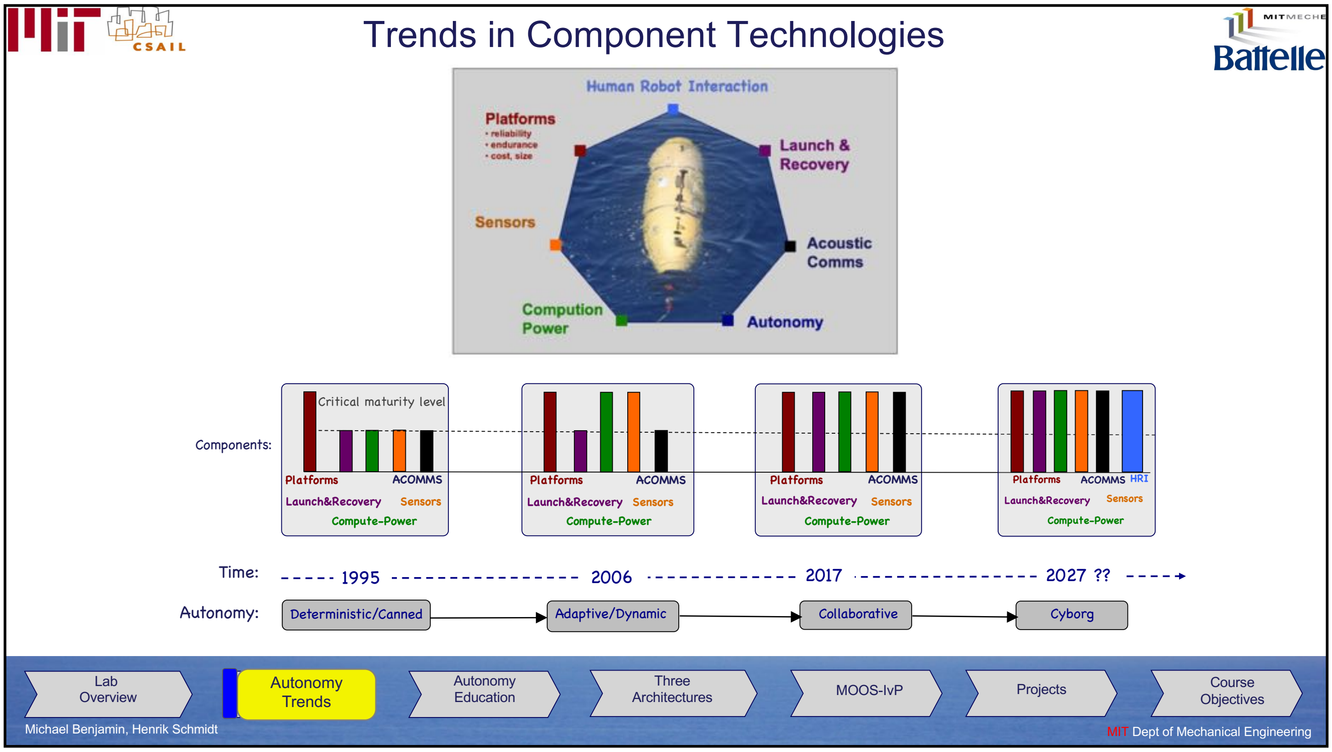


Marine Autonomy



Trends in Component Technologies

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



Trends in Component Technologies

Autonomy Education

Robot Software is an Ecosystem

Data Logging

Middleware

Log Data Manipulation

Autonomy Behaviors

Navigation

Autonomy Architecture

Sensor Drivers

Vehicle Simulation

Mission Viewers

Robot Software is an Ecosystem

Sensor Processing

(Acoustic) Communications

Health Monitoring

Comms Simulation

Payload Interfaces

Environmental Simulation

Log Data Playback

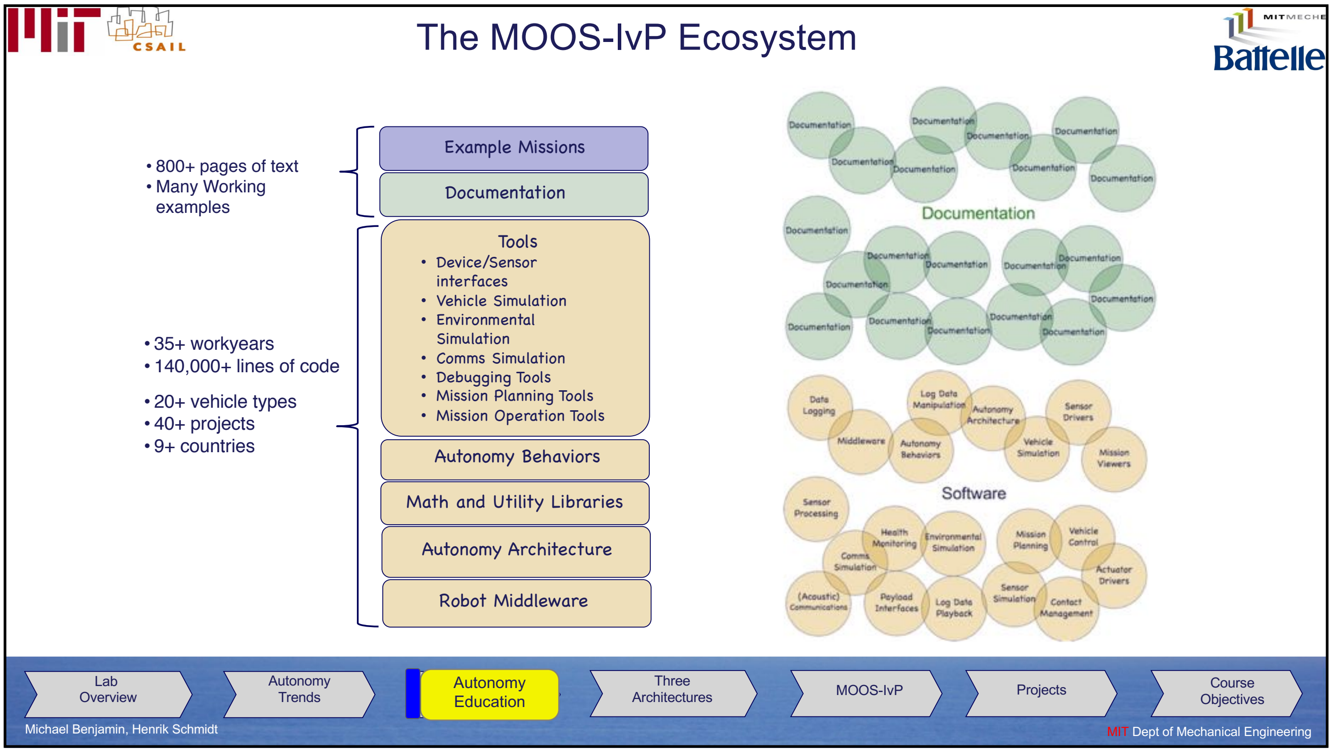
Mission Planning

Sensor Simulation

Vehicle Control

Contact Management

Actuator Drivers



The MOOS-IvP Ecosystem

- 800+ pages of text
- Many Working examples

- 35+ workyears
- 140,000+ 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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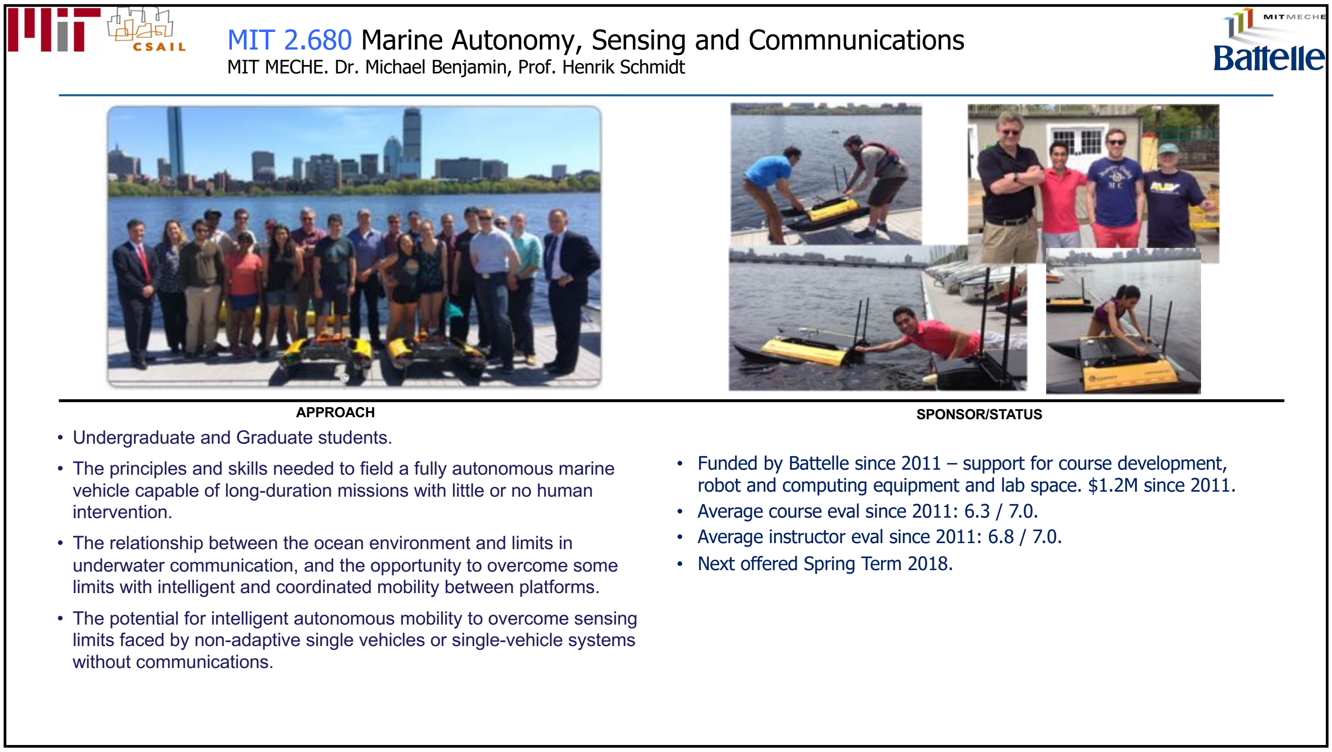
MIT Dept of Mechanical Engineering



MIT 2.680 Marine Autonomy, Sensing and Commnunications

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

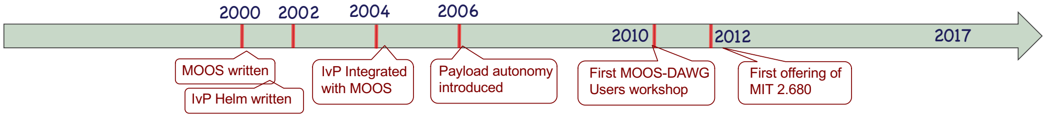
APPROACH

- 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



- Build 100% of the ecosystem yourself

- Build 40% of ecosystem

- Learn from apprenticing

- Build 20% of ecosystem

- Learn from documentation
- Learn from apprenticing

- Build 5% of ecosystem

- 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)

MIT 2.680 Students

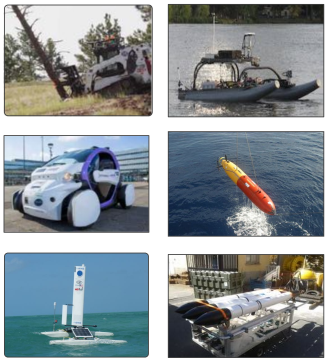
(May 16th 2017)

Architectures

Robot Architectures: Ground, Air and Sea

Robot Software

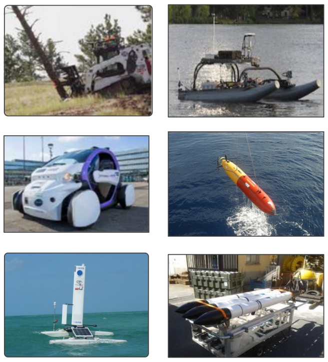
(What's Inside?)

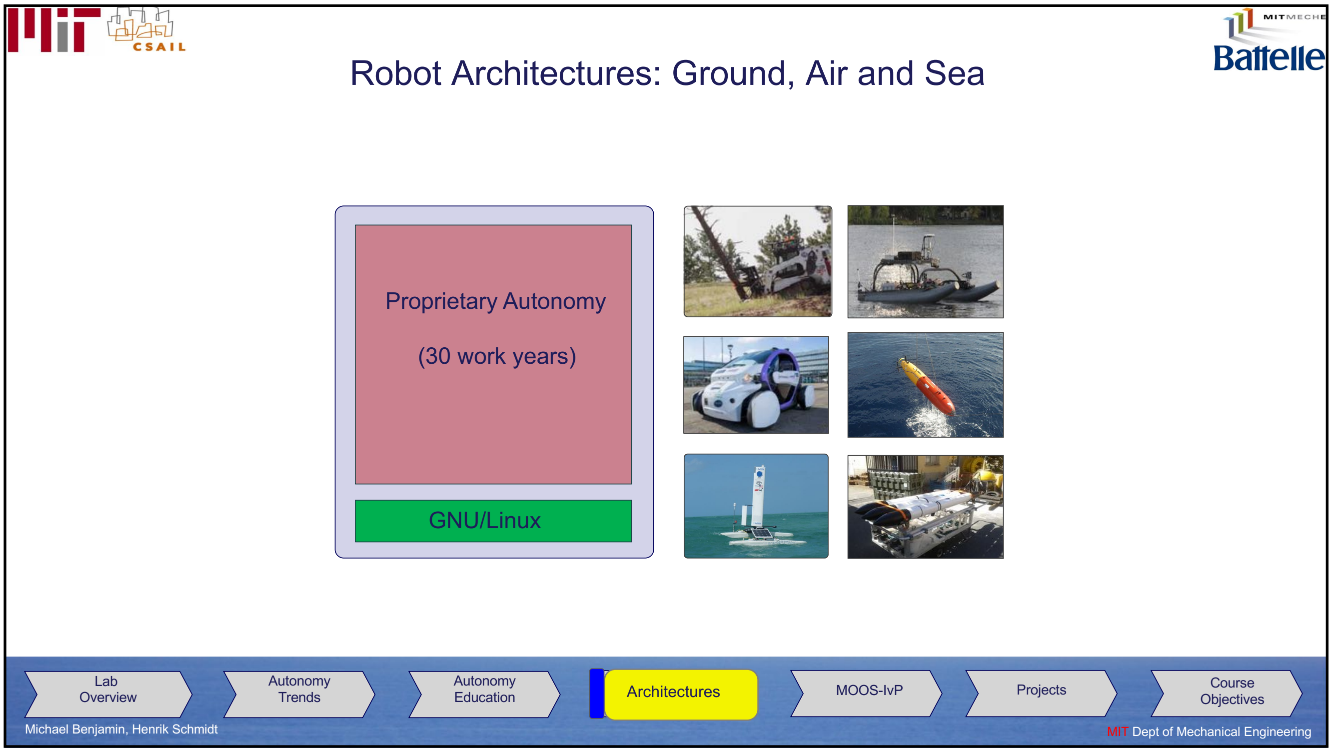


Robot Architectures: Ground, Air and Sea

Proprietary Autonomy

(50 work years)





Robot Architectures: Ground, Air and Sea

Proprietary Autonomy

(30 work years)

GNU/Linux

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

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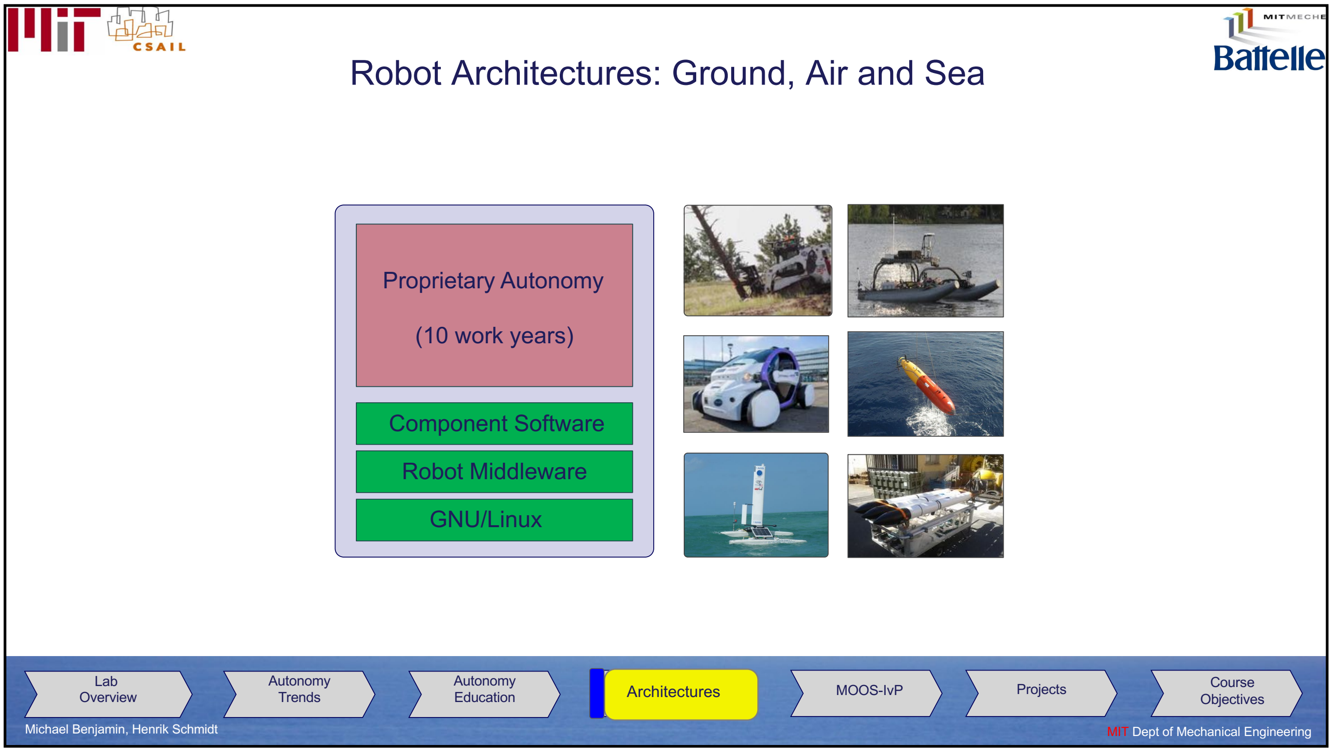

Robot Architectures: Ground, Air and Sea

Proprietary Autonomy

(10 work years)

Component Software

Robot Middleware

GNU/Linux

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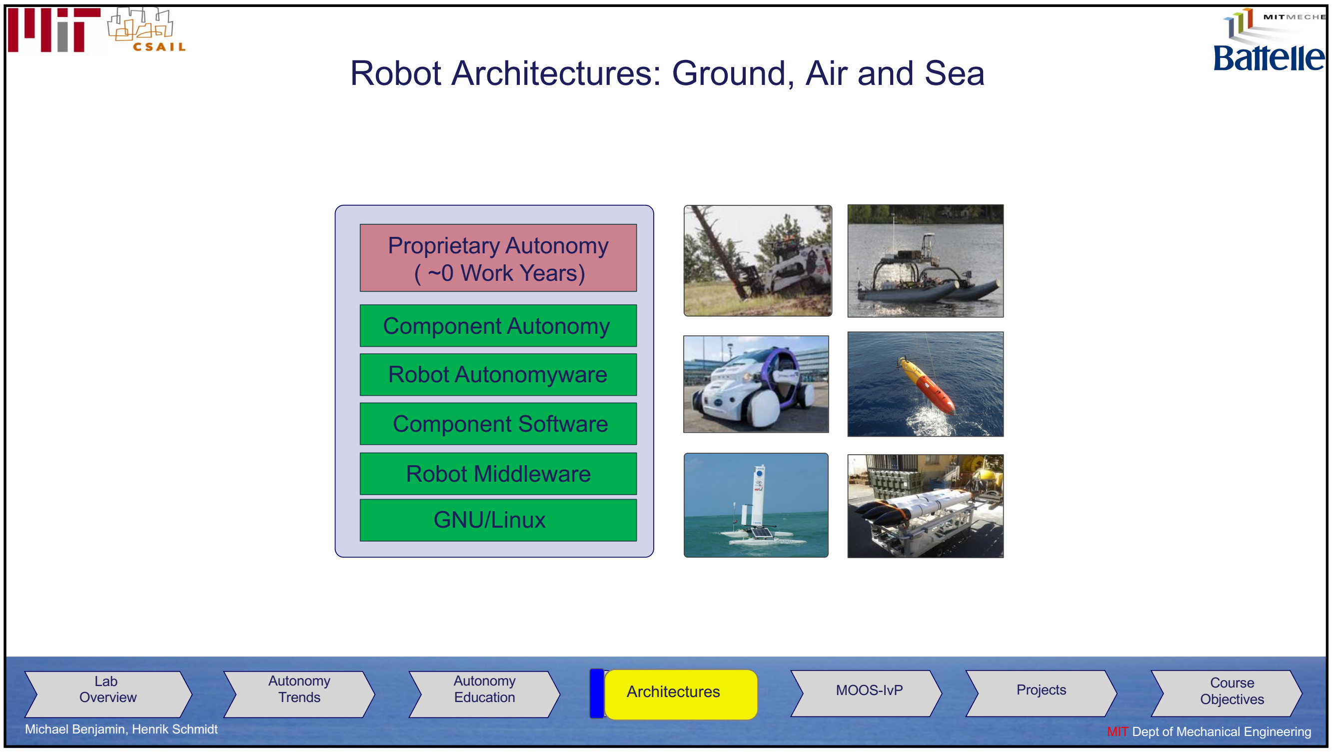

Robot Architectures: Ground, Air and Sea

Proprietary Autonomy
(~0 Work Years)

Component Autonomy

Robot Autonomyware

Component Software

Robot Middleware

GNU/Linux

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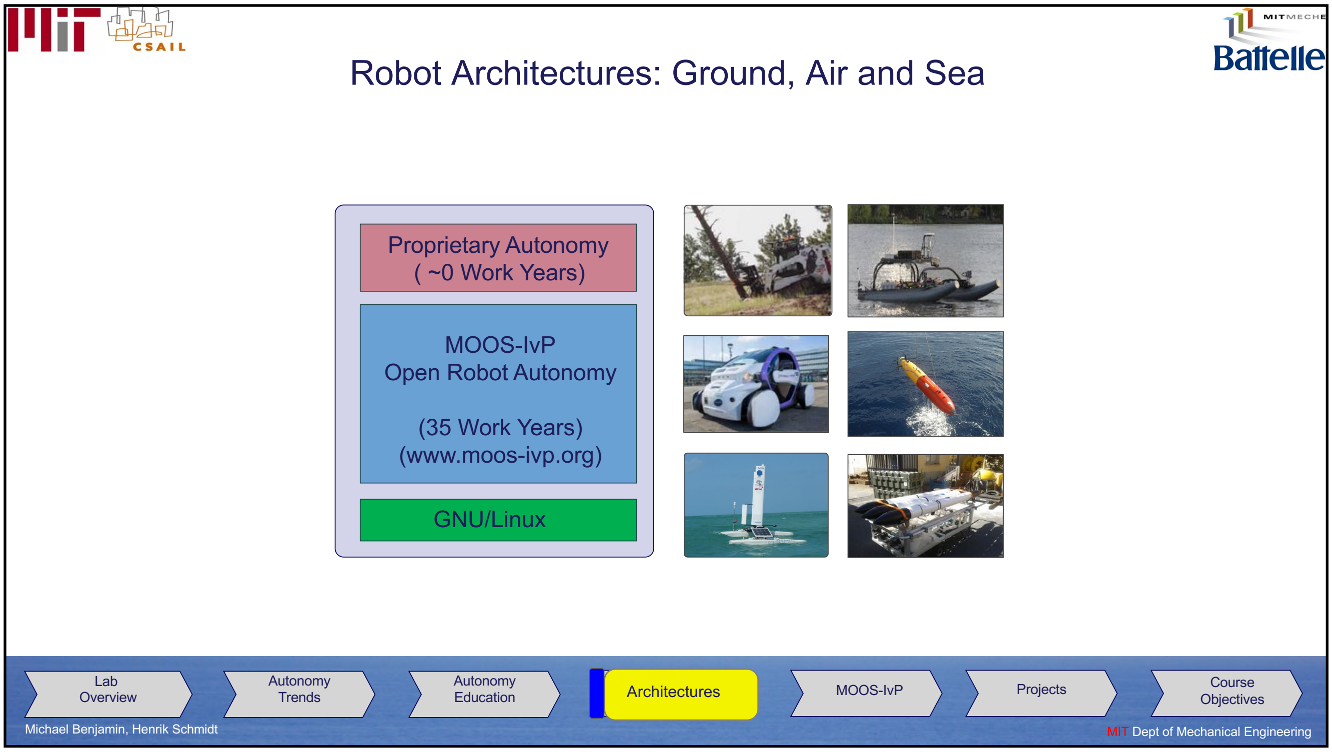

Robot Architectures: Ground, Air and Sea

Proprietary Autonomy
(~0 Work Years)

MOOS-IvP
Open Robot Autonomy

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

GNU/Linux

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

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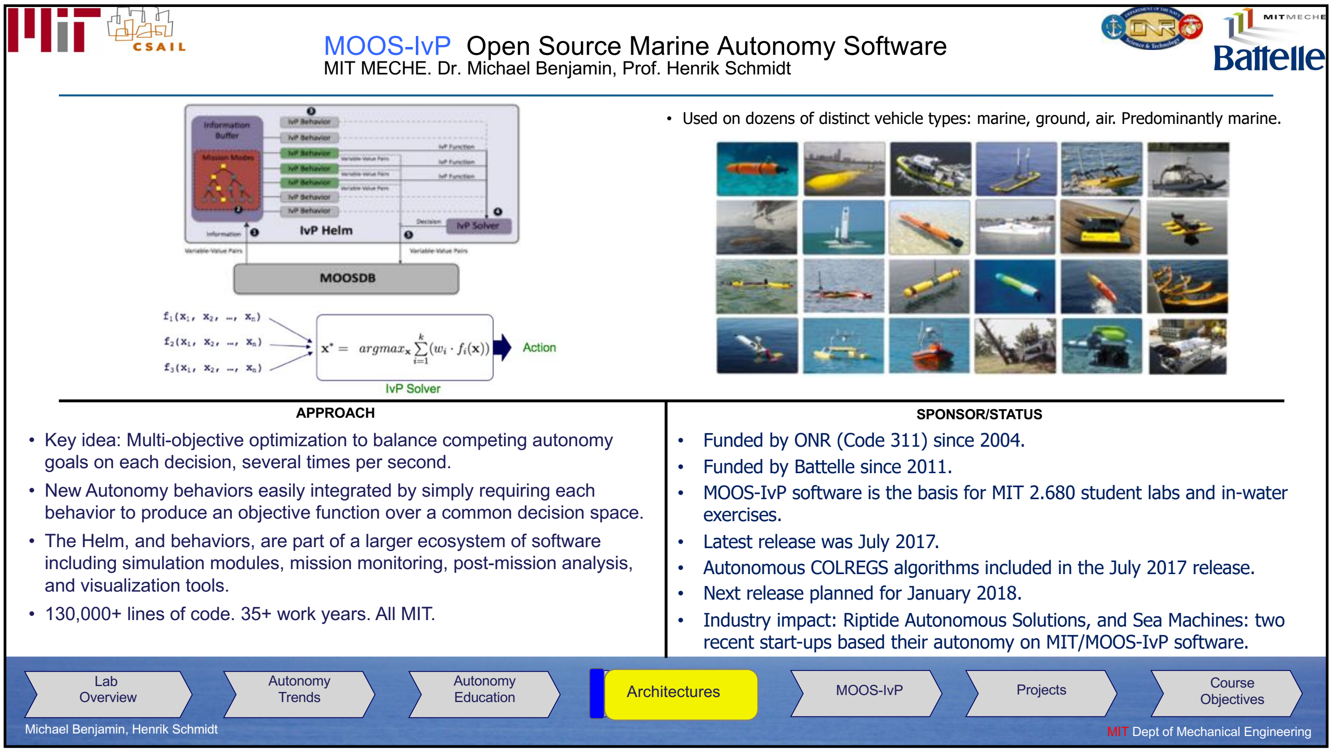

MOOS-IvP Open Source Marine Autonomy Software

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

$$\mathbf{x}^* = argmax_{\mathbf{x}} \sum_{i=1}^{k} (w_i \cdot f_i(\mathbf{x}))$$

- 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.

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

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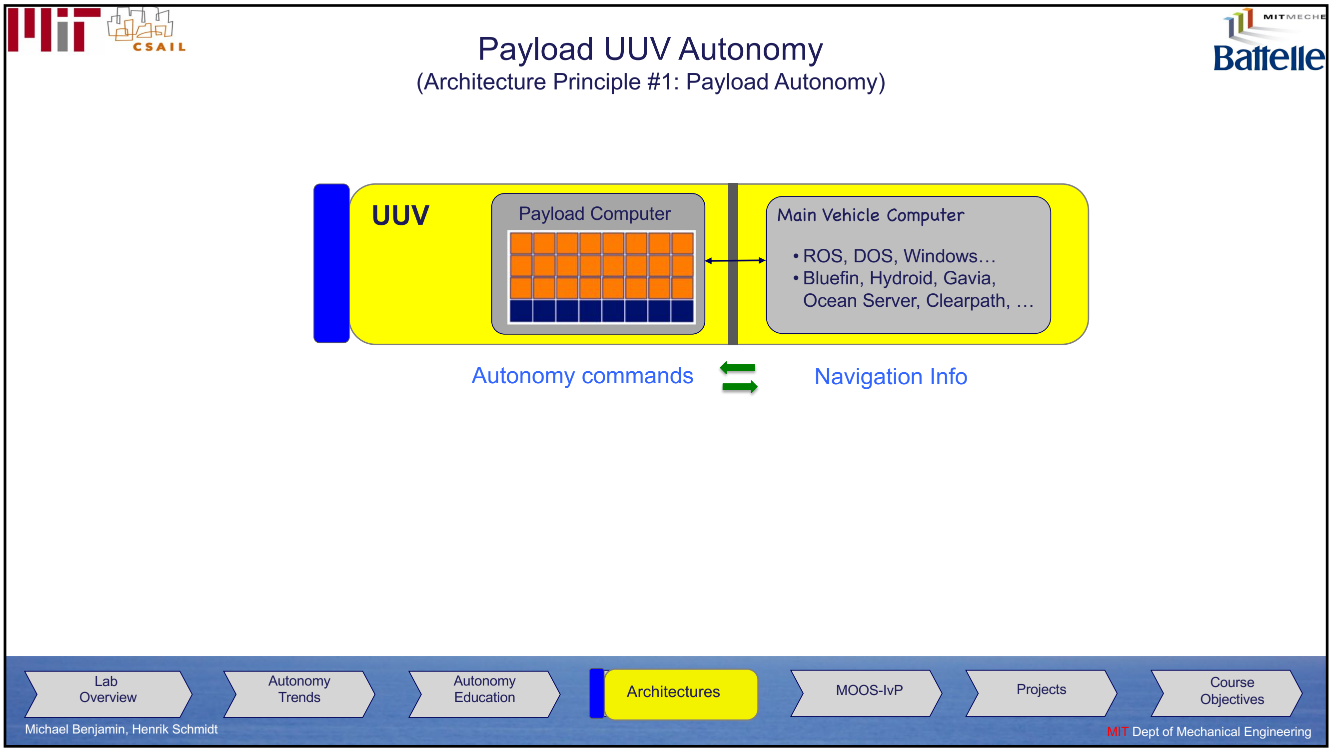

Payload UUV Autonomy

(Architecture Principle #1: Payload Autonomy)

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

Autonomy commands ⇄ Navigation Info

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

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Platforms Field-Deployed with MOOS-IvP Payload Autonomy

Aquabotix Endura
Riptide UUV
Bluefin Sandshark
Sea Machines USV
Liquid Robotics Wave Glider
Teledyne Z-Boat
WAM-V

Aquabotix Hybrid AUV/ROV
Bluefin-21
AMS Datamaran
Teledyne Gavia AUV
SeaRobotics SCOAP USV
Kingfisher M200/M300
Kingfisher M100

Emily USV
Bluefin-9
MIT/Hover Kayak
REMUS 600
REMUS 100
Ocean Explorer
RMS Scouts

Proteus UUV
Iver-2
SeaRobotics USV
H-Scientific USV
Bobcat tractor
VideoRay Pro4
Folaga Glider

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

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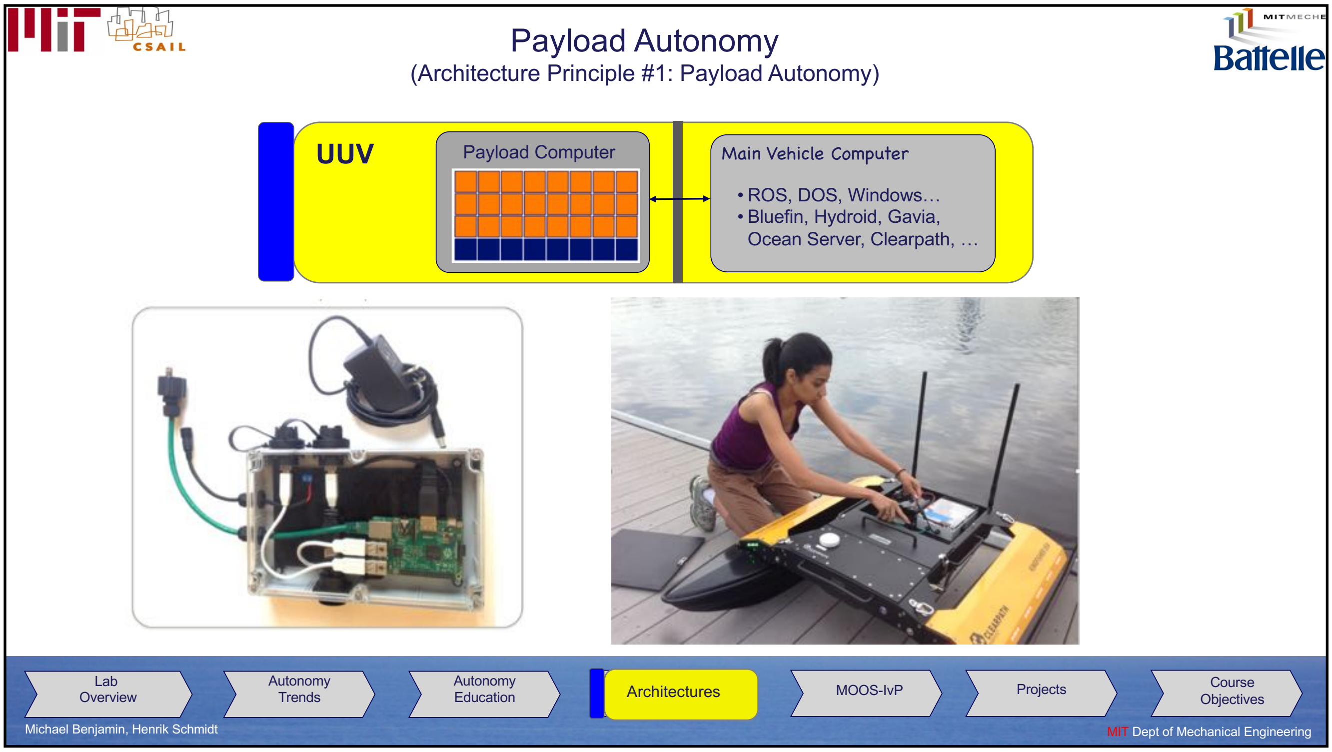

Payload Autonomy
(Architecture Principle #1: Payload Autonomy)

UUV

Payload Computer

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

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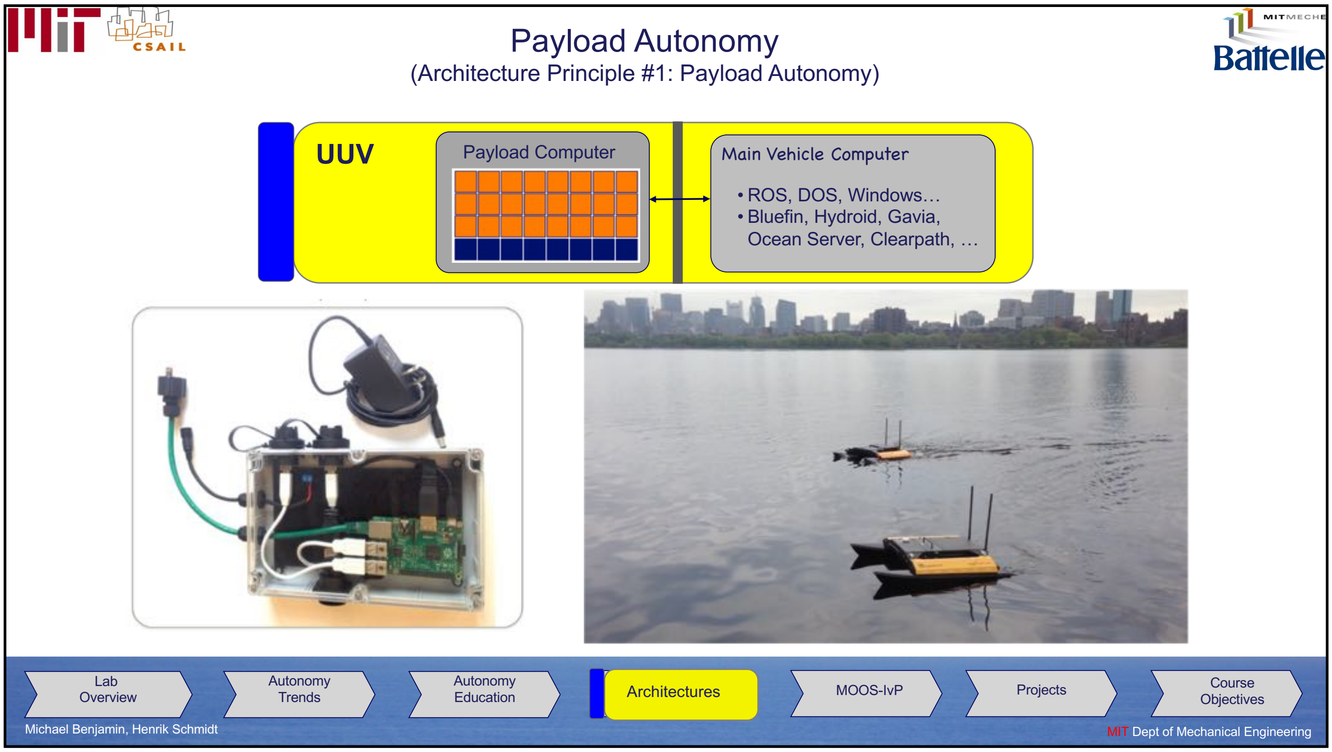
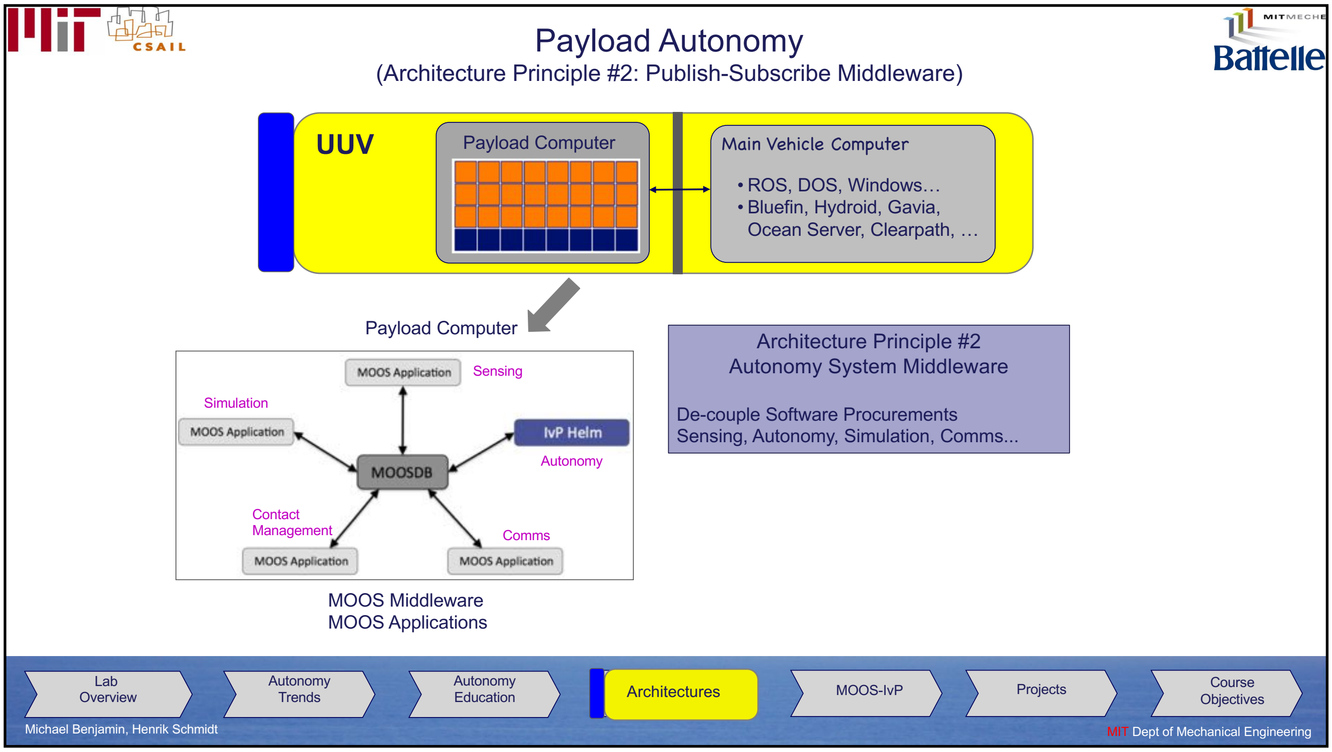


Payload Autonomy

(Architecture Principle #1: Payload Autonomy)

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



Payload Autonomy

(Architecture Principle #2: Publish-Subscribe Middleware)

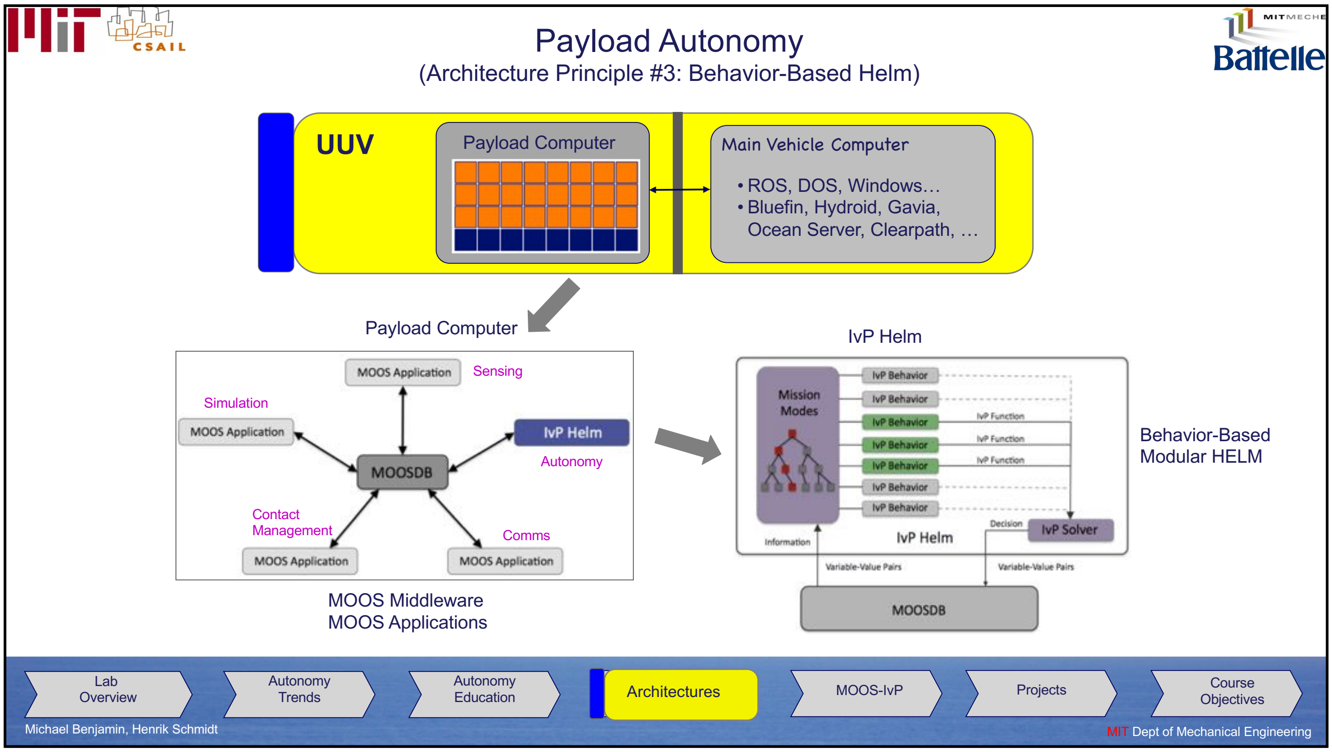
- ROS, DOS, Windows…
- Bluefin, Hydroid, Gavia, Ocean Server, Clearpath, …

Payload Computer

MOOS Middleware
MOOS Applications

Architecture Principle #2
Autonomy System Middleware

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



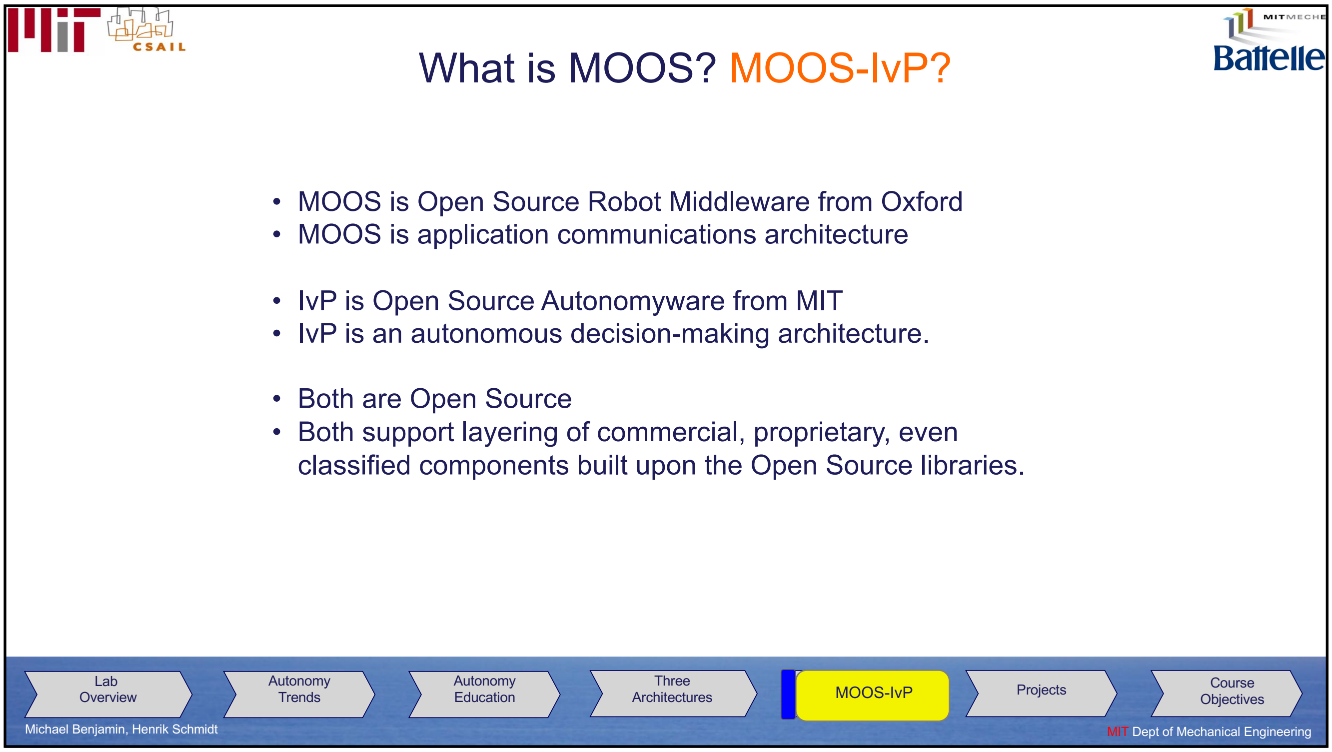
Payload Autonomy

(Architecture Principle #3: Behavior-Based Helm)

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.

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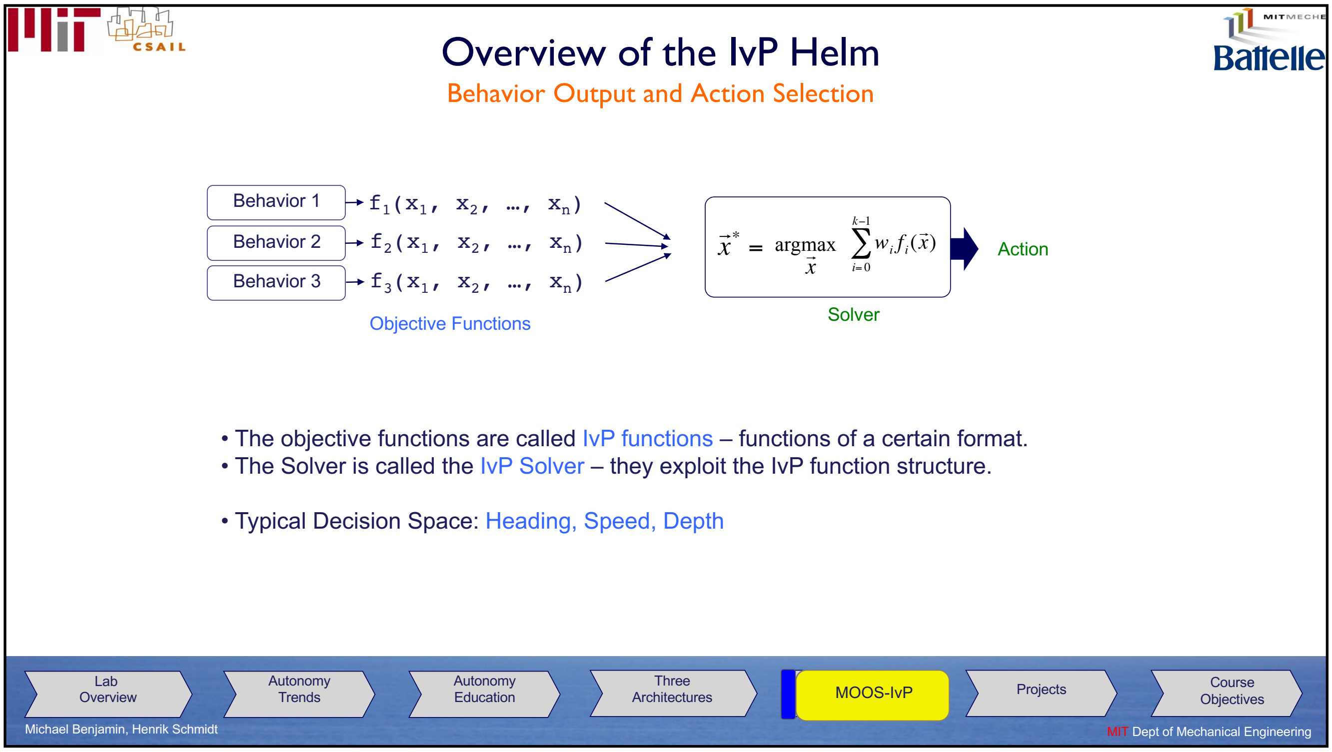

Overview of the IvP Helm

Behavior Output and Action Selection

$f_1(x_1,\ x_2,\ \dots,\ x_n)$

$f_2(x_1,\ x_2,\ \dots,\ x_n)$

$f_3(x_1,\ x_2,\ \dots,\ x_n)$

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

- 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

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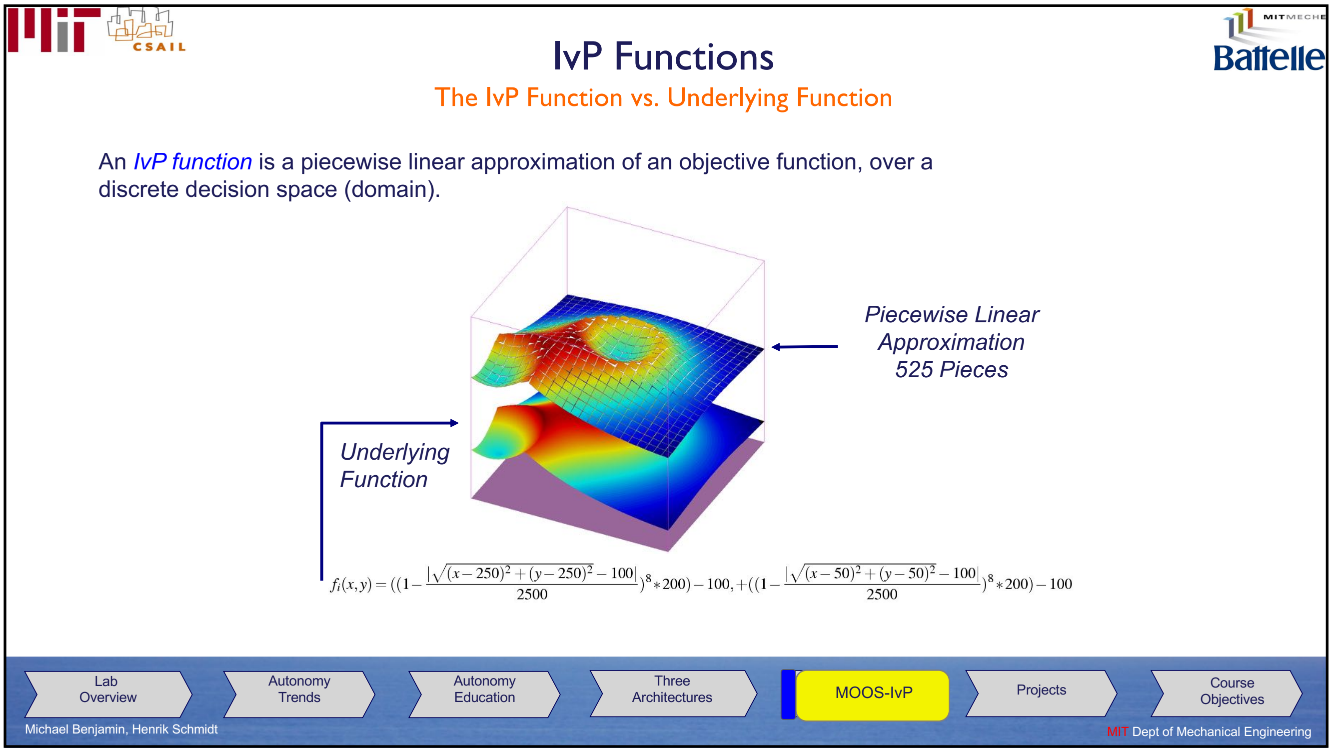

IvP Functions

The IvP Function vs. Underlying Function

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

Piecewise Linear Approximation 525 Pieces

Underlying Function

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

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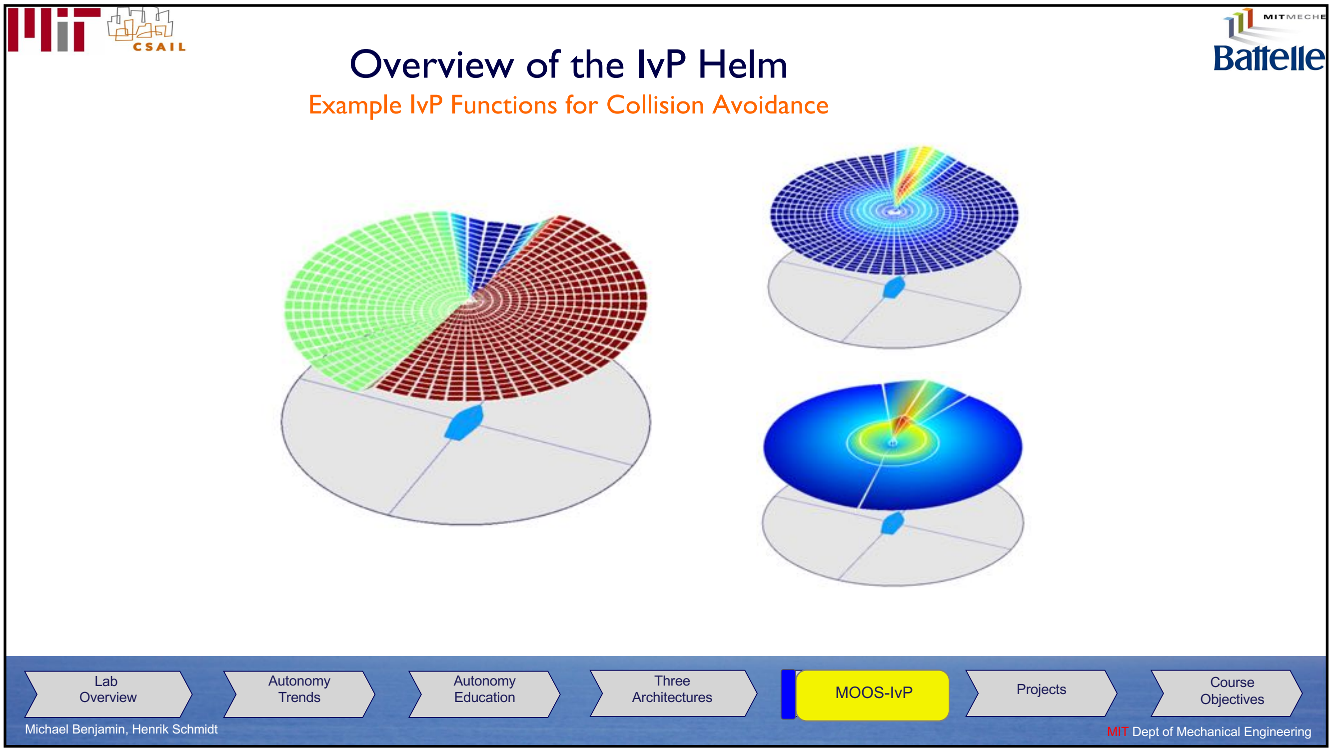

Overview of the IvP Helm

Example IvP Functions for Collision Avoidance

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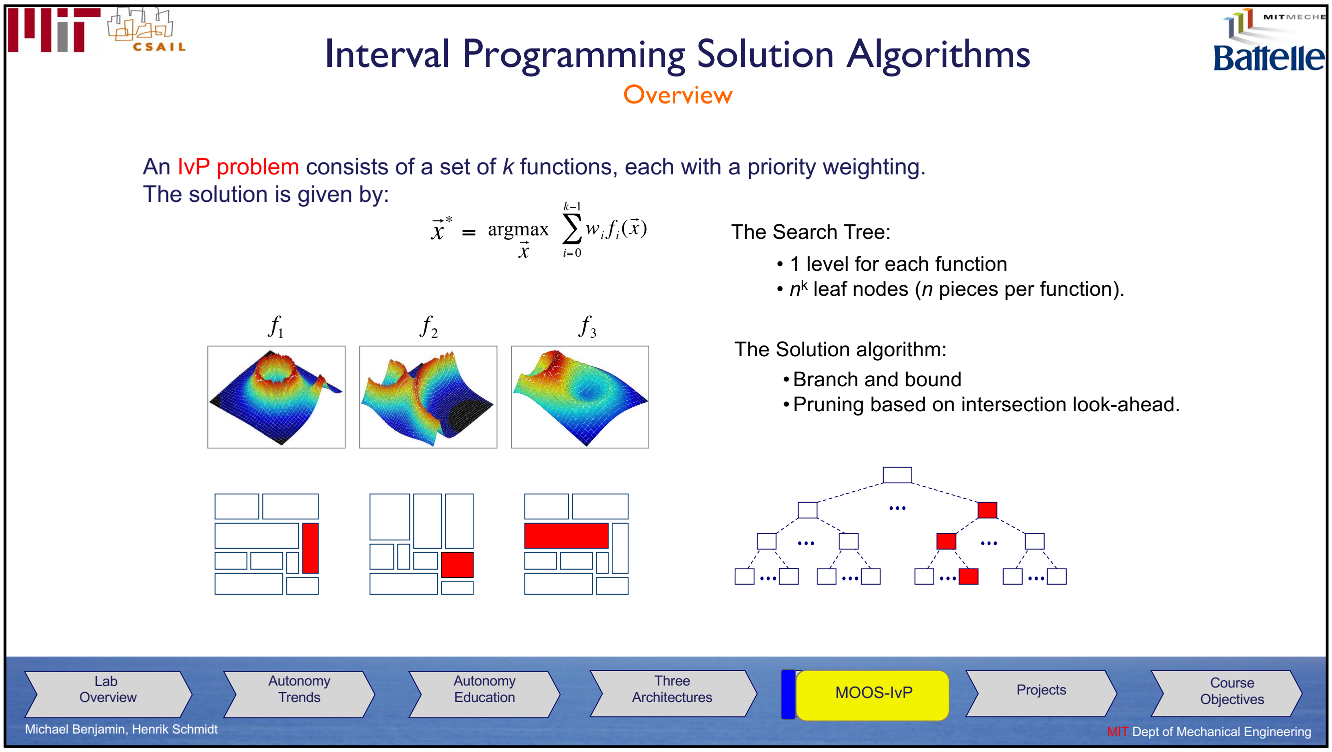


Interval Programming Solution Algorithms

Overview

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

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

The Search Tree:

- 1 level for each function
- n^k leaf nodes (*n* pieces per function).

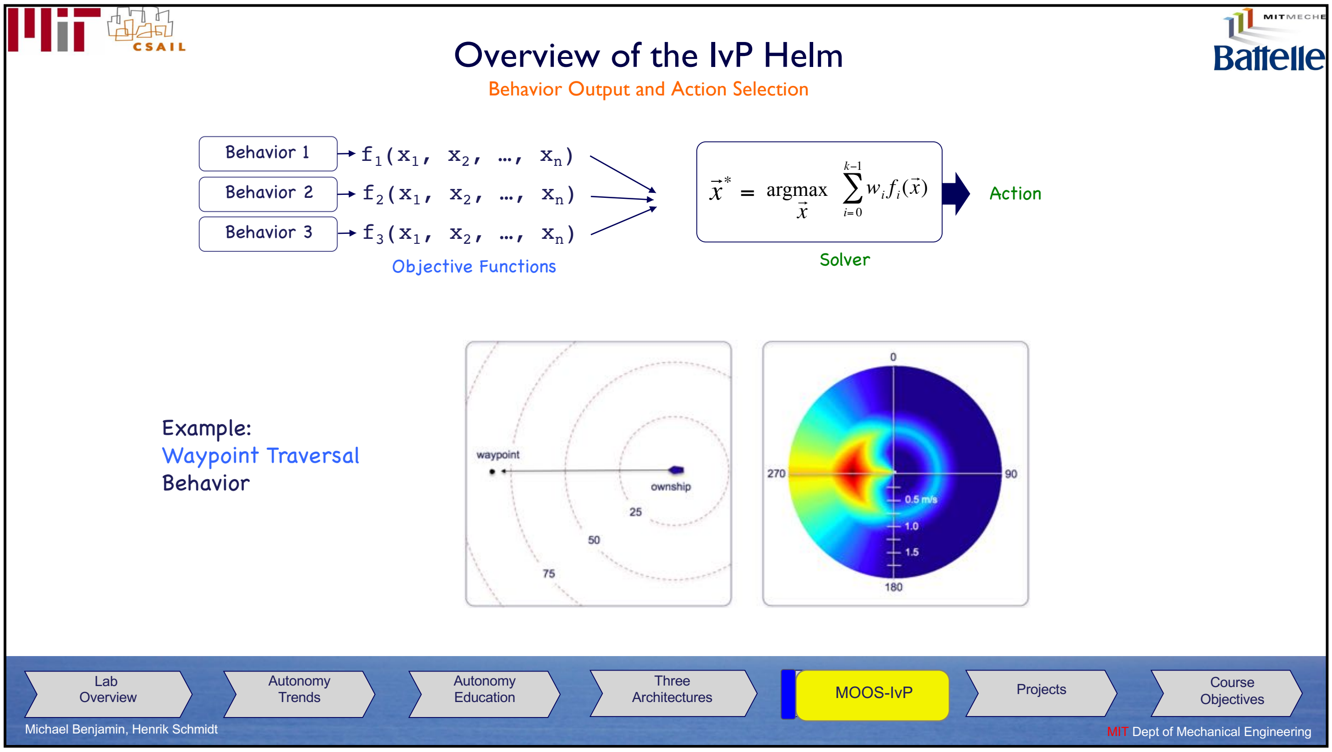
The Solution algorithm:

- Branch and bound
- Pruning based on intersection look-ahead.

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

Michael Benjamin, Henrik Schmidt

MIT Dept of Mechanical Engineering



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

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

Solver

Action

Example:
Waypoint Traversal
Behavior

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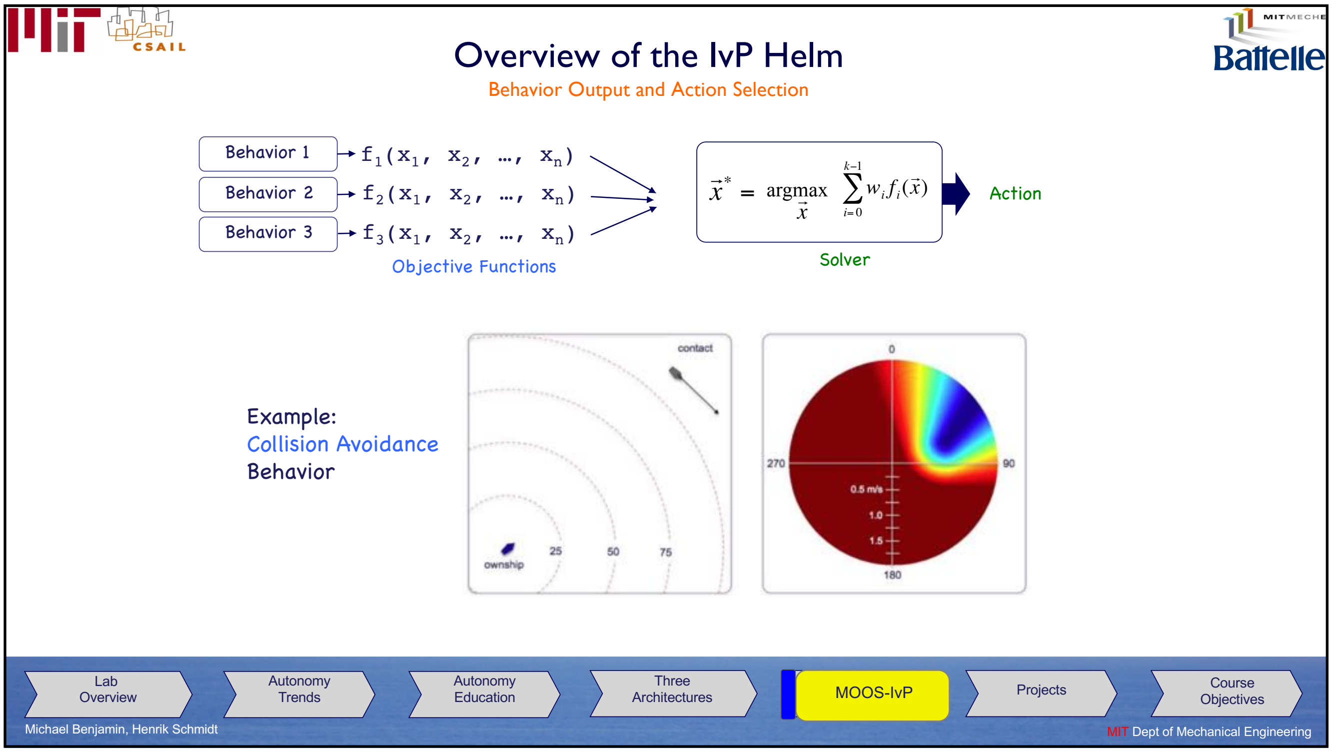

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Action

Example:
Collision Avoidance
Behavior

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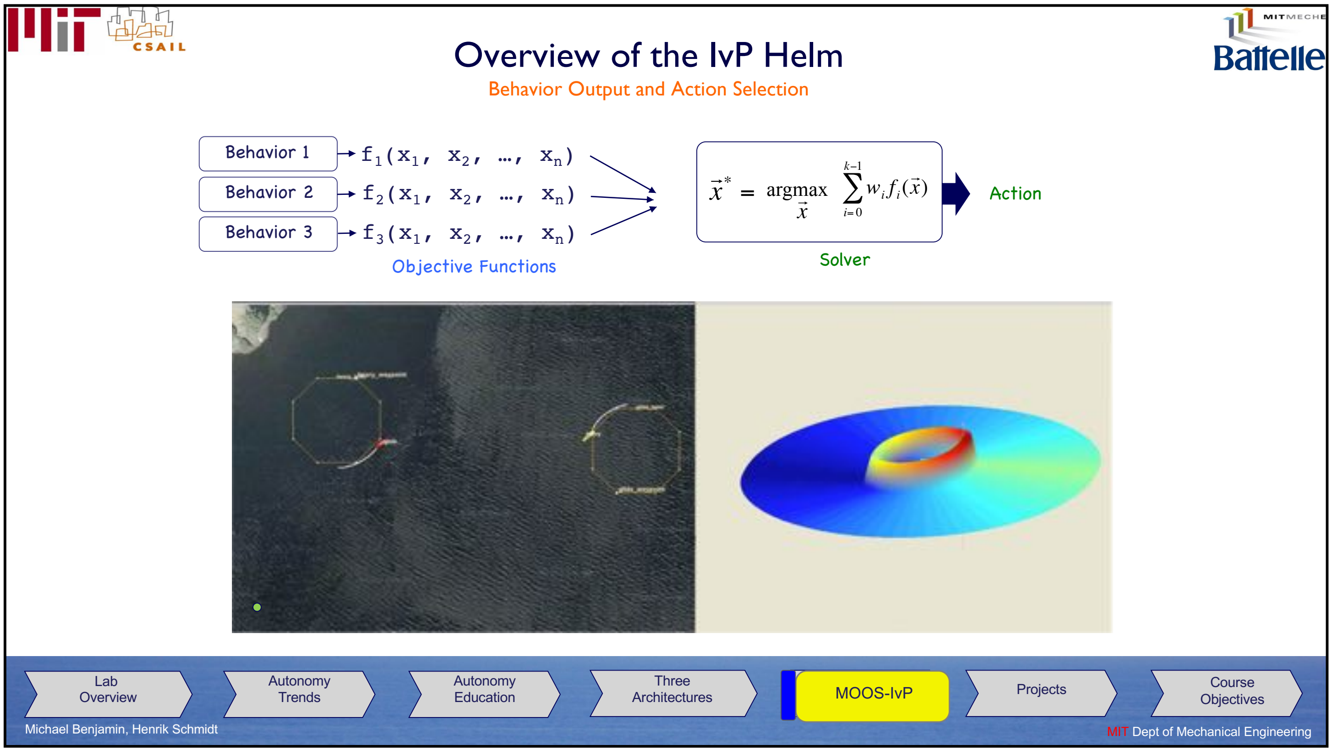

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Projects

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.

Humans are very good at improvising

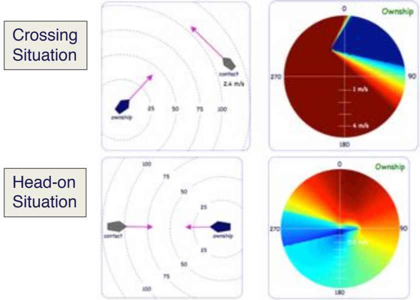
link to PortOfAmsterdam.mov

January 6th, 2018

Iranian Tanker *Sanchi*
Hong Kong-flagged bulk carrier *CF Crystal*

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)

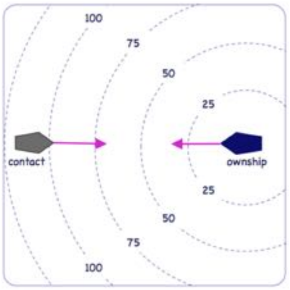
- The objective is to avoid collisions with other autonomous and non-autonomous vehicles.
- COLREGS are the rules of the road for seagoing vessels.
- They provide a protocol of roles and required actions between vessels.
- They were written for humans, not autonomous systems.

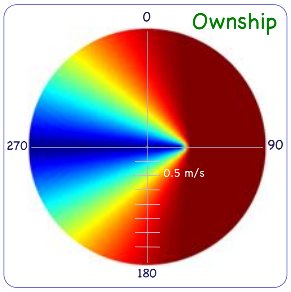
Collision Avoidance without COLREGS

link to col_avd_normal.mov

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.

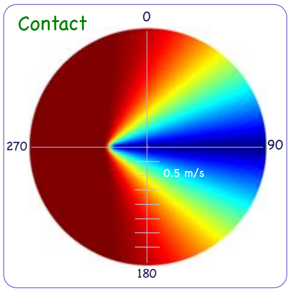


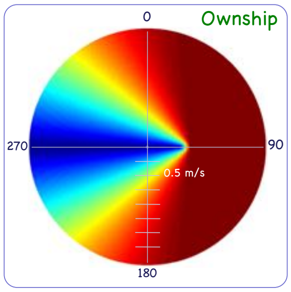


What's Wrong with Non Protocol Based Collision Avoidance

- 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.



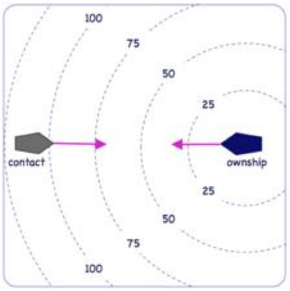


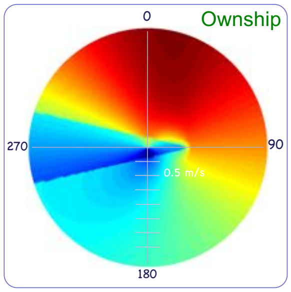
COLREGS Collision Avoidance

- 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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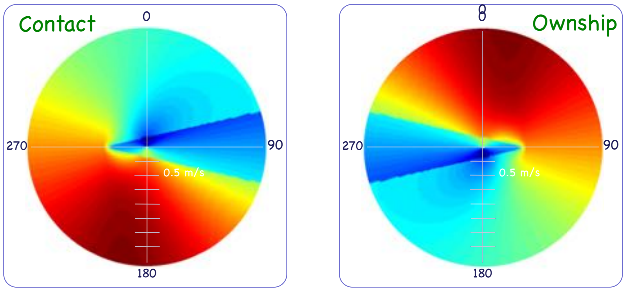
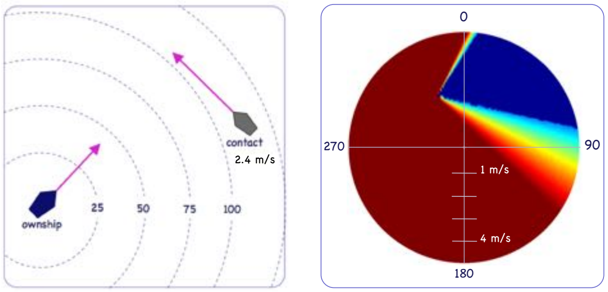


COLREGS Collision Avoidance

- 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.



COLREGS Collision Avoidance

(sponsored by ONR)

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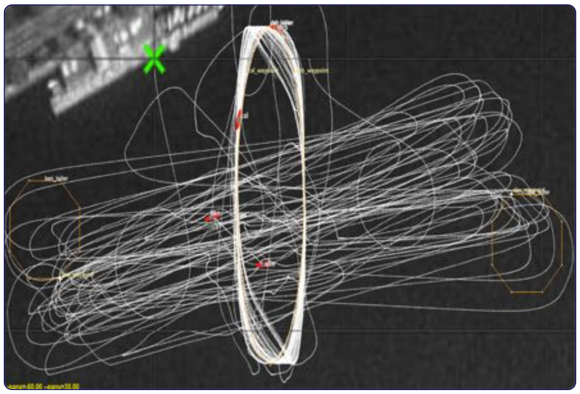
- They provide a protocol of roles and required actions between vessels.

Collision Avoidance
with COLREGS

`link to col_avd_colregs.mov`

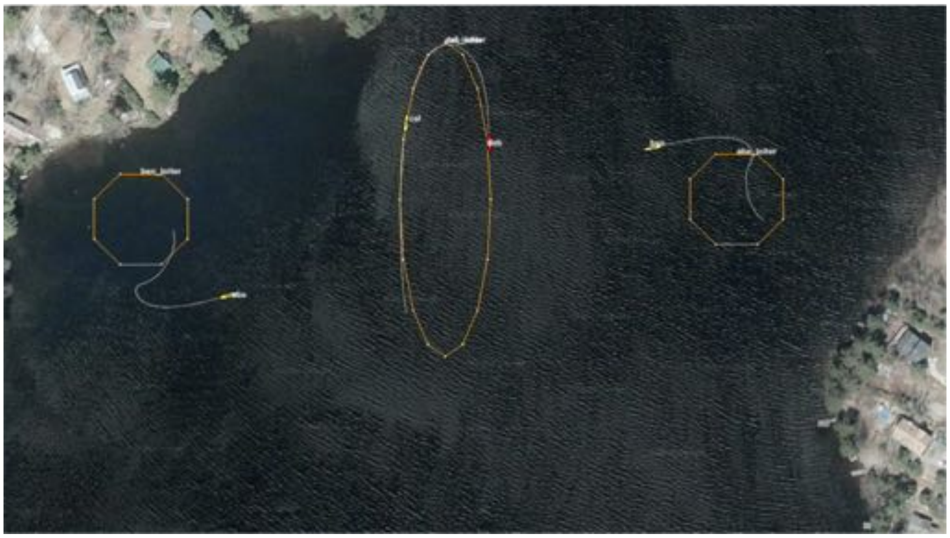
COLREGS - Testing / Validation

In-Water Tests



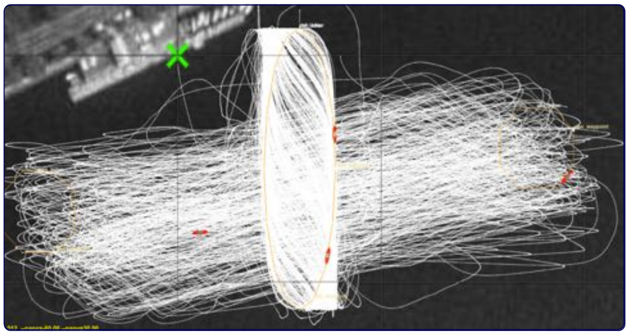
Simulation

COLREGS
Testing / Validation

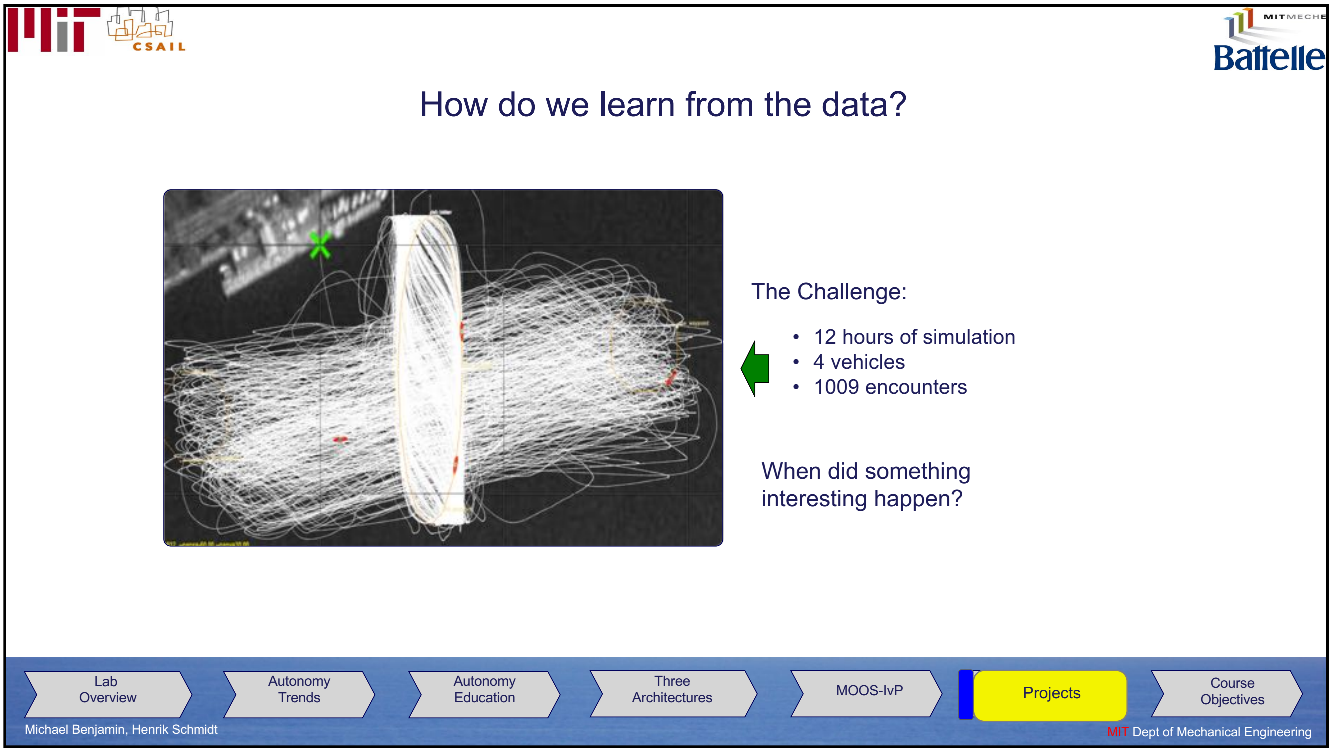


COLREGS
Testing / Validation

Simulation



Data

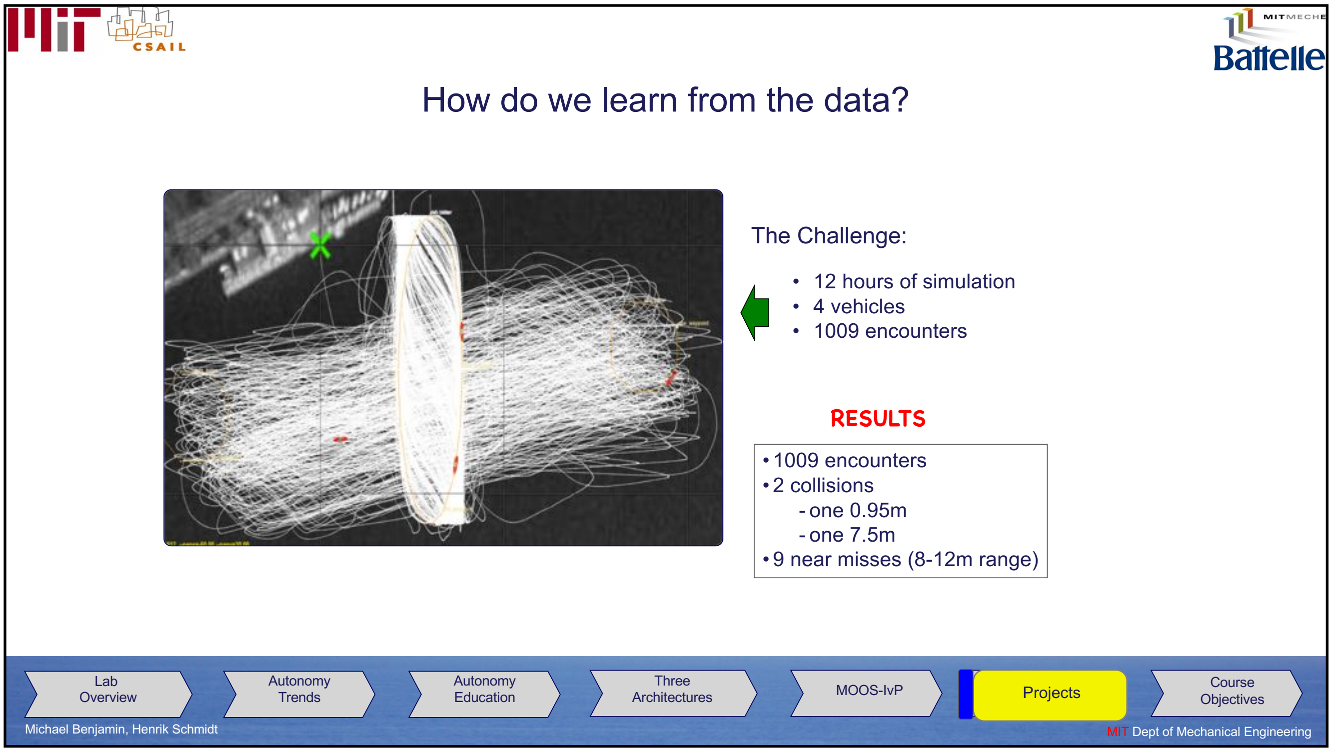


How do we learn from the data?

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
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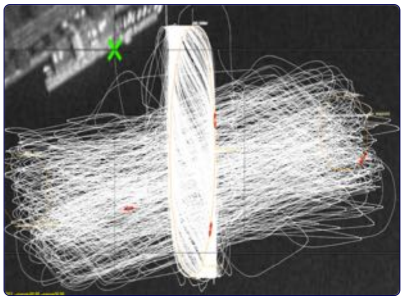
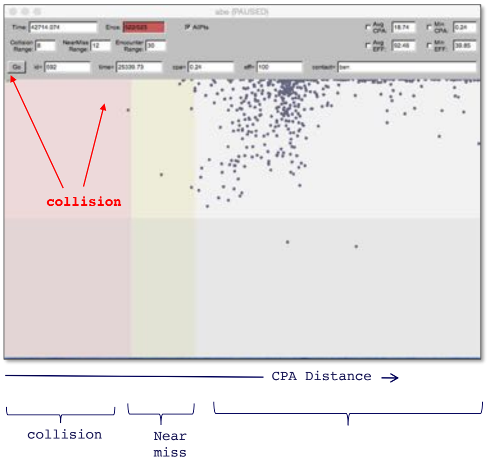
RESULTS

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

Auto Generated Encounter Plots



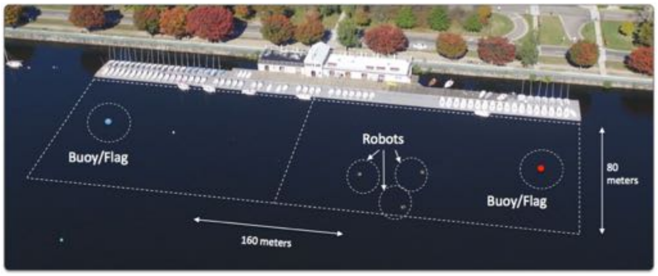


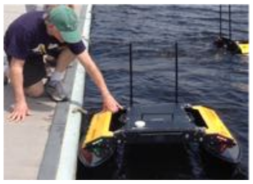
Encounter Plots

- 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.

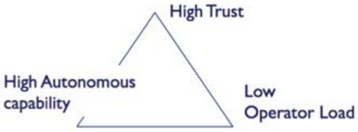
Aquaticus

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*.

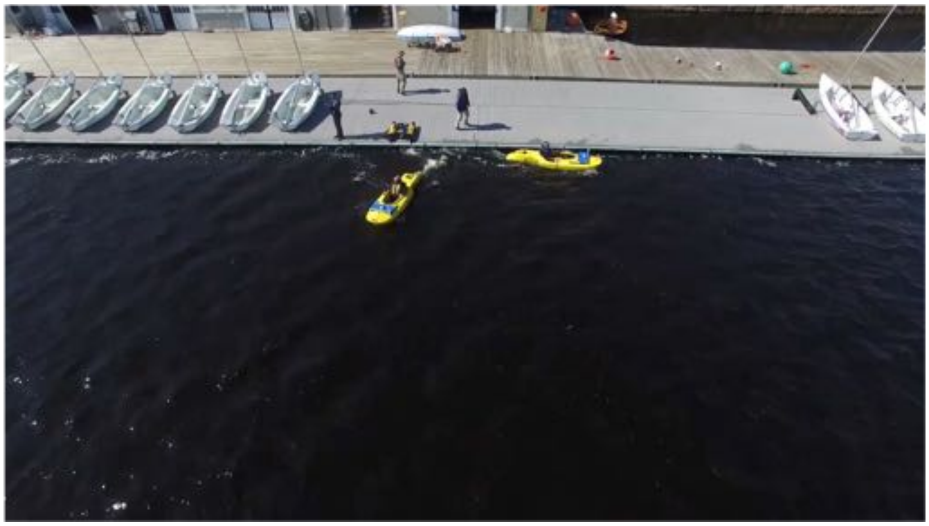
link to cutter_super_short.mov

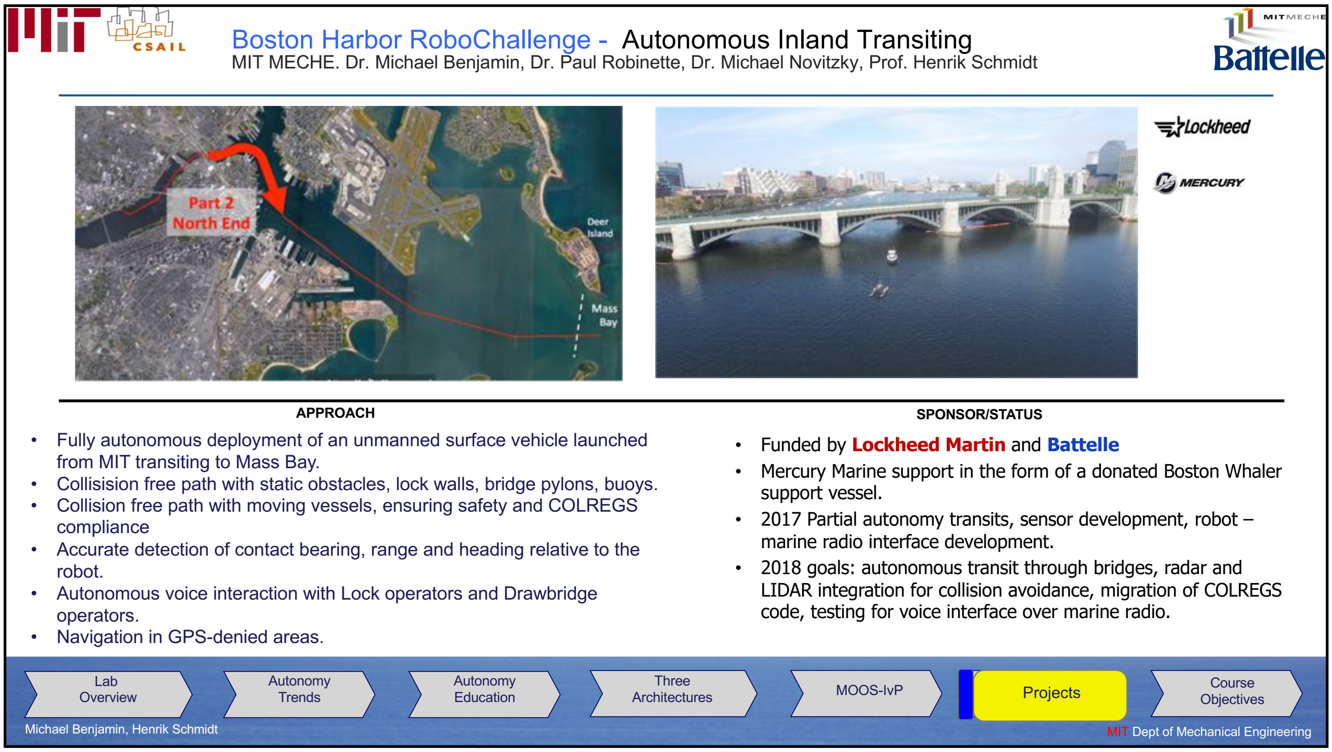


This is a tradeoff space – the right mix is not immediately obvious for a given application or set of humans.

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

Aquaticus





Boston Harbor RoboChallenge - Autonomous Inland Transiting

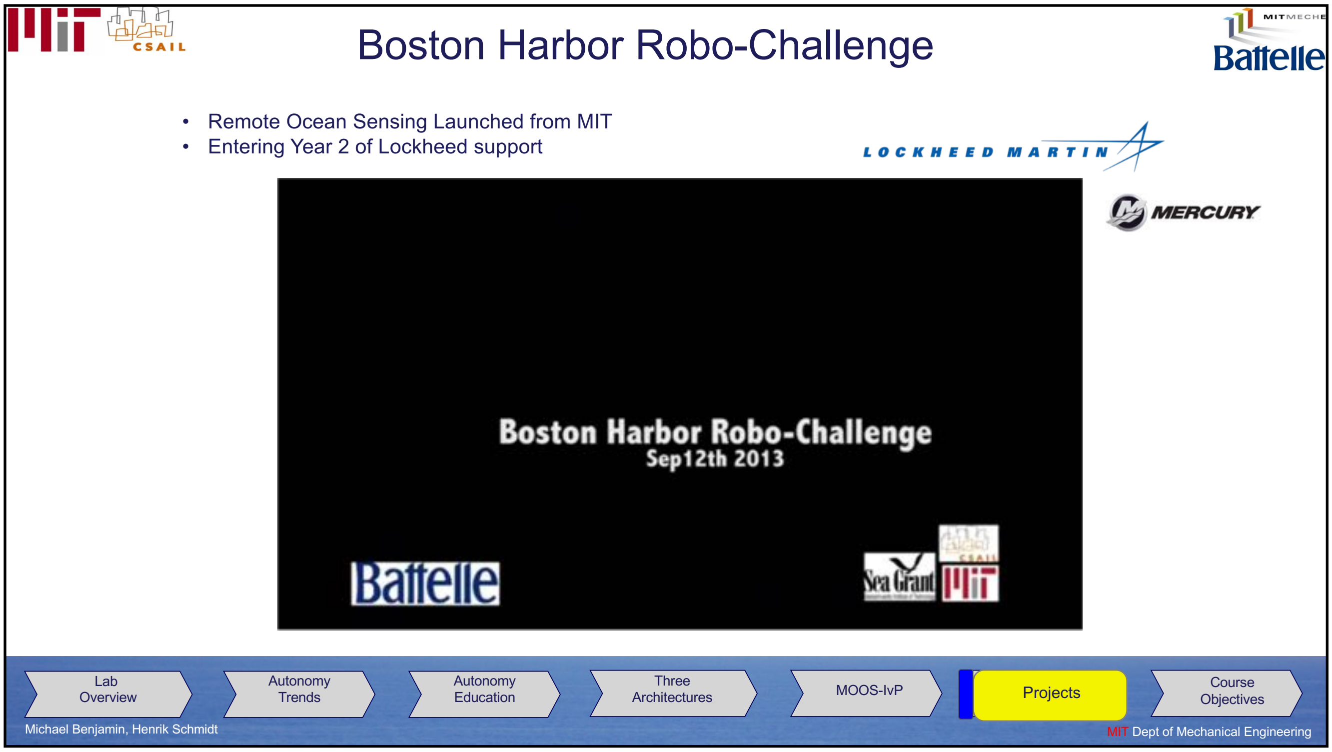
MIT MECHE. Dr. Michael Benjamin, Dr. Paul Robinette, Dr. Michael Novitzky, Prof. Henrik Schmidt

APPROACH

- Fully autonomous deployment of an unmanned surface vehicle launched from MIT transiting to Mass Bay.
- Collisision 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.



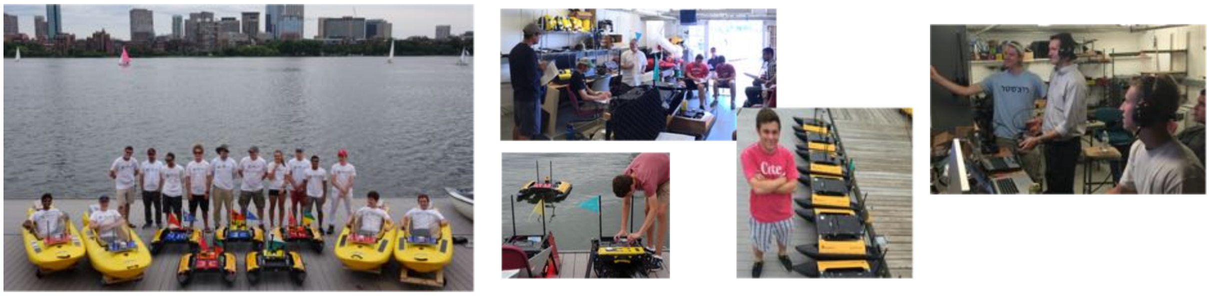
Boston Harbor Robo-Challenge

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

Boston Harbor Robo-Challenge
Sep12th 2013

Summary Marine Robotics Internship Program

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

The 2014 Winning Team with US ambassador to Singapore

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