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Swarm Autonomy Algorithm and Software Toolbox

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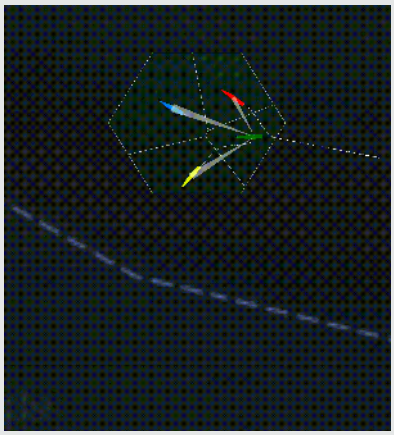

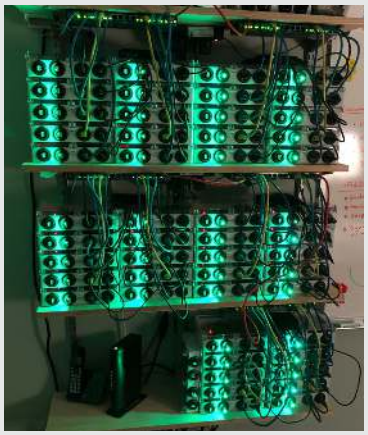

Oct 2nd 2023

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From the Proposal: This proposed work will develop new algorithms and software for scalable autonomous swarms. MIT will leverage and augment our open-source autonomy codebase with new and advanced extensions supporting scalable autonomous swarms. Four overlapping families of algorithms will comprise the initial research focus:

(a) Voronoi based methods for deploying swarms of platforms to cover, patrol or search an operational region of interest. Applications include distributed anti-submarine warfare, or wide area search for mine countermeasures or search for malicious actors.

(b) Decentralized linear convoying and mustering. Linear convoys have immediate and direct applicability in both surface and ground vehicle domains for efficient transiting requiring full autonomy or human control for only the lead vehicle. Underwater convoys can form deceptive countermeasures/decoys.

(c) High-value asset (HVA) swarm defense and attack methods. Defensive posture swarms can provide a deterrent or early warning system, but vehicles need to be deployed only with mission goals and constraints with no regard to identity or launch order, to allow ease of use for mission managers and robustness as the available number of robotic nodes increases or decreases.

(d) Adversarial competitions: competitions provide a context for engagement with students and Lockheed stakeholders around concrete mission parameters and metrics. Adversarial competitions can also be simulated in headless Monte Carlo simulations providing datasets for other Lockheed or MIT groups to derive machine learning counter-tactics.

(e) New COLREGS optimizations that will be developed to address vehicles with dynamic and varying turn abilities due to towed payloads or bio-fouling, or general thruster failure, and robustness of COLREGS to degraded sensors and higher contact densities found in swarms.

(f) Our lab is also interested in developing and introducing new advanced class in swarm autonomy.

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MIT Marine Autonomy Lab: People

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Levels of Autonomy vs Focus Areas

Project Focus Areas

(a) Voronoi based methods

(b) Decentralized linear convoying and mustering.

(c) High-value asset (HVA) swarm defense

(d) Adversarial competitions, headless Monte Carlo simulations

(e) New COLREGS optimizations

(f) new advanced class in swarm autonomy.

Levels of Autonomy

- **Level 0** - single scripted
- **Level 1** - single adaptive
- **Level 2** - collaborative independent
- **Level 3** - collaborative contacts
- **Level 4** - collaborative tactical
- **Level 5** – Collaborative tactical/human

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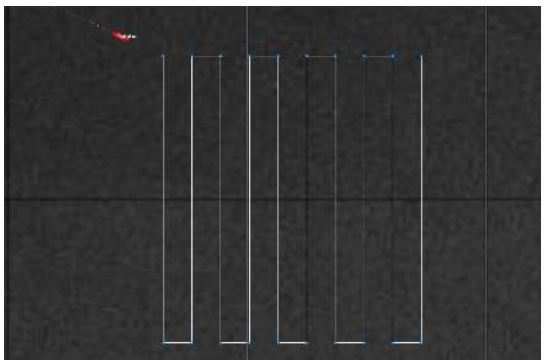
Level 0: Single Scripted Autonomy

- Pre-determined Path or event sequence
- No Sensor Input other than navigation, e.g. GPS
- Pre-determined mission completion based on event sequence or time

Level 0 - single scripted
Level 1 - single adaptive
Level 2 - collaborative independent
Level 3 - collaborative contacts
Level 4 - collaborative tactical
Level 5 – Collaborative tactical/human



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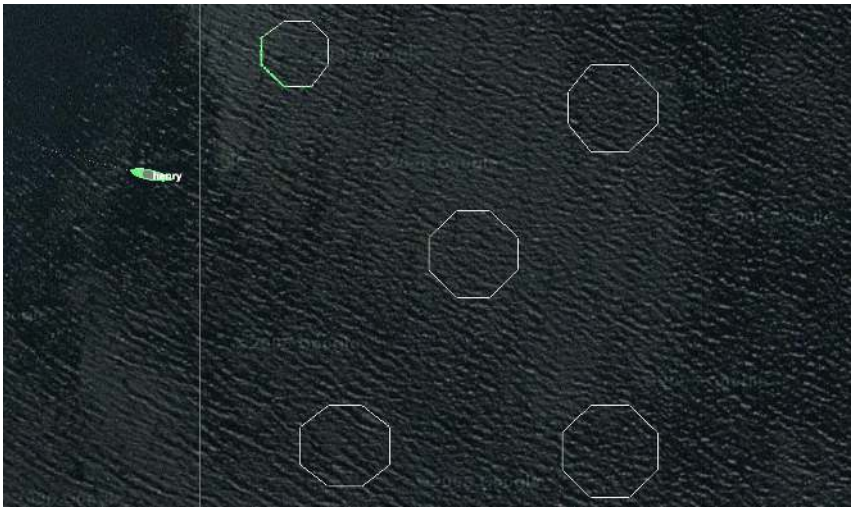
Level 1: Single Adaptive Autonomy

- Modes determined by sensed events
- Path adjustment based on obstacles or other vessels.
- Path adjustments based on environmental sensed events

Obstacle Avoidance based on LIDAR data

Level 0 - single scripted
Level 1 - single adaptive
Level 2 - collaborative independent
Level 3 - collaborative contacts
Level 4 - collaborative tactical
Level 5 – Collaborative tactical/human



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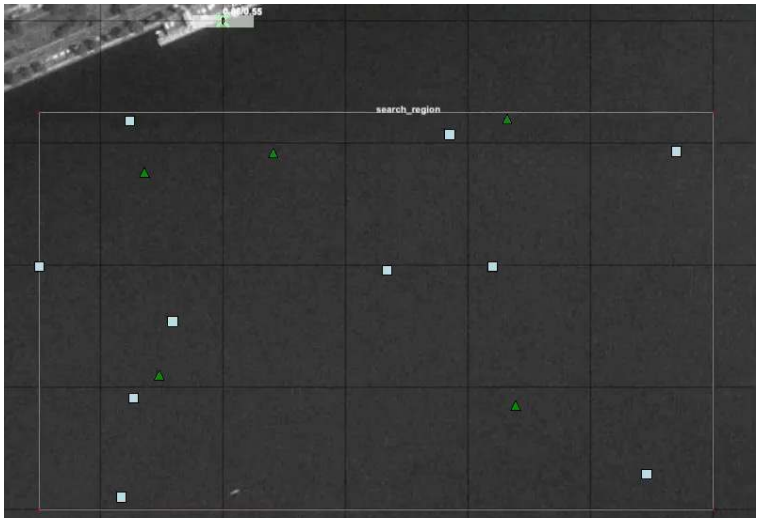
Level 2: Collaborative Independent

- Pre-determined Path for each vehicle
- No information shared between vehicles
- Coordination achieved by offline pre-mission planning



Simulation two vehicles conducting an MCM broad-area search mission, each assigned to one half of the search region.

- **Level 0** - single scripted
- **Level 1** - single adaptive
- **Level 2** - collaborative independent ←
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Level 3: Collaborative Contacts

- Vehicles share contact information (Similar to AIS)
- Similar information could be obtained with passive sensor
- No tactical information shares. Coordination through protocol only.

Vehicles switch between East/West Loiter Regions

- **Level 0** - single scripted
- **Level 1** - single adaptive
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- **Level 3** - collaborative contacts ←
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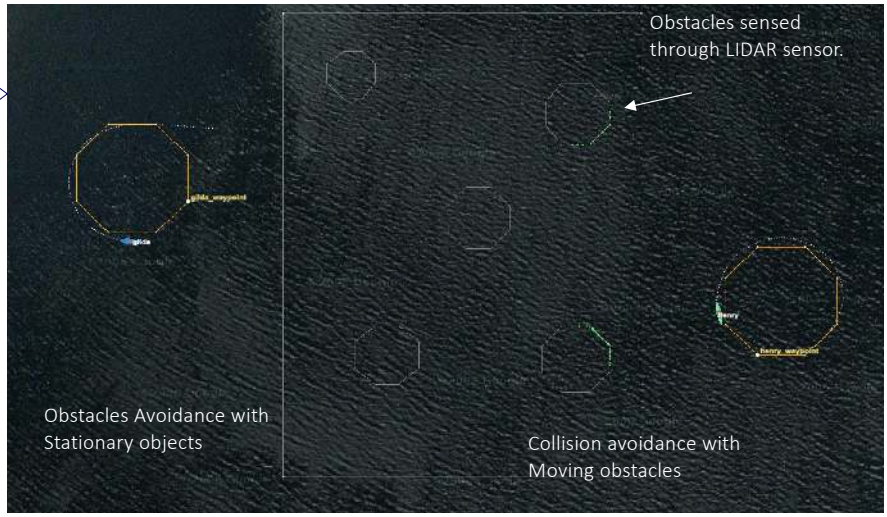

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Level 3: Collaborative Contacts (Example 2)

- High-Value Asset Defense
- Vehicles only share each other's position, speed and heading (again, similar to AIS)

Position information:
- Avoid Collisions
- Achieve even spacing

- **Level 0** - single scripted
- **Level 1** - single adaptive
- **Level 2** - collaborative independent
- **Level 3** - collaborative contacts ←
- **Level 4** - collaborative tactical
- **Level 5** – Collaborative tactical/human

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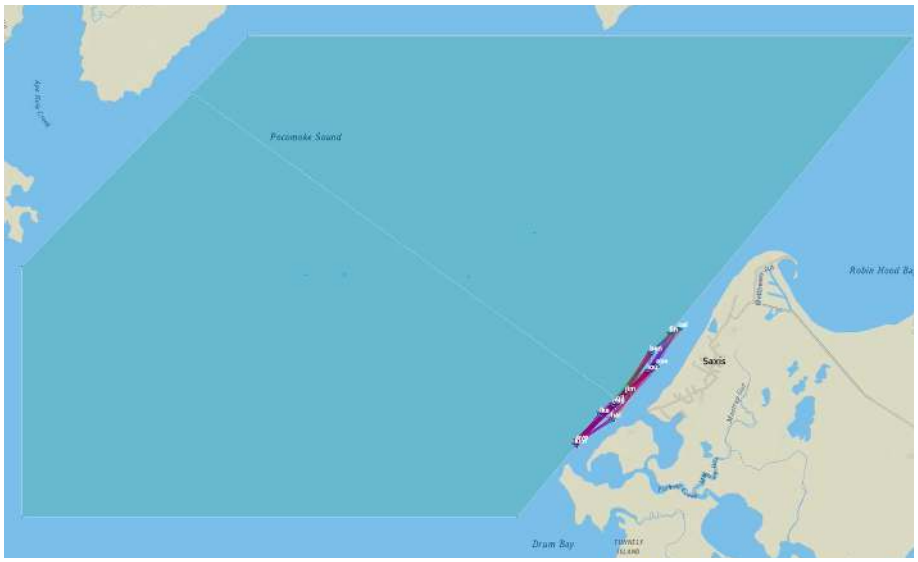
Level 3: Collaborative Contacts (Example 3)

- Cover the search area with balance between each vehicle
- Vehicles only share each other's position, speed and heading (again, similar to AIS)

Field will adjust to failures of some vehicles, or additional vehicles entering the field.



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Level 4: Collaborative Tactical

Collaborative:
- Share joint responsibility for encircling the HVA
- Adjust speed to maintain even spacing
- Reach consensus on best vehicle to investigate points of interest

Inter-vehicle auctions:
- Determine who interdicts
- Each vehicle produces a bid

Level 0 - single scripted
Level 1 - single adaptive
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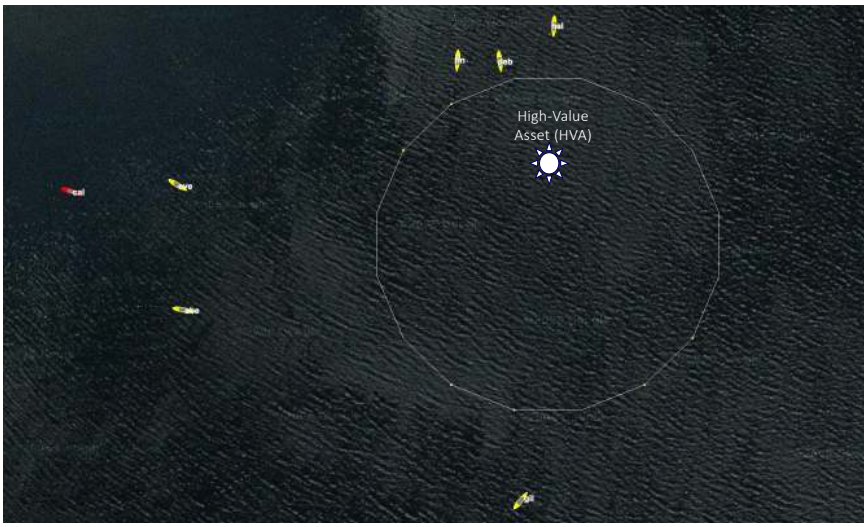
Level 5 – Collaborative tactical/human



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Level 4: Collaborative Tactical (Example 2)

Collaborative:
- Group receives a command to form a convey to a destination
- Commander does not pick the ordering
- Order is based on most reasonable given position and headings

Inter-vehicle auctions:
- Determine who leads
- Cascading sequence of bids to determine followers

Level 0 - single scripted
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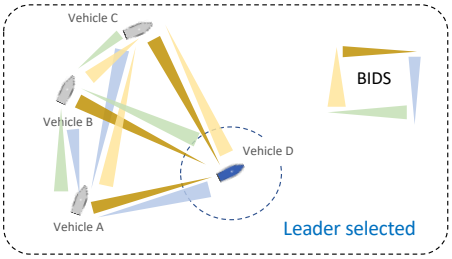

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Collaborative Autonomy: Messaging

Inter-vehicle Messaging
Determines
Collaboration Possibilities

Message Content **Message Reliability**

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Message *Content*

Message Content

Inter-Vehicle Comms Message Content

- THIN: Position/Pose
- SEMI-RICH: Position/Pose + Status or Intent, *no acknowledgements*
- RICH: Unlimited Data Types, plus acknowledgements

Information **cannot** be obtained by passive sensors

Information **can** be obtained through passive sensors

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Message *Reliability*

Message Reliability

Inter-Vehicle Comms Performance

- LOSSY: Frequent drops. Worse at higher ranges
- SEMI-RELIABLE: Decent comms, mitigated with re-sends
- RELIABLE: Perfect comms at all ranges

Dropped Messages **can** be mitigated by re-send / acks

Dropped messages **cannot** be mitigaged by re-send / acks

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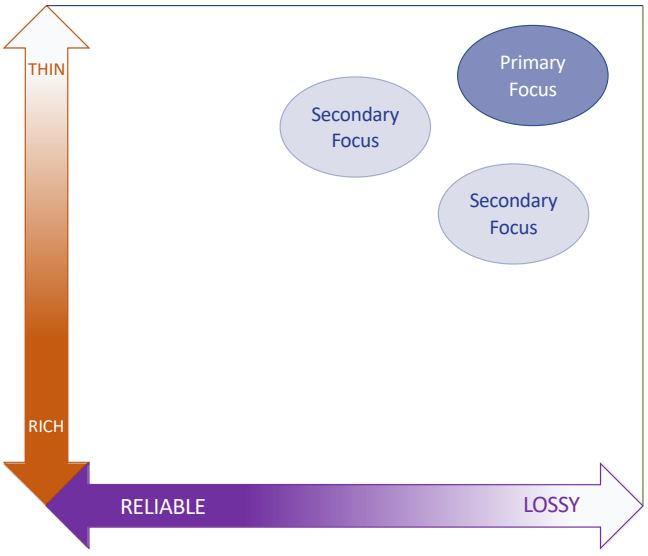
Mission Focus Based on Comms



Swarm Toolbox:
We are interested in autonomy that concedes:

- Rare comms from shore to vehicles
- Lossy comms generally
- Messages limited in content type
- Range limited, local-neighbor only

Note:
The first point above implies that group decision-making, role assignments etc, need to be distributed and decided among the vehilces, either through (a) protocol, or (b) inter-vehicle auctions.

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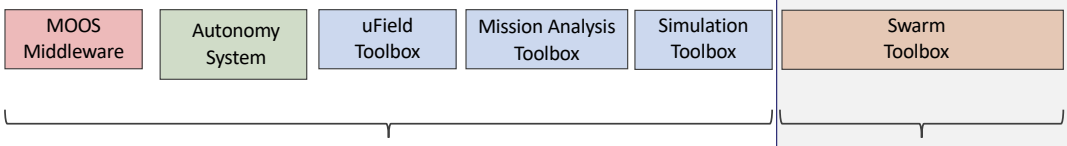
Swarm Autonomy Algorithm and Software Toolbox

The MOOS-IvP Open-Source Autonomy Project

- In Development since ~1998.
- First launched online in 2006.
- Latest release in August 2022.



MOOS-IvP Public code

- ~40 work years of effort
- Ported to dozens of platform types
- Full documentation and training

Non-Public code

- ~5 work years of recent efforts

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Project Focus Areas

1. Voronoi Based Methods
2. Linear Convoying and Mustering
3. HVA Swarm Defense
4. Adversarial Competitions
5. Automated Monte Carlo Sims
6. COLREGS Optimization
7. UUV Swarm Autonomy Class

What is the current status?
What are the goals during the Project?

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Area 1: Voronoi Based Methods

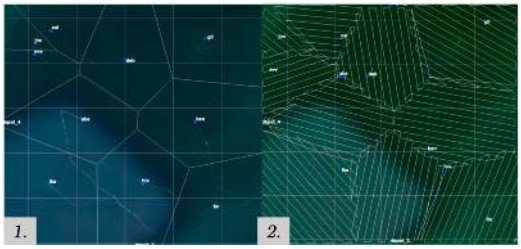
Current Status:

- Capable of launching and dispersing N vehicles in a given convex polygon
- Algorithm robust to additional vehicles and loss/return of a vehicle.

What are the goals during the Project?

- Perpetual motion algorithms to support broad areas search, ASW detection likelihood
- Motion policies to optimize recovery rotation of vehicles at launch point.
- Variations to support sailing platforms.

- Identify performance metrics
- Integrate metrics evaluation software
- Automated Monte Carlo Test and Evaluation



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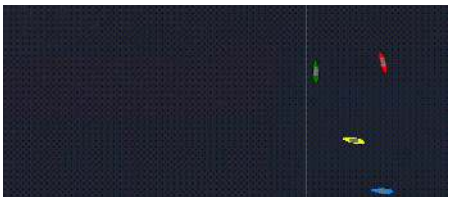
Area 2A: Linear Convoy Ordering

Current Status:

- Convoy ordering auctions based on position relative to destination

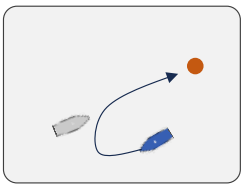


What are the goals during the Project?

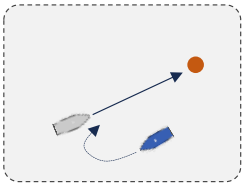
- Ordering auctions that use initial heading, turn radius and collision avoidance considerations.
- Handle vehicles able to turn in place, e.g., differential thrust USVs

- Identify performance metrics
- Integrate metrics evaluation software
- Automated Monte Carlo Test and Evaluation

- In-Water Heron Testing complementing simulation



Now: Blue wins because it is Closest to the destination.



TBI: Blue bids lower due to distance considering turn radius, and likely collision.

Competing Metrics: (a) CPA distance, (b) time, (c) distance

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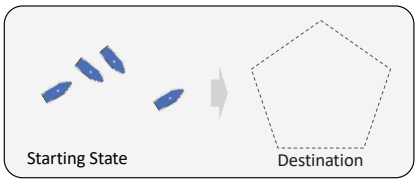
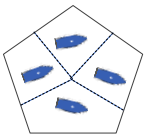
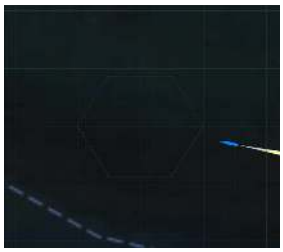
Area 2B: Convoy into Mustering

Current Status:

- Mustering implemented based on Voronoi methods
- Field-tested on Herons and DARPA Sea Train platforms





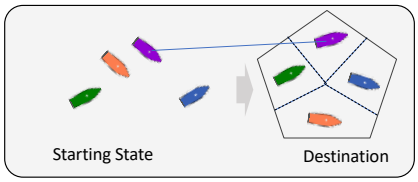


What are the goals during the Project?

- Explore variations that utilize decentralized consensus on Voronoi partition and assignment.
- Heuristically bias the partition and assignment on approach geometry

- Identify performance metrics
- Integrate metrics evaluation software
- Automated Monte Carlo Test and Evaluation

- In-Water Heron Testing complementing simulation



TBI: Sub-zones of the muster regions and rough assignment consensus before approaching the region. Fall back to ad-hoc adjustments nearer to the destination.

Metrics: (a) CPA distance, (b) time, (c) distance (d) region balance

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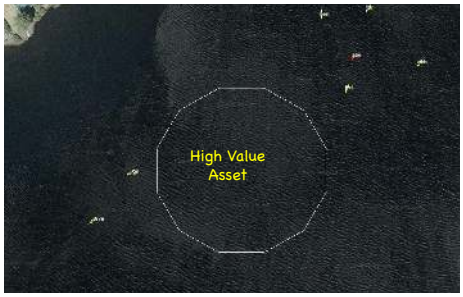
Area3: HVA Swarm Defense

Current Status:

- Protection around stationary vehicle
- Scalable to N vehicles, COLREGS collision avoidance

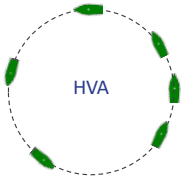


What are the goals during the Project?

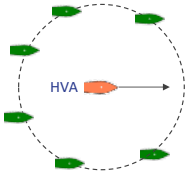
- Asymmetric defense on bearing angle(s) of high vulnerability.
- Posture transition from stationary HVA to transiting HVA.
- Asymmetric defense on bearing angle to allow passage of friendlies.

- Identify performance metrics
- Integrate metrics evaluation software
- Automated Monte Carlo Test and Evaluation

- In-Water Heron Testing complementing simulation



TBI: Asymmetric protection



TBI: Protection for transiting HVA

Metrics: (a) balance of protection, (b) time to achieve balance after disruption, (c) CPA distance during mission

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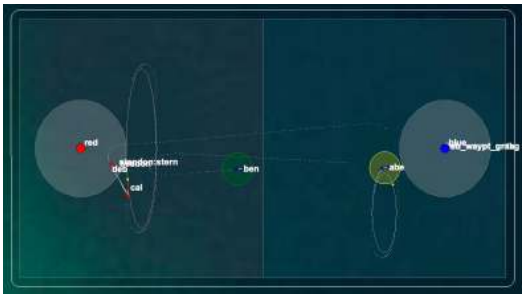
Area 4: Adversarial Competitions

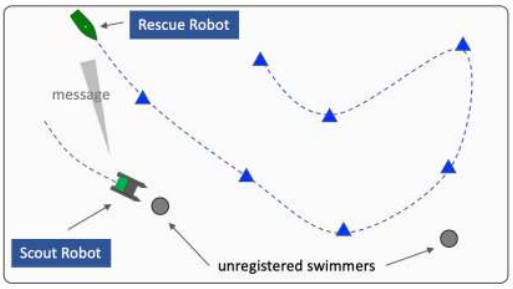
Current Status (Aquaticus):

- Up to 4-4 capture-the-flag
- Moved from MIT to West Point
- Marine Autonomy Lab supporting West Point in the AI Strategic Challenge – A Five Eyes OSD funded project.
- Most competitors using ML to learn attack/defense behaviors, embedded in MOOS-IvP environment.



Current Status (Autonomous Rescue):

- Essentially an Easter Egg Hunt, with one robot searching and the other robot collecting.
- Capstone Lab sequence in MIT 2.680 Spring Class
- Final labs: 2 Herons vs 2 Herons



What are the goals during the Project?

- Automated Monte Carlo Test and Evaluation
- Build structure for anonymous competition submissions

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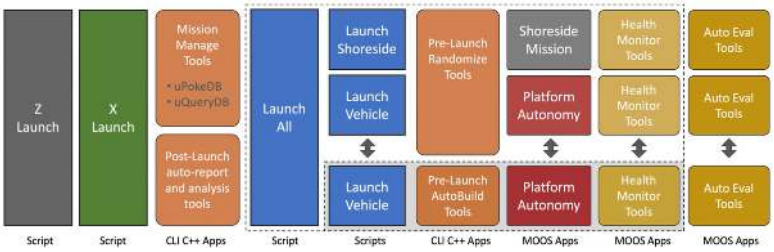
Area 5: Headless Monte Carlo Sims

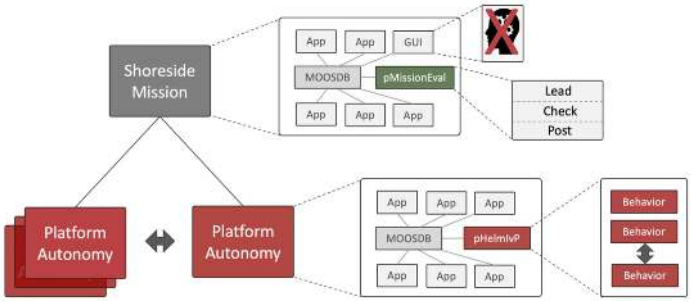
Current Status:

- Mission Launch structure protocols well-defined with wrapper scripts for launching batches of mission with varying parameters.
- Post-mission data archiving tools complete
- Post-mission data visualization tools under development.



What are the goals during the Project?

- Further automation to support our own evaluation of swarm autonomy, and head-to-head competitions
- Support for third-party submissions. To support labs in the MIT autonomy class and future swarm class, and to support hosting of competitions with MIT external partners.



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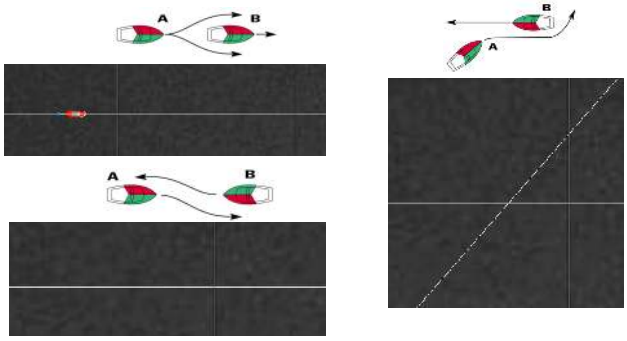
Area 6: COLREGS Optimization

Current Status:

- COLREGS behavior release in 2017, 2019.
- Rules 13-17.
- Multi-vehicle Ops handled naturally through IvP multi-objective optimization.
- Heavily optimized CPAEngine C++ implementation for evaluating CPA options, [1], [2]

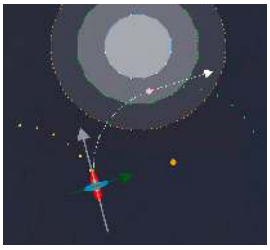
[1] Michael R. Benjamin, *Capturing Velocity Function Plateaus for Efficient Marine Vehicle Collision Avoidance Calculations*, OCEANS 2018 MTS/IEEE Kobe Japan, May 2018.
[2] Michael R. Benjamin, *Fast-CPA: A Layered Caching Algorithm for Rapid Closest Point of Approach Calculations in Marine Collision Avoidance*, OCEANS 2017 MTS/IEEE Anchorage, Anchorage, AK, September 2017.

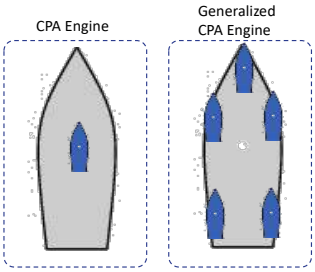


What are the goals during the Project?

- Integrate Dubins Path model into CPAEngine
- Generalized CPA Engine
- Relaxed Stand-On policy variations
- In-water jousting missions

- Identify performance metrics
- Integrate metrics evaluation software
- Automated Monte Carlo Test and Evaluation





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Area 7: UUV/Swarm Course

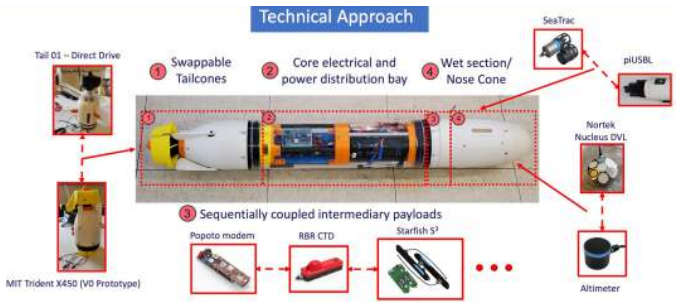
Current Status:

- Currently there is no dedicated UUV technology class at MIT.
- Currently there is no swarm autonomy class at MIT.
- There is strong interest, esp among the ~30 Navy students
- MIT has developed the Sea Beaver UUV with seed funds from DARPA TTO.

What are the goals during the Project?

Outside of SwarmBox scope:
- Explore low-cost Acomms and Nav solutions
- Further refine electronics and tailcone
- Explore external interest in the course with NAVSEA centers and the Academies.
- Search for curriculum funding.

Within SwarmBox scope:
- Develop lectures and course material based on SwarmBox threads



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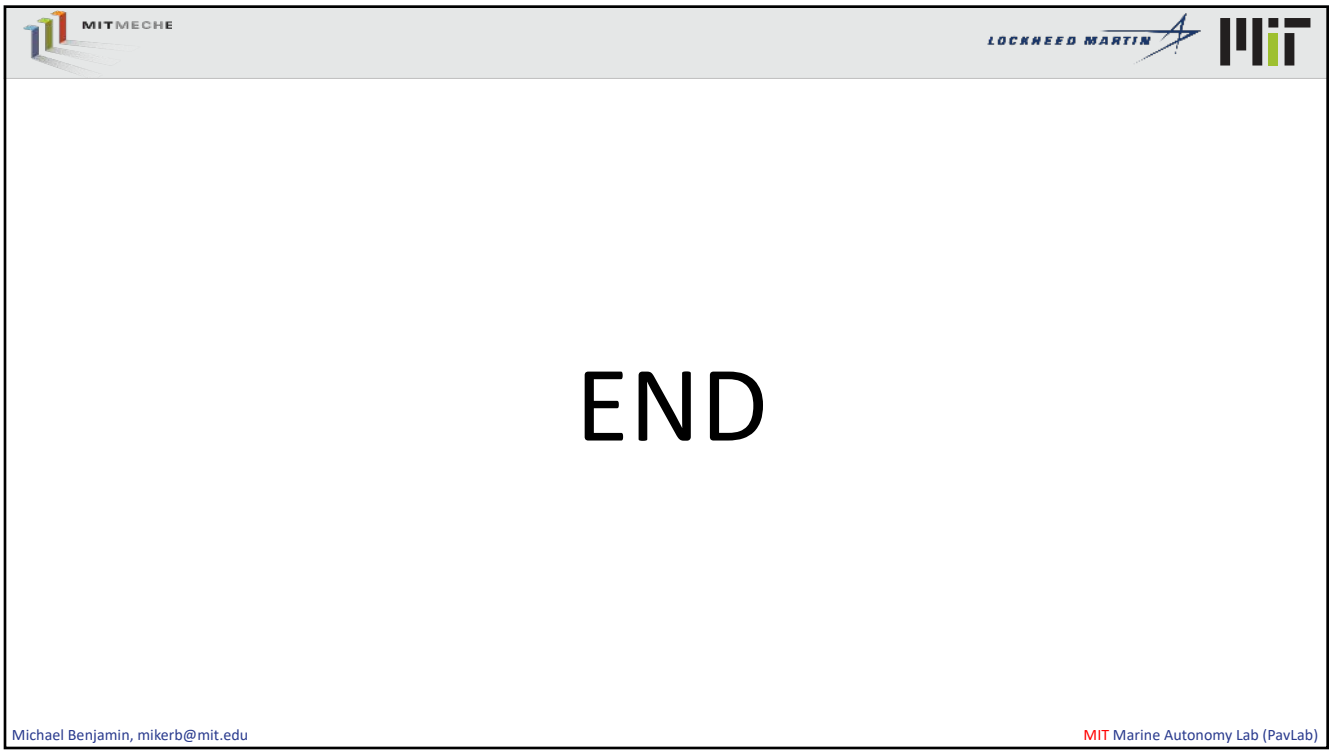
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