

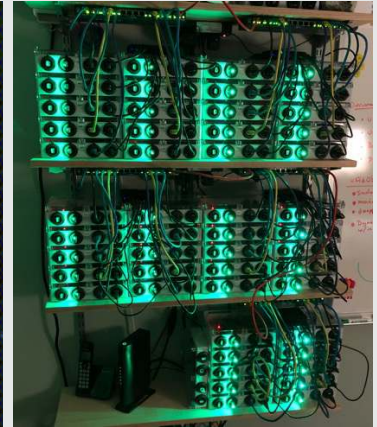
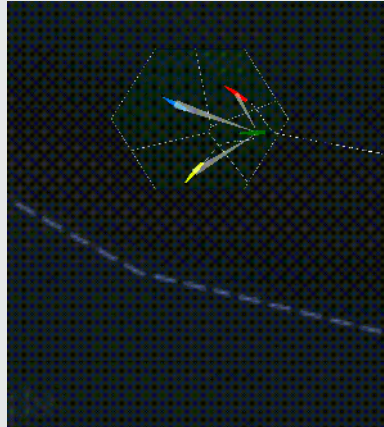


## Swarm Autonomy Toolbox and Simulation Cluster



Aug 10<sup>th</sup>, 2022

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MIT Building 5-214  
[mikerb@mit.edu](mailto:mikerb@mit.edu)



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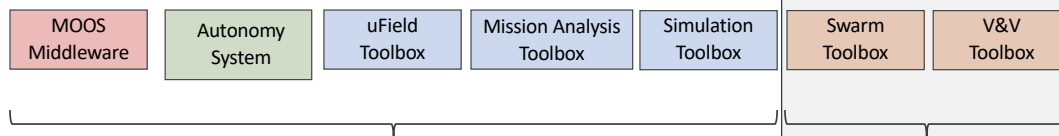


## Marine Autonomy Software



### 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

2




## Message Content



**Inter-Vehicle Comms Message Content**

- THIN: Position/Pose
- SEMI-RICH: Position/Pose + Status or Intent
- 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



**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  
mitigated by re-send / acks

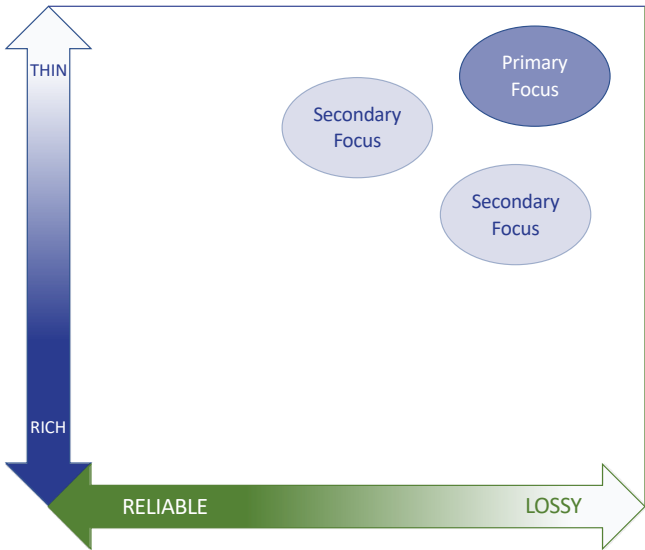
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## Marine Autonomy Software





**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 vehicles, either through (a) protocol, or (b) inter-vehicle auctions.


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## Mission Example: Protection of HVA



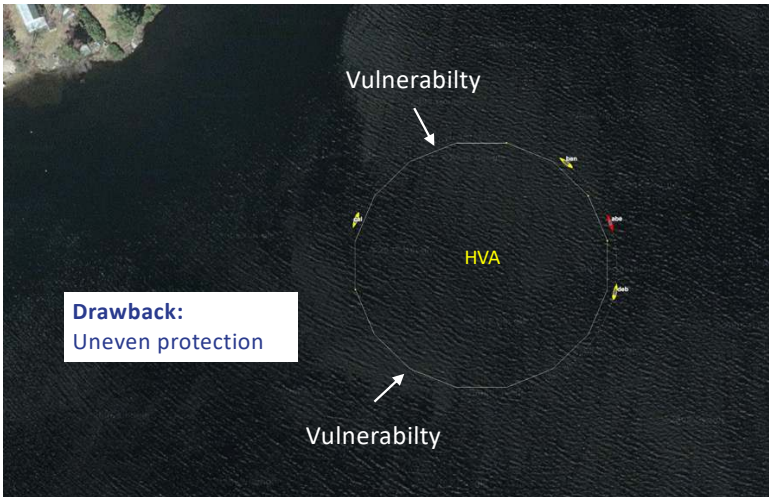
**First Example:**  
Deploy N vehicles to encircle a point presumably containing a *high value asset* (HVA)

**Behaviors used:**

- Loiter (traverse a shared circle)
- Collision Avoidance

**Information Shared:**

- Loiter Circle (mission planning)
- Vehicle position (communicated locally)




HVA = High Value Asset


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## Balanced Protection of HVA




**pEncircle:**  
A Swarm Toolbox MOOS App that runs on each vehicle.

**Subscribes For:**

- Ownship speed and position
- Nearby contact position and speed

**Publishes:**


- An updated speed to the loiter behavior
- Slowing when closer to the vehicle in front.
- Accelerating when closer to the vehicle in the rear.




HVA = High Value Asset

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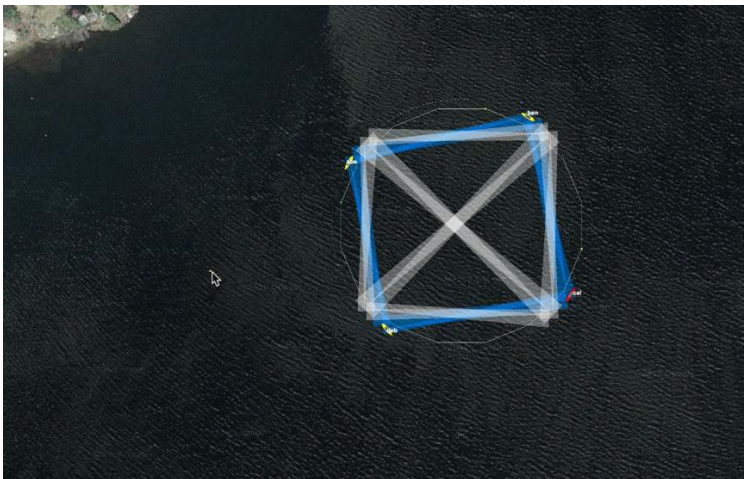
## Protection of HVA Plus Intercept



**Next Step in Protecting HVA:**  
When vehicles are encircling an HVA, they may need to intercept or investigate a contact of interest.

The command to intercept may originate from the HVA or one of the vehicles.

The vehicles should decide among themselves who should intercept.



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## Protection of HVA Plus Intercept

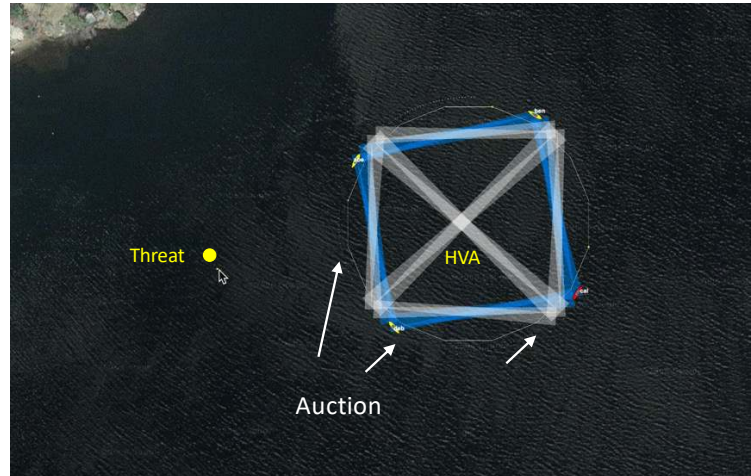


### Decentralized Auctions:

The ability to self-select which vehicle should intercept the perceived threat is implemented in a *decentralized auction*.

Decentralized auctions and handling of tasks in this manner, has required a substantial augmentation of the IvP Helm.

This is a new *software layer* – The helm operating without this feature, or the Swarm Toolbox generally, is exactly the same.



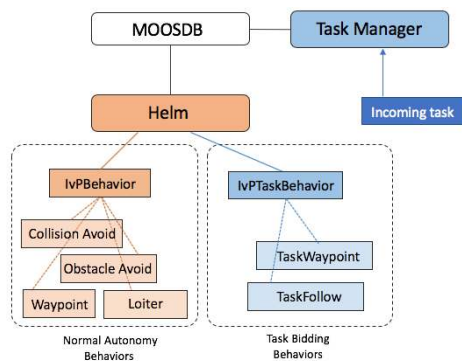
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## Decentralized Task Allocation

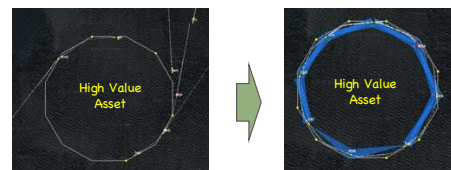


- New extension of MOOS-IvP autonomy software, comprised of new Helm behaviors, new MOOS applications and new utilities for pre-mission and post-mission support.
- Decentralized task allocation, allowing an operator to specify a desired state without tasking individual behaviors.

### Example:

- Phase 1: Group surrounds and protects a "high value asset".
- Vehicles are only aware of each other's position, heading and speed
  - Collision avoidance behaviors coordinated with mission behaviors.

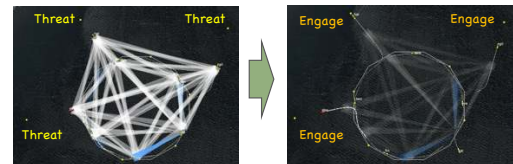
No pre-arranged order.



Phase 2: Members of the group intercept identified threats

- Vehicles conduct inter-vehicle auction. Selected vehicle assigned.

No pre-arranged assignment



Phase 3: Resume Posture

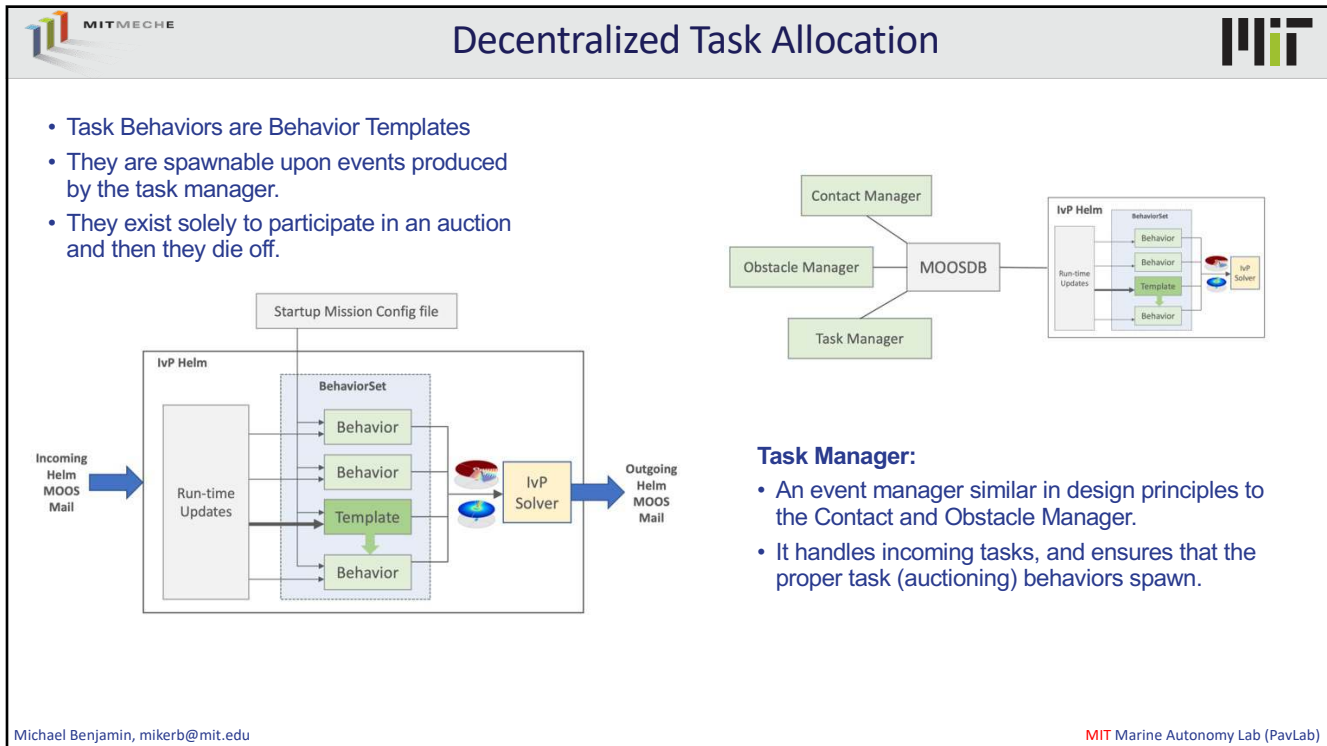


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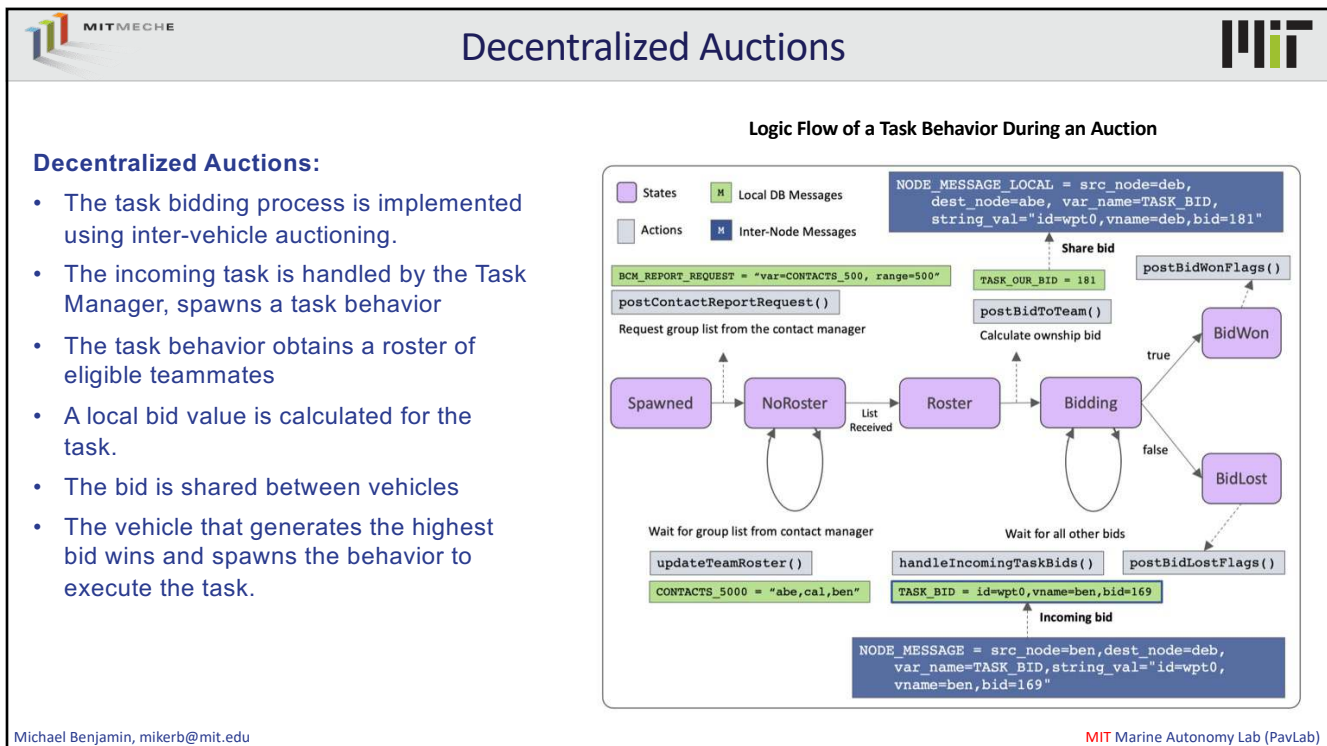
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## Decentralized Auctions



**Algorithm 2**

```


1: procedure ONRUNSTATE()
2:   if state = spawned then
3:     postContactReportRequest()
4:     state ← noroster
5:   else if state = noroster then
6:     if roster.received = true then
7:       state ← roster
8:     end if
9:   else if state = roster then
10:    postBidToTeam().
11:    state ← bidding
12:   else if state = bidding then
13:    if allbids.received = true then
14:      if our_bid > highest_other_bid then
15:        postBidWonFlags()
16:        state ← bidwon
17:      else
18:        postBidLostFlags()
19:        state ← bidlost
20:      end if
21:    end if
22:  end if
23:  if state = bidwon or state = bidlost then
24:    initiateBehaviorCompletion()
25:  end if
26: end procedure

```


**Logic Flow of a Task Behavior During an Auction**

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## Linear Convoying



# Linear Convoying

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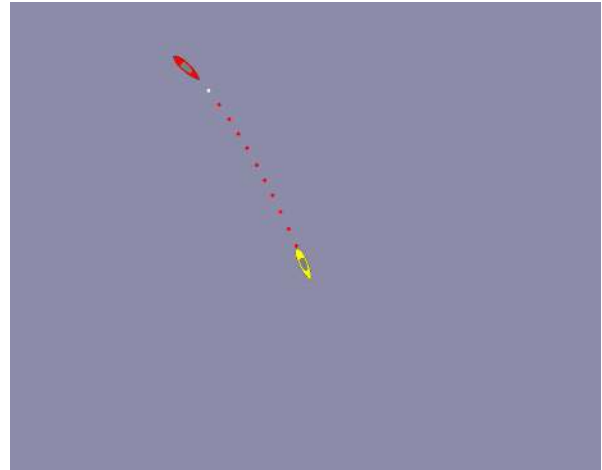
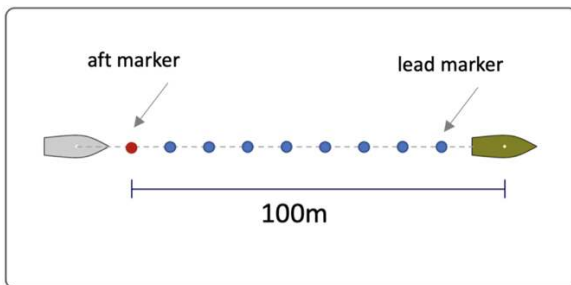
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## What is Linear Convoying



- A **Linear Convoy** of multiple vehicles involves several vehicles in a follow-the-leader formation with prescribed separation distance between vehicles.



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## Reasons for Convoying



Convoying provides a reduction in drag and greater efficiency



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## Reasons for Convoying



Convoying provides *protection* for vulnerable or important individuals



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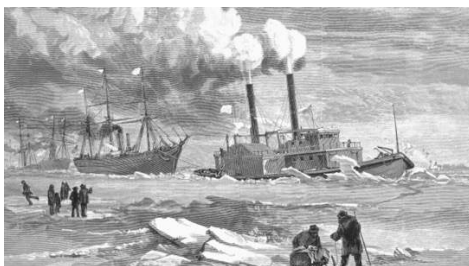
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## Reasons for Convoying



An better-capable leader afford the followers to be less-capable and just follow.




Breaking the ice blockade in the Delaware River




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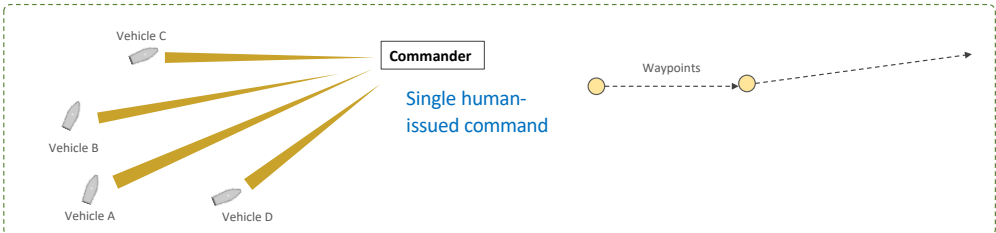


## Decentralized Linear Convoying

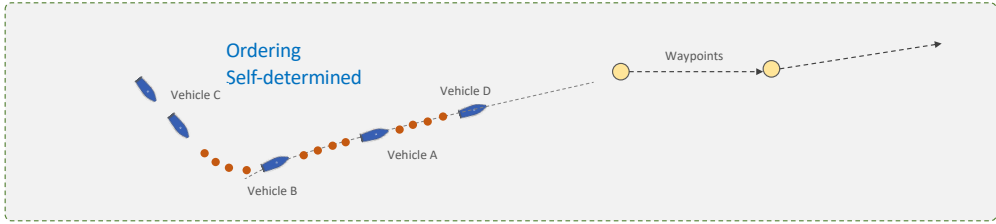


**When it is time to convoy, a single command is sent to the group.**

- The *leader* is determined among the group (with criteria controlled by the operator)
- The *order* of the group is determined among the group




Single human-issued command




Ordering Self-determined

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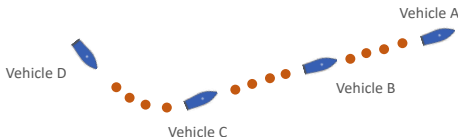
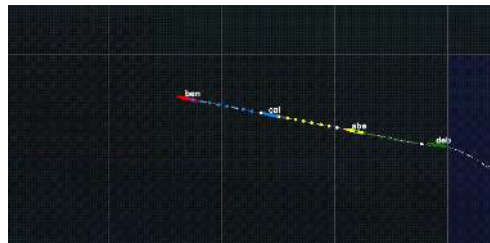
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## Convoy Behavior



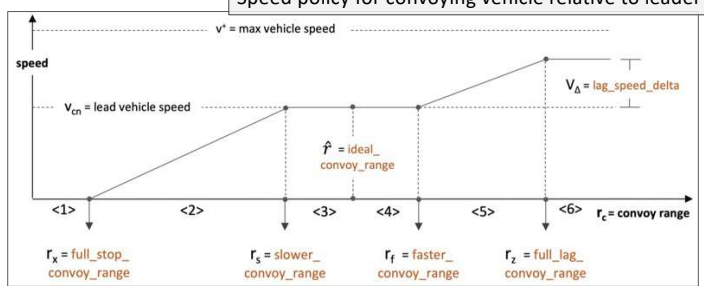
- The Convoy behavior enables a vehicle to form/maintain a linear convoy
- Each conveying vehicle follows a leader vehicle
- Sequencing can be explicitly set or derived from a decentralized auction*

- Behavior will moderate path following via markers and moderate speed to maintain a desired separation.
- Markers either inferred from observed position, or transmitted explicitly from lead vehicle.


Michael Benjamin, Tyler Paine, Supun Randeni,  
*Autonomy Algorithms for Stable Dynamic Linear Convoying of Autonomous Marine Vehicles*, OCEANS 2021 MTS/IEEE, October, 2021.

**Speed policy for conveying vehicle relative to leader**




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## Decentralized Convoy Decisions



The IvP Helm uses decentralized decision-making to determine Convoy roles:

- Who is the leader?
- What is the order of the followers?


The operator would like to just say “go” and leave the details to the group.




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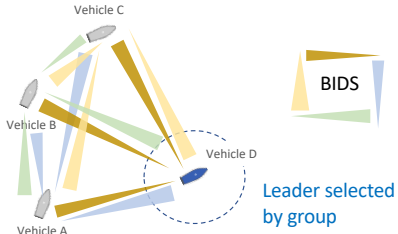


## Decentralized Convoy Decisions



Each vehicle receives the task to transit, and generates its own bid to be the leader

- The bid is sent to all other vehicles
- When each vehicle has received all the other bids, the leader emerges




**Leader Auction**

- All vehicles auction and determine which vehicle is the leader
- Currently the leader bid is based only on range from ownship to the first waypoint, but will be generalized to include orientation, and other vehicle state such as fuel or system status.


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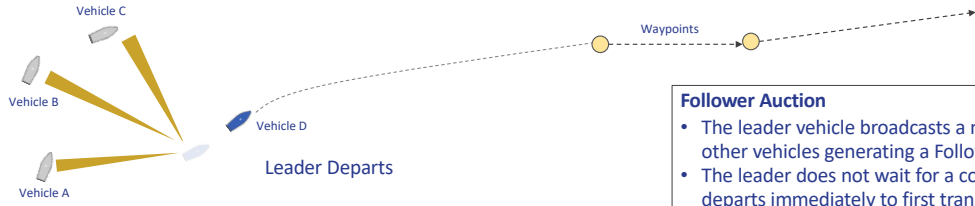


## Cascading Tasks



After the leader has been identified, it begins the transiting task to a given set of waypoints.

- A new task is sent by the leader to all other remaining vehicles
- The new task is identify the first follower behind the leader




**Follower Auction**


- The leader vehicle broadcasts a message to all other vehicles generating a Follow (Convoy) Task.
- The leader does not wait for a consensus and departs immediately to first transiting waypoint

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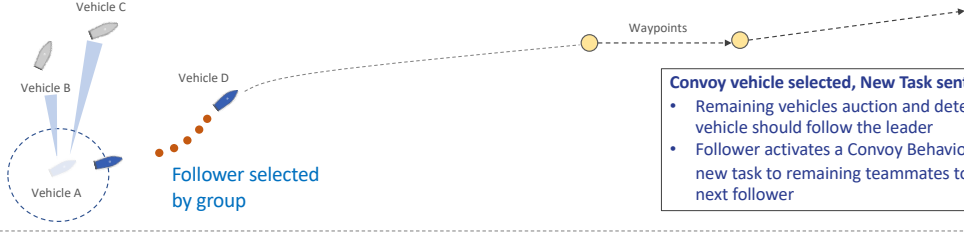
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## Cascading Tasks



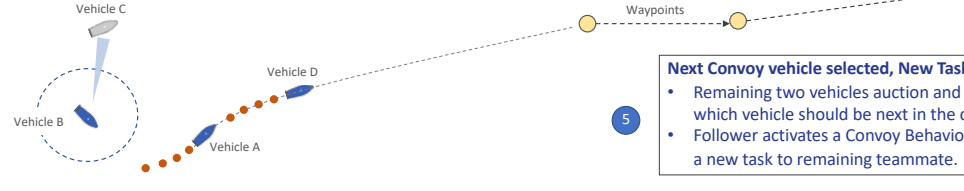
As each follower emerges, the new follower generates a new task to the remaining vehicles.



**Convoy vehicle selected, New Task sent**

- Remaining vehicles auction and determine which vehicle should follow the leader
- Follower activates a Convoy Behavior, generates a new task to remaining teammates to select the next follower

---




**Next Convoy vehicle selected, New Task sent**


- Remaining two vehicles auction and determine which vehicle should be next in the convoy.
- Follower activates a Convoy Behavior, generates a new task to remaining teammate.

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## Field Testing



- Four Clearpath Robotics Heron Unmanned Surface Vessels were tested on the MIT campus at the MIT Sailing Pavilion on the Charles River.
- Vehicles were deployed near the dock, with arbitrary starting orientations
- Vehicles were equipped with GPS, and IMU to have local X-Y planar position, heading and speed.
- Vehicle position/pose was continuously shared between vehicles.
- The maximum vehicle speed is 2.0 meters/sec.
- Roughly 8 convoy missions were executed







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## Convoy Behavior






The Charles River, looking from Cambridge to Boston MA, Sept 1<sup>st</sup>, 2021

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# Swarm Autonomy

## Distributed Coverage

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

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## Implicit Distributed Coverage

**Problem Statement (mission):**

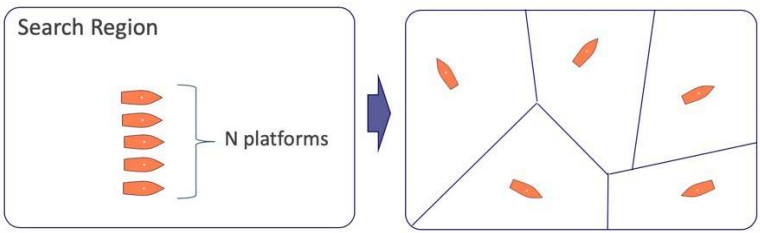
- Given a search region to be monitored by N platforms:
- Move N vehicles in the region to cover the region evenly

No shared information other than position. (**Implicit** coordination)

$a_i$  = Area of polygon  $i$

$t_i$  = Time of travel for vehicle  $i$

$d_i$  = Distance travelled vehicle  $i$



**Impact areas:** Distributed ocean sampling, climate change monitoring, plume mapping, anti-submarine warfare.


Minimize:  $\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (a_i - a)^2}$

Minimize:  $T = \sum_{i=1}^N t_i$


Minimize:  $D = \sum_{i=1}^N d_i$

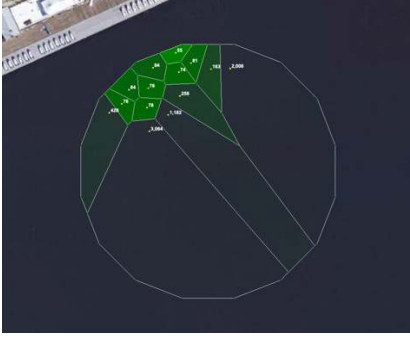
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## Initial algorithm: The Iterative Voronoi Adjustment algorithm



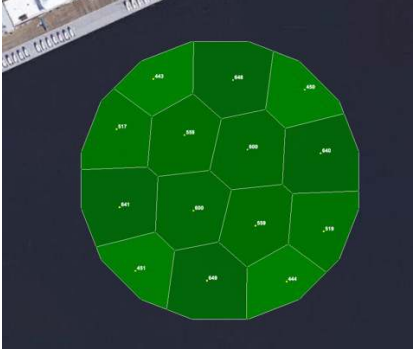


➔ Voronoi decomposition calculated at outset of initial deployment

Lloyd's Algorithm

- ➔ The vehicle moves toward the center of its own local polygon
- ➔ Voronoi decomposition is updated upon the move
- ➔ Repeat until a stable distribution is reached.


➔




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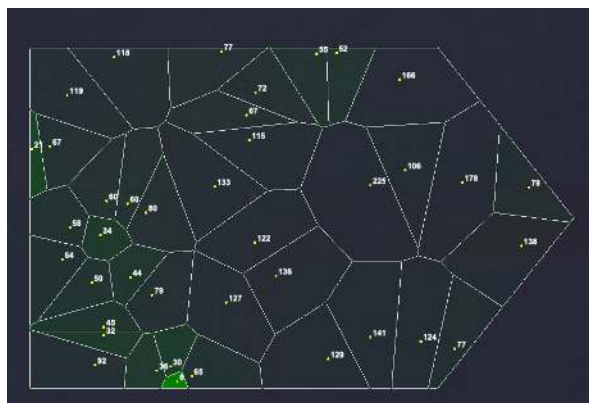
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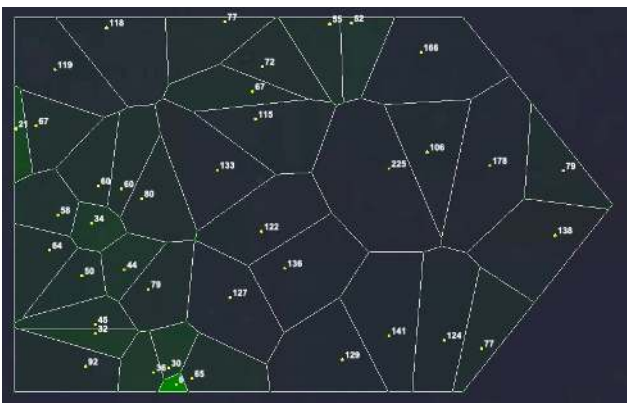


## Modified Lloyd's Algorithm





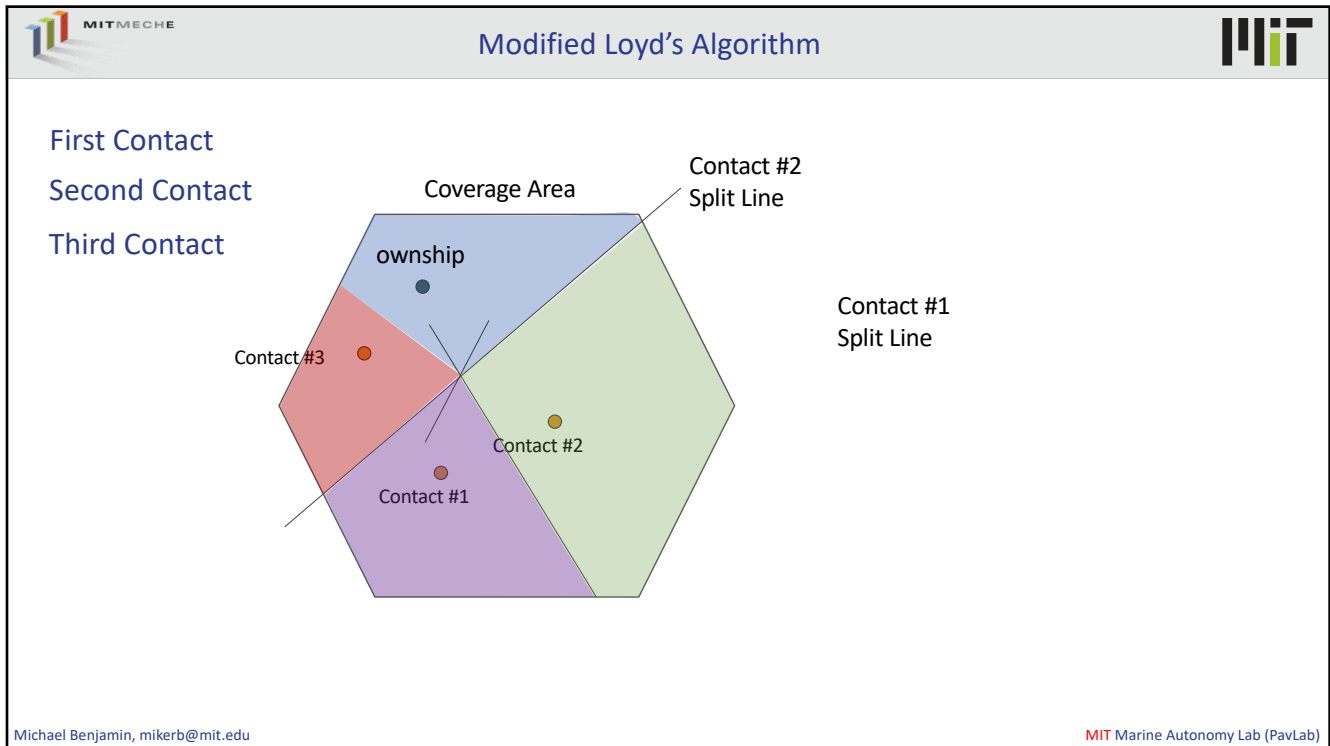
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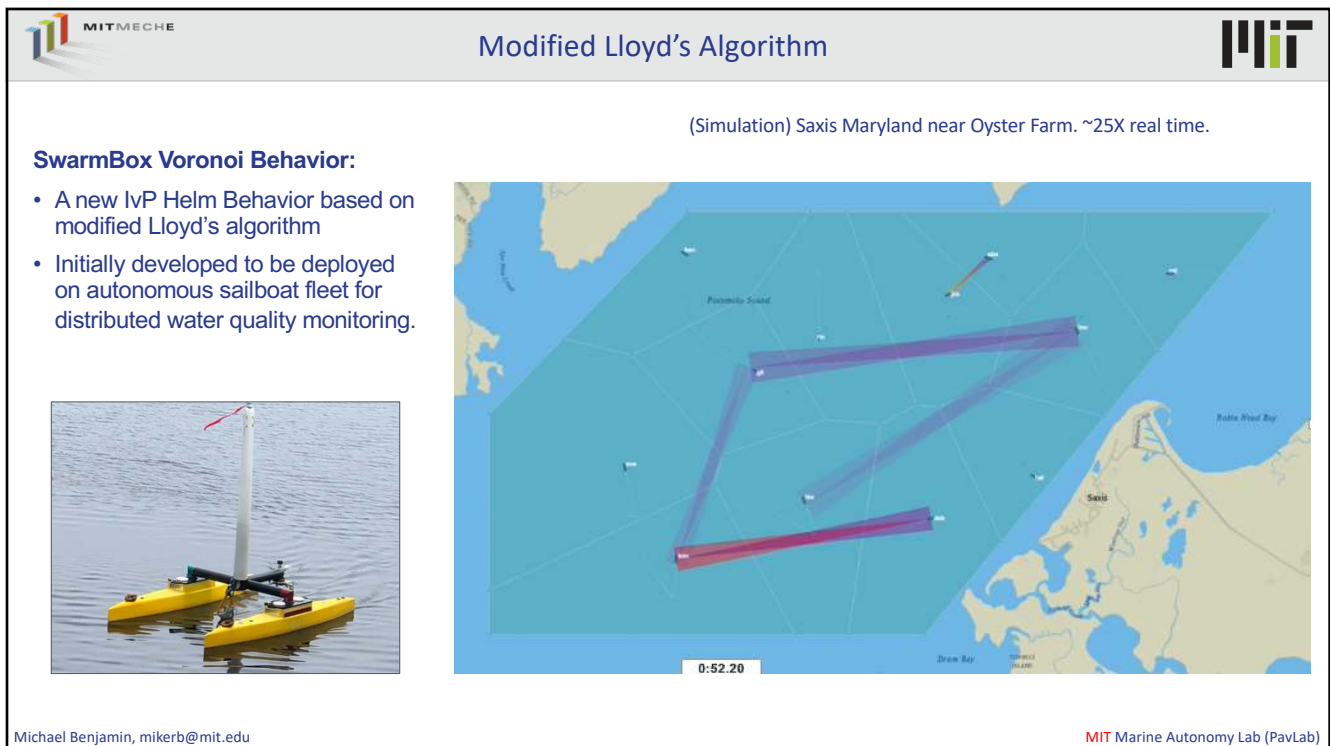
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# The Sea of Japan Exemplar Mission

## Distributed Sensing on the 50-node MTASC

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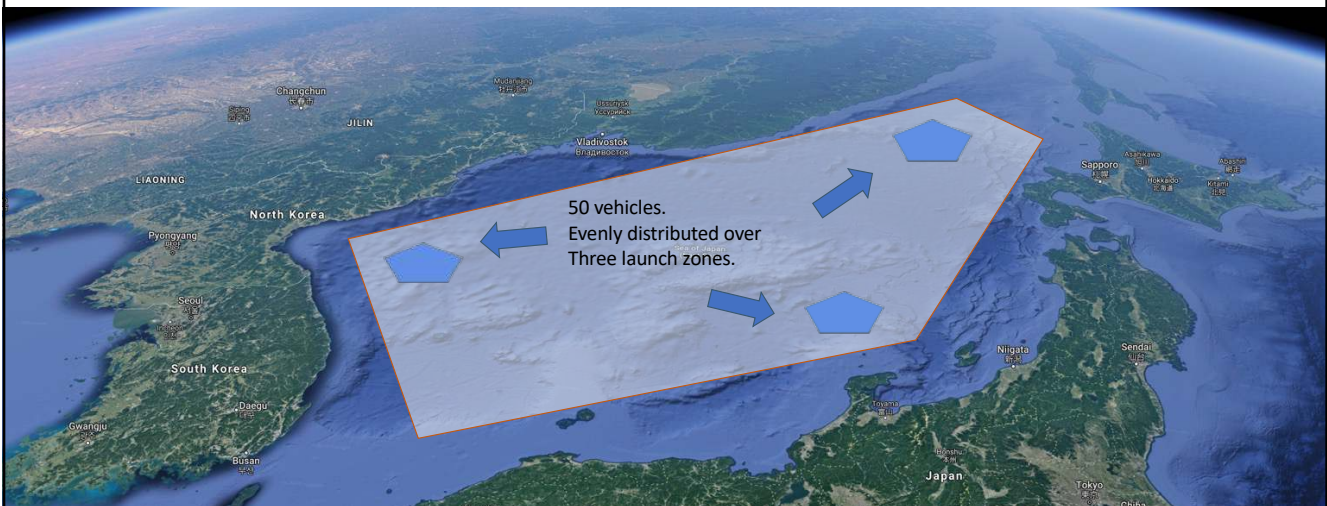
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## Sea of Japan Exemplar Mission



**Sea of Japan: Roughly One Million Square Kilometers**



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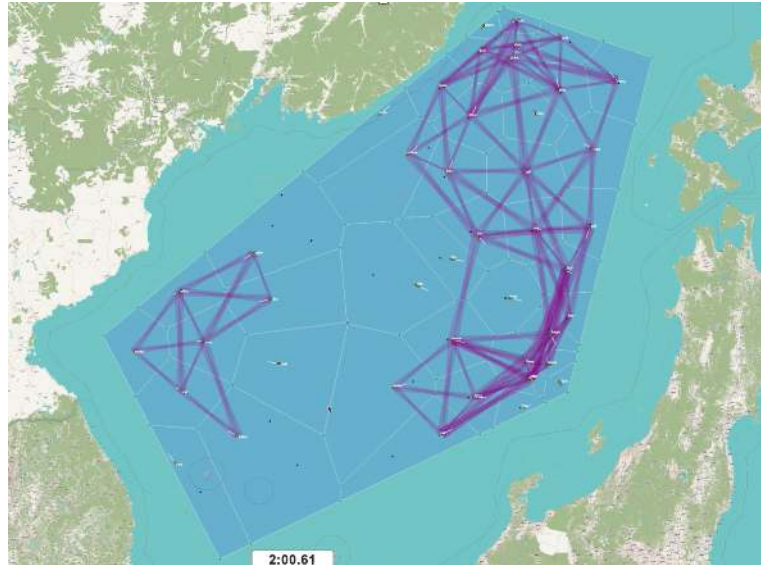
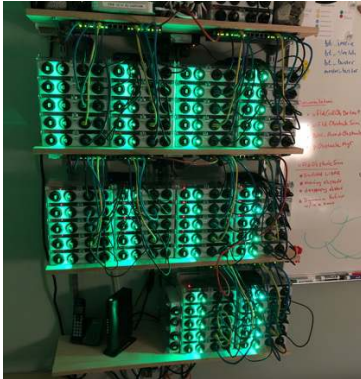


## Sea of Japan Exemplar Mission



**Sea of Japan: Roughly One Million Square Kilometers**

**Sea of Japan:** 50 vehicle simulation at 90x real-time (20m/s vehicle speed). 50 RasPi cluster each simulating a single vehicle over a network.



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## MTASC


Multi-Agent Tactical Autonomy Simulation Cluster

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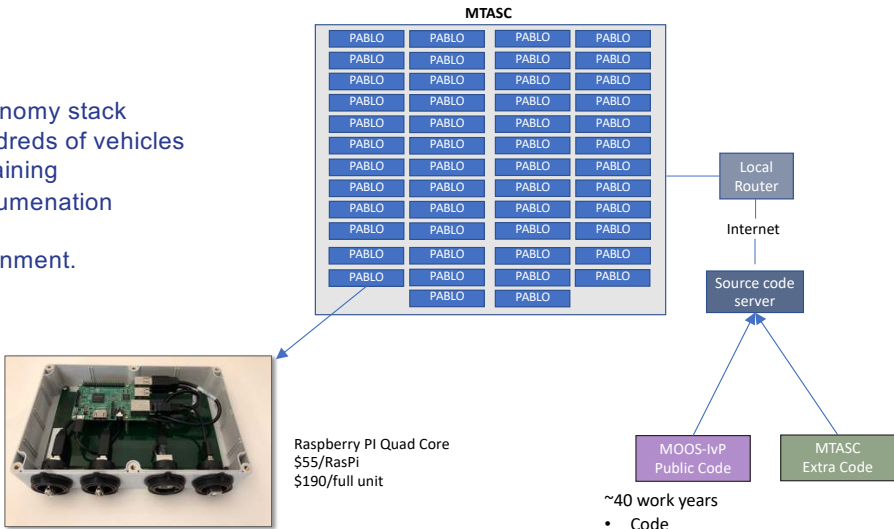


## MTASC – Hardware Overview



**Motivations:**

- Access to the full autonomy stack
- Scalable to many hundreds of vehicles
- Open software with training
- Open design with documentation
- Reasonable cost
- Air-gapped test environment.



**MTASC**

Raspberry Pi Quad Core  
\$55/RasPi  
\$190/full unit

~40 work years

- Code
- Documentation
- Training Labs

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## MTASC – Multi-Agent Tactical Autonomy Simulation Cluster



**PABLO: Payload Autonomy Box**

- A Raspberry Pi encased in a water-tight box
- High performance, Low Cost, No cooling
- Each PABLO can be dropped into MIT Heron USV
- Each PABLO can simulate a mission 100x real time.

The first MTASC Prototype








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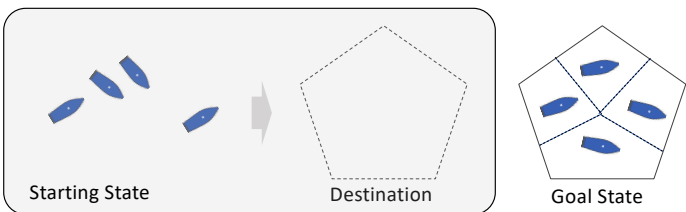


## Muster Behavior



- The Muster behavior is used for deploying all vehicles to a given region.
- On arrival they will adjust their locations to each keep distance
- No pre-arranged sequence, position or other role is assigned or shared.*


- They only share the assignment – the muster region itself.
- They periodically share position information.



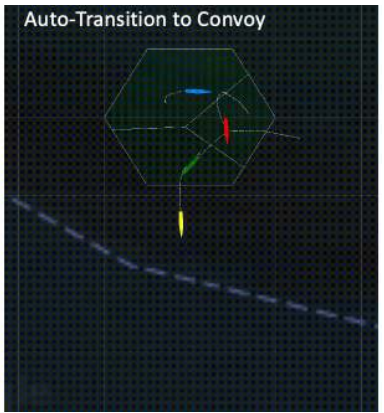
Starting State      Destination      Goal State

**Group can be configured to**

- Auto-detect muster completion
- Auto-generate convoy auction/formation




Muster and HOLD      Muster and HOLD




Auto-Transition to Convoy

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## Recent Field Results



August 2022 @ MIT Sailing Pavilion  
Seven Heron Unmanned Surface Vehicles



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Recent Field Results




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Seven Heron Unmanned Surface Vehicles



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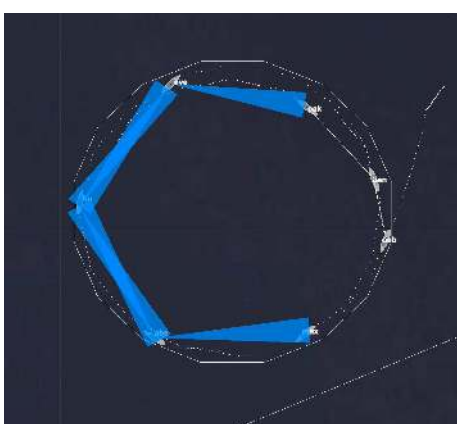


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END

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