Ship Protection in a Busy Harbor using Multiple Unmanned Surface Vehicles

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Broad Problem

Terrorist threats against ships

- are real (USS Cole, Limburg, Somalian pirates)
- can be difficult to distinguish from normal boat traffic
- in harbors are a high possibility due to predictability of ship movement and low manueverability

Unmanned Surface Vehicles (USV) offer a potential solution. Relative to manned systems, USVs are:

- safe (no danger for sailors due to threat or rough seas in small boat)
- low cost
- scalable

Specific Problem: Scenario

Scenario:

- Ship [or high value asset] (“HVA”) at anchor or transiting at slow speed through harbor
- Specified number of potential targets (“targets”) (normal small boat traffic) with arbitrary destinations within the harbor
- Specified number of USVs (“friends”) actively protecting ship
- USVs investigate targets approaching (or near approaching) ship by cutting range to target and using on-board sensors

Specific Problem: Assumptions

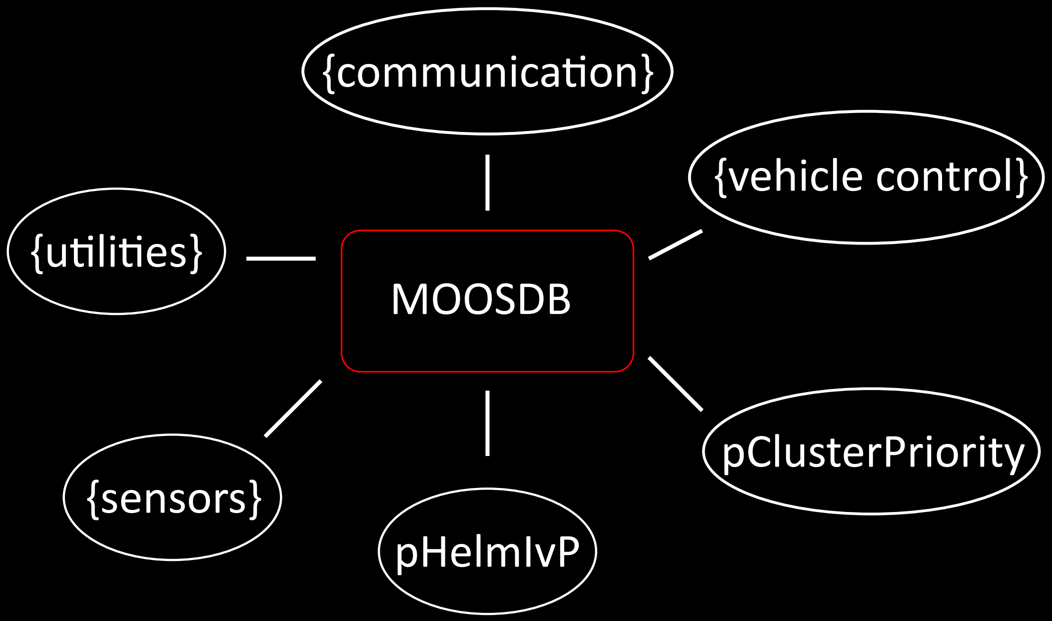
Simulation Initial Assumptions:

- Ship radar is capable of accurately picking up target positions within harbor
- Ship to USV communications is robust (though not necessarily high throughput)
- USVs have short range sensors useful (to human) for determining target's potential threat (video / still camera, lidar, etc.)
- USVs may have hailing system to warn away (accidental) intruders from ship

Software Architecture (MOOS)

Publish / subscribe infrastructure

- comprised of individual processes (“MOOS modules”)
- modules communicate through central database (“MOOSDB”)
- allows for rapid prototyping and “plug-in” functionality with contributions from many authors



Why MOOS?

Backseat / frontseat model:

MOOS runs as "backseat driver" sending commands for heading, speed, [depth] to "frontseat" (vehicle control, manufacturer specific)

- Allows for platform independence (MOOS-IvP autonomy has run on many unique USVs / AUVs)
- Allows for rapid transition between simulation and on-vehicle (runtime) tests

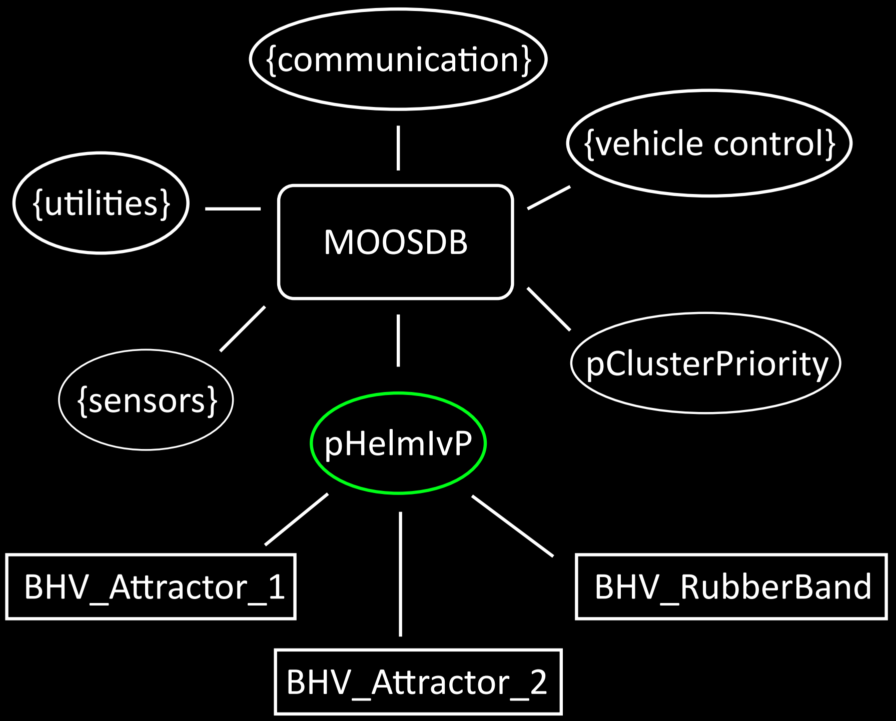
Mandarina USV:

Common Modules	Runtime Only	Simulation Only
11	4	4

Autonomy Infrastructure (MOOS-IvP)

Behavior based autonomy

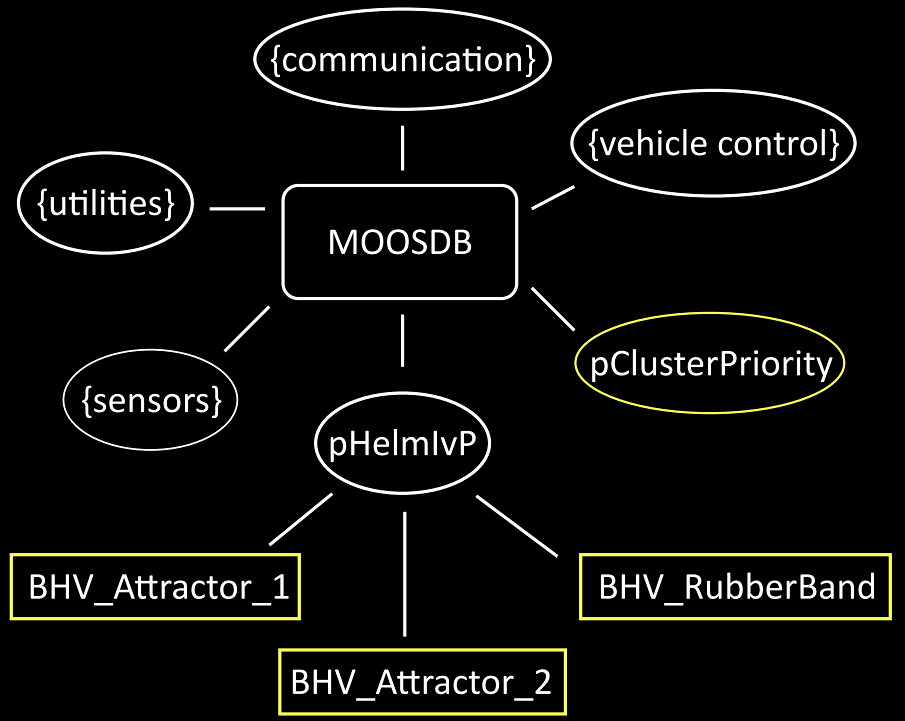
- Set of behaviors govern action space (heading and speed for USV)
- Each behavior generates an objective function -- function of utility over the entire heading-speed plane
- IvP Helm (pHelmIvP) optimizes over all running behaviors to choose mutually beneficial or (in case of mutual exclusivity) highest priority action



Cluster Defense Overview

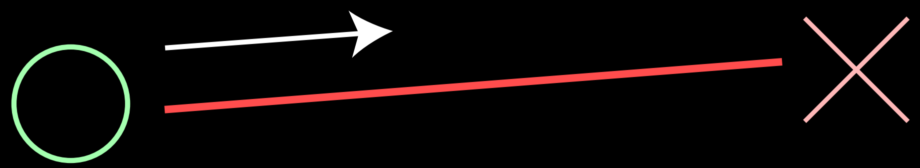
Two behaviors and one MOOS module govern USV actions in this work:

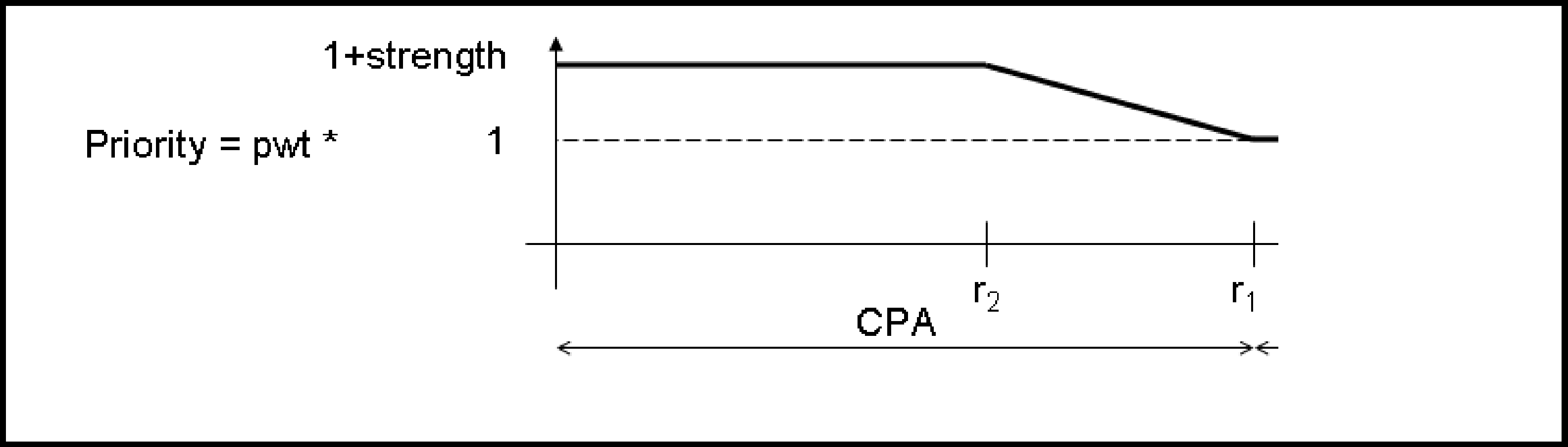
- BHV_Attractor: seeks to draw vehicles towards targets to investigate.
- BHV_RubberBand: seeks to bring vehicles back to defense positions around ship.
- pClusterPriority: balances priorities for both behaviors in the context of multiple USVs / multiple contacts.

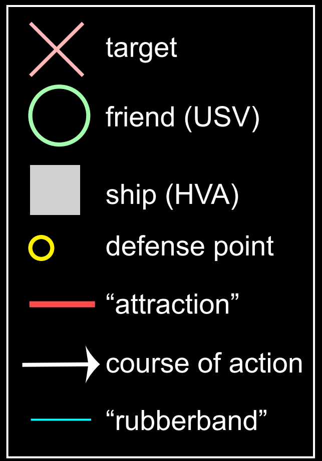


Autonomy: BHV_Attractor

- seeks to cut range to a target. An instance is run for every target
- objective function governs over heading



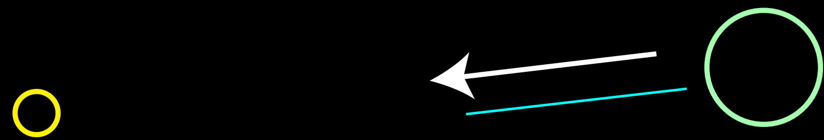


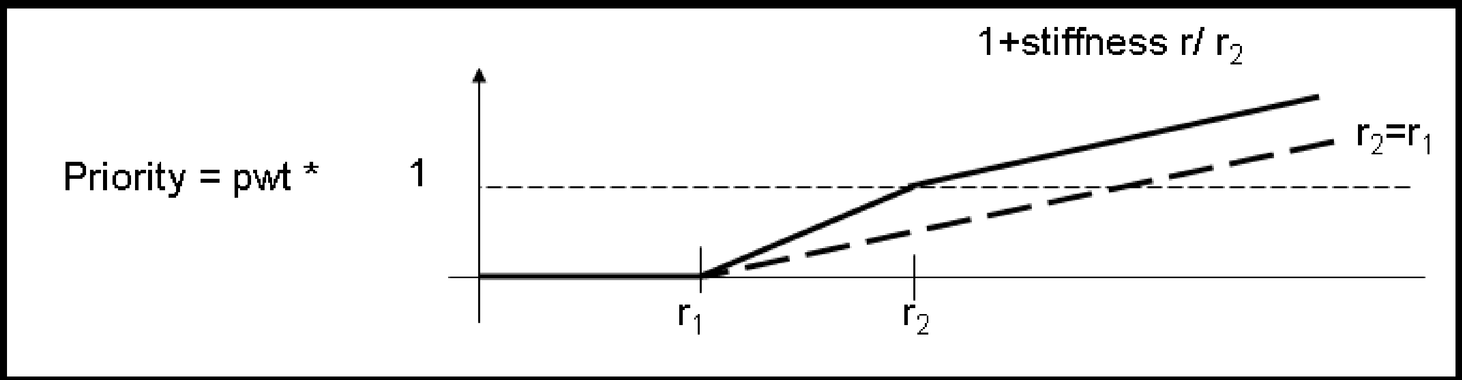


CPA: closest point of approach (USV <-> target)
pwt: priority weight set by pClusterPriority
results presented: r1 = 0 m, r2 = 100 m, strength = 0.5

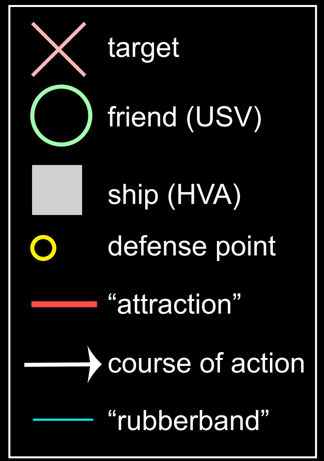
Autonomy: BHV_RubberBand

- seeks to station keep near a fixed point (assigned by pClusterPriority). one instance is run.
- objective function governs over heading and speed





CPA: closest point of approach (USV <-> target)
results presented: r1 = 15 m, r2 = 30 m, stiffness = 2, pwt = 50



Autonomy: pClusterPriority

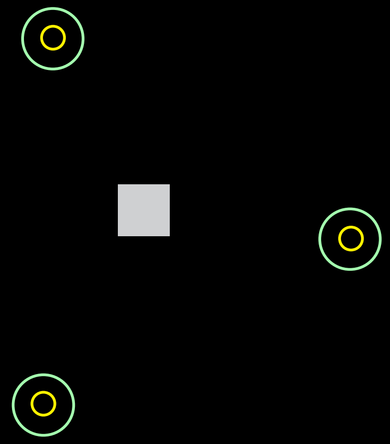
- prioritizes contacts based on closest point of approach
- rebalances individual BHV_Attractor priorities within the cluster of USVs

$$
\begin{aligned}
A(d, \overline{d}, cpa) &= A_0 * C(cpa) * e^{-\alpha(d-\overline{d})/\overline{d}} \\
C(cpa) &= cpa * \frac{C_{min} - C_{max}}{cpa_{cutoff}} + C_{max}
\end{aligned}
$$

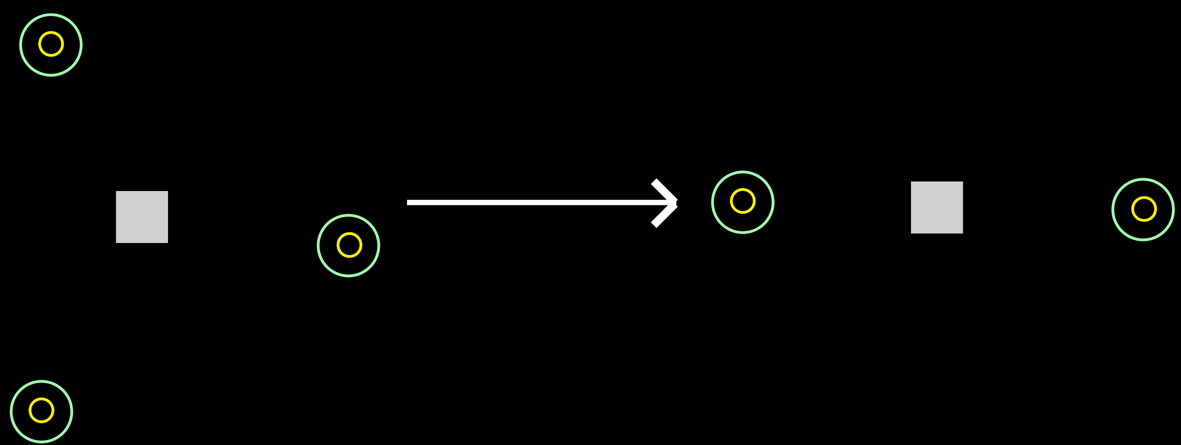
symbol	value used here	description
A	computed	priority weight of BHVAttractor
A_0	100	normalizing constant
d	computed	distance to target
$\overline{d}$	computed	average friends' distance to target
α	2	"strength" of decay
C	computed	closest point of approach (CPA) scaling factor
cpa	computed	CPA of target to ship within cpa_{time} seconds
cpa_{time}	120 s	time to "look forward" for CPA
C_{max}	2	maximum CPA scaling factor
C_{min}	0.5	minimum CPA scaling factor
cpa_{cutoff}	500 m	range beyond which $C = C_{min}$

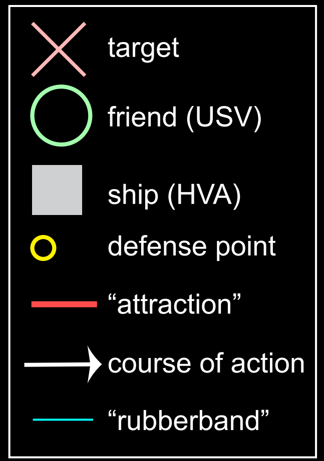
Autonomy: pClusterPriority

- sets initial defense locations on evenly spaced points of circle around ship:



- rebalances USVs in case of loss (or addition) of one:

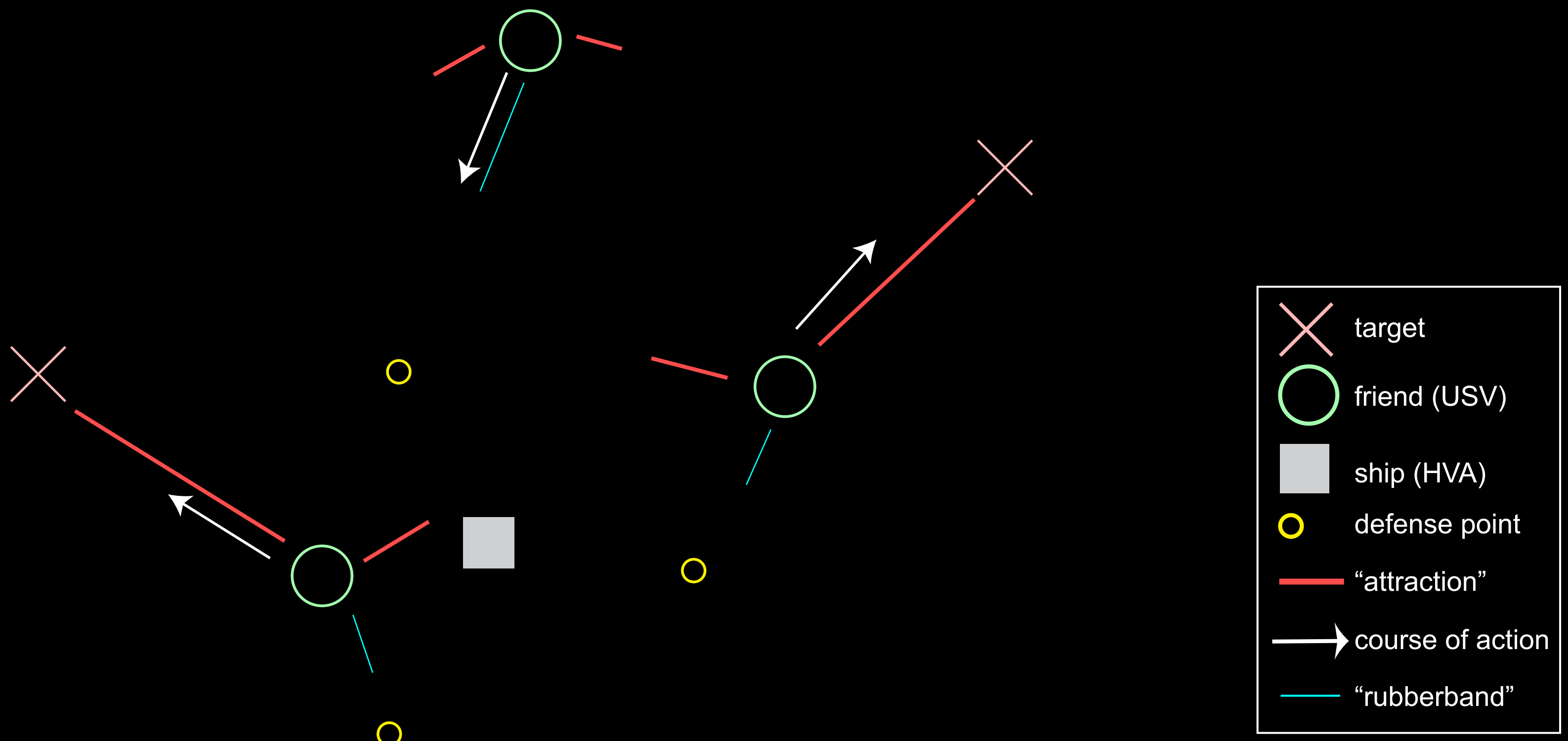




Autonomy: Combined Actions

Together these three pieces perform a task analogous to zone defense in basketball:

- Each USV investigates target(s) nearest to them and other USVs back off when another USV is near.
- When targets are not near or potentially threatening, USVs return to defense points and station-keep



Performance Evaluation: Qualitative

Successes:

- USVs investigate most targets of highest interest (heading close or directly toward ship).
- USVs usually do not overlap investigation at the expense of another target.
- System requires only knowledge of targets' and ship's <speed, heading, position> and friends <position>. No other data must be shared for autonomy to function.

Needs Improvement:

- USVs close to each other can sometimes form an unwanted team at the expense of defending ship from new targets.
- BHV_Attractor should govern over speed to avoid wasting power when full speed is not needed.

Performance Evaluation: pScorer

Quantitative performance evaluation of dynamic complex systems is hard:

- Highly nonlinear; analytic solutions require (often unrealistic) simplifying assumptions
- Want a performance evaluation that works equally for runtime (on vehicles) and simulation

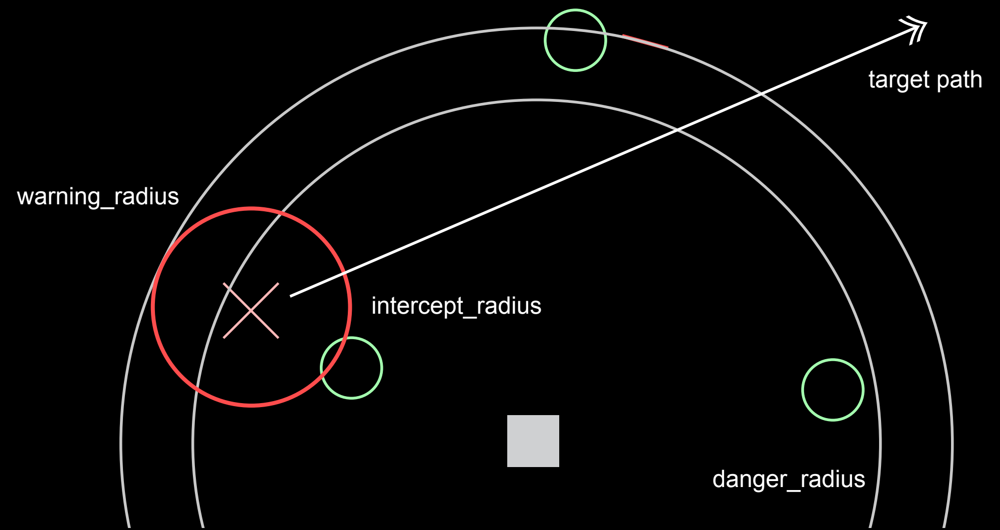
A modular scoring process (MOOS Module "pScorer") was designed that tries to accomplish this with plug-in evaluation "Metrics"

- Each Metric produces a score and perfect score based on the task it is designed to evaluate.
- pScorer combines the scores of all Metrics to produce a (weighted) mean normalized score.
- In a Monte Carlo simulation (with I.I.D. random variables), the score should eventually converge.

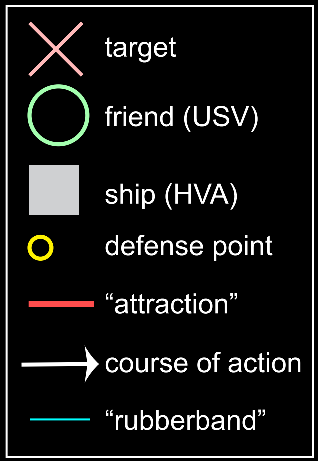
Metric: Cluster_Intercept

Targets outside "warning radius" are ignored. Targets within "danger radius" are scored:

- Score is an exponential based on *range to ship* at which target is first intercepted (farther is better).
- Perfect Score is interception at "danger radius"
- Interception requires a USV entering "intercept radius"



For all results here: warning_radius = 1200 m
danger_radius = 1000 m
intercept_radius = 20 m



pScorer Results

description	vehicles station keep (baseline)	full system, 1 USV	full system, 3 USVs
defense radius (m)	300	300	300
number of USVs	3	1	3
number of simultaneous contacts	10	9	10
time (hrs)	5	5	5
overall score (%)	19.3	23.5	26.8

Extending pScorer

One Metric does not adequately evaluate the performance of this system.

New Metrics that could be designed:

- Coverage: determines how well vehicles (over time) are covering the area around the ship to deal with unexpected targets. [next week].
- Power usage: average power consumption.
- Communications performance: throughput and timeliness of data, weighted by importance.

pScorer could be used for completely different tasks (with appropriate Metrics):

- Oceanographic sampling balanced with acoustic communications [on return to MIT].
- ASW

Acknowledgment / References

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