A Hierarchical Multi-ASV Control System Framework for Adversarial ASV Detainment

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Introduction

Abstract
We examine a multi-robot autonomous surface vehicle detainment problem, in which a heterogeneous fleet of naval vessels attempts to intercept and entrap (potentially) adversarial enemy vessels in the minimum amount of time.

This problem presents interesting challenges relating to:
1) Behavior modeling and intent-recognition of the adversary
2) Multi-robot allocation and control for minimum-time, minimum risk detainment of multiple ships
3) Hybrid human-in-the-loop decision-making in a distributed, fast-evolving scenario.

We've developed an initial approach in simulation that uses a hierarchical command structure whereby a human issues directives to autonomous vessel groups which then independently engage with their objective.

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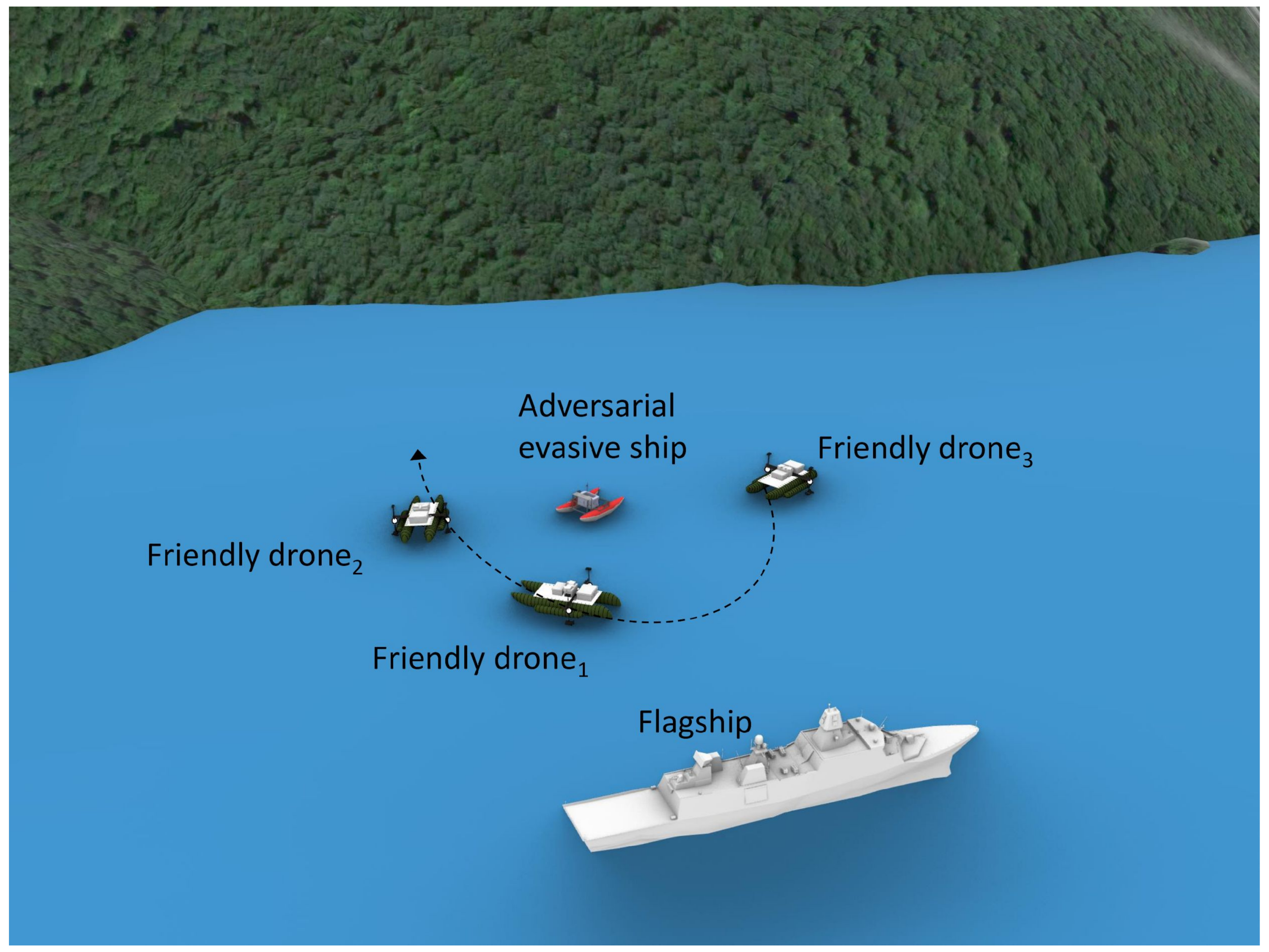


Problem Statement

Team composition:
- friendly side, given a human operator H in the loop
- robotic flagship set $F = \{f_1, f_2, f_3, \ldots, f_i\}$
- sub-member drone set $D_i = \{d_i^1, d_i^2, d_i^3, \ldots, d_i^j\}$ for each flagship

Our fleet attempts to capture enemy ships $E = \{e_1, e_2, e_3, \ldots, e_k\}$

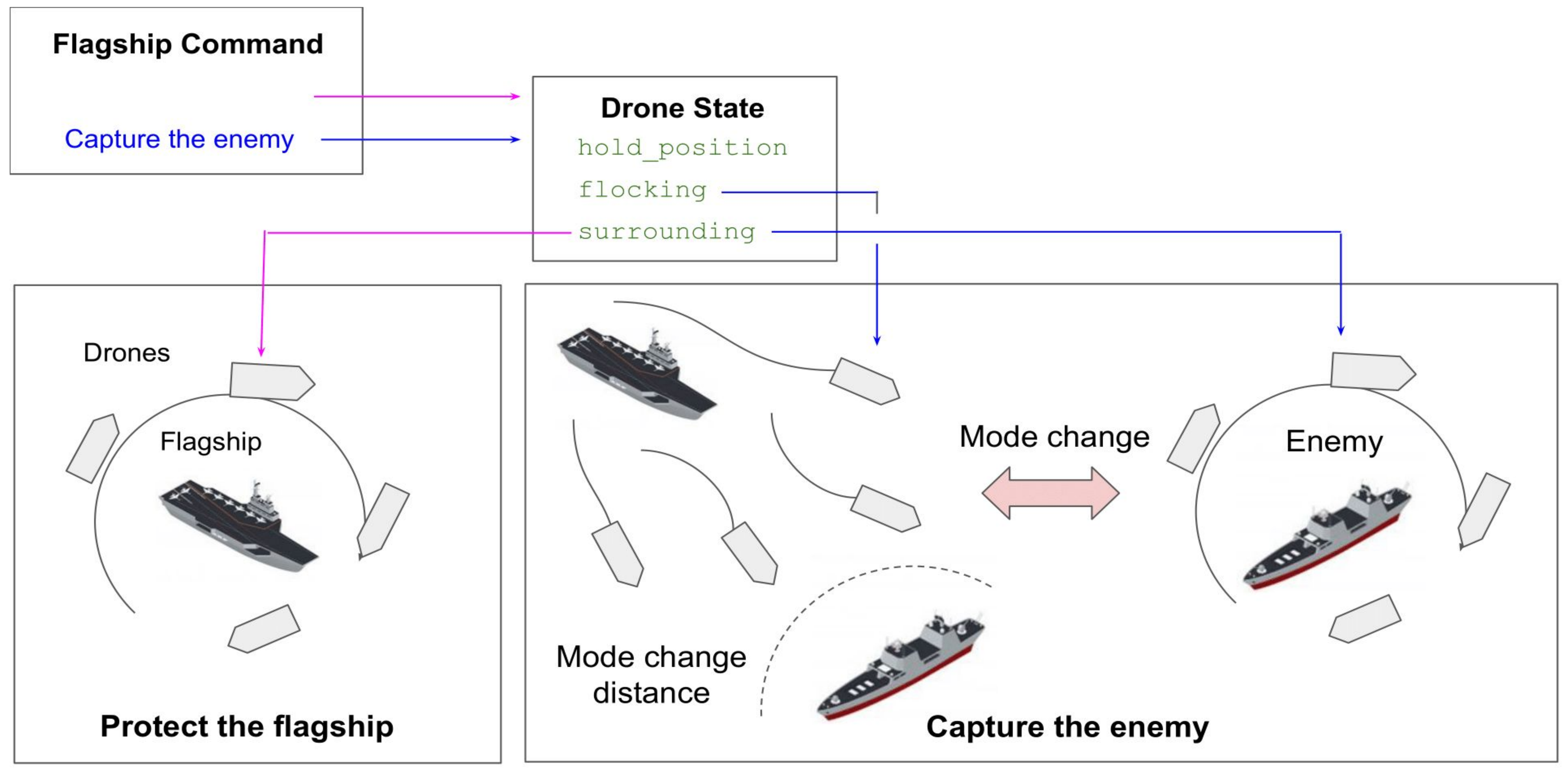
Communication and control: Chain of command $H > F > D$ whereby H may issue directives to autonomous flagships F which then control and direct their fleet of drones.

to establish a control scheme $H > F > D$ such that D achieves a detainment of E in the ***minimum*** amount of time T_E where $T_E = \sum_{m=1}^{k} t_{e_m}$ and t_{e_m} is an individual detaining time of an enemy m being captured $1 \leq m \leq l$

Preliminary Implementation

We designed & implemented a hierarchical control system that allows for high level human directives to be automatically put into practice by an heterogenous flagship-drone autonomous fleet. The following is a typical order of events:

1. Human commander issues a "capture the enemy" command to a flagship
2. The flagship plans a trajectory and starts navigating towards the enemy. Simultaneously , it issues a "flocking approach" command to its drones.
3. The drones navigate towards the enemy, with a *pursuit* virtual force added to the standard separate/align/cohere flocking forces.
4. As drones approach the enemy, the flagship issues "surround" commands, which causes the nearby drones to start encircling the enemy ship.

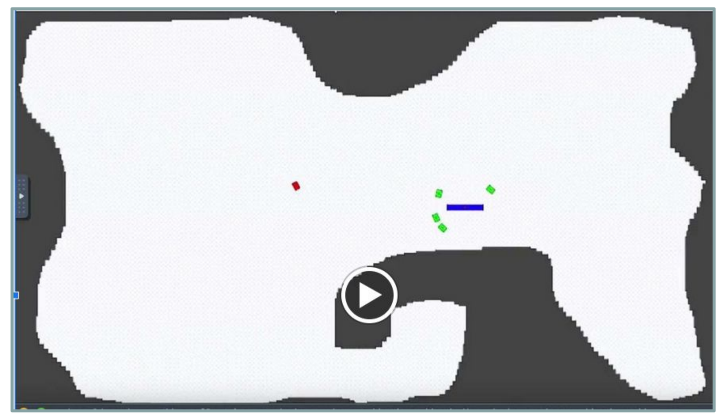


Simulation Results

Tested preliminary implementation tested using a lightweight 2D simulator.
- Enemy ship, flagship, and drones spawned within 320m x 180m environment, N=162 simulated trials.
- Defined the following criteria:
  - *Furthest ship distance (FSD):* max distance between the enemy ship and the detaining drones.
  - *Max perimeter edge length (MPEL)*: max distance between any two detaining drones adjacent to each other on the convex hull.
  - *Detainment*: true when enemy ship is within the convex hull of drones and both FSD and MPEL are under predefined thresholds.

Measured metrics:
- *Detainment success*:
  - Maintained for 5s
  - 120 sec time limit.
- *Detainment time (DT)*
  - Elapsed time to detainment success

Condition	Mean DT	Std Dev.	Successes	Tests
hold position	49.59 sec	23.26s	54	54
wander	56.06 sec	24.09s	49	54
evade	59.67 sec	18.80s	54	54
3 drones	52.11 sec	18.37s	76	81
6 drones	57.86 sec	25.36s	81	81
near (50m)	41.46 sec	20.28s	53	54
medium (100m)	46.42 sec	11.62s	52	54
far (over 200m)	77.60 sec	13.77s	52	54



Lightweight simulation
Flagship (blue) and drones (green) attempt to capture the enemy (red)

Follow-up Research Questions

R1: How can the system on the friendly side reliably predict and estimate the intent of the enemy ASVs?
- Current system assumes knowledge of enemy position & heading.
- Real world scenarios require better perception ability, including tracking targets and classifying their behavior.

R2: How can we coordinate a decision-making process between the human and the autonomous agents?
- Human input is necessary and desirable for many practical applications, such as port security, where the potentially pursued "enemies" are simply civilian ships and enforcement must be performed in a fair and resource-constrained fashion.
- Goal: control interface that provides operator with context and focused information needed to make critical high-level decisions and communicate with detained or flagged-suspicious vessels.

R3: How can the system on the friendly side distribute the ASVs and allocate tasks in case there are multiple enemies to be captured?
- Preliminary work limit scenario to a single flagship / drone contingent and a single enemy vessel.
- Scaling this to multiple vessel groups chasing multiple adversaries presents an interesting question on resource allocation, especially when operating under uncertainty, with dynamic enemy behavior.

Next Steps

System Development
- Extend control system to multi-flagship, multi-enemy scenario.
- Develop autonomous logic for intent recognition and resource allocation.
- Expand human-swarm interface, allowing flagship to coordinate swarms of drones and request human operator input when necessary.

Real Robot Implementation
- Seek to implement & evaluate control system using our fleet of custom built inflatable pontoon boats (see picture).

Acknowledgments

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