

Cooperative Autonomy for Contact Investigation

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Abstract—Autonomous surface and underwater vehicles present a safe and low-cost solution for various contact investigation tasks, such as harbor surveillance for potentially threatening small craft or submarines. Since such a task may involve many contacts of interest, such as all the normal boat traffic in a busy harbor, a single unmanned surface vehicle (USV) is unlikely to be able to reasonably investigate all the contacts. Instead, multiple USVs can be deployed to investigate contacts simultaneously. In this paper we present a system that performs this task using the MOOS-IvP autonomy infrastructure. The approach is analogous to “zone defense” in basketball, and only requires that each vehicle have knowledge of its collaborators’ positions. The resulting network requires only requires a small amount of communication data to be transmitted, making it applicable in the often low-throughput ocean environment.

I. INTRODUCTION

A. Background

Terrorists threats against large ships are real and growing. The bombings of the USS Cole in Aden harbor in 2000 [1] and the Limburg oil tanker off Yemen in 2002 [2] are examples of the danger that radicals pose to both civilian and military ships. Even more recently, pirates off the coast of Somalia seized the Maersk Alabama [3] and a number of smaller vessels. In 2003, an Independent Review of Australian Shipping [4] stated that “International shipping is arguably the weakest link in our national security system.” Also along those lines, the Australian Strategic Policy Institute released a policy paper [5] outlining the major potential maritime terrorist threats, one of which is “a small-boat suicide attack against a high-value target such as a warship, cruise liner, ferry, chemical tanker or oil tanker alongside in an Australian port or moving within the port.” It is this type of threat that the work presented here hopes to address.

Detecting potential threats in a busy harbor is a difficult task, given the amount of normal small boat traffic. Picking out a potential danger “signal” from all the background “noise” of innocuous vessels cannot be done simply with radar or other shipboard sensors. We propose using unmanned surface vehicles, due to their low cost and improved safety over manned craft, to investigate harbor traffic at close range to give the human operator much more data to work with when determining the contact’s potential threat. In order to have several vehicles navigate a harbor successfully, they must be nearly fully autonomous, with proper collision avoidance and

other relevant safety features. An autonomous system is also substantially more scalable than a human operated or tele-operated system.

B. Specific Problem and Assumptions

In this work we design a system intended to protect a *ship* at anchor or transiting at slow speed through harbor. At any given time, there are a specified number of potential targets (referred to later simply as *targets*) with arbitrary destinations within the harbor. In the majority of cases, potential targets are normal small boats and do not represent a threat. However, in order to find the rare case of a threat, we must attempt to investigate the most threatening targets at all times. To investigate these targets, we have a specified number of unmanned surface vehicles (hereafter, USVs or *friends*) actively protecting the ship. The USVs get in position to investigate targets approaching the ship by cutting range to the targets and using on-board sensors to identify the rare threatening small craft.

A complete solution of this problem involves working with real sensors and their limitations. Since we are initially interested in developing the autonomy system, we will make some simplifying assumptions about the sensors available to the USVs. We assume that:

- The ship or shore-based radar is capable of accurately picking up target positions within harbor.
- Ship to USV communications are robust (though not high throughput).
- USVs have short range sensors (video / still camera, lidar, etc.) which are useful for determining targets’ potential threats.
- USVs may have a hailing system to warn away (accidental) intruders from the ship.

C. MOOS-IvP

The software architecture used for this work is a robotic autonomy system referred to as MOOS-IvP, which is described in detail in [6]. MOOS-IvP allows for rapid transition from simulation to runtime on actual vehicles, making it an ideal choice for developing systems intended for use on real platforms. MOOS-IvP is comprised of two pieces, the MOOS interprocess communication infrastructure and pHelMivP, an autonomy-level behavior-based control system.

MOOS, the Mission Oriented Operating Suite, is a publish-subscribe infrastructure for asynchronous interprocess communication between a number of distinct processes or MOOS Modules (collectively, a MOOS Community). Each MOOS Module communicates only by publishing data to the central data bus (the MOOSDB) and by receiving data from the MOOSDB for which it had previously subscribed. This allows for rapid prototyping by partitioning the vehicle software system into modules that can largely be developed and debugged individually.

pHelmIVP, the Interval Programming Helm, is a behavior based decision engine that commands the low level control of the vehicle by producing a desired heading, speed, and depth for the vehicle. pHelmIVP allows for an arbitrary number of behaviors to compete for the vehicle's action, producing a "best option" by evaluating the entire objective *function* of each behavior over the entire (feasible) heading-speed-depth space, rather than just arbitrating over a *single* desired heading, speed, and depth from each behavior.

MOOS-IVP has been used in a number of projects involve subsea and surface marine vehicles, such as the work presented in [7].

II. CLUSTER DEFENSE SYSTEM COMPONENTS

A. Overview

Two behaviors and one MOOS module (Fig. 1) govern the primary actions of the USVs:

- **BHV_Attractor**: seeks to draw USVs towards targets to investigate with short-range sensors.
- **BHV_RubberBand**: seeks to bring USVs back to defense positions around ship.
- **pClusterPriority**: balances priorities for both behaviors in the context of multiple USVs and multiple contacts.

Each USV runs one instance of **BHV_Rubberband** and **pClusterPriority** and one instance of **BHV_Attractor** for each known target. Other background safety behaviors such as collision avoidance are also run.

B. BHV_Attractor

The behavior **BHV_Attractor** seeks to cut range to a target (i.e. the USV is *attracted* to the target). An instance is run for every target on each friends' computer. The objective function governs over heading, and has a peak in the direction of the contact from the USV. The height of the objective function (the priority) decreases linearly within a certain capture closest point of approach of the USV to the target, and is constant outside that range. This linear decrease tries to keep the USV from colliding with the target (since the priority of the background collision avoidance behaviors can take precedence). See Fig. 2a for a graphical depiction of this behavior.

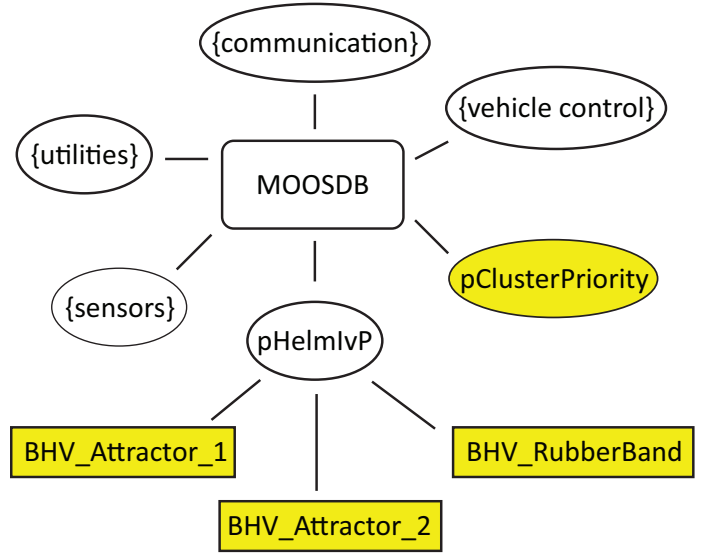


Fig. 1: MOOS-IVP community for performing the cluster defense task. Highlighted in yellow are the modules (two behaviors and one process) that comprise the autonomy reasoning for this task.

C. BHV_Rubberband

This behavior seeks to station keep near a fixed point (assigned by **pClusterPriority**). One instance is run on each USV. The objective function governs over heading and speed. The purpose of the **BHV_Rubberband** is to keep the vehicles from traveling too far away from the protected ship. The further the USVs get from their station-keeping point, the higher the priority of the **BHV_Rubberband** objective function, thus acting like a virtual rubber band from the USVs to their station points. Fig. 2b gives a sketch of the outcome of running this behavior.

D. pClusterPriority

This process prioritizes targets based on closest point of approach (CPA) and rebalances individual **BHV_Attractor** priorities within the cluster of USVs. The closest friend to the target has the highest priority weight given to the **BHV_Attractor** and is thus the most likely to pursue that contact. This priority increases exponentially as the closest vehicle gets closer (relative to its friends), producing a "latch-on" effect to a single target instead of potentially fickle behavior if no such weighting is given.

The priority weight for the i th friend on the j th target, A_{ij} , which modifies the overall priority of the **BHV_Attractor**, is given by

$$A_{ij}(d_{ij}, \bar{d}_j, cpa) = A_0 \cdot C_j(cpa) \cdot D_{ij}(d_{ij}, \bar{d}_j) \quad (1)$$

where A_0 is a normalizing factor, C weights targets based on their future proximity to the ship (closest point of approach), and D weights friends based on their proximity to the target. All the symbols and values used in the results are summarized in Table I.

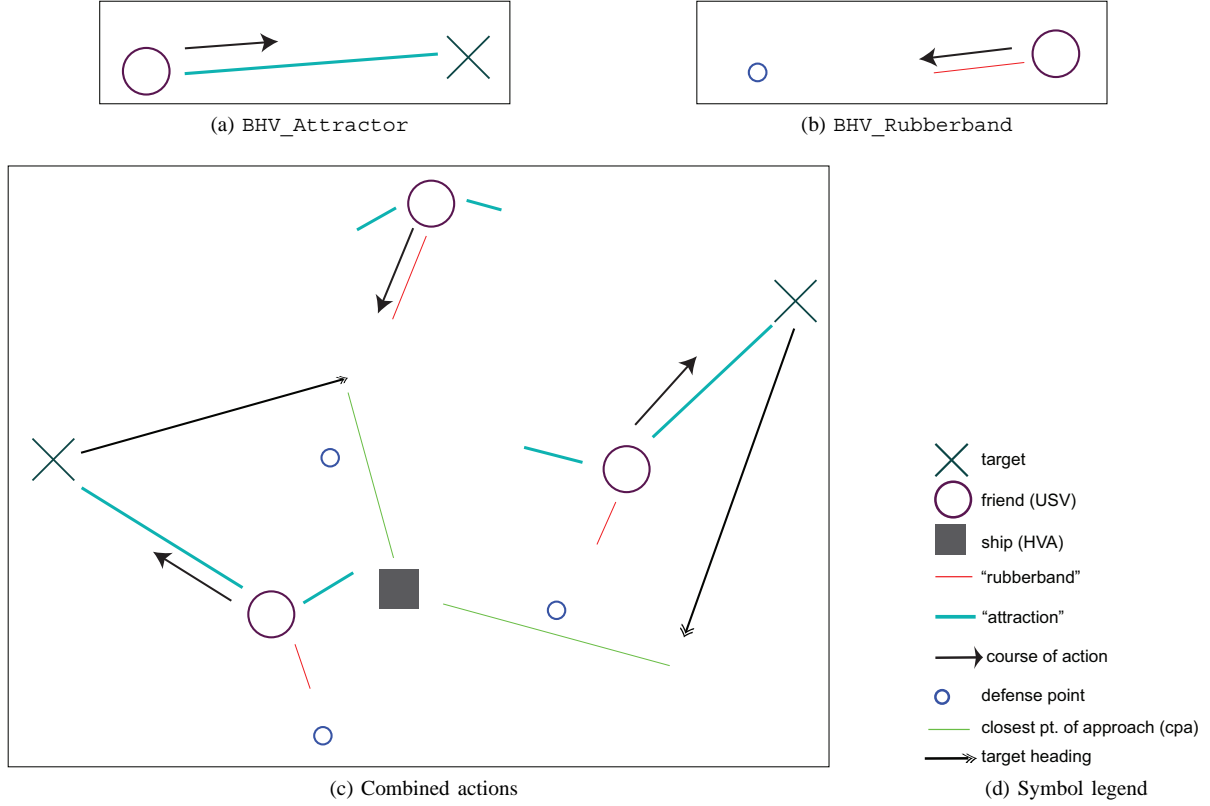


Fig. 2: Snapshots of the vehicle actions. If just BHV_Attractor is running (a), the vehicle heads towards the target. If just BHV_Rubberband is running (b), the vehicle heads towards its defense point around the ship and station-keeps. When both behaviors are running along with the weighting given by pClusterPriority, the vehicles act as shown in (c), with the two friends each investigating the closest target.

TABLE I: pClusterPriority variables

Symbol	Value used in results	Description
A_{ij}	computed	priority weight of BHV_Attractor for target j for friend i
A_0	100	normalizing constant
d_{ij}	computed	distance from the i th friend to the j th target
\bar{d}_j	computed	average friends' distance to target j
α	2	"strength" of decay
C_j	computed	closest point of approach (CPA) scaling factor
cpa_j	computed	CPA of j th 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 $C = C_{min}$

The closest point of approach (cpa) weight, C_j , makes targets that are heading towards the ship (i.e. have the lowest cpa if they continue on the same course) have the higher

priority:

$$C_j = \begin{cases} cpa_j \cdot \frac{C_{min} - C_{max}}{cpa_{cutoff}} + C_{max} & \text{if } cpa_j \leq cpa_{cutoff} \\ C_{min} & \text{if } cpa_j > cpa_{cutoff} \end{cases} \quad (2)$$

C_j is highest when $cpa_j = 0$ and lowest when $cpa_j \geq cpa_{cutoff}$, where cpa_{cutoff} is some threshold range beyond which the target's priority is equally low.

The closest friend weight, D_{ij} , gives priority to the friend(s) closest to the j th target, and is described as a decaying exponential.

$$D_{ij} = e^{-\alpha(d_{ij} - \bar{d}_j)/\bar{d}_j} \quad (3)$$

where d_j is a given friend's distance to the j th target and \bar{d}_j is the mean distance of all the friends to that target. D_{ij} is highest when target j and friend i are colocated and all other friends k (where $k \neq i$) are at infinity.

pClusterPriority also sets the initial defense locations on evenly spaced points of circle around the ship and rebalances USVs in case of loss (or addition) of a USV, evidenced by some period of communications dropout.

E. Combined Actions

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

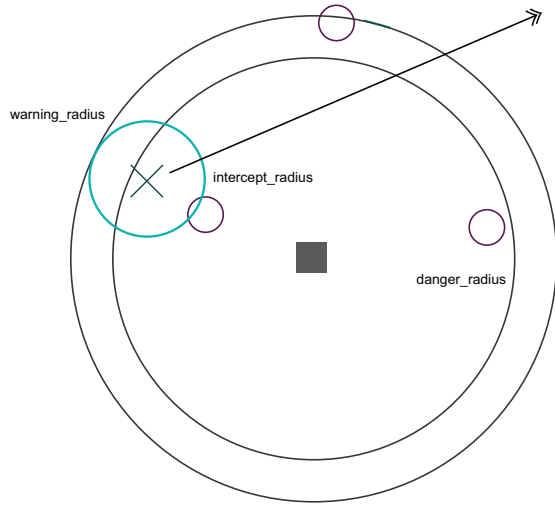


Fig. 3: Diagram of the parameters for the Cluster_Intercept performance Metric. A target entering the warning_radius triggers a score. A perfect score is interception of the target by a USV before the target reaches the danger_radius. Interception is counted when a USV enters the intercept_radius.

- Each USV investigates target(s) nearest it and other USVs back off when another USV is close to the target.
- When targets are not near or potentially threatening, the USVs return to their defense points and station-keep.
- The defense points move with the ship so in the absence of targets, the USVs simply track the ship's motion in their respective positions.

For the example case of two targets and three friends, Fig. 2c shows the behavior priority weights and expected actions for all three friends.

III. SIMULATION RESULTS AND PERFORMANCE EVALUATION

See Figs. 4 and 5 for a simulation of a ship transiting through a harbor protecting by three USVs carrying out the investigation of potential targets using the behaviors and dynamic weightings given in this paper.

A. Qualitative Evaluation

The system as designed is largely successful in achieving the desired behavior for the scenario given in section I-B. The USVs investigate most targets of highest interest, defined as those heading close or directly toward ship. Also, the USVs usually do not overlap investigation at the expense of another target. Importantly for a marine environment where communications are always uncertain, the system requires only knowledge of targets' and ship's speed, heading, position and friends' position. No other data must be shared for the autonomy to function.

However, there are a couple areas that need improvement. The USVs close to each other can sometimes form an unwanted "team" at the expense of defending ship from new

TABLE II: pScorer results

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

all other parameters held constant with values given in Table I.

targets. This "double-teaming" might be avoided by including a penalty for one USV being near another USV. Also, BHV_Attractor should govern over speed to avoid wasting power when full speed is not needed.

B. Quantitative Evaluation

1) *pScorer*: Quantitative performance evaluation of dynamic complex systems is hard; since they are highly non-linear, analytic solutions require often unrealistic simplifying assumptions. Also, we 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 representing quantities such as initial heading and target positions), the score should eventually converge.

2) *Metric Cluster_Intercept*: For evaluating the work presented here, we designed a Metric called Cluster_Intercept. For producing the score of this Metric, targets outside a "warning radius" from the ship are ignored. Targets within a "danger radius" from the ship are scored where the score is an exponential based on range to ship at which target is first intercepted (farther is better). A perfect score is interception at "danger radius," and interception requires a USV entering an "intercept radius" from the target. These radii are diagrammed in Fig 3.

3) *Evaluation of current system*: The pScorer results for the system presented here (using values given in Table I) are given in Table II. The score improves from doing nothing (vehicles simply station-keep) with a single active vehicle. When two more vehicles are added, the score improves further. Thus, multiple vehicles do a better job than a single vehicle, but we presume at some point there will be diminishing returns from adding more vehicles.

4) *Extending pScorer*: One Metric does not adequately evaluate the performance of this system. New Metrics that could be designed include:

- Coverage: determines how well vehicles (over time) are covering the area around the ship to deal with unexpected targets.



Fig. 4: Simulation of cluster defense of three USVs (green) protecting one ship (purple) from many potential targets (red). The ship has transited from the bottom right (near the seawall) to the upper left. The colors fade from dark (start of mission) to light (end of mission). See Fig. 5 for a snapshot view of this mission. Throughout the mission, the USVs have actively investigated many potential targets. The parameters used in this simulation are given in Table I.

- Power usage: average power consumption.
- Communications performance: throughput and timeliness of data, weighted by importance.

IV. CONCLUSION

We presented an autonomy system for harbor contact investigation that makes use of a simple sports analogy of “zone defense” to distribute the investigation of the targets amongst USVs. This system requires only a small amount of shared information, namely the position of the ship and friends, and the position, heading, and speed of each target. This makes the system suitable for multi-vehicle collaboration in the marine environment, where communications are often uncertain and slow.

We presented a technique for quantitative evaluation of complex systems based on a flexible scoring mechanism. While we used this `pScorer` and associated Metrics to evaluate a system whose parameters were tuned qualitatively, we expect that in the future it will be advantageous to invert the problem and use the scorer to search the parameter space for an optimal solution. Techniques such as simulated annealing or heuristic search could be applied to this inverted problem.

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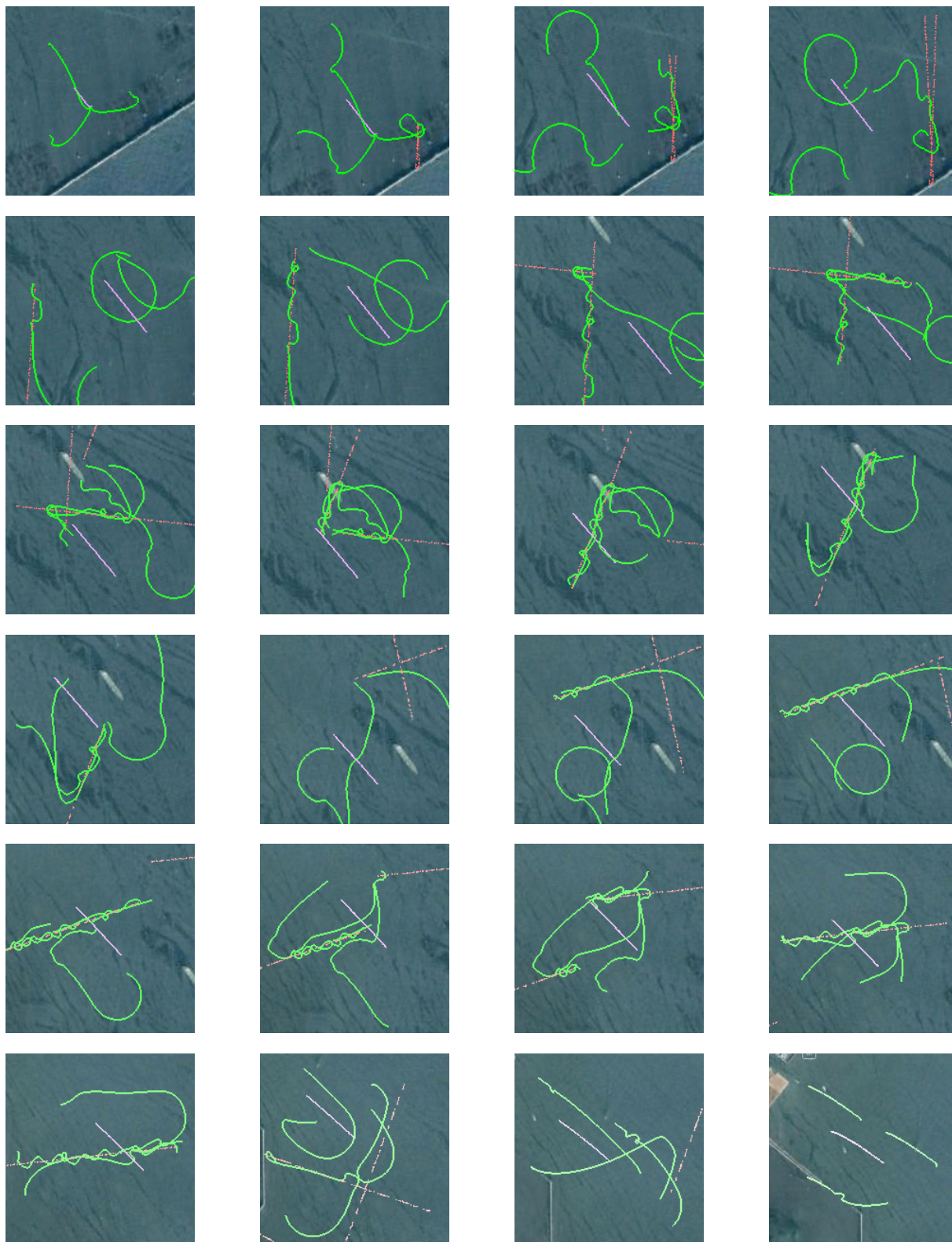


Fig. 5: Frame by frame look at Fig. 4, starting in the upper left. Green lines are the history track of friends, red are targets, and purple is the ship.

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