A Primitive-Based Approach to Good Seamanship Path Planning for Autonomous Surface Vessels

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Abstract— **This paper offers a multi-layer planning approach for autonomous surface vessels (ASVs) that must adhere to good seamanship practices and the International Regulations for Prevention of Collisions at Sea (COLREGS) [1]. The approach combines novel situational awareness logic with motion primitive-based planners in a receding horizon framework. Further, ship domain and ship arena concepts are used to develop risk metrics that capture COLREGS compliance and the notion of good seamanship. By relying on metrics-driven motion planning as opposed to rule-based conditions, the proposed framework scales naturally to non-trivial single-vessel and multi-vessel situations. The planner is evaluated using adaptive, simulation-based testing to statistically compare the performance to other standard methods. Finally, proof-of-concept field experiments are presented on a subscale platform.**

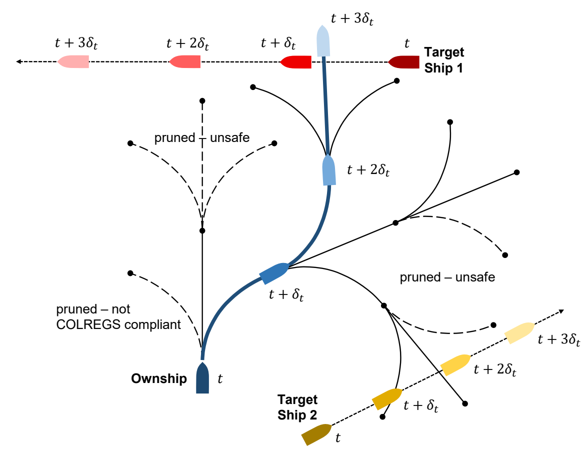

Fig. 1: Primitive-based receding horizon planning that encodes good seamanship principles for multi-vessel scenarios.

I. Introduction

Autonomous surface vessel (ASV) navigation remains a challenging problem due to the many competing requirements of these systems. For example, ASVs must not only satisfy mission objectives and traditional collision avoidance, but they must also act in accordance with more abstract "good seamanship" principles that human operators would exhibit. This includes predictable maneuvering, taking early action, and obeying navigation protocols according to the International Regulations for Prevention of Collisions at Sea [1], referred to as COLREGS. These protocols include maneuvering expectations that all vessels must follow to reduce confusion when there is a collision risk with another vessel. The challenge in developing ASV software to comply with these expectations, however, is that portions of the protocols were intentionally left vague so as to leave room for interpretation and common sense decision-making. Further, there are many aspects of good seamanship not explicitly written in these protocols, particularly regarding multi-vessel encounters. In these circumstances, some COLREGS protocols may not be applicable because they would produce conflicting expectations for each vessel. Thus, a robust ASV system must be capable of COLREGS compliance while remaining flexible enough to not blindly adhere to a rule-based system in more complicated scenarios.

Early work in this area focused on reactive planning methods using behavior-based interval programming methods [2], line of sight methods [3], or extensions to velocity obstacles [4], [5]. More recent work has focused primarily on deliberative planning approaches. Eriksen provides a recent collection of works [6], [7], [8] detailing each component in an overall ASV navigation system, where [6] provides a planning approach that evaluates an exhaustive set of motion primitive-based trajectories. Similar tree-based designs are described in a COLREGS-modified RRT planner [9], resolution-adaptive primitive sampling approaches [10], [11], and MPC-based approaches [12], [13]. Recent work has also begun to model the probabilistic intent of other vessels during planning [14].

This work aims to apply a hybrid planning approach, a portion of which is illustrated in Fig. 1, that adheres to COLREGS protocols in single-vessel encounters, but also incorporates a generalized formulation to capture the essence of good seamanship and COLREGS compliance in more complicated scenarios. Specifically, the main contributions of this work apply the concepts of ship domain and ship arena to quantify good seamanship principles, which are then used to improve the situational awareness and multi-vessel avoidance of the planner when compared to more standard approaches based on closest point of approach (as in [11], [10], [15], [5]). Further, the combination of both ship domain and ship arena gives a more complete picture of the overall risk rather than only considering penetration within a single safety zone [6]. These improvements are statistically measured against traditional approaches using adaptively-generated simulation scenarios (as opposed to one-off analysis on handcrafted scenarios). This paper is organized with Section II providing background information, Section III detailing the planning approach, and Sections IV and V performing simulation analysis and field experiments, respectively.

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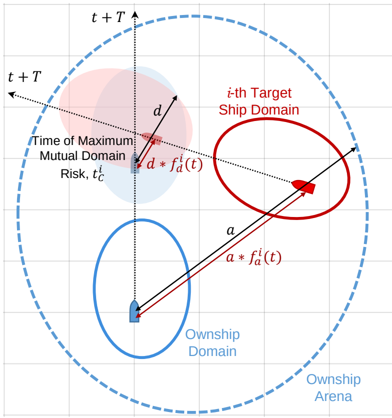


Fig. 2: Illustration of the overall risk methodology. Θ_C^i is calculated as the maximum mutual domain risk with the i-th target ship over a future time horizon $t + T$. Θ_A^i is calculated based on the i-th target ship's degree of penetration within ownship's arena [16].

II. Preliminaries

A. Ship Domain / Ship Arena

Maritime safety assessment has traditionally used metrics related to the closest point of approach (CPA) [17], [18], defined as the location where two objects with fixed velocity vectors reach their minimum separation distance. Ship domain and ship arena are analogous concepts that use generalized geometries to alleviate problems with CPA-based analysis. Ship domain is often defined as the area around a ship that should be kept clear of other vessels, while ship arena is defined here as the area around ownship where evasive action should be considered if a risk of collision exists. Previous work by the authors [16] leveraged these concepts to quantify good seamanship in multi-vessel scenarios for performance evaluation purposes. This section aims to summarize the developments of [16] such that this paper can further adapt those findings for use in path planning design.

Although different domain geometries have been proposed [19], [20], we adopt a decentralized ellipse as shown in Fig. 2. A decentralized ellipse captures the essence of COLREGS by emphasizing the fore and starboard sectors of the geometry while remaining simple enough that the governing equations can be solved analytically [21]. Scale factors $f_d^i(t)$ and $f_a^i(t)$ measure the i-th target ship's degree of penetration at time t into ownship's domain and arena, respectively. Thus, $f^i(t) = 0$ implies the vessels are coincident while $f^i(t) = 1$ implies the target ship lies on the ellipse boundary.

B. Quantifying Good Seamanship

Good seamanship is evaluated by considering two parts: (i) the future collision risk between all vessels (based on ship domain projections) and (ii) the degree to which ownship should take evasive action (based on penetration within ownship's arena).

1) Collision Metric: Let the domain scale factor be translated into a domain risk metric, $r_d \in [0, 1]$, using a logistic function according to the following:

$$r_d(t) = \frac{1}{1 + e^{k(f_d(t) - f_0)}}, \tag{1}$$

where k and f_0 are parameters that define the shape of the logistic curve [16]. The mutual domain risk between ownship and the i-th target ship can then be defined as

$$r_d^{OS,i}(t) = r_d^{OS}(t) + r_d^i(t)\left(1 - r_d^{OS}(t)\right), \tag{2}$$

where $r_d^{OS}(t)$ is calculated from the perspective of ownship and $r_d^i(t)$ is calculated from the i-th target ship perspective. Subsequently, the collision risk metric $\Theta_C^i(t)$ between ownship and the i-th target ship is defined as the maximum value of the mutual domain risk over a future time horizon T:

$$\Theta_C^i(t) = \max_{\tau \in [t, t+T]} r_d^{OS,i}(\tau), \tag{3}$$

$$t_C^i = \operatorname*{argmax}_{\tau \in [t, t+T]} r_d^{OS,i}(\tau). \tag{4}$$

2) Action Metric: The degree to which ownship should take evasive action against the i-th target ship is formulated based on the target ship's penetration within ownship arena:

$$\Theta_A^i(t) = \frac{1}{1 + e^{k(f_a^i(t) - f_0)}}. \tag{5}$$

This representation appropriately penalizes delayed avoidance maneuvers in a geometry consistent with COLREGS.

3) Seamanship Risk Metric: Finally, a seamanship risk metric $\Theta_S^i(t) \in [0, 1]$ is calculated as the combination of the collision and action metrics:

$$\Theta_S^i(t) = \Theta_C^i(t)\Theta_A^i(t). \tag{6}$$

Intuitively, $\Theta_S^i(t) = 0$ means that the i-th target ship currently poses no risk, either because there is no future collision risk ($\Theta_C^i(t) = 0$) or the target ship is too far away ($\Theta_A^i(t) = 0$).

III. Planning Approach

This section now proposes a unique approach for ASV path planning by naturally extending COLREGS compliance to multi-vessel encounters through the good seamanship metrics of Section II.

A. Overall Architecture

To narrow the focus of this paper, perception challenges are not addressed. Thus, the two key components of the overall decision-making are modules relating to situational awareness and path planning. The situational awareness module categorizes a scenario with respect to relevant hazards / vessels in the environment including the COLREGS type, requirements of ownship, etc. The planning module then consists of a three-layered architecture with (i) a high-level, primitive-based branch and bound planner, (ii) a mid-level dynamics-based RRT*, and (iii) a low-level trajectory follower. The high-level branch and bound planner uses the output from the situational awareness logic to prescribe a sequence of waypoints over a receding planning horizon that exhibit good seamanship and other aspects of COLREGS compliance, mission efficiency, and safety considerations (Fig. 1). This coarse waypoint sequence is connected by the mid-level dynamics-based RRT* to produce a continuous and

Algorithm 1 SITUATIONAL AWARENESS

procedure OVERALL_SITUATION($x_{OS}, \mathcal{V}$)
  for each $V^i \in \mathcal{V}$ **do**
    if $\Theta_C^i > \tilde{\Theta}_C$ & $t_C^i < \tilde{t}_C$ **then** $\mathcal{V}^* \leftarrow (\mathcal{V}^* \cup \{V^i\})$
      $\mathcal{C}^i \leftarrow$ COLREGS type and expectation ▷ see [15]
      if $\mathcal{C}_{exp}^i =$ STAND-ON & $\Theta_S^i > \tilde{\Theta}_S$ **then**
        $\mathcal{C}_{exp}^i \leftarrow$ GIVE-WAY ▷ Ownship *in extremis*
      end if
    end if
  end for
  if size($\mathcal{V}^*$) $= 0$ **then** $\mathcal{S}_{state} \leftarrow$ CLEAR; $\mathcal{S}_{exp} \leftarrow$ ANY
  else if size($\mathcal{V}^*$) $= 1$ **then**
    $\mathcal{S}_{state} \leftarrow$ COLREGS; $\mathcal{S}_{exp} \leftarrow \mathcal{C}_{exp}^i$
  else $\mathcal{S}_{state} \leftarrow$ CONGESTION
    if any($\mathcal{C}_{exp}^i$) $=$ GIVE-WAY **then** $\mathcal{S}_{exp} \leftarrow$ GIVE-WAY
    else $\mathcal{S}_{exp} \leftarrow$ STAND-ON
    end if
  end if
   return $\mathcal{S} \leftarrow \{\mathcal{V}^*, \mathcal{S}_{state}, \mathcal{S}_{exp}\}$
end procedure

feasible trajectory at a much finer time scale, which is then tracked using line of sight guidance techniques [22].

B. Situational Awareness

The module performing situational awareness is meant to incorporate all perception information into a simplified world model $\mathcal{S}$ on which path planning can operate. Following the procedure of Alg. 1, we define $\mathcal{V}$ to be the set of all perceived target ships and $\mathcal{V}^*$ to be the set of *relevant* target ships considered during planning, i.e., those for which Θ_C^i and t_C^i satisfy user-specified thresholds $\tilde{\Theta}_C$ and $\tilde{t}_C$, respectively. COLREGS is categorized for each relevant target ship and $\mathcal{S}$ is defined according to the number of relevant target ships as well ownship's expectation for each relevant target ship.

C. Branch and Bound Planner

Let the planning space be defined as $\mathcal{X} = \mathcal{X}_p \times \mathcal{X}_\psi \times \mathcal{X}_v \times \mathcal{T}$ such that each node $\boldsymbol{x} = [p, \psi, v, t] \in \mathcal{X}$ consists of a planar position $p \in \mathcal{X}_p \subset \mathbb{R}^2$, a heading angle $\psi \in \mathcal{X}_\psi$, a velocity $v \in \mathcal{X}_v$, and a time $t \in \mathcal{T}$. Further, let a trajectory $X = \{\boldsymbol{x}_k\}_{k=1}^n$ be a sequence of n state nodes separated by timestep δ_t. The branch and bound planner of Alg. 2 implements a receding horizon strategy such that a final trajectory of $n = H$ nodes is computed up to a local planning horizon $T = H\delta_t$.

The edges of the branch and bound tree consist of primitive curves with constant velocity and turn rate ω. A full dynamic model would require several integration steps to generate each segment, resulting in significant increases to computation time. Thus, for high-level planning at this stage, we utilize a kinematic trajectory parameterization that can be solved in closed form, while more rigorous dynamic constraints are handled by the other layers of the overall system. More formally, the trajectory parameter is $\boldsymbol{z} = (\delta_v, \delta_\psi) \in \mathcal{Z}$ corresponding to desired changes in speed and heading, respectively. A set of M parameterizations $\{\boldsymbol{z}_k\}_{k=1}^M$ is generated at each n-th stage of the tree. Further, turn rate and linear acceleration are saturated within conservative values of the system's allowable bounds to promote dynamic feasibility in the mid-level planner: $\omega = \min(\max(\frac{\delta_\psi}{\delta_t}, \omega_{min}), \omega_{max})$ and $a = \min(\max(\frac{\delta_v}{\delta_t}, a_{min}), a_{max})$. At a time $t^* = t + \delta_t$, the mapping $\varphi : \mathcal{Z} \to \mathcal{X}$ then takes the following form:

$$v(t^*) = v(t) + \delta_t a, \tag{7a}$$

$$\psi(t^*) = \psi(t) + \delta_t \omega, \tag{7b}$$

$$p_x(t^*) = p_x(t) + \tfrac{v(t^*)}{\omega}\big(\sin(\psi(t) + \delta_t\omega) - \sin\psi(t)\big), \tag{7c}$$

$$p_y(t^*) = p_y(t) - \tfrac{v(t^*)}{\omega}\big(\cos(\psi(t) + \delta_t\omega) - \cos\psi(t)\big). \tag{7d}$$

When $\omega = 0$, the position updates follow a constant speed and heading projection. This formulation assumes that the transients from potential velocity discontinuities are small when compared to the longer time scales of surface vessel interactions and can be handled by the mid-level planner.

The choice of δ_t, H, and M are crucial to generating desired maneuvers. To ensure that control actions are considered both before and after the relevant vessel interactions while minding computational constraints, this work chooses $\delta_t = \max\big(\min_i(t_C^i)/\ell,\ \tilde{\delta}_t\big)$, where $\tilde{\delta}_t$ is a nominal minimum value for the time step. This formula scales δ_t based on the time until maximum mutual domain risk, such that longer planning horizons are accommodated if the interaction is far away. The choice of ℓ sets the number of control actions considered until t_C^i ($\ell = 4$ is used in Sections IV and V). Values for the trajectory parameters are chosen from discrete sets at each level of the tree:

$$\delta_v \in \begin{cases} \{-v, -0.5v, 0\} & \text{if } n = 1, \\ \{0\} & \text{otherwise,} \end{cases} \tag{8}$$

$$\delta_\psi \in \tfrac{\pi}{180}\{-60, -45, -30, 0, 30, 45, 60\}\ \forall\, n. \tag{9}$$

This strategy chooses a single speed at the beginning of the trajectory that minimizes M and allows the depth of the tree H to be maximized based on the available computing resources of the system. It also ensures that any chosen heading change is readily apparent as required by COLREGS.

D. Cost Function

The final cost function $J \in [0, 1]$ for evaluating potential trajectories consists of a weighted average of mission (J_M), safety (J_S), and COLREGS (J_C) subcomponents as follows:

$$J = \frac{w_M J_M + w_S J_S + w_C J_C}{w_M + w_S + w_C}, \tag{10}$$

where w_M, w_S, and w_C are weights for the mission, safety, and COLREGs criteria, respectively ($w_M = 1$, $w_S = 20$, and $w_C = 5$ are used in Sections IV and V).

1) Mission Cost: Mission cost $J_M \in [0, 1]$ at the k-th node is calculated as the normalized distance to the current desired goal waypoint

$$J_M = \frac{||p_k - p_{goal}|| - d_{goal}^+}{d_{goal}^- - d_{goal}^+}, \tag{11}$$

where the maximum travel distance over the planning horizon acts as a normalization factor such that $d_{goal}^+ = \max(||p_{start} - p_{goal}|| - v_{max}T, 0)$ and $d_{goal}^- = ||p_{start} - p_{goal}|| + v_{max}T$.

Algorithm 2 BRANCH & BOUND PRIMITIVE PLANNING

procedure BB_PLANNER($\boldsymbol{x}_{start}, \boldsymbol{x}_{goal}, \mathcal{S}$)
  Initialize J_{LB}, δ_t, H, M; Set $J^* \leftarrow \infty$
  $[X^*, J^*] \leftarrow$ BB_RECURSION($\{\boldsymbol{x}_{start}\}, 0, 1$)
  return X^*
end procedure

procedure BB_RECURSION(X_P, J_P, n)
  $J_{max} \leftarrow J_P + J_{LB}(H - n + 1)$
  if $J_{max} < J^*$ & $n \leq H$ **then**
    Sample primitives: $\{\boldsymbol{z}_k\}_{k=1}^M$
    Extend nodes from X_P: $\{\boldsymbol{x}_k = \varphi(\boldsymbol{z}_k)\}_{k=1}^M$
    Calculate cost $\{J_k\}_{k=1}^M$ ▷ Eq. (10), $\boldsymbol{x}_{goal}$, $\mathcal{S}$
    Sort $\boldsymbol{x}_k$ by increasing J_k
    for each $\boldsymbol{x}_k$ **do**
      $J \leftarrow J_P + J_k$; $X_k \leftarrow (X_P \cup \{\boldsymbol{x}_k\})$
      if $J < J^*$ **then** $J^* \leftarrow J$; $X^* \leftarrow X_k$
      end if
      $[X^*, J^*] \leftarrow$ BB_RECURSION(X_k, J, $n + 1$)
    end for
  end if
  return X^*, J^*
end procedure

2) Safety Cost: Safety cost $J_S \in [0, 1]$ at the k-th node is calculated using the seamanship-based risk metric defined in Section II-B. Following developments from [16], for a scenario involving $i = 1, \ldots, N$ target ships, the risk associated with the overall scenario is the union of individual risk metrics, translated to J_S through the following recursion:

$$\text{WHILE } i \leq N$$
$$J_S = \begin{cases} \Theta_S^i(\boldsymbol{x}_k) & \text{if } i = 1 \\ \Theta_S^i(\boldsymbol{x}_k) + J_S\left(1 - \Theta_S^i(\boldsymbol{x}_k)\right) & \text{if } 1 < i \leq N. \end{cases} \tag{12}$$

This formula prescribes that the safety cost is *at least* as large as the highest risk from the i-th target ship, with additional risk from other vessels only adding to the safety cost.

3) COLREGS Cost: The COLREGS component of the cost function $J_C \in [0, 1]$ is informed by the work of Woerner [23], [15]. Portions of the algorithms from these works have been modified here to evaluate the COLREGS compliance of sequential nodes in the planner waypoint sequence. Several additional penalties that generalize to multi-vessel encounters are also applied as outlined in the general methodology of Alg. 3. These include making maneuvers more predictable by reducing changes in control actions (i.e., minimizing indecision), preferring course changes to speed changes, and ensuring that any control actions taken are readily apparent.

4) Cost Lower Bound: The lower bound on the overall cost $J_{LB} \in [0, 1]$ is used to prune branches unlikely to contain the optimal solution. This value is determined from the estimated mission cost-to-go at each stage of the tree assuming ownship were to travel directly towards the goal:

$$J_{LB} = \frac{w_M(||p_{start} - p_{goal}|| - d_{goal}^+)}{H(w_M + w_S + w_C)(d_{goal}^- - d_{goal}^+)}. \tag{13}$$

Algorithm 3 COLREGS COST METHODOLOGY

procedure COLREGS_COST($X, \mathcal{S}$)
  Set user-specifed values for p_M, p_I, p_E, p_S; Set $Q_C \leftarrow 1$
  if $\mathcal{S}_{state}$ = COLREGS **then**
    $Q_C \leftarrow$ COLREGS score according to [15]
  end if
  $Q_C \leftarrow p_M Q_C$ ▷ Penalize non-obvious maneuvers
  $Q_C \leftarrow p_I Q_C$ ▷ Penalize action indecision
  $Q_C \leftarrow p_E Q_C$ ▷ Penalize turns to port when *in extremis*
  $Q_C \leftarrow p_S Q_C$ ▷ Penalize speed-only actions; prefer turns
  return $J_C \leftarrow 1 - Q_C$
end procedure

IV. PERFORMANCE EVALUATION

We now evaluate the proposed system in simulation against two more traditional planners: (i) a variant of the proposed planner utilizing CPA-based avoidance criteria / costs instead of the domain-based seamanship approach and (ii) a COLREGS-supplemented velocity obstacles (VO) planner (similar to the approach in [4]). The goal is to not just measure performance on handcrafted scenarios, but to evaluate the system over a wide array of testing conditions. We extend a previous evaluation framework developed by the authors [24] to perform simulation-based testing [25] of the ASV software through adaptive generation of both single-vessel and multi-vessel scenarios. This strategy for scenario generation efficiently searches the space of all possible test conditions (i.e., the testing space) and more effectively identifies unknown failure modes when compared to randomized designs, particularly in high-dimensional spaces [24], [25].

A. Testing Parameters

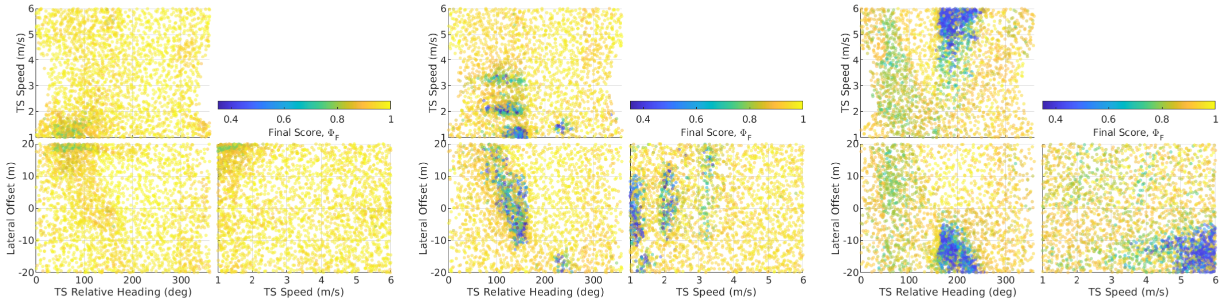
The ASV started at the origin and traveled towards a constant goal point for each scenario. For conciseness, the target ships maintained constant heading and speed and were spawned based on variations to three testing parameters to adaptively generate new scenarios: (i) the relative heading of the oncoming target ship, (ii) the speed of the target ship, and (iii) a lateral offset to the projected intersection point between the vessels. Two studies were performed using these parameters for each planning method:

- A 3,000-scenario study varying the three parameters above for a single target ship (i.e. a 3D testing space).
- A 10,000-scenario study varying the three parameters above for two target ships (i.e. a 6D testing space).

Values for the test parameter ranges (indicated in Fig. 3) were chosen based on a subscale test platform such that the simulation results could be verified with on-water testing. Results that consider target ships with their own collision avoidance logic will be discussed in follow-on work.

B. Evaluation Criteria

ASV performance $\Phi_F = f(\phi_M, \phi_S, \phi_C) \in [0, 1]$ on single-vessel encounters is scored according to the methodology in [24]. This evaluation includes a combination of mission criteria ϕ_M related to time and distance traveled for ownship to reach its goal, safety criteria ϕ_S related to



(a) Seamanship-based planner (b) CPA-based planner (c) VO-based planner

Fig. 3: Performance landscapes of each planning strategy for the single-vessel study. Adaptive, simulation-based testing is used to characterize regions of poor performance based on variations to the target ship (TS) parameters.

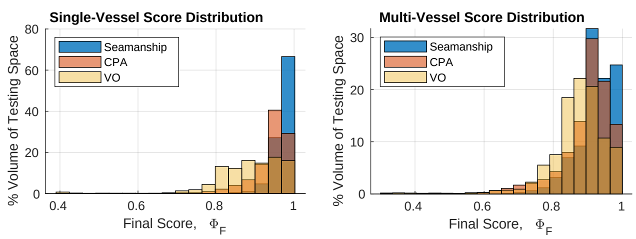


Fig. 4: Histograms for each planner representing the percent volume of the testing space occupied with respect to different scoring bins for the single-vessel study (left) and multi-vessel study (right).

minimum standoff geometry, and COLREGS compliance ϕ_C according to [15].

For multi-vessel encounters, the quantitative COLREGS evaluation of [15] is not as applicable. The scoring criteria is modified for these simulations such that $\Phi_F = f(\phi_M, \phi_S, \mathbb{S}) \in [0, 1]$, where $\mathbb{S}$ is the full seamanship performance score of [16].

C. Analysis

1) Single-Vessel Study: The 3D performance landscapes for the single-vessel study are shown in Fig. 3, where each point represents a simulation and corresponding Φ_F value. Qualitatively, it is evident that the proposed seamanship-based planning strategy has significantly fewer and less severe failure modes when compared to the CPA-based planner and the VO-based planner.

Further, the left plot of Fig. 4 shows a histogram for each planner representing the volume of each Φ_F bin as a percentage of the the total testing space volume (deemed $Vol(\Phi_F)\%$), calculated by summing the Voronoi volumes of scenarios within each Φ_F bin. Table I summarizes the testing space percentage for $\Phi_F > 0.9$, showing that the seamanship-based planner has high performance scores in 98.5% of the testing space and significantly outperforms the other planners. Table I also shows that the seamanship-based planner has no collisions in contrast to the other planners.

2) Multi-Vessel Study: The right plot of Fig. 4 displays an identical analysis for the 6D multi-vessel study with performance metrics captured in Tab. I. In these more challenging scenarios, the seamanship-based planner again outperforms the other planners in achieving high scores throughout the testing space and minimizing the collision rate.

TABLE I: Performance metrics for each ASV planning method.

Planner		Seamanship	CPA	VO
Single-Vessel Study	$Vol(\Phi_F > 0.9)\%$	98.5	83.9	48.5
	Collision%	0	0.85	1.01
Multi-Vessel Study	$Vol(\Phi_F > 0.9)\%$	78.6	64.9	40.2
	Collision%	0.04	2.06	5.46

V. Field Experiments

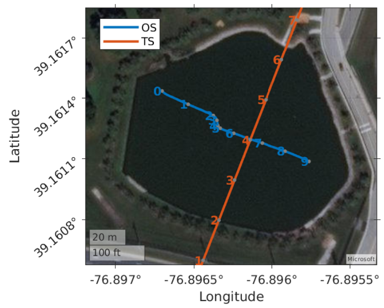
Field experiments with a subscale test platform (Fig. 5(a)) were performed to both demonstrate the proposed planning method on hardware and provide confidence to the simulation analysis. To replicate the simulations as closely as possible, the experiments utilized virtual target ships that were corrupted with state noise and sent to the test platform via radio. A total of 50 scenarios were tested on the water drawn from both the single-vessel and multi-vessel studies to capture different COLREGS scenarios. Each field test was scored using the same criteria as Section IV; the distribution of scores and their difference from the simulation results is shown in Fig. 6. Overall, the field tests exhibited similar performance to that seen in simulation with negligible score difference. Candidate results from a subset of particularly challenging scenarios are shown in Fig. 5.

A. Single-Vessel Scenarios

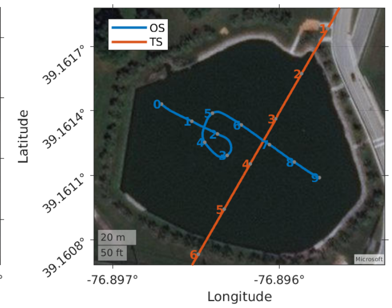
1) Crossing Give-way – Fig. 5(b): The ASV is expected to give way to the target ship in this crossing scenario. Due to the target ship's high speed relative to the ASV, the planner produces a trajectory which both slows down while also performing a COLREGS-compliant heading change at time markers 2–5. The ASV then resumes progress to the goal after the situation is clear.

2) Noncompliant Crossing Stand-on – Fig. 5(c): The ASV is now expected to stand on while the target ship gives way in this crossing scenario. The planner correctly maintains course and speed until the target ship is deemed noncompliant after time marker 2, requiring the ASV to take evasive action. The resulting avoidance maneuver resembles the standard "paperclip maneuver" taught to ship captains for precisely this situation. When *in extremis*, COLREGS prohibit turning to port because the vessels would then be on a collision course if the target ship gave way as it should.

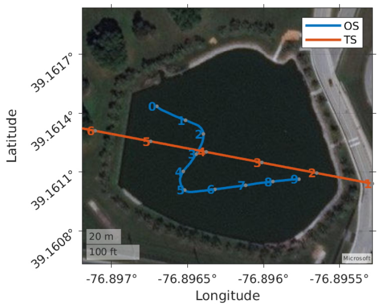
(a) Subscale test platform



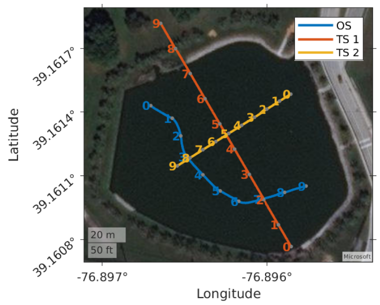
(b) Crossing give-way



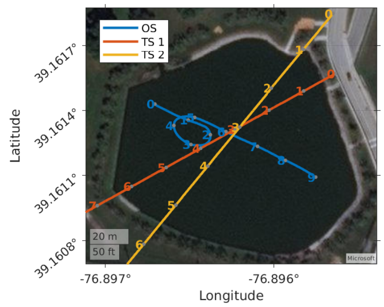
(c) Noncompliant crossing stand-on



(d) Offset head-on



(e) Two-vessel conflicting expectation



(f) Two-vessel noncompliant crossing

Fig. 5: Field test results from a subset of challenging scenarios performed with the subscale test platform in (a). The numbers on each trajectory correspond to snapshots in time for ownship (OS) and each target ship (TS).

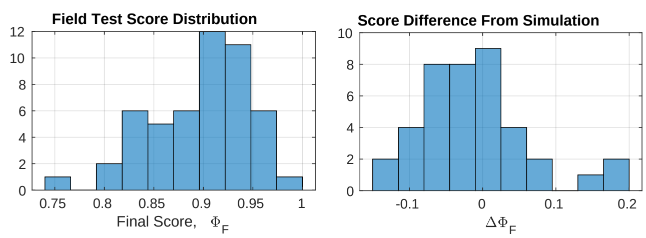


Fig. 6: Φ_F distribution for the set of 50 field tests (left) and the score difference ($\Delta\Phi_F$) compared to simulation (right).

The appropriate maneuver then is to reduce collision risk by turning to starboard, continuing to monitor the situation, and performing a full roundabout to de-escalate the situation if necessary. This result falls naturally out of the seamanship-based planner without the need for a preplanned maneuver or rule-based conditions to account for this situation.

3) Offset Head-on – Fig. 5(d): It is highly preferred in COLREGS for vessels to pass port-to-port when meeting on reciprocal courses (captured by the decentralized ellipse ship domain). This scenario is difficult because the vessels are already on each other's starboard side. While "correct" maneuvering for these offset head-on edge cases is debated, for small offsets such as this scenario, it is generally accepted that the vessels should attempt to pass port-to-port if maneuvers are made early. The ASV properly exhibits this behavior here, while other scenarios within the testing set with greater offsets produce avoidance maneuvers to port.

B. Multi-Vessel Scenarios

1) Conflicting Expectations – Fig. 5(e): This scenario features a roundabout geometry where, according to single-vessel COLREGS protocols, the ASV would be expected to give way to the first target ship while somehow also standing on to the second target ship. With these conflicting expectations, the seamanship-based approach is still able to produce an avoidance maneuver that minimizes risk by prioritizing its responsibility to avoid the first target ship off its starboard bow through the geometry of each ship domain and arena. The resulting maneuver correctly treats the situation as a roundabout where each vessel would be expected to proceed counterclockwise around the encounter.

2) Double Noncompliant Crossing Stand-on – Fig. 5(f): In this multi-vessel crossing scenario the ASV would be expected to stand-on to both vessels. Once one target ship becomes noncompliant, however, the ASV again performs a paperclip avoidance maneuver, albeit a tighter one in order to avoid both vessels at proper range.

VI. Conclusion

This work presented a planning approach for ASVs that quantifies good seamanship principles through the use of ship domain and ship arena concepts into a multi-layer trajectory generation process. The approach naturally applies to both single-vessel scenarios, where adherence to COLREGS protocols is required, and multi-vessel scenarios where COLREGS are ill-defined. This strategy was then shown to outperform more traditional planning strategies based on CPA and velocity obstacles through adaptive, simulation-based testing. Field experiments demonstrated that this approach can be transferred for operational use.

Future work is planned to incorporate GPU parallelization to both increase the planning horizon and consider non-constant target ship trajectory prediction. Improvements to the system are then planned to be demonstrated on a full-scale 6 meter vessel.

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