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A Data-Driven Dynamic Hybrid Ship-Domain Framework for Self-Propelled Aquaculture Vessels

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Abstract: Self-propelled aquaculture vessels integrate navigation, aquaculture production, station-keeping, relocation and emergency sheltering functions. Their principal dimensions, beam, low-speed manoeuvring capability, aquaculture structures and operational states differ from those of conventional transport ships. When AIS encounter samples for this ship type are limited, direct use of merchant-ship domains may underestimate low-speed manoeuvring and lateral-clearance requirements. This paper proposes, at the methodological level, an AIS-driven dynamic hybrid ship-domain framework based on similar-vessel transfer. AIS-derived empirical boundaries of similar reference vessels are used as the data basis, while manoeuvrability constraints, operational-state constraints and an expert-defined lower safety bound are introduced as corrections. The framework is intended to guide subsequent model construction, parameter calibration and performance validation, and may provide a methodological basis for safety-boundary modelling in collision-risk identification, early warning and collision-avoidance decision-making for unmanned aquaculture vessels. Its engineering applicability requires further verification using AIS data from target waters, manoeuvring simulations, numerical experiments and simulator-based tests.

1. Introduction

The ship domain describes the safety space that a vessel should maintain during encounters and is a basic concept in maritime traffic risk assessment and collision-avoidance decision-making (Fig.1). Fujii and Tanaka introduced the idea of the safety space occupied by a ship from the perspective of traffic capacity [1]. Goodwin developed a sector-based domain from traffic observations and revealed the asymmetry of safety distances in different relative bearings [2]. Wang later proposed the quaternion ship domain for spatial collision-risk representation [3]. These studies transformed the ship domain from an empirical safety-distance concept into a spatial model for risk discrimination.

The widespread use of the Automatic Identification System (AIS) has further shifted ship-domain research from empirical parameter setting to data-driven modelling. Hansen et al. estimated the minimum comfortable safety space perceived by navigators from AIS data [4]. Zhang and Meng proposed a probabilistic ship domain for collision-risk assessment [5]. Du et al. incorporated evasive manoeuvres and perceived collision risk into empirical-domain construction [6]. Lei et al. showed that AIS data-driven ship-domain scales are associated with factors such as ship length and speed in bridge waters [7]. Silveira et al. fitted AIS-derived empirical polygonal domains into quaternion ship-domain parameters [8]. These studies indicate that AIS data can be used to extract empirical safety boundaries under specific ship-type, scale and waterway conditions.

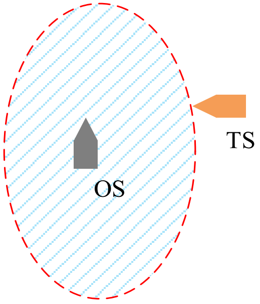

Fig.1 Schematic diagram of the ship domain(OS-Own ship, TS-target ship)

Self-propelled aquaculture vessels provide a new application scenario for ship-domain modelling. Such vessels have navigation attributes while also undertaking aquaculture production, offshore station keeping, low-speed relocation and emergency sheltering. Tank-based aquaculture vessels involve internal-water sloshing and coupled hydrodynamic responses [9], while flow-through or perforated aquaculture vessels are affected by side openings, net-panel damping, frame structures and wave-current loads [10]. These structural and operational characteristics may change the safety margins required during port entry, relocation, approach to aquaculture areas and complex traffic-convergence situations.

Existing AIS-driven ship-domain models are mainly derived from conventional ships and typical traffic waters. Operational self-propelled offshore aquaculture vessels are still limited, and their historical AIS encounter samples are insufficient, especially in high-risk convergence conditions. Direct modelling from their own AIS data restricts statistical stability and scenario coverage, whereas direct adoption of merchant-ship domains may fail to represent their low-speed, wide-beam, restricted-manoeuvring and state-dependent characteristics. This study therefore develops a methodological framework that extracts empirical domains from transferable reference vessels in existing AIS data and then corrects them using aquaculture-vessel manoeuvring constraints and expert-defined safety lower bounds.

2. Methodological Basis

2.1. Transferability of AIS-driven ship domains

AIS data include vessel position, speed, course, ship type, dimensions and navigation status, and can be used to construct encounter samples and extract empirical safety boundaries. A typical data-driven ship-domain workflow consists of AIS data cleaning, trajectory reconstruction, encounter identification, transformation into the own-ship coordinate system, relative-motion calculation and boundary estimation. Its methodological basis is that observed passing distances and avoidance behaviours in historical encounters reflect, to some extent, empirical safety preferences under specific waterway, ship-type and traffic conditions.

Aquaculture vessels have insufficient AIS samples for large-scale statistical modelling. However, merchant ships, engineering vessels, fishing vessels and special-purpose vessels that may encounter aquaculture vessels in target waters usually provide abundant AIS data. These samples contain information on traffic density, relative-bearing distribution, low-speed traffic behaviour, avoidance-initiation distance and empirical boundaries for different target-ship types. Therefore, the data-driven component in this study is used mainly for screening similar reference vessels and constructing empirical domains rather than directly training a domain from aquaculture-vessel AIS data. Since ship domains are associated with ship type, scale, waterway and encounter situation [4-7], transfer bias can be reduced by selecting samples with similar dimensions, motion behaviour and waterway conditions.

2.2. Modelling constraints for self-propelled aquaculture vessels

Large self-propelled offshore aquaculture vessels can be broadly grouped into tank-based and flow-through types. A tank-based aquaculture vessel uses a large hull as the culture carrier, with internal culture tanks and systems for water circulation, oxygenation, feeding and water-quality monitoring. Previous studies have shown that internal tanks and loading states can affect the hydrodynamic responses of aquaculture vessels [9]. Domain modelling for this type should therefore consider large hull scale, low-speed relocation, loading state and internal-water motion effects on manoeuvring response.

Flow-through, perforated or cage-type aquaculture vessels achieve water exchange through side openings, perforated structures, net panels and frame structures. Existing studies have analysed the hydrodynamic performance of flow-through aquaculture vessels with side openings [10]. Their open structures, large beam, net-panel damping and lateral-current effects make low-speed drift and lateral safety margins more prominent. Although both types of aquaculture vessels share sparse samples and limited manoeuvrability, their modelling emphases differ (Table 1).

Table 1. Ship-domain considerations for two types of self-propelled aquaculture vessels

Type	Main structural characteristics	Candidate similar reference vessels	Key factors affecting the ship domain
Tank-based aquaculture vessel	Large hull, internal culture tanks, water-circulation system, varying loading states	Large low-speed displacement vessels; low-speed manoeuvring vessels in port areas; cargo ships of similar scale	Hull scale, low-speed relocation, loading state, internal-water sloshing, manoeuvring margin during port entry and departure
Flow-through/perforated/cage-type aquaculture vessel	Side openings, perforated structures, net panels, truss or frame structures, significant lateral-current effects	Large low-speed wide-beam vessels; engineering work vessels; vessels with restricted manoeuvrability; nearshore special-purpose vessels	Lateral safety margin, wind-current sensitivity, low-speed drift, net/perforation damping, operational-state transitions

3. Data-driven Dynamic Hybrid Ship-domain Framework

To address the lack of AIS data samples, prominent low-speed manoeuvring features and complex operational states of aquaculture vessels, this section constructs a data-driven dynamic hybrid ship-domain framework at the methodological level. The framework is not a calibrated and validated engineering model, but a basis for subsequent sample construction, parameter calibration and performance testing.

3.1. Screening AIS samples of similar vessels

Reference-vessel screening considers static dimensions, motion behaviour, manoeuvring state and waterway environment. Dimensional similarity includes length, beam, length-beam ratio and draught. Motion-behaviour similarity includes speed distribution, proportion of low-speed navigation, trajectory curvature, rate of turn and acceleration/deceleration. Operational-state similarity includes port-area low-speed manoeuvring, engineering operations, restricted manoeuvrability and relocation navigation. Waterway-environment similarity includes nearshore waters, port approach channels, aquaculture-area vicinity, typhoon-shelter relocation routes and traffic-convergence waters.

The overall similarity between the i-th candidate reference vessel and the aquaculture vessel can be expressed as

$$Sim_i = w_G Sim_G + w_K Sim_K + w_O Sim_O + w_W Sim_W \tag{1}$$

where Sim_G, Sim_K, Sim_O and Sim_W denote dimensional, motion-behaviour, manoeuvring/operational-state and waterway-environment similarities, respectively, and w_G, w_K, w_O and w_W are their weights. For tank-based vessels, higher weights should be assigned to vessel scale and low-speed relocation. For flow-through or cage-type vessels, greater emphasis should be placed on beam, low-speed lateral drift, restricted manoeuvring and waters near aquaculture areas. The similar-vessel set is defined as

$$\Omega_S = \{V_i | Sim_i >= \delta\} \tag{2}$$

where V_i is the i-th candidate reference vessel and delta is the similarity threshold. This mechanism narrows the AIS-driven data source from all conventional ships to transferable reference samples, reducing the errors caused by directly transferring average merchant-ship domains.

3.2. Extraction of reference empirical ship domains

Once Ω_S is determined, the reference empirical domain can be extracted from its encounter samples. Head-on, crossing, overtaking and multi-ship convergence situations are identified using relative distance, DCPA, TCPA and relative bearing. With the reference vessel as the origin and its heading direction as the x-axis, target-ship positions are transformed into the own-ship coordinate system to obtain relative-position point clouds.

A directional-sector quantile method can determine the empirical boundary. The relative bearing θ is divided into sectors, and the high quantile of relative-distance samples (85%-90%) in each sector is extracted to represent the empirical safety boundary maintained by reference vessels. The discrete empirical boundary is then fitted into quaternion ship-domain parameters [8]:

$$\Theta_{ref} = [R_f, R_a, R_p, R_{stb}, \alpha_f, \alpha_a, \alpha_p, \alpha_{stb}] \tag{3}$$

where R_f, R_a, R_p and R_{stb} denote the reference safety scales in the fore, aft, port and starboard directions, and α_f, α_a, α_p and α_{stb} denote shape parameters for the corresponding quadrants. The continuous radial boundary for any relative bearing is

$$R_S(\theta) = G(\theta; \Theta_{ref}) \tag{4}$$

3.3. Manoeuvrability constraints

The reference domain of similar vessels represents only a general empirical boundary. Low-speed manoeuvring, turning response, stopping distance, lateral drift and environmental disturbances alter the time and space required for aquaculture vessels to complete safe avoidance. Let $T_{A,req}(\theta,\sigma)$ denote the required avoidance time of the aquaculture vessel at relative bearing θ and operational state σ, and let $T_{S,req}(\theta)$ denote the corresponding time of the similar reference vessel. The manoeuvrability constraint factor is

$$\varGamma_M(\theta,\sigma) = max[1, T_{A,req}(\theta,\sigma)/T_{S,req}(\theta)] \tag{5}$$

When $\varGamma_M(\theta,\sigma) > 1$, the aquaculture vessel requires more time to avoid collision in that direction, so the domain should be enlarged.$T_{A,req}$can be determined using the MMG model, turning tests, stopping tests, low-speed transverse-movement capability or numerical manoeuvring simulations [11]. The corrected boundary is

$$R_A^M(\theta,\sigma) = R_S(\theta) * \varGamma_M(\theta,\sigma) \tag{6}$$

The forward constraint reflects braking, advance and turning response. Lateral constraints reflect beam, cross-current drift, side openings and net-panel damping. The aft constraint reflects overtaking, low-speed following and restricted manoeuvrability.

3.4. Operational-state constraints

The aquaculture-vessel domain should vary with operational state. Five states are considered, relocation navigation, entering or leaving a port or aquaculture area, low-speed manoeuvring near aquaculture facilities, station-keeping or dynamic positioning, and emergency sheltering relocation. Their available manoeuvring space, risk tolerance and conflict patterns differ. If M(σ) denotes the operational-state factor, the physically constrained domain is

$$R_A^P(\theta,\sigma) = R_S(\theta) * \varGamma_M(\theta,\sigma) * M(\sigma) \tag{7}$$

M(σ) may be calibrated through onboard operation records, simulations and expert assessment. During relocation, it is governed mainly by speed, traffic density and encounter type. Near aquaculture facilities, it should account for cage boundaries, mooring facilities, auxiliary vessels and lateral drift. During emergency sheltering, available time windows, traffic congestion and wind-wave-current effects should be considered.

3.5. Expert lower-bound safety check

Expert knowledge is not used as the primary fitting method, but as a lower-bound safety check. Opinions from aquaculture-vessel masters, pilots, maritime-administration personnel, ship-manoeuvring experts and aquaculture-equipment designers can define the minimum acceptable boundary for low-sample, high-risk or uncertain scenarios. The final boundary can be written as

$$R_{final}(\theta,\sigma) = max[R_S(\theta) * \varGamma_M(\theta,\sigma) * M(\sigma), R_{exp}(\theta,\sigma)] \tag{8}$$

where $R_{exp}(\theta,\sigma)$is the expert-defined lower safety bound. Expert judgement does not replace data-driven and physical models; it prevents underestimation when samples are insufficient or risks cannot be fully quantified.

3.6. Output form and collision-risk discrimination

After $\mathrm{R}_{\mathrm{final}}(\theta,\sigma)$ is obtained, the final boundary can be re-parameterized into quaternion-domain parameters by directional extraction or curve fitting:

$$\Theta_A(\sigma) = [R_f^{final}, R_a^{final}, R_p^{final}, R_{stb}^{final}, \alpha_f, \alpha_a, \alpha_p, \alpha_{stb}] \tag{9}$$

In an autonomous collision-avoidance system, the boundary can support three levels of discrimination: perception domain, warning domain and danger domain. The perception domain increases target tracking and trajectory-prediction frequency; the warning domain triggers candidate avoidance-plan generation; and the danger domain triggers autonomous avoidance, remote-operator notification or manual takeover [12]. $R_{final}(\theta,\sigma)$ is the danger-domain boundary, while the perception and warning domains can be expanded outward according to relative closing speed and decision lead time.

4. Discussion

Compared with a fully data-driven ship domain, the proposed framework uses similarity screening to reduce ship-type transfer bias and uses manoeuvring-response and expert-knowledge constraints to reduce the risk of underestimating safety boundaries under low-sample conditions. Compared with models relying only on expert experience, it retains information on real traffic behaviour in the target waters. Compared with purely physical models, it preserves empirical safety preferences observed in actual encounters.

The key issues are the calibration of similarity indicators and manoeuvrability correction factors. If similar-vessel selection is too broad, the reference domain may degenerate into an average empirical domain for ordinary ships. If it is too narrow, the sample size may be insufficient and the boundary may become unstable. Empirical studies should therefore use sensitivity analysis to determine the similarity threshold delta and compare the stability of $R_S(\theta)$ under different reference-sample sets.

The framework still has limitations. AIS static dimensions and ship-type information may contain errors, and AIS does not directly provide rudder angle, propeller state or actual manoeuvring intention. Motion behaviour must therefore be inferred from proxy variables such as trajectory curvature, speed variation and rate of turn. Publicly available manoeuvrability parameters for aquaculture vessels are also lacking, so required avoidance time must be determined using model tests, numerical simulations or onboard records. Expert lower-bound constraints involve subjectivity and should be constrained using consistency tests, simulator experiments or operational data. Thus, this paper should be understood as an initial methodological framework; subsequent studies must conduct parameter calibration and validation using AIS data from target waters, manoeuvring simulations and navigator-in-the-loop simulator experiments.

5. Conclusion and Outlook

Autonomous collision avoidance for self-propelled aquaculture vessels requires a dynamic ship domain adapted to their low-speed, wide-beam, structurally distinctive and operationally complex characteristics. Because AIS encounter samples for such vessels are limited, direct construction of a purely data-driven domain is not yet feasible. Conversely, direct transfer of merchant-ship domains may underestimate lateral safety margins and avoidance lead time.

This study proposes a methodological framework for a similar-vessel-transfer-based dynamic hybrid ship domain. It confines the AIS-driven component to empirical-boundary extraction from similar reference vessels and introduces aquaculture-vessel manoeuvrability constraints, operational-state correction and expert-defined safety lower bounds. Compared with generic ship-domain models, the framework is more targeted and interpretable for aquaculture-vessel applications. Future work should build similar-vessel sample libraries, calibrate manoeuvrability parameters, quantify the influence of open structures on low-speed manoeuvring, examine the consistency of expert lower bounds, and validate the framework using onboard data or simulator experiments. The framework provides methodological guidance for safety-boundary modelling in collision-risk identification, early warning and intelligent collision-avoidance decision-making for unmanned aquaculture vessels.

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