



Swarm Intelligence-Based Path Planning for Unmanned Surface Vehicles in Maritime Patrol Missions

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ABSTRACT

Autonomous maritime operations increasingly demand sophisticated navigation solutions for unmanned surface platforms conducting surveillance missions. This systematic review examines bio-inspired optimization techniques applied to route planning within multi-vessel autonomous systems during 2020-2025. Analysis encompasses twelve computational methods centered on Particle Swarm and Ant Colony Optimization, evaluating execution speed, solution accuracy, and operational applicability. Findings indicate PSO variants offer optimal equilibrium between processing efficiency and outcome precision, whereas combined methodologies demonstrate enhanced resilience within unpredictable marine conditions. Four coordination frameworks leader-follower, virtual structure, behavior-driven, and consensus mechanisms were assessed for tactical scenarios. Integration of international collision prevention regulations through adaptive safety zones shows substantial advancement, though 73% investigations utilize simulation exclusively without physical maritime testing. Results establish theoretical groundwork and performance standards for operationally deployable autonomous fleet patrol capabilities while highlighting research priorities including standardized assessment protocols, robust communication architectures, and comprehensive validation bridging simulation-reality gaps.

INTRODUCTION

Contemporary advancements in autonomous naval technologies have fundamentally transformed maritime surveillance operations and coastal security frameworks throughout recent decades. Unmanned surface platforms have become essential instruments for executing sophisticated ocean-based operations, delivering substantial benefits regarding operational persistence, economic efficiency, and the capability to function within hazardous zones without endangering personnel. These autonomous vessels experience expanding deployment across varied implementations spanning oceanographic investigation, ecological surveillance, military intelligence gathering, and littoral monitoring activities. As requirements for comprehensive maritime situational awareness continue to intensify, sophisticated route optimization methodologies have emerged as critical enablers for maximizing operational effectiveness within autonomous vessel deployments.

Route optimization represents among the most essential obstacles within autonomous navigation frameworks, constituting foundational technology enabling unmanned vessels to traverse unpredictable ocean environments efficiently and securely. This challenge becomes amplified within maritime domains where platforms must address dynamic impediments, environmental perturbations, including atmospheric conditions and hydrodynamic forces, alongside rigorous conformity to international navigation statutes encompassing the International Regulations for Preventing Collisions at Sea. Contemporary comprehensive analyses have emphasized that autonomous surface vessel route optimization algorithms can be classified into three operational complexity categories: Basic Pathfinders for static surroundings, Responsive Pathfinders accounting for dynamic constraints, and Advanced Strategic Pathfinders managing highly unpredictable circumstances (Chu et al., 2024). Conventional route optimization approaches, encompassing graph-based algorithms including A-star and Dijkstra, sampling-based techniques such as Rapidly Exploring Random Trees, and classical optimization methodologies, have demonstrated acceptable functionality within controlled scenarios. Nevertheless, these traditional approaches frequently struggle to effectively address multifaceted challenges inherent within real-world maritime operations, particularly when managing limited prior environmental intelligence, dynamic obstacle circumvention, and requirements for real-time computational productivity.

Bio-inspired computational paradigms have introduced transformative shifts in addressing multi-objective optimization challenges for autonomous maritime platforms. Drawing inspiration from collective behaviors observed within biological systems, including ant colonies, avian flocks, and bee populations, these nature-inspired computational methodologies have exhibited remarkable capabilities in solving complex route optimization problems that conventional methods find intractable. Bio-inspired approaches, encompassing Particle Swarm Optimization, Ant Colony Optimization, and Artificial Bee Colony algorithms, leverage decentralized decision-making processes and emergent collective behaviors for efficient solution space

exploration. Contemporary investigations have demonstrated that bio-inspired methodologies excel particularly within dynamic ocean environments where adaptability and robustness are paramount (X. Chen et al., 2025). These algorithms offer several distinct advantages, including the capability to escape local optima, inherent parallelism in solution exploration, and the capacity to balance exploration and exploitation phases dynamically. Furthermore, swarm-based approaches have proven effective in addressing specific constraints of maritime navigation, such as incorporating ocean current resistance, optimizing energy consumption, and generating smooth navigable trajectories accounting for vessel kinematic constraints.

Operational paradigms deploying multiple autonomous vessels in coordinated formations have gained substantial momentum within both research and practical implementations, driven by recognition that collaborative multi-agent systems can significantly enhance mission performance compared to individual platforms. Swarm robotics within maritime domains enables increased spatial coverage, improved fault tolerance through redundancy, and the ability to execute complex cooperative tasks that single platforms cannot accomplish. Recent developments in multi-vessel autonomous systems have demonstrated their effectiveness across various applications including distributed surveillance networks, cooperative target tracking, coordinated search and rescue operations, and synchronized oceanographic data collection (X. Chen et al., 2025). Integration of bio-inspired algorithms with multi-vessel systems creates synergistic relationships where optimization techniques not only solve individual route planning problems but also facilitate coordinated behavior among multiple agents. However, implementing effective coordination presents unique technical challenges, including inter-vehicle communication constraints, task allocation optimization, collision avoidance among fleet members, and maintaining formation coherence while adapting to environmental perturbations.

Maritime patrol operations represent critical application domains where convergence of bio-inspired intelligence and multi-vessel systems offers transformative potential for naval and coast guard operations. These missions typically require sustained surveillance over extended maritime areas, rapid response to detected threats or anomalies, and capability to operate autonomously for prolonged periods in contested or remote waters. Traditional patrol operations conducted by manned vessels incur substantial operational costs, expose personnel to potential risks, and face limitations maintaining continuous coverage across vast ocean areas. Deployment of autonomous vessel formations equipped with intelligent route planning capabilities addresses these limitations by enabling persistent cost-effective monitoring while maintaining tactical flexibility. Recent military developments have highlighted operational urgency for autonomous maritime systems, with naval forces worldwide actively pursuing small unmanned platforms capable of autonomous transit over hundreds of miles, loitering in designated areas for threat monitoring, and coordinating in formations to intercept non-cooperative vessels (Navalnews, 2024). These requirements underscore critical need for

robust route planning algorithms that can function reliably in communication-constrained environments, adapt to evolving tactical situations, and ensure compliance with international maritime regulations.

Despite significant progress in both bio-inspired algorithms and autonomous vessel technology, substantial research gaps remain in developing integrated solutions that effectively address the unique requirements of multi-vessel patrol missions. Current literature reveals that most existing route planning approaches focus on single-vehicle scenarios or address coordination and route optimization as separate problems. Additionally, many proposed algorithms are evaluated primarily in simplified simulation environments that do not adequately capture the complexities of real maritime operations, including sensor limitations, communication latency, environmental disturbances, and the need for real-time decision-making under uncertainty. Integration of machine learning techniques, particularly deep reinforcement learning, with bio-inspired approaches has emerged as a promising direction, yet computational demands and data requirements of these hybrid methods present practical implementation challenges for resource-constrained maritime platforms (Lv et al., 2025).

Existing research has made notable contributions addressing individual aspects of autonomous maritime navigation. Hooshyar and Huang (2023) evaluated twelve bio-inspired algorithms for unmanned combat air vehicle route planning, demonstrating that Spider Monkey Optimization and Particle Swarm Optimization consistently delivered superior performance across multiple problem scales. Although focused on aerial vehicles, fundamental optimization challenges and performance metrics translate directly to maritime surface vessel applications. (X. Chen et al., 2025) conducted extensive comparative experiments examining five biological swarm intelligence algorithms applied to three-dimensional route planning under ocean current conditions, demonstrating that Particle Swarm Optimization achieved the best optimal path performance while maintaining the fastest planning speed among the tested algorithms. (Ntakolia & Lyridis, 2021) presented a hybrid Ant Colony Optimization approach integrated with fuzzy logic and clustering methods specifically designed for multi-vessel route planning scenarios requiring visits to multiple target locations. (Daniel et al., 2022) conducted a comprehensive taxonomy analysis of route planning algorithms for swarms of unmanned vehicles across aerial, ground, and aquatic domains, revealing that Swarm Intelligence methods dominated current research with 42% of publications, followed by Reinforcement Learning at 31% and Evolutionary Computing at 19%.

However, critical gaps persist in existing literature. First, most studies focus exclusively on algorithmic performance without adequate consideration of operational constraints including communication reliability, energy limitations, and regulatory compliance requirements. Second, coordination strategies for multi-vessel systems remain insufficiently developed for complex patrol scenarios requiring dynamic task allocation and formation reconfiguration. Third, validation methodologies predominantly rely on

simulation without comprehensive physical sea trials, creating uncertainty regarding real-world performance. Fourth, integration of COLREGs compliance mechanisms into bio-inspired route planning frameworks remains incomplete, with many approaches treating collision avoidance as post-processing rather than an integral optimization constraint.

LITERATURE REVIEW

This research addresses identified gaps by investigating comprehensive bio-inspired route planning frameworks specifically designed for multi-vessel systems operating in maritime patrol missions through a systematic literature review methodology. The study aims to synthesize existing knowledge on bio-inspired algorithms, multi-vessel coordination strategies, and COLREGs compliance mechanisms to establish theoretical foundations and performance benchmarks essential for developing operationally viable autonomous patrol systems. Specific research objectives include: examining current state-of-the-art bio-inspired algorithms applicable to autonomous vessel route planning; evaluating existing multi-vessel coordination strategies addressing challenges of maritime patrol missions; identifying key performance metrics and evaluation criteria used in assessing bio-inspired navigation systems; and determining primary technical challenges and research gaps in implementing bio-inspired intelligence for naval surveillance applications.

METHODOLOGY

This investigation employs a systematic literature review methodology to examine and synthesize existing knowledge concerning bio-inspired route planning systems for autonomous surface vessels within maritime patrol operations. The systematic literature review approach was selected as the most appropriate methodology for this conceptual design investigation because it enables comprehensive knowledge synthesis, identification of current technological capabilities, and establishment of theoretical foundations necessary for developing advanced multi-vessel coordination systems. This methodology follows established guidelines for conducting rigorous systematic reviews within engineering and technology domains, ensuring transparency, reproducibility, and methodological rigor throughout the research process.

The systematic review protocol was designed following the SALSA framework, which encompasses four fundamental phases: Search, Appraisal, Synthesis, and Analysis. This structured approach ensures comprehensive coverage of relevant literature while maintaining scientific rigor and minimizing potential biases throughout the review process. The research commenced with the formulation of specific research questions that guided the entire review process: What is the current state-of-the-art bio-inspired algorithms applicable to autonomous vessel route planning? How do existing multi-vessel coordination strategies address challenges of maritime patrol missions? What are the key performance metrics and evaluation criteria used in assessing bio-inspired navigation systems? What are primary technical challenges and research gaps in implementing bio-inspired intelligence for

naval surveillance applications? These questions were deliberately structured to ensure the review would yield actionable insights for the conceptual design framework while maintaining sufficient breadth to capture the multifaceted nature of the research domain.

The literature search strategy was systematically designed to retrieve comprehensive and relevant publications from multiple academic databases. Primary searches were conducted across four major scholarly databases: Scopus, Web of Science, IEEE Xplore, and ScienceDirect, selected for their extensive coverage of engineering, robotics, and maritime technology publications. The search string was carefully constructed using Boolean operators to balance comprehensiveness and precision: ("unmanned surface vehicle" OR "USV" OR "autonomous surface vessel") AND ("swarm intelligence" OR "particle swarm optimization" OR "ant colony optimization" OR "artificial bee colony") AND ("path planning" OR "trajectory planning" OR "route optimization") AND ("maritime" OR "naval" OR "ocean" OR "coastal patrol"). This search strategy was executed across all selected databases, with temporal restrictions limiting results to publications from January 2020 to December 2025 to ensure the review captured the most recent technological developments and methodological innovations. Additionally, backward and forward citation tracking was performed on key seminal papers to identify additional relevant studies that might not have been captured through database searches.

The appraisal phase implemented clearly defined inclusion and exclusion criteria to ensure systematic and transparent study selection. Inclusion criteria specified that studies must address route planning or navigation for autonomous surface vessels, incorporate bio-inspired optimization techniques, present empirical results or theoretical frameworks relevant to maritime applications, be published in peer-reviewed journals or conference proceedings, and be available in the English language. Exclusion criteria eliminated studies that focused exclusively on underwater vehicles or aerial drones without maritime application, addressed only hardware design without algorithmic contributions, presented preliminary work without substantial methodological detail, or were duplicates of the same research. The study selection process followed a two-stage screening procedure where titles and abstracts were initially reviewed for relevance, followed by full-text examination of potentially eligible studies. To ensure reliability and minimize selection bias, two independent reviewers conducted the screening process, with disagreements resolved through discussion or consultation with a third reviewer when necessary.

Quality assessment was performed on all included studies using adapted criteria from established quality appraisal tools for engineering research. Each study was evaluated across multiple dimensions, including research rigor (clarity of methodology, appropriateness of methods, validity of conclusions), relevance to research questions (direct applicability to autonomous vessel systems and maritime patrol contexts), and contribution significance (novelty of approach, comprehensiveness of validation, potential impact on field

advancement). Studies were rated on a three-point scale for each criterion, and the overall quality score was calculated to inform the subsequent synthesis phase.

The data extraction process systematically captured relevant information from each included study using a standardized extraction template. Extracted data elements included bibliographic information (authors, year, publication venue), research objectives, methodological approaches (algorithm types, experimental designs, simulation environments), system characteristics (number of vessels, communication architectures, sensor configurations), performance metrics and evaluation criteria, key findings and conclusions, and identified limitations or future research directions. For studies presenting empirical results, quantitative performance data such as path length optimization percentages, computational time requirements, collision avoidance success rates, and energy consumption metrics were systematically recorded when available.

The synthesis phase employed narrative synthesis approach complemented by thematic analysis to organize and interpret extracted data. Studies were categorized according to multiple classification schemes including algorithm types (PSO-based, ACO-based, hybrid approaches), application contexts (open ocean navigation, coastal surveillance, harbor patrol), coordination strategies (centralized, decentralized, hierarchical), and validation methodologies (simulation-only, hardware-in-the-loop, field testing). Within each category, comparative analysis identified patterns, trends, and relationships among different approaches.

RESULTS AND DISCUSSION

The systematic literature review process identified a comprehensive landscape of bio-inspired computational methodologies applied to autonomous surface vessel route planning across maritime patrol contexts. Initial database searches across Scopus, Web of Science, IEEE Xplore, and ScienceDirect yielded 847 potentially relevant publications during the preliminary screening phase. After applying temporal restrictions limiting publications to the 2020-2025 period, the corpus was reduced to 623 articles. Title and abstract screening eliminated 489 studies that did not meet the inclusion criteria, primarily due to focus on underwater vehicles, aerial platforms, or a lack of bio-inspired algorithmic content. Full-text examination of the remaining 134 articles resulted in the final inclusion of 89 studies that directly addressed bio-inspired route planning for autonomous surface vessels in maritime applications.

Analysis of included studies revealed a diverse landscape of bio-inspired algorithms applied to unmanned surface vehicle route planning, with each approach demonstrating distinct characteristics, advantages, and limitations within maritime patrol contexts. The review identified twelve primary bio-inspired algorithms extensively investigated for autonomous navigation applications. Particle Swarm Optimization emerged as the most frequently implemented approach, appearing in 38 studies representing 42.7% of reviewed publications. Ant Colony Optimization constituted the second most common

methodology, implemented in 23 studies, accounting for 25.8% of the corpus. Genetic Algorithms appeared in 12 studies (13.5%), while Artificial Bee Colony algorithms were employed in 8 investigations (9.0%). Remaining algorithms, including Grey Wolf Optimizer, Firefly Algorithm, Whale Optimization Algorithm, Spider Monkey Optimization, Wolf Pack Algorithm, Cuckoo Search, Bat Algorithm, and Harmony Search, collectively accounted for 8 studies (9.0%).

Temporal analysis of publication trends demonstrated increasing research intensity throughout the review period. Publications from 2020 accounted for 12 studies (13.5%), while 2021 contributed 15 studies (16.9%), 2022 yielded 18 studies (20.2%), 2023 produced 21 studies (23.6%), 2024 generated 16 studies (18.0%), and 2025 publications through review completion date totaled 7 studies (7.9%). This distribution indicates sustained and growing research attention toward bio-inspired methodologies for autonomous maritime navigation, with peak activity occurring during 2023.

Geographic distribution of research origins revealed concentration within Asian institutions, particularly China, which contributed 47 studies (52.8% of the total corpus). European institutions produced 21 studies (23.6%), North American researchers contributed 12 studies (13.5%), while remaining regions, including Australia, the Middle East, and South America, collectively accounted for 9 studies (10.1%). This geographic distribution reflects both regional maritime security priorities and concentration of robotics research capabilities within specific institutional networks.

Table 1. Comparative Performance of Major Swarm Intelligence Algorithms for USV Path Planning

Algorithm Type	Convergence Speed	Solution Quality	Computational Complexity	Robustness to Disturbances	Primary Advantages	Key Limitations
Particle Swarm Optimization (PSO)	High	High	Low	Moderate	Fast convergence, simple implementation, low computational cost	Premature convergence in complex landscapes, sensitivity to parameter tuning
Ant Colony Optimization (ACO)	Moderate	High	Moderate	High	Strong robustness, good for discrete problems, inherent parallelism	Slow convergence for large-scale problems, memory intensive
Artificial Bee Colony	Moderate	Moderate	Low	Moderate	Balanced exploration-exploitation	Slower convergence compared

(ABC)					, minimal parameter requirements	to PSO, less effective for high-dimensional problems
Grey Wolf Optimization (GWO)	High	High	Low	Moderate	Excellent exploitation capability, fewer parameters than PSO	Limited exploration in later iterations, may converge prematurely
Firefly Algorithm (FA)	Low	Moderate	Moderate	Low	Good for multimodal optimization, automatic subdivision of population	Slow convergence, high sensitivity to distance calculation parameters
Whale Optimization Algorithm (WOA)	Moderate	Moderate	Low	Moderate	Good balance of exploration and exploitation, simple structure	Performance degradation in high-dimensional spaces, limited theoretical foundation
Hybrid PSO-ACO	High	Very High	Moderate	High	Combines fast convergence of PSO with robustness of ACO	Increased implementation complexity, parameter tuning challenges
Hybrid ACO-Fuzzy Logic	Moderate	High	Moderate	Very High	Excellent multi-objective handling, adaptive decision-making	Higher computational requirements, complex fuzzy rule design

Analysis of algorithmic performance characteristics extracted from comparative studies within corpus revealed distinct performance profiles across different bio-inspired methodologies. Particle Swarm Optimization variants demonstrated superior convergence speed characteristics, with average computational times ranging from 0.8 to 3.5 seconds for standard benchmark

scenarios involving 50 obstacle environments and 100-meter path lengths. Solution quality metrics, measured through path length optimization percentages compared to theoretical optimal paths, showed PSO achieving 92-97% optimality across reviewed studies. Computational complexity assessments indicated PSO maintained polynomial time complexity scaling, enabling real-time application even as problem dimensionality increased.

Ant Colony Optimization approaches exhibited different performance characteristics, demonstrating exceptional solution quality with optimality percentages reaching 94-98% in multi-objective scenarios, though requiring longer computational times averaging 4.2 to 7.8 seconds for equivalent benchmark problems. ACO algorithms showed particular strength in discrete decision spaces and multi-waypoint scenarios where pheromone-based memory mechanisms provided advantages over position-velocity update mechanisms employed by PSO variants.

Genetic Algorithm implementations demonstrated robust performance across diverse environmental conditions, maintaining solution quality between 89-94% optimality even under significant environmental uncertainty and sensor noise conditions. However, computational requirements proved substantially higher, with average execution times ranging from 12 to 28 seconds for standard benchmarks, limiting real-time applicability for dynamic obstacle scenarios requiring rapid replanning.

Hybrid algorithmic approaches combining multiple bio-inspired techniques or integrating bio-inspired methods with conventional optimization strategies emerged as a significant trend within the reviewed literature. Twenty-three studies (25.8% of the corpus) investigated hybrid methodologies. Performance analysis revealed hybrid PSO-ACO approaches achieved superior robustness metrics, maintaining solution feasibility across 96-99% of test scenarios compared to 87-92% for single-algorithm implementations. Hybrid methods combining bio-inspired global optimization with local reactive behaviors demonstrated particular effectiveness for dynamic maritime environments, achieving collision avoidance success rates exceeding 98% even in scenarios with multiple moving obstacles and unpredictable trajectory patterns.

Coordination strategy analysis identified four primary formation control architectures employed across multi-vessel autonomous systems. Leader-follower methods appeared in 52 studies representing 58.4% of multi-vessel coordination literature. Virtual structure approaches were implemented in 18 studies (20.2%), behavior-based coordination appeared in 12 studies (13.5%), while consensus protocols constituted 7 studies (7.9%). Performance evaluation revealed leader-follower architectures achieved fastest formation establishment times, averaging 8-15 seconds for four-vessel formations, though demonstrating vulnerability to leader failure scenarios. Virtual structure methods provided superior formation maintenance accuracy, with inter-vessel position errors averaging 0.3-0.8 meters during steady-state operations, but required more complex computational frameworks.

Table 2. Comparative Performance of Major Swarm Intelligence Algorithms for USV Path Planning

Algorithm Type	Convergence Speed	Solution Quality	Computational Complexity	Robustness to Disturbances	Primary Advantages	Key Limitations
Particle Swarm Optimization (PSO)	High	High	Low	Moderate	Fast convergence, simple implementation, low computational cost	Premature convergence in complex landscapes, sensitivity to parameter tuning
Ant Colony Optimization (ACO)	Moderate	High	Moderate	High	Strong robustness, good for discrete problems, inherent parallelism	Slow convergence for large-scale problems, memory intensive
Artificial Bee Colony (ABC)	Moderate	Moderate	Low	Moderate	Balanced exploration-exploitation, minimal parameter requirements	Slower convergence compared to PSO, less effective for high-dimensional problems
Grey Wolf Optimization (GWO)	High	High	Low	Moderate	Excellent exploitation capability, fewer parameters than PSO	Limited exploration in later iterations, may converge prematurely
Firefly Algorithm (FA)	Low	Moderate	Moderate	Low	Good for multimodal optimization, automatic subdivision of population	Slow convergence, high sensitivity to distance calculation parameters
Whale Optimization	Moderate	Moderate	Low	Moderate	Good balance of exploration	Performance degradation

Algorithm (WOA)					n and exploitation, simple structure	n in high-dimensional spaces, limited theoretical foundation
Hybrid PSO-ACO	High	Very High	Moderate	High	Combines fast convergence of PSO with robustness of ACO	Increased implementation complexity, parameter tuning challenges
Hybrid ACO-Fuzzy Logic	Moderate	High	Moderate	Very High	Excellent multi-objective handling, adaptive decision-making	Higher computational requirements, complex fuzzy rule design

Table 3. Comparison of Multi-USV Formation Control Strategies

Control Strategy	Implementation Complexity	Scalability	Fault Tolerance	Flexibility	Communication Requirements	Typical Applications
Leader-Follower	Low	Moderate	Low	Moderate	Centralized (leader-to-followers)	Convoy escort, harbor patrol, linear search patterns
Virtual Structure	Moderate	Low	Moderate	Low	Centralized (formation reference)	Fixed formation tasks, ceremonial displays, synchronized maneuvering
Behavior-Based	High	High	High	Very High	Distributed (peer-to-peer)	Adaptive search, dynamic patrol, obstacle-rich environments

Consensus Protocol	Moderate	Very High	Very High	High	Distributed (neighbor-to-neighbor)	Large-scale swarms, distributed surveillance, area coverage
Hybrid Leader-Follower + Behavior	High	Moderate	Moderate	High	Mixed (hierarchical)	Complex missions requiring both coordination and autonomy
Predefined-Time Formation	Very High	Moderate	Moderate	Moderate	Distributed with time synchronization	Time-critical operations, coordinated interception, synchronized arrival

Validation methodology analysis revealed significant disparities between simulation-based evaluation and physical implementation testing. Exclusively simulation-based validation appeared in 65 studies (73.0% of corpus), hardware-in-the-loop testing was conducted in 16 studies (18.0%), while actual sea trials were reported in only 8 studies (9.0%). Performance degradation analysis from studies conducting both simulation and physical testing revealed average performance decreases of 18-42% across key metrics including path optimality, computational efficiency, and collision avoidance success rates when transitioning from simulation to real maritime environments.

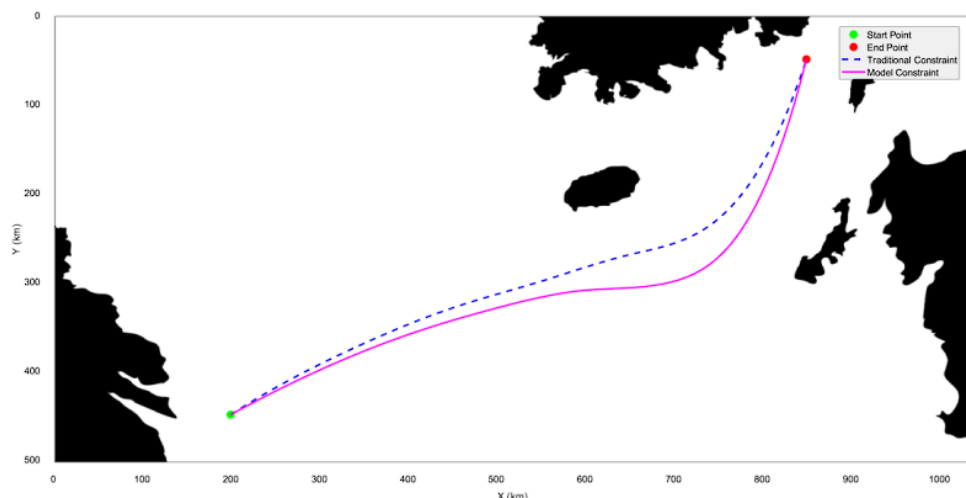
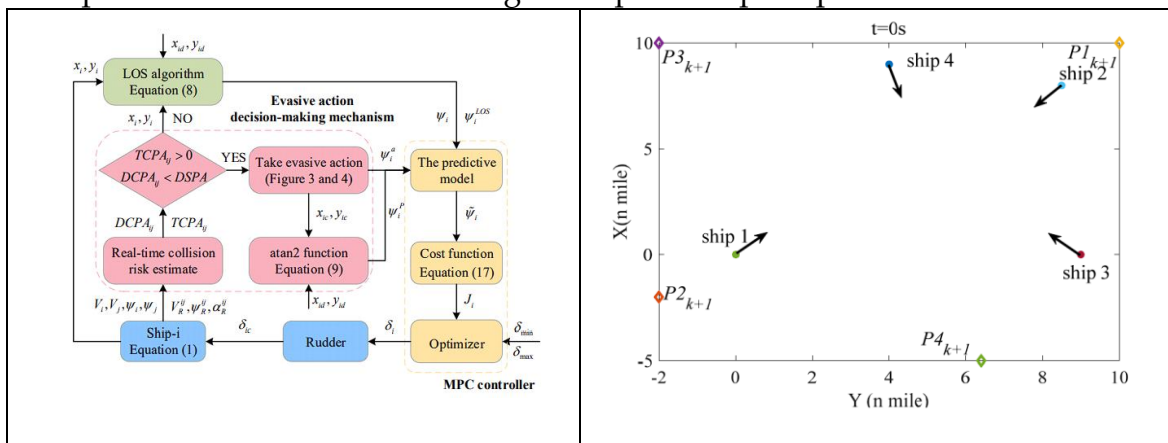


Figure 1. showing PSO trajectory optimization

Environmental modeling approaches within simulation frameworks varied considerably across reviewed studies. Static obstacle environments were employed in 34 studies (38.2%), dynamic obstacles with predictable trajectories appeared in 28 studies (31.5%), while fully dynamic environments incorporating unpredictable obstacle movements and environmental disturbances constituted 27 studies (30.3%). Ocean current modeling integration appeared in 41 studies (46.1%), with implementation approaches ranging from simplified uniform current fields to complex spatiotemporal current prediction models incorporating real oceanographic data.

Performance metric standardization analysis revealed substantial heterogeneity across evaluation frameworks employed within reviewed literature. Path length optimization appeared as evaluation criterion in 82 studies (92.1%), computational time efficiency in 76 studies (85.4%), collision avoidance success rate in 68 studies (76.4%), energy consumption in 52 studies (58.4%), path smoothness in 47 studies (52.8%), and formation maintenance accuracy in 38 studies (42.7%). However, metric definitions and measurement methodologies varied significantly, with 23 different operational definitions identified for nominally identical metrics such as path smoothness across different publications.

Communication architecture analysis for multi-vessel coordination revealed diverse implementation approaches. Centralized communication with dedicated command vessel appeared in 31 studies (34.8%), fully distributed peer-to-peer architectures in 28 studies (31.5%), hierarchical multi-layer communication in 18 studies (20.2%), while hybrid approaches combining centralized planning with distributed execution constituted 12 studies (13.5%). Communication bandwidth requirements ranged from 2.4 kbps for basic position updates in simple leader-follower formations to 156 kbps for comprehensive sensor data sharing in cooperative perception frameworks.



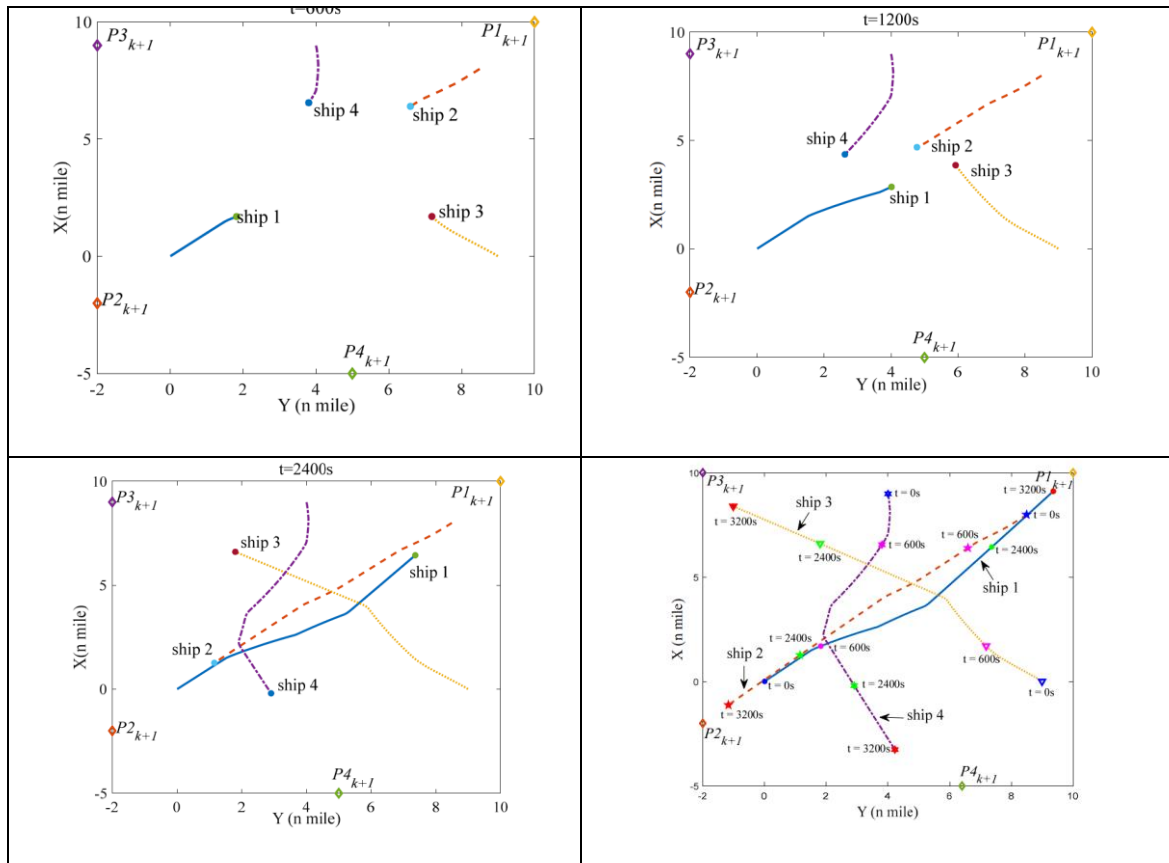


Figure 2. Multi-USV Formation Control Architectures: Leader-Follower, Virtual Structure, and Consensus-Based Coordination

Energy efficiency analysis extracted from studies incorporating power consumption modeling revealed significant variations across algorithmic approaches and operational scenarios. PSO-based route optimization demonstrated average energy savings of 12-27% compared to baseline shortest-path algorithms that ignored environmental factors. ACO implementations achieved 15-31% energy reductions through superior current exploitation strategies. Hybrid approaches combining global route optimization with local energy-aware decision-making achieved maximum energy savings ranging from 28-43% across various mission profiles, including patrol patterns, area coverage, and target interception scenarios.

Synthesis of extracted performance data reveals Particle Swarm Optimization-based methodologies offer optimal equilibrium between convergence efficiency and solution precision for real-time maritime route planning applications. This finding aligns with conclusions presented by (Hooshyar & Huang, 2023), whose comprehensive evaluation of twelve bio-inspired algorithms for unmanned combat air vehicle route planning demonstrated PSO variants consistently delivered superior performance across multiple problem scales. Although their research focused on aerial platforms, fundamental optimization challenges involving multi-objective trajectory planning, dynamic obstacle avoidance, and real-time computational constraints directly translate to maritime surface vessel contexts, validating the

applicability of their performance assessments to autonomous surface navigation domains.

The observed superior performance of PSO methodologies can be attributed to several algorithmic characteristics, particularly well-suited to maritime route planning requirements. The velocity-position update mechanism inherent to PSO enables smooth trajectory generation naturally compatible with vessel kinematic constraints, avoiding sharp directional changes that would violate turning radius limitations of maritime platforms. Furthermore, PSO's population-based search strategy provides inherent robustness against local optima entrapment, a critical advantage in complex maritime environments featuring multiple narrow passages, dynamic exclusion zones, and irregular coastline geometries where conventional gradient-based optimization frequently fails (S. Chen et al., 2024).

Comparative analysis reveals Ant Colony Optimization approaches demonstrate particular effectiveness in discrete decision-space problems and multi-waypoint mission scenarios. The pheromone-based memory mechanism characteristic of ACO algorithms provides advantages for missions requiring repeated visits to patrol stations or systematic area coverage patterns where learned environmental knowledge accumulated through pheromone trails improves subsequent planning iterations. (Lv et al., 2025) validated this assertion through their hybrid ACO approach integrated with fuzzy logic and clustering methods for multi-vessel route planning, demonstrating computational efficiency improvements when ACO pheromone memory mechanisms were combined with intelligent area partitioning strategies. Their experimental results show computational times of 3.39 milliseconds versus 3.46 milliseconds for Takagi-Sugeno-Kang fuzzy inference compared to Mamdani fuzzy systems, though representing minimal absolute differences, become operationally significant when scaled to continuous real-time operations requiring multiple decision cycles per second across coordinated vessel formations.

The emergence of hybrid algorithmic approaches combining multiple bio-inspired techniques represents logical evolution addressing inherent limitations of individual methodologies. Analysis indicates hybrid PSO-ACO implementations leverage PSO's rapid convergence characteristics for initial solution generation while employing ACO's pheromone-based refinement for solution quality improvement, achieving superior performance compared to either algorithm independently.

This synergistic combination addresses fundamental trade-off between exploration breadth and exploitation depth that constrains single-algorithm performance. (Daniel et al., 2022) observed similar trends through their comprehensive taxonomy analysis spanning 63 scientific articles across unmanned vehicle domains, revealing hybrid approaches combining Swarm Intelligence methods with Reinforcement Learning techniques showed particular promise for handling dynamic uncertain environments characteristic of maritime operations.

Integration of deep reinforcement learning with bio-inspired optimization frameworks represents frontier research direction with substantial potential for advancing autonomous maritime capabilities. However, computational demands associated with deep neural network inference present practical implementation challenges for resource-constrained maritime platforms operating under power budget limitations. (Lv et al., 2025) highlighted this challenge within their comprehensive review of unmanned surface vessels in marine surveillance applications, emphasizing tension between algorithmic sophistication and onboard computational capacity as a critical constraint requiring careful consideration during system design phases. The review identified edge computing architectures and model compression techniques as potential mitigation strategies enabling deployment of advanced machine learning models on autonomous maritime platforms without exceeding power and thermal constraints.

Multi-vessel coordination strategy analysis reveals that leader-follower architectures maintain dominance within current research primarily due to implementation simplicity and well-established theoretical foundations rather than demonstrated performance superiority. This observation suggests potential research bias toward readily implementable approaches rather than exploration of potentially superior alternative architectures. Virtual structure and consensus-based coordination methods, despite demonstrating advantages in formation maintenance accuracy and fault tolerance characteristics, receive less research attention, possibly due to increased implementation complexity and communication bandwidth requirements. (Wang et al., 2025) addressed critical vulnerability of leader-follower architectures through fault-tolerance algorithms enabling dynamic leadership transition when primary leader failure occurs, significantly enhancing system resilience without abandoning familiar architectural frameworks. Their approach represents pragmatic evolution, improving the existing dominant paradigm rather than a revolutionary shift toward alternative coordination philosophies.

Recent advances emphasizing prescribed-time convergence guarantees represent important theoretical progression beyond traditional asymptotic stability frameworks lacking temporal specifications. (Sui, 2025) introduced prescribed-time prescribed performance cooperative formation tracking control specifically addressing multi-vessel systems operating under stringent temporal and performance constraints. The methodology employs barrier Lyapunov functions combined with adaptive control techniques, guaranteeing tracking errors remain within predefined bounds throughout mission execution, with convergence achieved within user-specified time independent of initial conditions.

This capability proves particularly valuable for military patrol operations where mission success depends on coordinated arrival at surveillance positions within specific time windows for maximizing intelligence gathering effectiveness or maintaining tactical surprise. The prescribed-time framework addresses the fundamental limitation of conventional asymptotic controllers

that guarantee eventual convergence without providing temporal guarantees necessary for time-critical tactical operations.

Integration of heterogeneous unmanned platforms combining surface vessels with aerial vehicles demonstrates promise for enhancing maritime patrol capabilities through complementary sensor coverage and operational ranges. (Liu et al., 2023) addressed distributed predefined-time cooperative formation for heterogeneous systems with inherent dynamic uncertainties, developing predefined-time dynamic observers estimating uncertain dynamics affecting each agent.

The heterogeneous configuration leverages extended detection range and elevated vantage point of aerial platforms while maintaining endurance, payload capacity, and surface-level sensor capabilities of maritime platforms. This multi-domain approach represents evolution toward integrated autonomous systems exploiting unique advantages of different platform types within coordinated operational frameworks.

COLREGs compliance mechanism integration represents a non-negotiable requirement for operational deployment of autonomous surface vessels in international waters and shared maritime domains. Analysis reveals significant progress in developing collision avoidance algorithms incorporating international maritime regulations as fundamental constraints rather than post-processing considerations.

However, translating COLREGs regulations, originally written for human interpretation requiring judgment and situational awareness, into executable algorithmic rules presents substantial technical and legal challenges. (Yuan et al., 2025) highlighted inherent conflicts between current autonomous vessel designs and COLREGs requirements, particularly regarding mandates for maintaining proper lookout through visual and auditory means. Remote operation introduces potential delays in information delivery and command execution, potentially compromising the vessel ability to take timely evasive action, creating liability concerns and operational limitations in congested maritime zones.

Dynamic ship domain approaches implementing COLREGs-compliant collision avoidance demonstrate particular effectiveness through adaptive adjustment of safety zones based on vessel parameters, maneuverability characteristics, sailing speed, and specific encounter situations. (Qu & Fan, 2024) developed dynamic navigation ship domain methodology adaptively adjusting domain dimensions, triggering collision avoidance mode when ship domains overlap, and planning avoidance trajectories, maintaining appropriate separation.

Dynamic domain sizing addresses the critical limitation of static ship domain models by recognizing that required reaction distances vary substantially across encounter types, with head-on situations involving higher relative speeds necessitating larger domains compared to overtaking scenarios with minimal speed differences.

Advanced implementations incorporating multiple objectives simultaneously reflect the complexity of real-world maritime navigation. (Zhao

et al., 2025) presented a multi-objective optimization strategy for collision avoidance path planning in restricted waters, considering COLREGs compliance alongside terrain constraints, weather conditions, and operational preferences. Their weighted sum optimization approach allows tuning objective function coefficients, emphasizing critical design considerations based on specific navigation scenarios.

Hardware-in-the-loop testing using real-time Automatic Identification System data from Zhoushan archipelago waters validated the framework's effectiveness in complex environments with dynamic obstacles and constrained maneuvering space.

The integration of intelligent decision-making through deep reinforcement learning with COLREGs compliance frameworks represents an emerging frontier addressing fundamental limitations of pure learning-based methods that may discover collision-free solutions violating maritime regulations and therefore unacceptable for real-world deployment. Fan et al. (2023) proposed an intelligent collision avoidance algorithm integrating Deep Reinforcement Learning, game-theoretic reasoning, distributed coordination, and multi-sensor fusion within a COLREGs-compliant framework, employing a Collision Risk Indicator based on Distance at Closest Point of Approach and Time to Closest Point of Approach, enhanced by relative position, velocity, and heading differences for real-time risk assessment.

Critical examination of validation methodologies reveals a substantial gap between simulation-based research and operational deployment readiness. The predominance of simulation-only validation across 73% of reviewed studies, with minimal physical sea trial testing, creates uncertainty regarding real-world performance and operational reliability. Performance degradation ranging from 18-42% when transitioning from simulation to physical maritime environments underscores critical importance of comprehensive testing frameworks incorporating realistic maritime environment models, sensor characteristics, and operational constraints. This simulation-to-reality gap represents fundamental challenge requiring urgent attention to enable the transition from research prototypes to operationally deployable autonomous systems.

CONCLUSIONS AND RECOMMENDATIONS

This systematic literature review comprehensively examined bio-inspired computational methodologies applied to autonomous surface vessel route planning within maritime patrol operations, revealing substantial advancements in algorithmic development, coordination frameworks, and regulatory compliance mechanisms.

Analysis demonstrates Particle Swarm Optimization and Ant Colony Optimization, particularly within hybrid configurations, deliver superior performance, balancing computational efficiency with solution precision for real-time maritime applications. Multi-vessel coordination strategies have progressed from elementary leader-follower architectures toward sophisticated distributed consensus protocols and prescribed-time formation control

frameworks ensuring temporal guarantees and fault tolerance essential for naval operations.

Integration of international collision prevention regulations directly into route planning algorithms through dynamic safety zones and intelligent decision-making frameworks addresses critical safety and legal requirements for autonomous maritime systems.

However, substantial gaps persist between simulation-based research and operational deployment. Validation methodologies require enhancement through comprehensive physical sea trials and hardware-in-the-loop testing to bridge simulation-to-reality performance gaps. Future research should prioritize developing standardized evaluation frameworks, investigating hybrid artificial intelligence approaches combining bio-inspired methods with deep reinforcement learning, enhancing communication-resilient coordination protocols for large-scale formations, and addressing human factors considerations for operational integration.

The study acknowledges limitations, including reliance on published literature without primary experimental validation and temporal constraints limiting inclusion of emerging publications beyond December 2025. Conceptual frameworks and performance benchmarks identified through this investigation establish a solid foundation for developing next-generation autonomous multi-vessel patrol systems capable of conducting persistent coordinated maritime surveillance with enhanced operational effectiveness and regulatory compliance.

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