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Review Article

Unmanned surface vessels in hydrographic surveying: Exploring technological progressions and development challenges

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This paper investigates the role of Uncrewed Surface Vessels (USVs) in hydrographic surveying, with a focus on synthesising recent advancements, evaluating operational efficiencies, and addressing challenges in their adoption. A novel aspect of this study is the systematic analysis of specific USVs, providing a comprehensive overview of their deployment in diverse hydrographic applications. By integrating insights from recent developments, the paper explores how USVs leverage technologies such as multibeam sonar, autonomous navigation systems, and artificial intelligence to enhance data accuracy, safety, and accessibility in remote or hazardous marine environments. The paper also highlights challenges, including regulatory gaps, autonomy standardisation, and environmental concerns, and proposes actionable strategies to mitigate these barriers. This review not only provides a detailed synthesis of current capabilities and limitations but also outlines future research directions to advance the integration of USVs into mainstream hydrographic practices. By offering a unique combination of case-specific analysis and broader thematic insights, this paper contributes to the growing body of knowledge on the transformative potential of USVs in maritime surveying.

[**Keywords**: Artificial intelligence, Autonomous navigation, Control system, Hydrographic surveying, Unmanned Surface Vessels (USVs)]

Nomenclature

		Symbols	
x	Position along the x-axis (longitudinal axis)	$X_{\dot{u}}$	Hydrodynamic derivative for surge motion
y	Position along the y-axis (lateral axis)	$Y_{\dot{v}}$	Hydrodynamic derivative for sway motion
z	Vertical position in the global coordinate system	$N_{\dot{r}}$	Hydrodynamic derivative for yaw rotational motion
$\dot{x}$	Rate of change of position along the x-axis (longitudinal axis)	$Y_{\dot{r}}$	Hydrodynamic derivative influencing yaw via sway motion
$\dot{y}$	Rate of change of position along the y-axis (lateral axis)	$N_{\dot{v}}$	Hydrodynamic derivative influencing sway via yaw motion
$\dot{z}$	Rate of change of position along the z-axis (vertical axis)	$Z_{\dot{w}}$	Hydrodynamic derivative for heave motion

u	Longitudinal velocity along the x-axis	X	External force acting in the surge direction
w	Vertical velocity (heave)	Y	External force acting in the sway direction
r	Yaw rate, rate of change of heading angle	N	External moment acting in the yaw direction
$\dot{u}$	Acceleration in the surge direction	Z	External force acting in the heave direction
$\dot{v}$	Acceleration in the sway direction		***Greek Symbols***
$\dot{r}$	Angular velocity or acceleration in the yaw direction	ψ	Heading angle
$\dot{w}$	Acceleration in the heave direction	φ	Roll angle
m	Mass of the USV	θ	Pitch angle
I_z	Moment of inertia about the vertical (yaw) axis		

Introduction

Hydrographic surveying has a long history, evolving from early manual techniques to modern operations driven by advanced technologies. The introduction of sonar systems in the 20th century significantly improved underwater mapping by increasing precision and efficiency, enhancing both data quality and navigational safety. This progression is exemplified by a conventional hydrographic survey operation featuring a side-mounted payload and a topside data acquisition setup (Fig. 1). Over time, the incorporation of GPS technology further refined hydrographic surveys by enabling precise vessel positioning, facilitating creation of detailed nautical charts and contributing to safer maritime operations[1,2].

Scope of the review

While previous studies have provided valuable insights into specific technologies and methodologies, they often focus on isolated aspects of hydrographic surveying. This review adopts a broader approach, synthesising advancements over the past decade and exploring the interplay between various technological components, including guidance systems, control frameworks, and real-world operational challenges, aiming to provide a comprehensive perspective on the evolution of hydrographic surveying technologies.

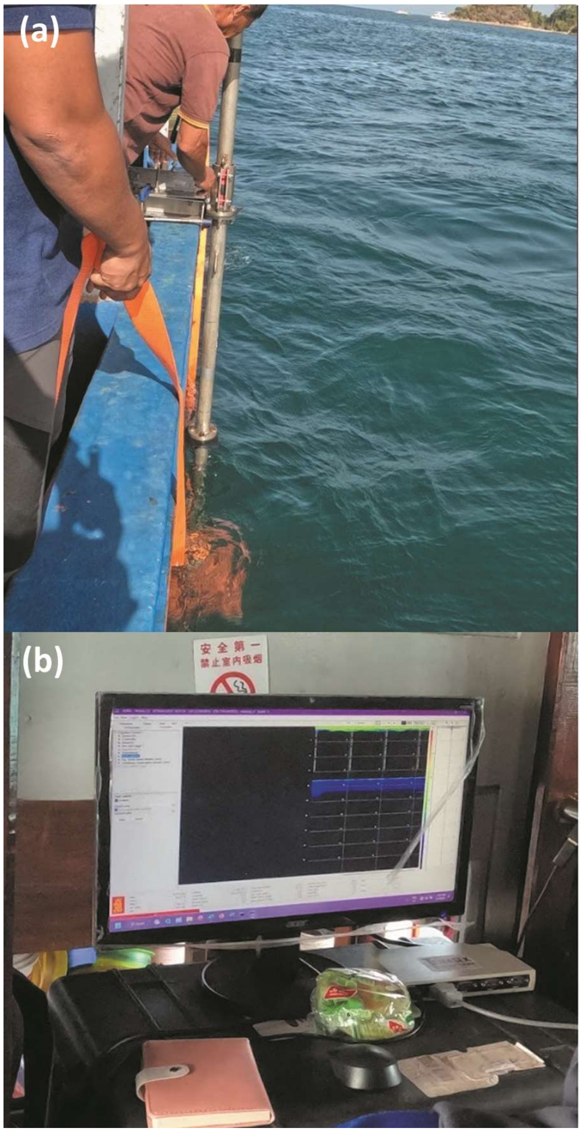

Fig. 1 — Overview of a conventional hydrographic survey operation: (a) Side-mounted payload featuring the Kongsberg Topas PS120 system; and (b) Topside data acquisition setup

The adoption of USVs marks a significant step forward in hydrographic surveying, with ongoing innovations in AI-driven control systems, advanced sensor integration, and multi-platform data fusion driving the field forward. By contextualising these developments, this review aims to highlight the critical trends shaping the future of hydrographic surveying and identify key areas for further research.

Data aggregation and bibliometric analysis

The methodology implemented for this review followed a structured and systematic approach, ensuring comprehensive coverage of relevant literature in the field of Uncrewed/Unmanned Surface Vehicles (USVs) and hydrographic surveying. A thorough search was conducted across major academic databases, including Scopus, IEEE Xplore, PubMed, and Google Scholar, using carefully selected keywords (Fig. 2). This initial search yielded approximately 200 articles, which were subsequently filtered through a two-stage process. Titles and abstracts were screened to assess relevance, reducing the dataset to 140 articles. Full-text reviews and thematic analyses were then conducted, further narrowing the selection to 120 articles. Thematic categorisation identified key topics, including

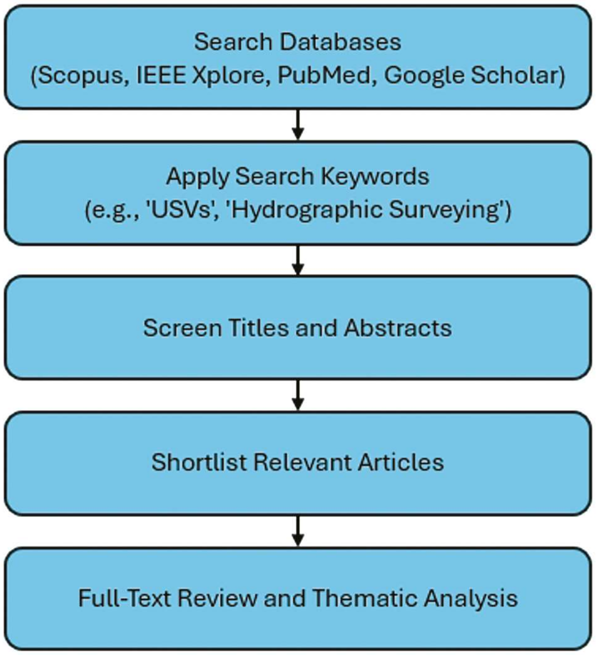

Fig. 2 — Data aggregation process for systematic data collection

guidance and control systems, data collection methods, and emerging research directions[2-4].

Advanced bibliometric tools were employed to gain deeper insights into research trends and thematic developments. VOSviewer was utilised to perform co-citation analysis and keyword mapping, revealing dominant themes such as autonomous navigation, advanced control systems, and environmental monitoring. This analysis helped visualise keyword co-occurrence networks, identifying key research hotspots in Guidance, Navigation, and Control (GNC) systems, as well as the growing role of Artificial Intelligence (AI) in enhancing USV autonomy[5-7]. Additionally, Bibliometrix, an R-based bibliometric analysis tool, was employed to conduct quantitative analyses, including citation trend analysis, which tracked the evolution of research focus over the past two decades[8,9].

Bibliometric analysis revealed a marked increase in research activity from 2003 to 2023, with a notable surge after 2014. This trend reflects a growing global interest in USVs, driven by their expanding applications in fields such as autonomous navigation, environmental monitoring, and marine resource exploration (Fig. 3). The integration of AI and machine learning algorithms for adaptive control systems has been a key driver of this surge[10-12].

Bibliometric mapping revealed valuable insights into country-specific research contributions, highlighting the global effort in advancing hydrographic USV technology. The regional distribution of hydrographic USV development reflects varying levels of investment and technological innovation, with China, USA, and Europe emerging as the leading contributors to research output and technological advancements in the field[13-15] (Fig. 4). Europe and North America have placed significant emphasis on autonomous navigation, energy-efficient systems, and multi-platform integration, fostering advancements in both technology and operational methodologies[2,3,16-18].

The USA, in particular, has focused on innovations in sensor integration, power systems, and AI-driven navigation solutions[19,20], while Europe has taken a leading role in developing sustainable USVs and establishing regulatory frameworks for autonomous maritime operations[20,21]. Although Asia and Australia contribute a smaller share of research, they are rapidly adopting USV technologies, with a strong focus on coastal monitoring, resource exploration, and environmental protection[15]. Meanwhile, China has been at the forefront of developing advanced Guidance, Navigation, and Control (GNC) systems and multi-agent coordination techniques, positioning itself as a key player in large-scale USV operations[22,23].

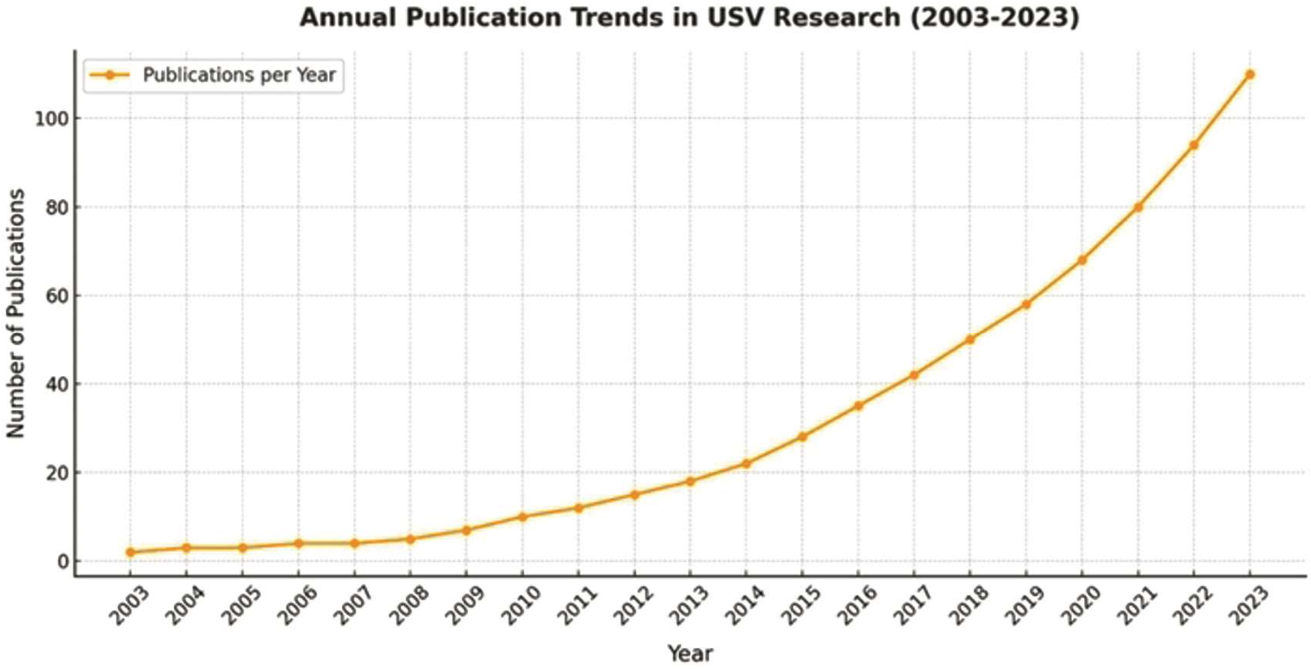

Fig. 3 — Annual publication trends in USV research (2003 – 2023)

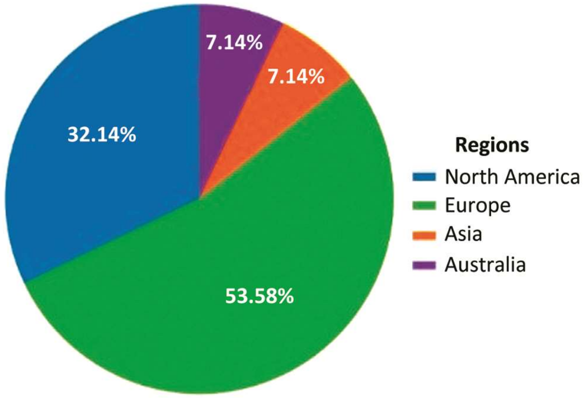

Fig. 4 — Global distribution of hydrographic USV development: Regional breakdown of USV advancements in hydrographic surveying

These regional contributions underscore the global nature of hydrographic USV research, with significant collaborative efforts aimed at addressing shared challenges such as operational range, autonomy, and data accuracy. Thematic evolution analysis further illustrated shifts in research priorities, highlighting emerging areas such as energy autonomy, multi-platform data fusion, and real-time decision-making[24,25]. Identifying these gaps was critical in shaping the proposed future research directions discussed in later sections of this article.

The adoption of USVs in hydrographic surveying is increasingly driven by economic and environmental considerations. Compared to conventional crewed vessels, USVs reduce operational costs by minimising fuel consumption, reducing crew requirements, and simplifying logistics. These benefits are particularly relevant in the offshore energy sector, where frequent surveys are necessary for exploration, maintenance, and environmental monitoring[16,26]. Additionally, USVs contribute to sustainability by employing hybrid power systems, such as solar and fuel cells, reducing carbon emissions[17,18]. Patterson *et al*.[26] noted that cost-effectiveness and sustainability are key drivers of USV adoption, making them a viable solution for industries seeking efficient operations with lower environmental impact. As the offshore energy sector continues to grow, USVs are expected to play a more prominent role in delivering cost-efficient and low-carbon surveying solutions.

Current advancements in hydrographic USVs

The integration of Uncrewed Surface Vehicles (USVs) into hydrographic surveying represents a significant evolution in data collection and analysis methodologies. Modern hydrographic operations increasingly rely on autonomous systems such as USVs, which offer enhanced safety and efficiency by enabling remote control from shore-based stations (Fig. 5). USVs have transitioned from basic remote-controlled platforms to sophisticated autonomous systems equipped with advanced sensors, AI, and energy-efficient propulsion technologies. These developments have enhanced surveying capabilities, improved efficiency, and expanded the operational range of USVs in both coastal and offshore environments (Table 1).

Fig. 5 — Autonomous hydrographic survey operation: (a) USV Suraya 1 (Class USV 1.08 m); and (b) Shore-based ground station for control and data acquisition

A notable enabler of these advancements is the miniaturisation of geophysical instruments, which

Table 1 — Operation of USVs in hydrographic surveying

USV operation	**Autonomous navigation**	**Data collection**	**Safety protocols**	**Operational efficiency**	**Data processing**
Navigation and mapping	✓	✓	✓	✓	
Bathymetric surveys	✓	✓	✓	✓	✓
Environmental monitoring	✓	✓	✓	✓	✓
Geophysical surveys	✓	✓	✓	✓	✓
Path planning and optimisation	✓		✓	✓	✓
Precision steering	✓		✓	✓	
Submerged landscape sensing	✓	✓	✓	✓	✓

allows smaller USVs to navigate shallow depths with greater accuracy. These compact platforms, as discussed by Mattei *et al.*[27], offer enhanced efficiency while reducing operational costs. The combination of USVs with satellite solutions has further enabled precise and cost-effective shallow water bathymetric assessments, particularly in previously inaccessible regions[6]. Additionally, multi-platform approaches utilising Unmanned Autonomous Vehicles (UAVs) and USVs have improved photogrammetric and bathymetric measurements, enhancing spatial resolution and operational flexibility in coastal and shallow water environments[7,11,13].

Modern hydrographic operations increasingly rely on autonomous navigation and control technologies. USVs are now equipped with Multi-Beam Echo Sounders (MBES), LiDAR, and AI-driven guidance systems, enabling high-resolution seafloor mapping with remote human supervision[12,14]. AI and Machine Learning (ML) algorithms have improved real-time data processing, allowing USVs to autonomously adapt to changing environmental conditions and optimise their navigation strategies[21,23]. Light-weight object detection algorithms, introduced by Zhang *et al.*[23], have further bolstered maritime safety by enhancing obstacle detection and collision avoidance capabilities.

Key advancements in navigation and steering systems have improved the reliability of hydrographic surveys. Low-cost Multi-Global Navigation Satellite Systems (GNSS), supported by autopilot technology, have enabled real-time monitoring and precise path planning[20,25]. Advanced geospatial modelling techniques have further enhanced the accuracy of bathymetric measurements, showcasing the ability of USVs to perform detailed data collection in dynamic marine environments[26,27].

The evolution of power systems has significantly extended the operational range of USVs. The introduction of fuel cell technologies, as highlighted by Miao *et al.*[28], has reduced reliance on conventional fuel-based systems, aligning with the increasing demand for sustainable marine operations[17,18]. These energy-efficient propulsion systems enable long-duration missions in both coastal and offshore waters while reducing carbon emissions. Emerging mapping techniques, adapted from Autonomous Underwater Vehicles (AUVs), now allow USVs to deliver high-resolution bathymetric data in coastal environments[15]. By incorporating multibeam sonar and LiDAR, these techniques improve the accuracy and reliability of hydrographic data, meeting the growing need for precise marine mapping[28-30].

Beyond hydrographic surveying, USVs are increasingly being used for environmental monitoring and disaster response, reflecting their growing role in addressing complex maritime challenges. For example, USVs have been effectively deployed for flood mapping and oil spill mitigation, providing timely and actionable insights during emergencies[31,32]. In flood-prone regions, the integration of UAVs and USVs has delivered critical hydrological data, aiding riskd mitigation efforts[32]. Similarly, sensor-equipped USVs have been used for real-time environmental monitoring, offering precise assessments of ecological impacts associated with offshore industries[33,34].

USVs offer several operational advantages, such as enhanced efficiency, reduced costs, and improved safety by minimising human exposure to hazardous environments. These benefits are particularly evident when compared to conventional manned survey operations, as highlighted in Table 2. Additionally, USVs can operate continuously under challenging weather conditions, ensuring consistent data collection and improved spatio-temporal resolution[20,25,35]. However, despite these advancements, challenges remain in ensuring reliable communication, robust collision avoidance, and regulatory compliance in international waters.

Table 2 — Comparison of USVs and conventional operation

Performance aspect	**Comparison**	**Description**
Operating costs	🟢	USVs reduce personnel and operational costs significantly due to uncrewed operation, especially in long-term missions
Initial setup costs	🔵	Investments in USV technology can be comparable to setup costs for conventional survey vessels, depending on scale
Maintenance requirements	🟢	USVs require simpler maintenance schedules and experience less wear compared to crewed vessels
Duration	🟢	Comparable to conventional boats, varies with design specifications
Velocity	🟢	USVs achieve higher speeds, enabling efficient data collection and reduced survey times.
Payload capacity	🔵	Comparable to conventional boats but varies by USV design and size. Some larger USVs can match crewed vessel capacity
Navigation accuracy	🟢	Advanced GPS and auto-navigation systems provide precise georeferenced survey data
Safety	🟢	Automation reduces human error and operational risks, especially in dangerous environments (e.g., shallow waters)
Environmental impact	🟢	Lower emissions and less intrusive, minimising ecosystem disruptions during operations.
Technological flexibility	🔴	Requires specialised personnel and continual updates to manage evolving technologies
Scalability	🟢	Easily deployable in numbers to cover large survey areas efficiently
Data processing capability	🟢	Onboard processing supports real-time data analysis, streamlining workflows
Regulatory compliance	🔵	Fewer legal frameworks exist for USVs compared to traditional crewed vessels, but this varies by region
Remote operability	🟢	Operated remotely, eliminating the need for crew onboard while maintaining functionality in remote regions
Adaptability to environmental conditions	🟢	Equipped to adjust operations based on real-time environmental data

🟢 USV clear advantage; 🔵 Near parity; and 🔴 USV clear disadvantage

Table 3 — Recent hydrographic USV development

Country	**USV name**	**Manufacturer/Developer**	**Level of autonomy**
Singapore	Venus USV(ref. 104)	ST Engineering	Fully autonomous
China	HydroBoat 1200(ref. 112)	SatLab Geosolutions AB	Remotely operated
	Apache 4(ref. 113)	CHCNAV	Remotely operated
Norway	Otter USV	Maritime Robotics	Semi-autonomous
	Sounder USV(ref. 105)	Kongsberg	Semi-autonomous
	REAV-47(ref.106)	Nordic USV	Fully autonomous
France	DriX H-8 USV(ref.101)	Exail	Fully autonomous
Portugal	LAUV(ref. 103)	OceanScan-MST	Fully autonomous
UK	USV Maxlimer(ref.109)	SEA-KIT	Semi-autonomous
Spain	MANTAS T-12(ref.110)	Maritime Tactical Systems	Remotely operated
Ireland	XO-450 USV(ref.111)	XOCEAN	Fully autonomous
USA	EchoBoat USV	Seafloor Systems	Remotely operated
	Surveyor(ref. 107)	Saildrone	Fully autonomous
	CEE-USV(ref.108)	CEE Hydrosystems	Remotely operated
Canada	USV 2.5(ref.102)	SeaRobotics	Remotely operated
Australia	Bluebottle USV	Ocius Technology	Fully autonomous

The ongoing evolution of hydrographic USVs, driven by interdisciplinary research and innovation, represents a transformative phase in maritime exploration. By combining advancements in robotics, AI, and precision mapping, USVs continue to improve scientific research and industrial applications in marine environments. These developments mark a significant milestone in the advancement of hydrographic surveying, as summarised in Table 3.

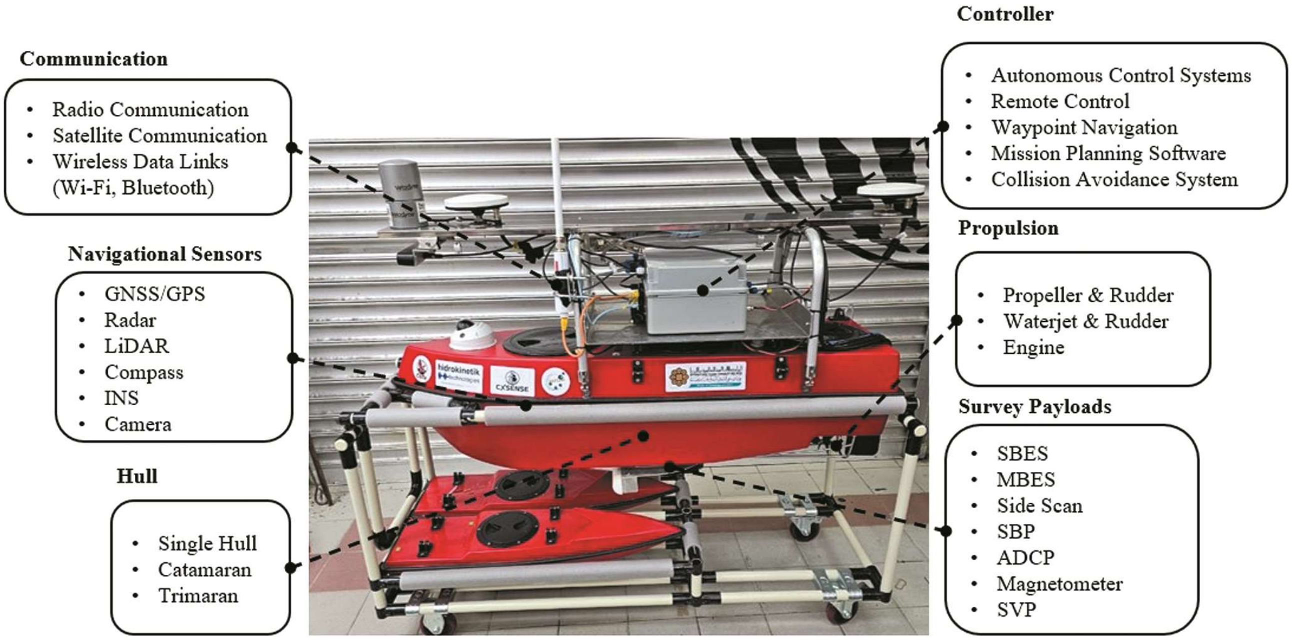

Fig. 6 — Conventional hydrographic USV configuration: Illustrates the typical setup including communication antennas, navigational sensors, hull design, control systems, propulsion units, and survey payloads

Hydrographic USVs architecture

The architecture of USVs for hydrographic surveying incorporates various essential components to ensure optimal performance, data accuracy, and operational efficiency (Fig. 6). The typical USV setup includes communication antennas, navigational sensors, hull designs, control systems, propulsion units, and survey payloads. Hull designs play a pivotal role in determining the stability and hydrodynamic efficiency of USVs. Designs such as catamarans or trimarans offer enhanced stability, particularly in turbulent waters, making them ideal for hydrographic operations. Recent studies have further explored innovative hull designs that minimise drag and improve manoeuvrability, contributing to better performance in diverse marine environments[20,27].

Building on hull design, propulsion systems are crucial for ensuring endurance and adaptability to varying operational environments. Propulsion configurations in USVs range from fully electric to hybrid systems, depending on the mission requirements. Electric propulsion systems offer quiet operation and minimal environmental impact, making them suitable for sensitive marine ecosystems, while hybrid propulsion systems extend operational range by combining fuel and battery power[18,20]. Furthermore, advancements in fuel cell technology have introduced sustainable energy solutions, enabling USVs to conduct long-duration missions with reduced environmental footprints[17,18]. To complement these propulsion systems, solar-assisted power supply solutions have been increasingly integrated into USVs, enhancing energy efficiency, particularly during extended offshore missions[21].

Next, navigation and control systems play a central role in enabling precise path-following, waypoint navigation, and real-time decision-making during hydrographic surveys. The integration of GPS, Inertial Navigation Systems (INS), and autopilot technologies ensures accurate positioning and trajectory control, even in dynamic environments[36]. Beyond conventional navigation methods, advanced technologies such as LiDAR SLAM-assisted positioning have further improved situational awareness in cluttered environments, providing robust solutions for complex operations[12,27]. Additionally, adaptive path-following algorithms that account for environmental factors, such as waves and currents, ensure reliable and safe operations in unpredictable marine conditions[37,38]. These advancements have significantly improved the reliability of USVs in challenging marine environments.

Moreover, USVs rely on guidance systems to maintain accurate course control and avoid obstacles during missions. Guidance systems are often categorised by their operational approach, with line-of-sight (LOS) methods commonly used for short-range missions due to their simplicity and efficiency[35]. For longer-range or more complex missions, advanced guidance techniques, such as those employing extended Kalman filters for position estimation and real-time path adjustment, have become essential[37]. Notably, Liu *et al.*[22] introduced the Angle Guidance Fast Marching Square (AGFMS) algorithm, which improves navigation efficiency by addressing motion constraints in real-time. Together, these advancements illustrate the growing sophistication of USV guidance systems in hydrographic surveying.

In addition, communication systems are indispensable for maintaining control and transmitting data during missions. USVs commonly utilise satellite, radio, and cellular communication links, depending on the operational range and mission requirements[38]. Advances in real-time data transmission have improved mission efficiency by enabling near-instantaneous feedback and adjustments during operations. Safety features, such as collision avoidance mechanisms and emergency response protocols, are also integral to USV architecture. These features leverage advanced sensor arrays and algorithms to detect obstacles in real-time and execute evasive manoeuvres when necessary, ensuring safe operations even in high-traffic marine environments[39].

Finally, launch and recovery systems complete the operational cycle of USVs by facilitating their deployment and retrieval. These systems are designed for both shore-based and ship-based operations, ensuring efficient and safe handling of USVs during mission start and completion. Automated Launch And Recovery Systems (ALARS) have become increasingly popular, as they reduce human supervision, minimise operational risks, and improve the overall efficiency of hydrographic surveys.

Hydrographic USVs sensors and payloads

Onboard sensor suites are essential for high-resolution data acquisition in hydrographic surveys where core sensors include Multi-Beam Echo Sounders (MBESs), Side-Scan Sonars (SSSs), Sub-Bottom Profilers (SBPs), and Conductivity-Temperature-Depth (CTD) sensors, which together provide detailed seafloor mapping and environmental data. Integrating these sensors with UAV platforms has proven particularly effective in coastal areas, enabling combined photogrammetric and bathymetric surveys. This dual-platform approach offers enhanced spatial resolution and operational flexibility, as highlighted in recent studies[40-42].

Moreover, advancements in onboard data processing allow USVs to handle large datasets in real-time, reducing post-processing time and delivering faster results. These real-time processing capabilities not only accelerate the data pipeline but also support adaptive decision-making during missions, thereby improving overall survey efficiency. With accurate data availability during operations, USVs can respond to environmental changes more effectively, ensuring high-quality results in diverse marine conditions.

Building on these real-time capabilities, precise navigation systems are crucial for ensuring that USVs maintain accurate trajectories and achieve reliable coverage of the survey area. Standard navigation systems include GNSS receivers, INS units, and Doppler Velocity Logs (DVLs), which provide accurate positioning, continuous orientation tracking, and velocity measurements. GNSS provides precise global positioning, while INS complements it by offering uninterrupted navigation data, especially in environments where GNSS signals may be weak or unavailable. DVLs further enhance the system by measuring velocity relative to the water, ensuring stable movement even in dynamic marine environments.

Furthermore, integrating GNSS and INS has been shown to significantly improve the accuracy and autonomy of USVs. As El-Diasty[43] demonstrated, this combination enables USVs to operate effectively in offshore areas with reduced human supervision. Recent innovations in navigation also include LiDAR-assisted positioning and Kalman filter-based sensor fusion, which improve real-time obstacle detection and collision avoidance[43,] These advancements have collectively enhanced the safety, precision, and autonomy of USV operations, allowing them to perform reliably even in complex and cluttered environments.

Once reliable navigation is established, the focus shifts to the surveying sensors that capture hydrographic data essential for mapping and monitoring. Surveying sensors form the backbone of hydrographic data collection, enabling USVs to gather precise bathymetric and geophysical information. MBES systems are widely regarded as the gold standard for bathymetric mapping due to their ability

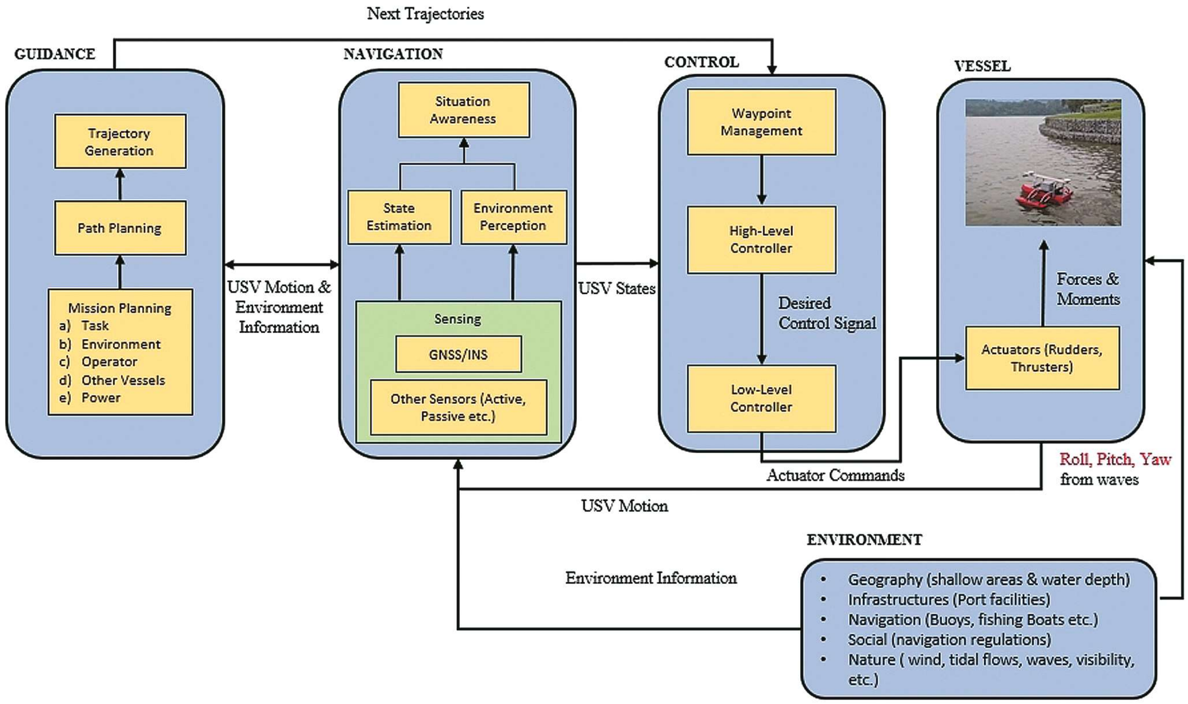

Fig. 7 — General structure of USV GNC systems: Depicts the arrangement of guidance, navigation, and control systems within a typical uncrewed surface vessel

to cover large areas with high accuracy. By emitting multiple sonar beams simultaneously, MBES can generate a swath of depth measurements across the seafloor, resulting in detailed bathymetric models. Gabr *et al.*[44] highlighted the importance of proper MBES calibration, demonstrating how it improves depth measurement accuracy, particularly when combined with Seabed Digital Bathymetry (SDB) models.

In addition to MBES, side-scan sonars and sub-bottom profilers are often used to enhance hydrographic data collection. Side-scan sonars are ideal for identifying underwater objects and features, while sub-bottom profilers provide valuable insights into sediment layers beneath the seafloor, enabling geophysical analyses of the seabed structure. Complementing these, CTD sensors gather vital environmental data such as salinity, temperature, and depth, which helps improve survey accuracy by accounting for environmental variations that may affect sonar performance.

Moreover, recent advancements in water quality sensors have enabled USVs to conduct simultaneous environmental monitoring and hydrographic surveys. By measuring parameters such as turbidity, dissolved oxygen, and chlorophyll levels, these sensors provide critical insights into the health of marine ecosystems. This dual-purpose capability enhances USVs value for both hydrographic and environmental applications, particularly in areas where human impact on marine environments requires constant monitoring[45].

To ensure that data collected by these sensors is actionable, robust onboard processing systems handle and store large datasets in real-time, streamlining the overall survey process. As highlighted by Specht *et al.*[41], real-time data processing significantly reduces the need for post-mission analysis, accelerating decision-making and increasing operational efficiency.

USV Guidance, Navigation and Control

Effective Guidance, Navigation, and Control (GNC) systems are the backbone of USV operations, ensuring precise path planning, accurate positioning, and stable control during hydrographic surveys. The integration of advanced sensors, real-time processing capabilities, and AI-driven algorithms has significantly enhanced the performance and autonomy of USVs in complex marine environments. A typical USV GNC system comprises three core subsystems: the guidance system, which plots the mission course; the navigation system, which determines real-time position and orientation; and the control system, which manages propulsion and steering to maintain stability during operations (Fig. 7).

Recent advancements in guidance systems have leveraged machine learning and reinforcement learning (RL) techniques to enable dynamic adaptation to changing maritime conditions. RL models optimise path planning and obstacle avoidance in real time, improving the USV's ability to navigate unpredictable environments[46]. Additionally, neural network-based systems enhance predictive navigation by identifying potential faults and providing early warnings, ensuring seamless operations under uncertain conditions[47]. Meanwhile, fuzzy logic controllers, known for their ability to handle imprecise data, have proven effective in obstacle avoidance, particularly in environments with incomplete sensor information[48].

Moreover, predictive control methods, such as Non-linear Model Predictive Control (NMPC), offer precise trajectory tracking and collision avoidance by accounting for vessel dynamics and environmental constraints. For instance, Mina *et al*.[8] proposed a multi-USV framework employing weighted potential field algorithms for dynamic obstacle avoidance, demonstrating the potential of predictive control techniques in coordinated hydrographic missions. Collectively, these AI-driven advancements enable USVs to perform complex, high-precision tasks autonomously, paving the way for broader applications in environmental monitoring and marine exploration[49,50].

Multi-agent coordination and swarm intelligence

Significant progress has been made in swarm intelligence for multi-USV operations, inspired by the cooperative behaviour of biological systems. Swarm intelligence algorithms enable coordinated hydrographic surveys and search-and-rescue missions by facilitating efficient multi-agent communication and collaboration[51]. These systems employ heuristic rules and distributed control, allowing multiple USVs to work together in real time without centralised oversight.

For example, machine learning models can predict environmental variables, such as wave heights and current speeds, enabling the USV swarm to adapt its navigation strategy dynamically. Collaborative operations improve survey efficiency by covering larger areas in shorter timeframes and reducing redundancy in data collection. Recent work by Liu *et al*.[22] on the angle guidance fast marching square method demonstrated improved motion control and coordination in multi-agent USV systems, particularly in cluttered environments.

Building on these guidance innovations, navigation systems have evolved to incorporate multi-sensor data fusion for enhanced accuracy. Core navigation technologies include GPS, Inertial Measurement Units (IMUs), and sonar-based positioning systems, which together ensure reliable real-time positioning during missions. These systems work in tandem to provide accurate waypoint navigation, path-following, and station-keeping capabilities, even in dynamic marine conditions[20,52] (Fig. 8).

To improve navigation reliability, extended Kalman filters are commonly used for precise position

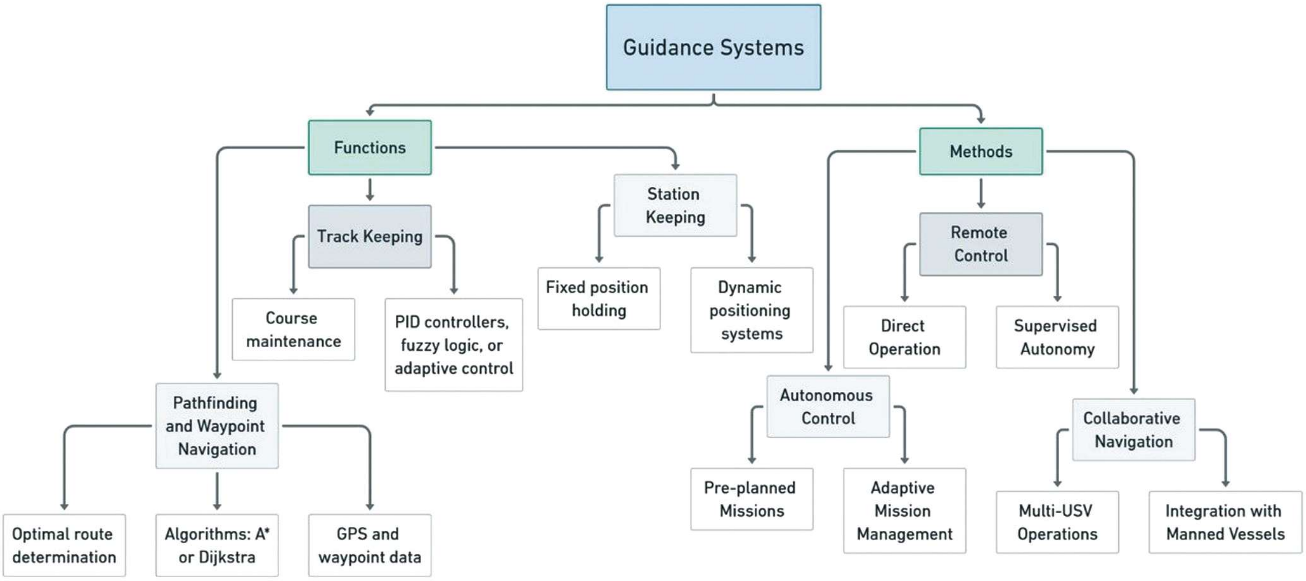

Fig. 8 — USV guidance systems: Overview of the guidance system components utilised in uncrewed surface vessels

estimation by integrating data from multiple sensors. Caccia *et al.*[53] demonstrated a dual-loop architecture combining GNSS and INS, resulting in higher accuracy during offshore operations. Similarly, LiDAR-assisted navigation and fast-marching algorithms have been introduced to improve obstacle detection and collision avoidance in confined areas[54].

Moreover, hybrid navigation approaches that integrate remote and autonomous control allow for adaptive management based on real-time sensor inputs. These systems offer flexibility by enabling operators to intervene during complex manoeuvres, ensuring both operational safety and mission success in high-risk environments[24,55].

Pathfinding and control techniques

Effective pathfinding and control are critical for optimising survey paths and maintaining precise trajectory during hydrographic operations. Pathfinding algorithms such as A* and Dijkstra are commonly employed for route planning, leveraging GPS data to calculate the most efficient survey path. Once a path is determined, control techniques such as Proportional-Integral-Derivative (PID) controllers, fuzzy logic controllers, and adaptive control methods are used to maintain the USV's course and ensure stability.

Track-keeping and station-keeping are vital functions during hydrographic surveys, particularly when high-precision data collection is required. PID controllers are often employed for trajectory correction, while fuzzy logic controllers adaptively handle disturbances caused by currents and wind. Advanced algorithms, such as those developed by Lewicka *et al.*[20], integrate bathymetric monitoring with USV guidance systems, enhancing path-following and data acquisition accuracy in real time.

In addition to autonomous navigation, collaborative navigation with manned vessels or other USVs has emerged as a key trend in hydrographic surveying. By coordinating operations, multi-platform systems can increase survey efficiency and improve data quality. For example, integration with UAVs allows simultaneous aerial and bathymetric data collection, offering a more comprehensive view of the surveyed area[19,35].

Real-time adaptation, driven by machine learning and AI models, further enhances USV autonomy by allowing them to adjust to environmental changes on the fly. This capability is particularly valuable in dynamic environments where pre-planned paths may need to be modified based on real-time sensor feedback[56-58].

Path Planning and Navigation for USV

Path planning is a critical component of USV autonomy, enabling safe and efficient navigation in dynamic maritime environments. Effective path planning ensures that USVs can autonomously navigate complex routes while avoiding obstacles and adhering to operational constraints. USV path planning incorporates global and local strategies to balance long-term route optimisation with real-time adaptability (Fig. 9).

Global and local path planning

At the global level, optimisation algorithms such as A* and *A-based Bacterial Foraging Optimization*

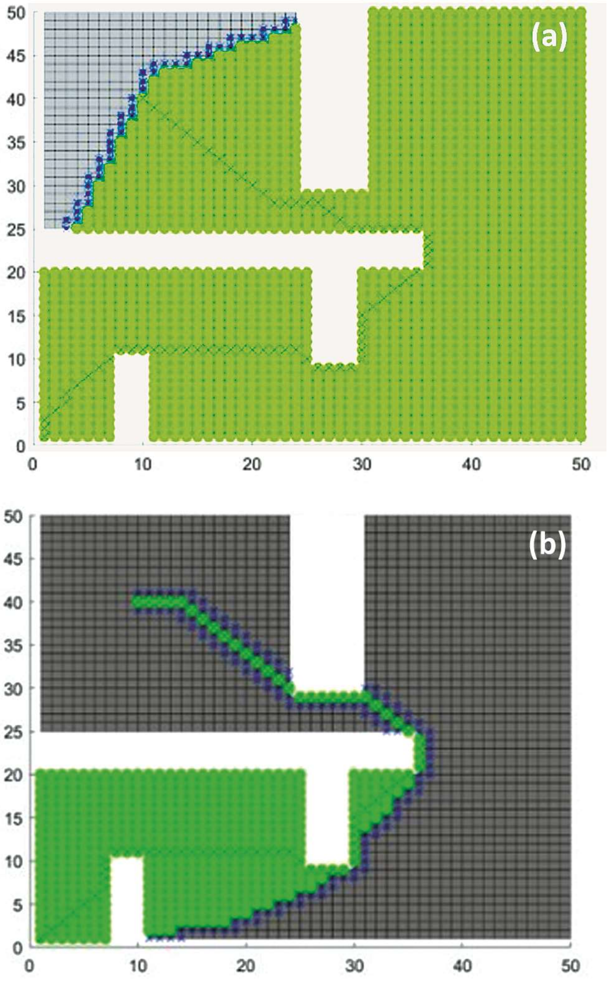

Fig. 9 — Grid-based path planning algorithm: (a) Graph traversal method illustrating systematic navigation through nodes; and (b) Heuristic-based method showcasing strategies for optimising path selection based on specific criteria

*(BFO)** determine near-optimal routes by accounting for static and dynamic obstacles, ocean currents, and environmental factors[19,24,54]. These methods focus on minimising travel distance and energy consumption while maximising safety and mission efficiency. Additionally, heuristic-based methods like Genetic Algorithms (GAs) and Particle Swarm Optimisation (PSO) provide robust solutions by iteratively refining potential routes through evolutionary processes and particle adjustments, respectively. These approaches excel in large-scale environments where multiple objectives, such as obstacle avoidance and time efficiency, must be balanced[19].

In contrast, local path planning focuses on real-time adjustments to immediate surroundings, ensuring safe navigation in response to dynamic changes. Techniques such as the Improved Dynamic Window Approach (IDWA) and Line-of-Sight (LOS) guidance methods[59-61] enable precise path correction and direct targeting of waypoints. Furthermore, potential fields algorithms[62] generate virtual force fields around obstacles, facilitating smooth collision-free movements, while hybrid methods combining global and local strategies ensure that USVs can adapt swiftly to new conditions[63,64]. These hybrid approaches demonstrate the sophistication and adaptability of modern USV path planning, providing robust frameworks for autonomous maritime operations.

Collision avoidance strategies

USVs operate in dynamic environments where collision risks are prevalent, making advanced collision avoidance systems essential. These strategies can be broadly categorised into protocol-free and protocol-based approaches[65].

Protocol-free methods employ reinforcement learning algorithms[66,67], allowing USVs to autonomously learn and adapt to varying maritime conditions without relying on predefined rules. By processing real-time sensor data and environmental inputs, these algorithms facilitate dynamic course adjustments to avoid obstacles. Deep reinforcement learning further enhances these methods by enabling USVs to navigate complex, cluttered environments and respond to unforeseen obstacles in real time[68]. This approach is particularly effective in unregulated or remote waters where traditional navigational protocols may not apply.

Conversely, protocol-based strategies adhere to established maritime regulations, such as the International Regulations for Preventing Collisions at Sea (COLREGs). These methods integrate rule-compliant algorithms with path-following and steering techniques to ensure safe and predictable navigation. Xu *et al.*[69] advanced this approach by introducing dynamic algorithms that utilise artificial potential fields and collision cones to adjust USV speed and heading, ensuring compliance with COLREGs while maintaining operational flexibility. The combination of protocol-free adaptability and protocol-based rule adherence ensures that USVs can safely navigate both regulated waterways and open seas, striking a balance between autonomy and safety[9,34,45].

Artificial Intelligence (AI) has emerged as a transformative force in USV path planning and collision avoidance. Recent advancements in AI-driven task assignment and multi-USV coordination[70] have enabled more efficient and collaborative operations. For instance, reinforcement learning-based swarm intelligence allows multiple USVs to perform large-scale missions cooperatively, enhancing both coverage and operational efficiency[71,72]. Additionally, predictive control techniques have been developed to address non-linear environmental disturbances, ensuring accurate trajectory tracking even under unpredictable conditions[63,73]. These AI-driven systems enhance path planning and real-time decision-making, positioning USVs as key players in future marine exploration and environmental monitoring missions[65,74].

USV State Estimation and Fault Tolerance

Accurate state estimation is essential for reliable USV navigation, particularly in dynamic marine environments where sensor data may be noisy or prone to errors. Advanced methods for state estimation integrate GPS-IMU data with Kalman filtering techniques, effectively mitigating noise and improving the accuracy of position, velocity, and orientation estimates[47]. Standard Kalman filters are suitable for linear systems; however, in non-linear scenarios, methods such as Unscented Kalman Filters (UKF) and Particle Filters (PF) provide more robust solutions by accounting for complex system dynamics and model uncertainties[33].

To further enhance reliability, fault-tolerant strategies have been developed to detect and compensate for sensor faults or system anomalies during missions. These strategies employ real-time fault detection mechanisms and adaptive algorithms to ensure continued operation despite partial system failures. Such resilience is critical for long-duration missions in remote or hazardous environments, where manual intervention may be impractical[43].

Modern USV operations benefit from the seamless integration of guidance, navigation, and control subsystems, creating a unified framework capable of autonomous decision-making and real-time adaptation. As shown in Figure 6, integrated GNC systems incorporate advanced algorithms for pathfinding, collision avoidance, and control, ensuring mission success even in challenging conditions. Additionally, collaborative operations with manned vessels or UAVs enable more comprehensive surveys, offering both surface and aerial perspectives for enhanced data accuracy and coverage[35,37].

Environmental perception

Environmental perception is integral to the autonomous operation of Uncrewed Surface Vehicles (USVs), equipping them to safely navigate complex and dynamic maritime environments. By integrating both passive and active perception methods, USVs achieve an enhanced understanding of their surroundings, which is essential for applications like hydrographic surveying and environmental monitoring.

Passive perception methods

1. *Monocular vision:* Monocular vision systems use a single camera to provide cost-effective solutions for visual perception in USVs. These systems play a significant role in tasks like object detection and autonomous navigation by interpreting visual data and supporting decision-making. Research by Li *et al.*[75], Park *et al.*[76], and Huang *et al.*[77] demonstrates how monocular vision contributes to situational awareness in maritime operations. Developments such as the Prior Estimation Network (PEN) for obstacle detection[78] and vision-based target tracking systems[49,55] illustrate their utility in navigating dynamic environments. These advancements show how monocular vision can enhance navigation in less complex settings while maintaining cost efficiency.

2. *Stereo vision:* Stereo vision systems, which employ two cameras to replicate depth perception, offer an improved ability to measure distances, detect obstacles, and create detailed 3D maps. By analysing image disparities, these systems enable more precise navigation and mapping, particularly in confined or cluttered waterways. Studies by Huang *et al.*[77] and Zhou *et al.*[56] highlight stereo vision's role in depth estimation and spatial mapping, while generating disparity maps aiding collision avoidance[57]. Although more resource-intensive than monocular systems, stereo vision significantly enhances USV autonomy and situational awareness in demanding operational conditions.

Active perception methods

Active perception technologies, including LiDAR, radar, and sonar, are fundamental for enabling USVs to operate effectively in diverse marine environments. LiDAR facilitates high-resolution topographic mapping by measuring light reflections, making it particularly useful for coastal mapping and shallow water surveys[8]. Radar complements this by providing reliable object detection and distance measurement in challenging visibility conditions, such as during fog or rain, thereby enhancing navigation safety[49]. Sonar remains crucial for underwater applications, enabling the detection of seafloor features and submerged objects, especially in low-visibility waters, which is essential for hydrographic surveys and marine exploration[5].

In addition to these core systems, specialised sensors such as Single Beam Echo Sounders (SBES), Multi-Beam Echo Sounders (MBES), and Acoustic Doppler Current Profilers (ADCPs) significantly expand USV capabilities. These sensors support precise underwater data collection, with ADCPs offering valuable insights into water velocity and ocean currents, enhancing the accuracy of bathymetric mapping and sediment analysis[17,39]. This combination of active perception tools allows USVs to navigate complex marine environments, collect detailed data, and perform a range of hydrographic tasks with improved precision and reliability, reflecting their growing role in modern maritime operations.

Situation Awareness

Situational awareness is a critical factor in ensuring the safe and efficient operation of USVs. Technologies such as marine radar are essential for acquiring real-time environmental data, particularly in collision avoidance scenarios or when GPS signals are weak or unavailable[15]. Autonomous navigation systems further enhance situational awareness by integrating sensor data to detect and avoid obstacles in congested or narrow waterways[62].

Recent research has also explored how USVs respond to environmental stimuli, such as acoustic signals. Studies on ultrasonic vocalisations provide insights into USV interactions with their surroundings, which may improve their ability to identify potential threats and adapt to environmental changes[79,80]. By combining active perception technologies with real-time environmental analysis, USVs are increasingly capable of maintaining operational safety and efficiency in complex maritime settings[81].

USV Modelling

The modelling of USVs forms the foundation for understanding their motion, stability, and control. This involves a detailed examination of their kinematics, model simplifications, and dynamics, each contributing to the accurate prediction of their behaviour in real-world maritime environments.

Kinematics

The initial phase in USV modelling is characterised by setting up a comprehensive 3D coordinate system[21], to precisely depict the vessel's spatial orientation and position as shown in Eq. (1), where $\vec{S}$ represents the state vector, which combines both positional coordinates $(x, y, z)$and orientation angles (φ, θ, ψ).

$$\vec{S} = x, y, z, \varphi, \theta, \psi^T \qquad \dots (1)$$

Highlighting the kinematics, it can be denoted that the rate of change in position is $(\dot{x}, \dot{y}, \dot{z})$, with r representing the yaw angle. The velocities in the body frame (u, v, w)correspond to movements in the surge, sway, and heave directions, respectively, with $\dot{r}$ indicating the yaw rate. These relationships can be mathematically articulated as shown in Eq. (2).

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} cos\, r & -\sin r & 0 \\ \sin r & cos\, r & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} u \\ v \\ w \\ r \end{pmatrix} \qquad \dots (2)$$

Model simplification

The USV kinematic model simplification, crucial for mathematical understanding, assumes fore/aft symmetry, making hydrodynamic coefficients in surge, sway, and yaw directions symmetric, thus streamlining force equations[82]. Specifically, in the surge direction, the force can be modelled as shown in Eq. (3), where F_x is the surge force, X_u a negative hydrodynamic coefficient indicating resistance, and u the surge velocity.

$$F_x = -X_u \cdot u \qquad \dots (3)$$

Additionally, assuming a low and constant surge speed reduces the complexity in modelling the USV's trajectory, making it easier to predict its behaviour with a steady forward velocity. The model also factors in the USV's capability for dynamic positioning and mooring, enhancing realism by allowing the vehicle to maintain or adjust its position autonomously in response to external conditions as represented in Eq. (4). Here, $\overrightarrow{\Delta P}$ indicates required positioning adjustments, and $\vec{C}$ the control actions against external forces, $\vec{F}_{external}$(refs. 82-85).

$$\overrightarrow{\Delta P} = \vec{C}(\vec{F}_{external} \qquad \dots (4)$$

Furthermore, the alignment of the centre of added mass with the centre of gravity simplifies stability and control analyses, facilitating the understanding of mass effects on the USV[42]. Lastly, operating in calm environments minimises the need to account for turbulent conditions, focusing the model on the USV's dynamics without external disturbances[85].

Dynamics

The dynamics of a USV are governed by Newton's second law for translational motion and by rotational dynamics for angular motion. The forces acting on the USV include thrust, drag, gravitational, buoyancy, and environmental forces such as wind, waves, and currents, while torques may arise from steering mechanisms and environmental interactions.

The dynamic model can be expressed in matrix form, encapsulating the relationship between forces/torques and the USV's acceleration. The simplified dynamic equations in matrix form, considering the forces and moments acting on the USV in the surge, sway, and yaw directions, are shown in Eq. (5).

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} \frac{1}{m-X_{\dot{u}}} & 0 & 0 & 0 \\ 0 & \frac{1}{m-Y_{\dot{v}}} & \frac{Y_{\dot{r}}}{I_z-N_{\dot{v}}} & 0 \\ 0 & \frac{N_{\dot{v}}}{I_z-N_{\dot{r}}} & \frac{1}{I_z-N_{\dot{r}}} & 0 \\ 0 & 0 & 0 & \frac{1}{m-Z_{\dot{w}}} \end{bmatrix} \begin{bmatrix} X \\ Y \\ N \\ Z \end{bmatrix} \qquad \dots (5)$$

This structured approach to USV modelling not only simplifies the representation of complex physical interactions but also aids in developing robust control systems for diverse maritime applications. By accounting for both internal dynamics and external environmental forces, these models provide a solid basis for advancing USV autonomy and performance in hydrographic surveying and other critical marine tasks.

Discussion

Challenges and future directions

The integration of hydrographic USVs with autonomous GNC systems has significantly advanced maritime operations. Technologies like extended Kalman filters have improved navigation accuracy by fusing multi-sensor data[68], while reinforcement learning has enabled USVs to adapt to dynamic conditions through real-time adjustments[86]. Despite these advancements, challenges still persist, particularly in path planning, energy efficiency, and environmental resilience. Effective path planning remains critical for USVs to navigate efficiently in uncertain environments. Combining heuristic-based global strategies with local path adjustment algorithms has proven effective in enhancing route selection and adaptability.

Future research must address the limitations of current systems by developing hybrid AI-driven decision-making frameworks. Such systems could enable USVs to dynamically respond to environmental changes, ensuring continuity in adverse conditions[81]. Additionally, advancements in energy-efficient propulsion systems, such as proton exchange membrane fuel cells, are essential for extending operational endurance while minimising environmental impact[86].

Multi-USV operations have emerged as a promising solution for large-scale hydrographic surveys. Leveraging swarm intelligence, these systems can achieve coordinated coverage while reducing time and operational effort[26]. Distributed control and communication frameworks further enhance the adaptability of multi-agent systems, allowing independent USVs to collaborate seamlessly[87]. However, stability in challenging environments, such as rough seas, remains a priority. Short-time wave prediction models integrated into control systems enable fleets to anticipate and adapt to changing conditions, ensuring mission efficiency and safety. Advancements in sensor technologies also play a critical role in expanding USV applications. Light-weight multispectral and hyperspectral imaging systems, combined with sensor fusion techniques, enhance situational awareness and data reliability[87]. These innovations refine hydrographic surveys and facilitate real-time environmental monitoring, providing actionable insights into marine ecosystems[88].

Regulatory and ethical considerations are vital to the broader adoption of USVs. Establishing comprehensive frameworks to address collision avoidance, communication protocols, and environmental impact assessments is essential to ensure operational consistency and safety[89,90]. Furthermore, eco-friendly designs and adherence to international maritime laws can mitigate ecological disruption, building public trust in autonomous marine technologies[91,92]. Looking ahead, integrating USVs with other platforms, such as manned vessels, UAVs, and AUVs, could further enhance their capabilities. By leveraging each platform's unique strengths, multi-platform systems can improve operational efficiency and enable more comprehensive marine data collection[93,94].

Conclusion

The rapid advancements in hydrographic Uncrewed Surface Vessels (USVs) are underpinned by significant innovations in Guidance, Navigation, and Control (GNC) systems, multi-sensor fusion, and AI-driven decision-making frameworks[95]. These technologies have collectively enabled USVs to navigate dynamic environments, optimise survey paths in real time, and maintain data accuracy under challenging conditions. Furthermore, energy-efficient propulsion solutions, such as hybrid fuel cells, have extended operational ranges while reducing environmental footprints, aligning with the global push for sustainable marine operations[96,97].

Looking forward, future research must prioritise improving adaptability in uncharted and extreme environments. Enhancements in state estimation techniques, leveraging advanced sensors and robust filtering methods like Unscented Kalman Filters (UKF), will play a crucial role in mitigating sensor noise and system uncertainties. Collaborative multi-agent systems, supported by swarm intelligence and real-time communication protocols, offer significant potential for expanding the scale and efficiency of hydrographic surveys[98-100]. These systems will enable coordinated operations across multiple USVs, further enhancing data coverage and mission reliability.

As the field progresses, the development of comprehensive regulatory frameworks will be vital to ensuring the safe and ethical deployment of autonomous USVs. Such measures will not only address operational challenges but also promote responsible innovation. With these advancements, USVs are poised to redefine hydrographic surveying by delivering unprecedented levels of precision, efficiency, and environmental sustainability. Their transformative potential will continue to drive innovation in marine exploration, resource management, and environmental conservation, shaping the future of maritime operations.

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Conflict of Interest

The authors state that there are no conflicts of interest with any organisations or funding bodies.

Ethical Statement

All authors agreed to the ethical principles.

Author Contributions

MAN & ZZA: Conceptualization, investigation, methodology and writing original draft. ZZA & MIH: Supervision & validation, reviewing and editing, and funding acquisition.

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