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Review

Mission-Oriented Payloads and Platform Support for Unmanned Surface Vehicles: From Aquatic Observation to Operational Applications

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Abstract: Unmanned surface vehicles (USVs) are increasingly used for hydrographic surveying, environmental monitoring, ecological observation, infrastructure inspection, and underwater search. Previous studies often focus on autonomous navigation, vehicle design, platform types, or individual applications, leaving relationships among mission objectives, payloads, platform support, and data products unclear. This paper examines these relationships for USV tasks beyond routine navigation-related surface perception. The discussion separates mission payloads from platform-support modules and mission-execution units and considers six groups: hydrographic surveying and mapping; air-sea and environmental observation; water-quality, pollution, and biogeochemical monitoring; ecological surveys, fisheries, and acoustic monitoring; infrastructure inspection; and emergency search support. Within each group, attention is given to measured variables or targets, payload operation, platform dependence, field validation, and data products. Direct numerical comparison is often inappropriate because studies differ in vehicle architecture, payload configuration, environment, validation, and reporting. Hydrographic surveying and some inspection tasks show the clearest repeatable workflows and products. Field studies also demonstrate air-sea observation, water-quality mapping, ecological monitoring, fisheries acoustics, and underwater-search tasks, with performance dependent on platform design and operating conditions. Target-specific chemical sensing, pollution-source attribution, autonomous environmental DNA sampling, biogeochemical flux estimation, and complete rescue or recovery operations remain limited or platform-specific. Across applications, sensor specifications alone provide an incomplete indication of mission capability. Reliable results depend on positioning and attitude references, power, communications, installation geometry, environmental protection, calibration, and quality control. Further development is needed in modular payload integration, long-duration reliability, onboard processing, multi-platform cooperation, and consistent data and metadata practices.

Keywords: unmanned surface vehicle; mission payload; platform support; aquatic observation; sensor integration

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1 Introduction

Unmanned surface vehicles (USVs) are increasingly used as mobile platforms for aquatic observation, surveying, environmental monitoring, infrastructure inspection, and emergency operations. Their usefulness extends beyond autonomous navigation because they can carry mission-specific instruments and collect spatially referenced observations in shallow, coastal, inland, remote, or hazardous waters. Compared with crewed vessels, USVs can reduce personnel exposure, simplify repeated deployment, and support persistent measurements at relatively low operating cost. Their mobility also allows environmental or structural variables to be measured along planned routes and around selected targets. These observations can complement data from fixed stations, drifting platforms, satellites, crewed vessels, and underwater vehicles[1-3].

A large part of USV research has addressed the capabilities needed for safe and autonomous surface operation. Common topics include guidance, navigation and control, path planning, collision avoidance, communications, and data-driven decision making[4,5]. These capabilities are fundamental to vehicle autonomy, but sensors used for routine navigation-related perception do not necessarily produce the final observations required by an environmental survey, ecological investigation, underwater search, or infrastructure inspection. Cameras, thermal imagers, radar, and LiDAR are frequently studied for vessel detection, obstacle avoidance, water-surface segmentation, navigable-area recognition, and general situational awareness. In such cases, their main purpose is to support navigation and surface perception rather than to measure the environmental, ecological, underwater, or structural variables that constitute the mission product.

Previous publications have described USV applications in oceanography, hydrography, environmental monitoring, offshore operations, and other maritime sectors. Some studies have examined individual areas in greater depth, including air-sea observation and fisheries or plankton acoustics[2,6]. The relevant information nevertheless remains dispersed among autonomy-centered reviews, platform surveys, application classifications, domain-specific studies, and individual field demonstrations. Connections among mission objectives, measured variables, payload configurations, platform requirements, operating procedures, validation practices, and final data products are therefore difficult to compare across application areas.

Installing a sensor on a USV does not by itself create a complete mission capability. A multibeam echosounder, water-quality sonde, meteorological package, scientific echosounder, imaging sonar, or acoustic receiver can produce useful observations only when the platform supplies an appropriate spatial and temporal reference, stable power, suitable mounting geometry, acceptable motion conditions, adequate storage or communications, and sufficient endurance. Consequently, nominal sensor specifications alone are insufficient to characterize the performance of a complete USV mission. For example, even a high-performance multibeam echosounder may produce poor bathymetric results if positioning and attitude measurements, lever-arm and mounting-angle calibration, sound-speed correction, or motion compensation are inadequate.

The function of an instrument may also change between missions. Side-scan sonar, for example, can be used for seabed mapping, submerged-target search, or pipeline inspection. A conductivity-temperature-depth instrument may provide the primary temperature and salinity observations in an environmental mission, but during a hydrographic survey it may be used mainly to support sound-speed correction. A meaningful comparison must therefore consider the direct output of each instrument, its role in the workflow, its dependence on the platform, and its relationship with other mission components.

This paper examines USV sensing and operational applications beyond routine navigation-related surface perception. The discussion focuses on the quantities or targets observed directly by USVs, the payloads used to obtain those observations, the platform capabilities and operating procedures needed to produce interpretable data, and the field results reported for different applications. The available studies vary widely in vehicle architecture, payload configuration, environmental setting, mission duration, validation design, and reported performance indicators. Their results are therefore examined primarily in terms of payload function, platform dependency, operational workflow, data product, validation practice, and reported limitations rather than through direct numerical aggregation.

For clarity, the applications are organized into six groups: hydrographic surveying and mapping; air-sea and environmental observation; water-quality, pollution, and biogeochemical monitoring; ecological surveys, fisheries, and acoustic monitoring; infrastructure inspection; and emergency search support. The payloads discussed include single- and multibeam echosounders, side-scan and imaging sonars, acoustic Doppler current profilers, meteorological and radiation instruments, temperature and salinity sensors, multiparameter water-quality sondes, biogeochemical sensors, scientific echosounders, underwater cameras, acoustic telemetry receivers, hydrophones, magnetic instruments, and subsurface-detection systems. These instruments are not treated simply as a list of sensor types. Each is considered in relation to what it measures directly, the product it is intended to generate, its role during operation, the support it requires from the platform, and the main sources of uncertainty affecting its use.

The primary payload classification includes sensors mounted on the USV and instruments operated as integral parts of a USV mission. This includes hull-mounted

equipment and towed or deployable instruments whose operation is directly controlled from the surface platform. Sensors carried by independently operated autonomous underwater vehicles (AUVs) or remotely operated vehicles (ROVs) are discussed only when they are needed to explain a USV-centered cooperative workflow; they are not classified as USV payloads. Studies dealing exclusively with collision avoidance, surface-vessel detection, water-surface segmentation, navigable-area recognition, and other routine surface-perception functions fall outside the scope of the paper. Cameras, thermal imagers, LiDAR systems, and related processing methods are included only when they contribute directly to a mission product, such as ecological imagery, structural-inspection records, optical bathymetry, three-dimensional engineering measurements, or multisensor survey products.

1.1 Novelty and Contributions Relative to Existing Reviews

Existing reviews of USVs have examined the field from several complementary perspectives. Patterson et al. [1] systematically reviewed USV applications and factors influencing technological diffusion, while Liu et al. [4] provided a broad overview of vehicle development and associated technical challenges. More recent reviews have considered market-ready USV platforms[3] or advances in communication, navigation, control, and data-driven technologies[5]. Other studies have focused on individual application areas, including the role of USVs in the Global Ocean Observing System and air-sea observation[2], as well as their use in fisheries and plankton acoustics[6]. These studies provide important platform-, autonomy-, market-, or domain-specific perspectives. However, the relationships among mission objectives, measured variables, payload functions, platform-support requirements, operational procedures, validation evidence, and resulting data products have not been examined consistently across different application domains.

The novelty of the present review lies not in proposing another catalogue of USV platforms, sensors, or applications, but in applying a mission-oriented framework that systematically links mission objectives, payload functions, platform-support requirements, operational workflows, validation evidence, and resulting data products. Within this framework, mission payloads, platform-support modules, and mission-execution units are distinguished according to their functional roles. Their detailed definitions, functional boundaries, and representative examples are presented in Section 2.

Applying this framework enables several cross-domain conclusions that are less apparent from sensor- or platform-centered classifications alone. First, sensor performance at the mission level cannot be evaluated independently of platform motion, positioning and attitude quality, installation geometry, timing, energy availability, communications, calibration, environmental exposure, and data-quality procedures. Second, the maturity of an application depends on whether a complete and repeatable operational workflow produces a clearly defined and validated data product, rather than simply on whether a particular sensor has been successfully installed on a USV. Third, findings obtained from large or long-endurance platforms cannot necessarily be transferred directly to small or low-cost USVs because differences in payload capacity, motion characteristics, available power, mounting geometry, sensor exposure, endurance, and maintenance requirements may substantially affect measurement quality. Finally, missions involving sampling, preservation, towing, deployment, recovery, or other physical intervention introduce execution requirements that are distinct from both the sensing payload and vehicle autonomy.

The framework is therefore used throughout this review to compare four aspects of mission capability: the completeness of the mission workflow, the dependence of the payload on platform-support capabilities, the repeatability and validation of the reported field evidence, and the clarity and interpretability of the resulting data product. These criteria make it possible to distinguish between applications with established operational procedures and applications that remain dependent on specific platforms or isolated demonstrations. They also provide a common basis for identifying cross-domain technical bottlenecks, assessing evidence maturity, distinguishing transferable findings from platform-specific results, and deriving research priorities for future USV observational and operational systems.

1.2 Literature Search and Selection

To make the literature-selection procedure more transparent, a structured literature search was conducted using the Web of Science Core Collection. The primary search covered publications from 1 January 2010 to 26 August 2026, with 26 August 2026 used as the final search date. Because terminology for surface unmanned platforms varies among research communities, the search incorporated commonly used terms including unmanned surface vehicle, uncrewed surface vehicle, autonomous surface vehicle, USV, and ASV. These platform-related terms were combined with application-specific terms corresponding to the six application domains considered in this review.

The application-specific searches covered hydrographic surveying and mapping; air-sea and environmental observation; water-quality, pollution, and biogeochemical monitoring; ecological, fisheries, and acoustic monitoring; infrastructure inspection; and emergency search support. Search terms were selected to represent the principal measurements, targets, and mission types within each domain. Examples included bathymetry, hydrographic survey, mapping, multibeam and side-scan sonar for hydrographic applications; ocean

observation, air-sea measurement, meteorological variables, temperature, salinity, and radiation for environmental observation; water quality, pollution, pH, dissolved oxygen, chlorophyll, nutrients, and carbon-related variables for water-quality and biogeochemical applications; fisheries, fish, plankton, habitat, acoustic telemetry, and passive acoustic monitoring for ecological applications; bridge, pipeline, cable, and inspection for infrastructure applications; and search, rescue, emergency, and submerged-target terminology for emergency-search applications.

The six domain-specific searches returned 285, 327, 264, 262, 180, and 160 records, respectively, corresponding to 1,478 set-level hits before accounting for overlap among the thematic search sets. The six sets were subsequently combined in Web of Science using the Boolean OR operator, resulting in 1,233 unique records. The difference between the summed set-level count and the combined count reflects overlap among the thematic searches and is therefore not interpreted as the removal of 245 independent duplicate publications.

A pragmatic relevance screening was then conducted to identify literature directly related to the mission-oriented scope of this review. Priority was given to studies in which a USV or autonomous surface platform made a substantive contribution to sensing, measurement, monitoring, mapping, inspection, sampling, field deployment, or production of a mission-relevant data product within one of the six application domains. Studies whose primary contribution concerned path planning, collision avoidance, trajectory tracking, formation control, autonomous navigation, docking, or navigation-oriented perception were not treated as core application evidence when the sensing or perception system did not directly contribute to the environmental, hydrographic, ecological, engineering, or search product considered in this review.

An initial title-level screening was used to remove records that were clearly outside the mission-oriented scope. A total of 504 records were identified as clearly outside the core application literature, most commonly because their main contributions concerned vehicle navigation, path planning, collision avoidance, control algorithms, or topics unrelated to the six application domains. Studies dealing principally with platform design, energy supply, communications, positioning, integration, or other enabling technologies were retained separately as supporting literature when they contributed to interpretation of payload performance or operational limitations.

Journal articles and relevant conference papers were considered when they provided substantive information on sensor integration, field experiments, mission implementation, validation, or operational performance. Review articles were used primarily to establish the broader research context and to compare the present framework with previous classifications and technical perspectives. Technical reports and earlier foundational publications outside the primary 2010-2026 search period were retained selectively when they provided established instrumentation principles, standard procedures, or practical operational experience necessary for interpreting the application literature. Commercial information was not used as primary evidence for scientific performance or application maturity; peer-reviewed publications and reports from established institutions were preferred for these assessments.

The literature-selection process can be summarized as follows. The six thematic searches yielded 1,478 set-level hits, which were combined using Boolean OR to obtain 1,233 unique records. Title-level screening identified 504 records that were clearly outside the mission-oriented scope, leaving 729 records in the candidate search pool. This pool was used to identify representative application studies, while relevant methodological studies, review articles, foundational publications, and institutional reports were retained selectively according to the criteria described above.

The final review draws on 69 cited sources. Their selection emphasized direct relevance to the six application domains, clarity of the reported mission and resulting data product, availability of field or validation evidence, relevance of reported technical limitations, and avoidance of repetitive examples. The 729 candidate records were not subjected to a formal systematic full-text screening, and the 69 cited sources should not be interpreted as 69 eligible studies drawn exclusively from the Web of Science search. This procedure provides a transparent account of literature selection for a structured cross-domain narrative review rather than a formal systematic review or meta-analysis. For cross-domain comparison, evidence maturity is evaluated according to the completeness, repeatability, and validation of the reported mission workflow rather than according to the nominal readiness of an individual sensor. In this review, operationally established refers to applications for which multiple field studies or operational deployments demonstrate repeatable workflows, clearly defined data products, and established procedures for the principal supporting requirements. Field-demonstrated refers to applications supported by successful field evidence but still dependent on particular platforms, environmental conditions, specialized integration procedures, or limited validation datasets. Emerging refers to applications for which the available literature mainly demonstrates feasibility, prototype capability, or isolated field cases and for which important limitations in validation, reliability, integration, sampling, processing, or operational implementation remain unresolved. These categories are used as comparative evidence levels within this review and are not intended to represent formal technology-readiness levels. The literature search and selection workflow is summarized in Figure 1.

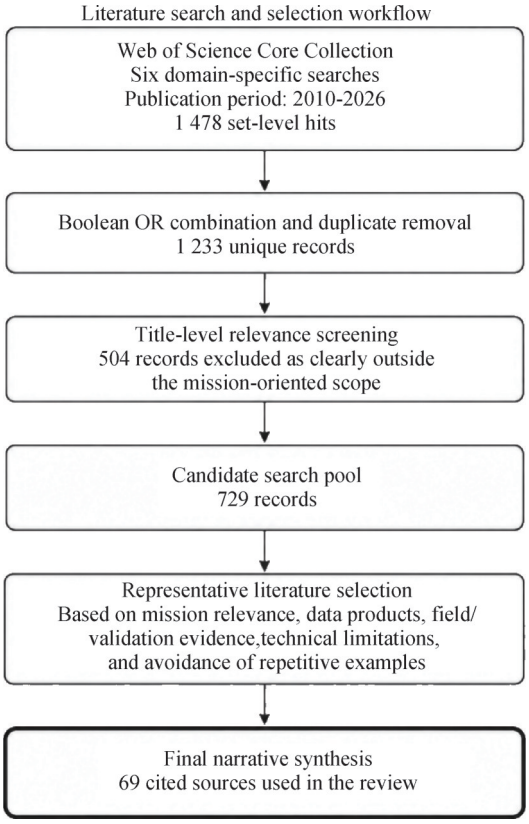


Fig.1 Literature search and selection workflow used in this review.

The remainder of the paper first examines the platform capabilities needed to support reliable payload operation and then classifies representative mission payloads according to their measurements and intended products. The following sections discuss the operational workflows, reported field results, platform roles, evidence maturity, and applicability limits associated with the six application groups. The final section synthesizes the common technical bottlenecks identified across these domains and develops research priorities related to modular payload integration, long-duration reliability, onboard processing and quality control, multi-platform cooperation, validation procedures, and standardized data and metadata management.

2 Platform Support and Mission Payloads

2.1 Platform Support Capabilities

Reliable payload operation depends on more than whether a USV can navigate or physically accommodate an instrument. The platform must provide a consistent position, attitude, and time reference; sufficient power; reliable communications and data handling; suitable mounting conditions; and adequate durability for the intended environment and deployment period. These capabilities determine whether payload data can be acquired continuously, interpreted correctly, and reviewed after the mission. This subsection therefore examines five platform-level requirements: positioning and attitude determination, power and energy management, communications and data links, stability and payload integration, and environmental adaptability and long-duration deployment.

Figure 2 illustrates the functional distinction among platform support modules, mission payloads, and mission-execution units. Platform support modules provide the references, power, communications, mounting arrangements, and operating conditions required by the mission system. Mission payloads directly generate hydrographic, environmental, ecological, search, or inspection data. Mission-execution units perform physical operations such as sampling, filtering, preservation, towing, deployment, recovery, release, and rescue.

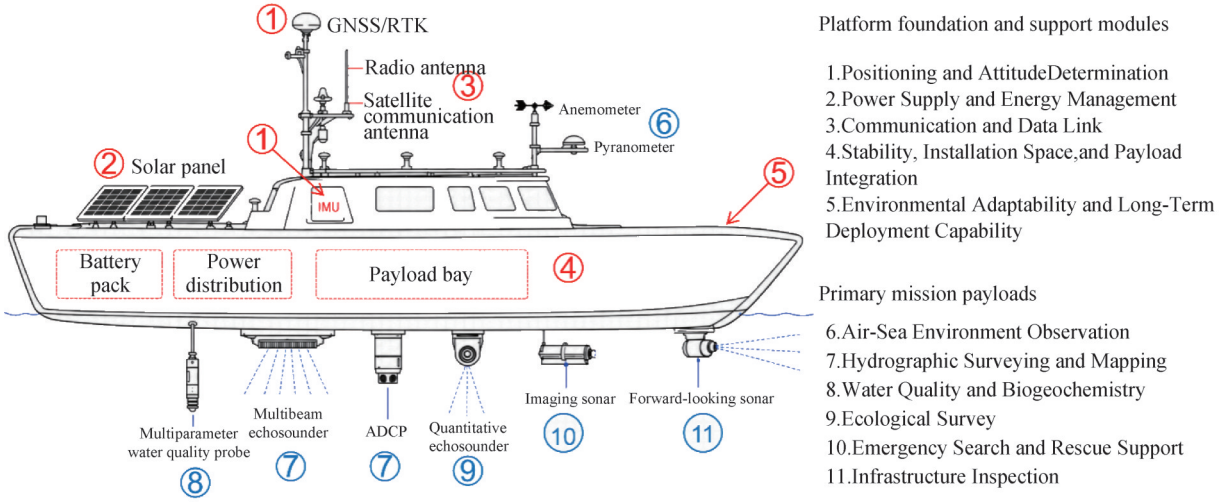


Fig.2 Functional distinction and typical installation locations of platform support modules, mission payloads, and mission-execution units on a USV

This distinction is functional rather than strictly equipment-based. The same instrument may serve different roles in different missions. For example, a conductivity-temperature-depth instrument may be a

mission payload when temperature and salinity are the intended observations, but it serves a supporting role when its measurements are used primarily for sound-speed correction in multibeam surveying.

2.1.1 Positioning and Attitude Determination

Positioning and attitude systems provide the spatial, angular, and temporal references required to georeference and combine payload observations. A typical configuration includes GNSS or RTK-GNSS, an inertial measurement unit, an inertial navigation system, a heading sensor, and a common time source. GNSS provides absolute position and velocity, while inertial sensors maintain a continuous motion estimate during short GNSS interruptions. Dual-antenna GNSS or an electronic compass can improve heading estimation during low-speed surveys, stationary observations, and close-range inspections. Time synchronization associates each payload record with the corresponding platform state[5,7,8].

These references directly affect mission products. Hydrographic surveys require roll, pitch, heading, position, and time corrections to maintain the geometric consistency of multibeam soundings, side-scan sonar strips, and repeated ADCP transects. Air-sea observations may require motion correction for wind measurements and tilt correction for radiation sensors. Ecological surveys, underwater searches, and engineering inspections require accurate event locations so that targets or anomalies can be revisited.

Installation geometry is as important as sensor accuracy. Lever arms, mounting angles, coordinate definitions, and the relative positions of GNSS antennas, inertial sensors, and mission payloads must be measured and documented. This is particularly important for small USVs, whose roll, pitch, and heading vary more rapidly under wind, waves, currents, and propulsion disturbances. A common reference framework is therefore necessary for motion compensation, spatial registration, multisensor fusion, and repeated surveys[7,9].

2.1.2 Power and Energy Management

Power availability constrains mission duration, payload selection, sampling strategy, and data continuity. Active acoustic instruments, such as multibeam echosounders, side-scan sonar, and ADCPs, can impose substantial continuous loads together with navigation, processing, and data-storage equipment. Their operation is also coupled with propulsion because hydrographic surveys often require stable speed and repeated track following. Lower-power meteorological, water-quality, and biogeochemical sensors are generally easier to integrate with long-endurance platforms, but their scientific value depends on continuous sampling and complete time series[2,5].

USVs may use batteries, renewable-energy-assisted electrical systems, or propulsion based on wind and wave energy. Battery-powered platforms are suitable for short surveys, rapid-response missions, and nearshore inspections, but their operating range is limited by stored energy. Solar assistance can extend deployment duration for low-power electronics and sensors, although performance depends on irradiance, weather, deck area, shading, and platform attitude. Wind- and wave-powered vehicles can support long-duration observations but generally have lower transit speeds and limited capacity for high-power payloads. Hybrid energy systems can reduce dependence on a single environmental energy source[10].

Energy management must account for average load, peak load, duty cycle, and mission duration rather than battery capacity alone. Propulsion, communications, onboard computing, navigation, and payloads compete for the same power budget. The platform therefore requires regulated power distribution, protection against voltage disturbances, and priorities for critical systems. When energy becomes limited, nonessential payloads may be deactivated or operated at lower sampling rates. Mission planning should treat available energy as a shared resource and balance survey coverage, platform speed, communication demand, and payload operation[11,12].

2.1.3 Communications and Data Links

Communication systems connect platform telemetry, payload status, mission commands, and selected data products. Short-range radio or wireless local-area networks are commonly used during commissioning, deployment, recovery, and local control. Cellular networks can support nearshore and inland-water operations, whereas offshore and open-ocean missions generally

require satellite links. These options differ in coverage, bandwidth, latency, reliability, and cost, and should therefore be selected according to the operating area and mission requirements[5,11,13].

The communication strategy should reflect the value and volume of different data types. Low-rate measurements, including temperature, salinity, pressure, wind, and platform-health information, can often be transmitted in near real time. Multibeam soundings, side-scan sonar records, continuous imagery, ADCP profiles, and high-resolution ecological-acoustic data are usually too large for continuous transmission through restricted links. In such cases, raw data are stored onboard, while compressed products, quality indicators, or detected events are transmitted for mission supervision[2,6].

Onboard processing can reduce communication demand and improve mission responsiveness. Preliminary quality control, compression, target detection, and anomaly screening can identify whether a survey line should be repeated or a sampling plan should be modified. These functions complement rather than replace full post-mission processing. Communication

links also allow shore-based operators to monitor position, speed, remaining energy, payload condition, and data quality and to update routes, sampling rates, duty cycles, or recovery plans. In cooperative missions, a USV may also act as a communication relay, data gateway, or surface-control node for underwater sensors, AUVs, ROVs, or other USVs[2,13].

2.1.4 Stability and Payload Integration

Platform stability and payload integration determine whether a sensor can maintain the geometry and operating conditions required by its measurement principle. Roll, pitch, and heave affect acoustic beam direction, submerged-sensor position, track keeping, and data quality. Hull size and form also influence deck area, payload capacity, transverse stability, maneuverability, and shallow-water access. Platform selection must therefore reflect payload mass, expected sea state, operating speed, survey accuracy, and deployment conditions[14].

Payload arrangement requires coordinated use of deck, hull, mast, and submerged mounting locations. Under-hull installations are commonly used for single- and multibeam echosounders, ADCPs, and other underwater acoustic instruments. Their performance can be affected by transducer draft, bubbles, wake, vibration, collision risk, and acoustic self-noise. Mast-mounted instruments, including meteorological sensors, radiometers, GNSS antennas, and communication equipment, benefit from improved ventilation or sky visibility but may increase wind loading, vibration, and the height of the center of gravity. Towed or deployable payloads require suitable structural interfaces and sufficient deck space, and their cables or outriggers can affect drag and heading control[6,15].

The combined mass and location of payloads must remain within the structural and stability limits of the platform. Equipment placement should minimize mutual obstruction and interference while maintaining access for cabling, calibration, maintenance, and recovery. Existing multipayload platforms illustrate that sensor accommodation cannot be separated from center-of-gravity control, power distribution, data connections, and operational safety[14,16].

Integration must also establish a common geometric description of the system. Sensor offsets, mounting angles, transducer draft, fields of view, rigid-body relationships, and coordinate systems should be recorded during installation and verified after equipment removal or maintenance. Without this information, data from different instruments cannot be reliably fused, mapped, or compared across deployments[15,17].

2.1.5 Environmental Adaptability and Long-Duration Deployment

Long-duration operation depends on the ability of the hull, payloads, power system, communications, and maintenance strategy to withstand the operating environment. Watertight sealing, corrosion resistance, structural durability, and protected connectors are required to withstand salt spray, water ingress, repeated wet-dry cycles, vibration, impact, and mechanical wear. These requirements apply not only to the hull but also to exposed brackets, sensor housings, battery compartments, cables, and through-hull interfaces[18].

Biofouling can increase hull resistance, alter sensor response, shorten maintenance intervals, and reduce the comparability of long-term records. Copper-based protection, mechanical wipers, and ultraviolet systems can reduce fouling, but their effectiveness depends on installation location, power demand, service life, and compatibility with the measurement system. Antifouling materials placed close to conductivity or salinity sensors may themselves affect observations. Fouling control must therefore be considered together with payload layout and deployment duration[2]. The consequences of environmental exposure also differ among sensor types and measurement principles. Optical and chemical sensors may be directly affected by fouling or contamination of exposed sensing surfaces, whereas the reviewed USV literature more commonly associates degradation of underwater acoustic measurements with transducer installation, bubbles, wake, vibration, platform motion, and acoustic self-noise[6,15,19].

Wind, waves, currents, temperature, solar irradiance, icing, and extreme weather also affect platform availability. USVs can operate in conditions that are difficult or unsafe for crewed platforms, including severe storms and high-latitude waters. However, harsh-weather capability does not eliminate the possibility of actuator, communication, energy, or payload failures. Long-duration systems require health monitoring, fault detection, safe recovery modes, and practical procedures for retrieval, repair, and redeployment[2,20].

Unattended deployment should not be interpreted as maintenance-free operation. Sensors, batteries, storage capacity, clocks, seals, and communication systems require predeployment checks. Platform and payload health should be monitored during the mission, followed by data retrieval, cleaning, inspection, and sensor-calibration review after recovery[18,21]. Long-duration capability must also be evaluated against mission speed, payload power demand, sea-state windows, and deployment and recovery requirements. Sail and wave-powered platforms favour slow and persistent observation, whereas actively propelled USVs provide faster response and greater maneuverability at the cost of shorter endurance[6,22].

These capabilities are interdependent. Position, attitude, and time references make payload data interpretable; power and communications determine how long observations can continue and how rapidly results become available; stability and integration preserve the required measurement geometry; and environmental

Table 1 summarizes the five platform support capabilities and their principal effects on payload operation.

Platform capability	Main engineering elements	Effects on mission payloads
Position, attitude, and time reference	GNSS/RTK, IMU/INS, heading sensors, time synchronization, and calibration of mounting angles and lever arms.	Supports georeferencing, motion compensation, strip registration, multisensor integration, and repeated measurements[7,9].
Power and energy management	Batteries, renewable-energy systems, regulated power distribution, energy budgeting, and payload duty-cycle control.	Constrains payload combinations, sampling rates, continuous operating time, mission range, and deployment duration[10,11].
Communications and data links	Short-range radio, cellular and satellite links, onboard storage, data compression, and edge processing.	Enables telemetry, remote mission adjustment, tiered data transmission, and coordination with other platforms[2,13].
Stability and payload integration	Hull stability, deck and submerged mounting, center-of-gravity control, observation geometry, and coordinate calibration.	affects beam pointing, sensor immersion, equipment obstruction, bubble and self-noise interference, and consistency among payload datasets[6,14,16].
Environmental adaptability and long-duration deployment	Watertight sealing, corrosion and fouling control, health monitoring, maintenance, and deployment and recovery planning.	Determines deployment duration, maintenance intervals, fault recovery, and the continuity and comparability of observations[2,18,20].

durability allows these conditions to be maintained throughout the deployment. Differences in platform size, energy supply, payload capacity, motion characteristics, and mounting interfaces therefore lead to different payload configurations and operating strategies.

2.2 Mission Payloads: Scope and Classification

Mission payloads are sensors and integrated measurement units that directly generate data for observation, surveying, monitoring, underwater search, or infrastructure inspection. This review excludes cameras, thermal imagers, LiDAR systems, and related algorithms when they are used only for vessel detection, water-surface segmentation, obstacle avoidance, or routine navigation. Optical instruments are included only when they contribute directly to mission products, such as underwater ecological imagery, structural inspection records, or survey-data fusion.

Mission payloads are classified here by mission objective and direct data product rather than by sensor name alone. The same instrument may serve different functions across applications. Side-scan sonar, for example, can map seabed texture, screen for submerged targets, or inspect pipelines and submarine cables. Table 2 therefore organizes payloads according to the mission questions they address. This functional classification describes what payloads measure and what products they generate, whereas application maturity is assessed separately in Section 3 according to workflow completeness, validation evidence, and operational repeatability.

The associations in Table 3 show that payload selection cannot be based on platform size or sensor type alone. Lightweight instruments are generally easier to operate on small nearshore platforms, whereas integrated acoustic surveys require greater stability, power, and mounting capacity. Persistent environmental and passive-acoustic observations favour low-power, long-endurance vehicles. Tasks requiring close access to the seabed or underwater structures often require cooperation between a USV and an underwater platform. The following subsections examine the direct products and operating requirements of each payload category.

Payload suitability also depends on platform capacity, available power, motion characteristics, mounting geometry, propulsion noise, and deployment duration.

2.2.1 Hydrographic Survey Payloads

Hydrographic work conducted from a USV generally requires four types of information: water depth, acoustic imagery of the bed, water-column velocity, and variations in water level. No single instrument provides all of these products. Single- and multibeam echosounders provide depth information, with MBES used when detailed swath coverage is required; side-scan sonar records acoustic texture and target signatures, an ADCP resolves current structure, and water-level instruments provide a time-dependent reference for interpreting the survey. Their functions overlap in some cases, but the instruments are not interchangeable [15,23].

Multibeam Echosounder

A multibeam echosounder (MBES) insonifies a fan-shaped sector beneath and to either side of the vessel.

Table 2 Classification of USV mission payloads beyond routine surface perception

Mission category	Mission questions	Typical payloads	Representative references
Hydrographic surveying and mapping	What are the water depth, seabed morphology, current structure, and water-level conditions?	Multibeam and single-beam echosounders, side-scan sonar, ADCP, and water-level sensors.	[15,23-28]
Air-sea and environmental observation	What are the near-surface atmospheric, radiative, and upper-ocean conditions?	Wind, air-temperature, humidity, pressure, precipitation, and radiation sensors; CTD instruments; temperature and salinity sensors; and thermistor chains.	[2,21,29-34]
Water-quality, pollution, and biogeochemical monitoring	What are the physicochemical state, pollution conditions, nutrient regime, and relevant ecological or carbonate-system variables?	Multiparameter sondes; temperature, pH, dissolved-oxygen, turbidity, conductivity, and ORP sensors; chlorophyll fluorometers; pCO_2 sensors; and nutrient analyzers.	[35-46]
Ecological surveys, fisheries, and acoustic monitoring	How are organisms, habitats, movements, and biological acoustic activity distributed?	Scientific and fish-finding echosounders, multifrequency acoustic systems, underwater and stereo cameras, spectral imagers, acoustic telemetry receivers, and hydrophone arrays.	[6,47-51]
Emergency search support	Where are submerged targets, persons, or physical evidence, and which areas require close verification?	Side-scan sonar for broad-area screening and forward-looking or imaging sonar for target approach and local verification.	[52,53]
Infrastructure inspection	What are the condition, scour, burial, alignment, and anomalies of underwater structures and linear assets?	Imaging, scanning, forward-looking, three-dimensional, multibeam, and side-scan sonar. Cooperating underwater platforms may carry sub-bottom profilers, magnetic or electromagnetic instruments, cameras, and laser scanners.	[54-58]

Note: Payloads are classified by their function in a mission. A CTD is a mission payload when temperature and salinity are the intended products, but it serves a supporting role when used mainly for sound-speed correction. Navigation, power, communication, and data-recording systems are platform support modules. Sampling, filtering, preservation, towing, deployment, release, recovery, and rescue mechanisms are mission-execution units.

Table 3 summarizes representative platform-payload associations reported across the literature.

Platform or operating configuration	Typical characteristics	Representative payloads	References
Small nearshore USVs	Shallow draft and simple deployment, but limited payload capacity, power, stability, and endurance.	Multiparameter sondes, temperature and salinity sensors, compact underwater cameras, and other lightweight, low-power instruments.	[35,37, 38,48]
Medium modular survey USVs	Greater stability, payload capacity, power, and access to submerged mounting interfaces; suitable for simultaneous operation of several instruments.	Multibeam and single-beam echosounders, side-scan sonar, ADCP, imaging and forward-looking sonar, scientific echosounders, and water-quality instruments.	[6,15, 16,23]
Long-endurance renewable-energy USVs	Suitable for persistent offshore observation, but generally constrained in speed, average available power, and operation of high-power instruments.	Meteorological and radiation sensors, upper-ocean temperature and salinity instruments, chlorophyll fluorometers, pCO_2 sensors, telemetry receivers, and hydrophone arrays.	[2,21,29, 50,51]
Surface-subsurface cooperative systems	The USV provides supervision, communication relay, acoustic positioning, or deployment and recovery support for an AUV, ROV, or towed body.	The USV may carry mapping sonar, while the underwater platform carries sub-bottom profilers, magnetic or electromagnetic sensors, close-range sonar, cameras, or laser scanners.	[57,58]

Note: These associations summarize representative cases rather than fixed compatibility rules. Actual configurations depend on payload mass and power demand, platform motion, mounting geometry, self-noise, operating speed, communication capacity, and environmental conditions.

Range and beam-angle observations are combined with position, attitude, time, and sound-speed information so that individual returns can be converted into a georeferenced swath of depth soundings. The recorded backscatter may provide additional evidence on seabed characteristics, although bathymetry remains the primary product[24]. The representative MBES measurement geometry and swath coverage are illustrated in Figure 3.

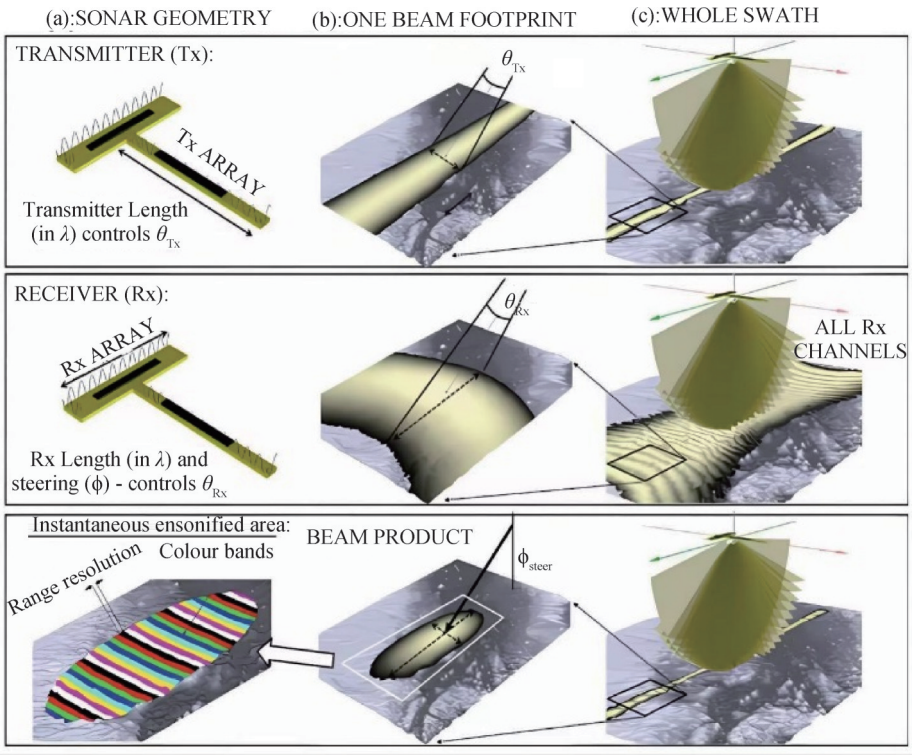


Fig.3 Measurement geometry and swath coverage of a multibeam echosounder, redrawn from [23].

A single-beam echosounder (SBES) measures depth beneath the vessel along the survey track. Its relatively simple installation, modest power demand, and low data volume make it suitable for small USVs, reconnaissance surveys, and repeated profiles in rivers, reservoirs, or confined waters. Its coverage is nevertheless limited to a narrow line and depends strongly on survey-track

spacing. An MBES instead builds a continuous corridor of soundings as the USV moves forward, producing a more detailed surface of seabed or riverbed geometry. Both products differ from side-scan imagery, which emphasizes acoustic appearance, and from ADCP measurements, which describe processes within the water column.

Bathymetric quality is not uniform across the swath. It varies with water depth, operating frequency, beamwidth, bottom-detection performance, transducer-to-bed range, and the treatment of sound speed. Footprints generally enlarge toward the outer beams, making small features more difficult to resolve. Errors in the sound-speed field alter acoustic ray paths and may shift both the depth and horizontal position of a sounding. For this reason, MBES surveys normally combine surface sound-speed measurements with a sound-speed profiler or a CTD, as appropriate, and require accurate positioning, attitude observations, time synchronization, and installation calibration[24].

The platform itself is also part of the measurement system. Roll, pitch, and heave alter beam orientation, while bubbles, wake, vibration, and propulsion noise may obscure or weaken the returned signal. A USV intended for high-resolution multibeam work must therefore provide adequate stability and payload capacity, precise navigation, a well-documented sensor geometry, and an installation that limits acoustic interference.

Side-Scan Sonar

Side-scan sonar is used when the acoustic appearance of the seabed is of greater interest than depth alone. It transmits beams to both sides of the survey line and records the travel time and strength of the returning echoes. The image formed from these records shows variations in backscatter and acoustic shadowing rather than a direct bathymetric surface. Typical uses include submerged-target detection, sediment-boundary mapping, bedform identification, and screening between bathymetric survey lines[25,26].

Objects with a strong acoustic contrast commonly appear as bright returns followed by shadows. The return-shadow combination can provide clues to target shape and approximate height. Changes in texture and intensity may also distinguish mud, sand, gravel, rock, bedforms, or artificial objects. In this respect, side-scan products add information on seabed appearance and target characteristics that is not contained in terrain geometry alone. The typical imaging geometry of side-scan sonar is illustrated in Figure 4.

The choice between hull mounting and a towfish involves a practical trade-off. A hull-mounted sonar is easier to integrate with the USV navigation solution and provides a more direct geometric relationship with the platform. Towing can place the transducer closer to the bed and reduce some forms of hull or propulsion interference, but the position and attitude of the towfish are less certain and must be reconstructed separately.

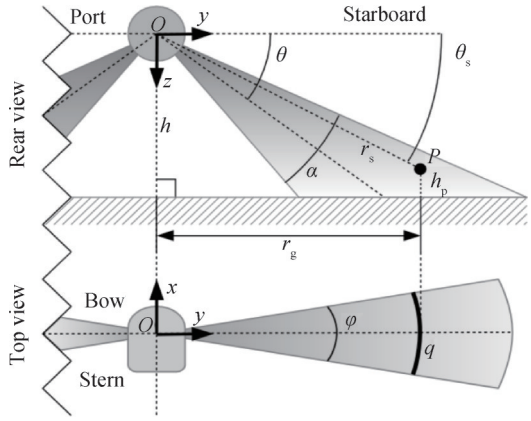


Fig.4 Typical imaging geometry of side-scan sonar, redrawn from[25].

Several effects must be addressed before individual sonar lines can be used as a mapped product. Track instability, changing survey altitude, unsuitable range settings, acoustic interference, and inaccurate positioning all reduce image consistency. Raw records may also contain a central nadir region and geometric distortions associated with slant range, platform motion, and seabed relief. Processing commonly includes slant-range correction, motion compensation, georeferencing, and the mosaicking of overlapping lines[25].

ADCP

An acoustic Doppler current profiler (ADCP) infers water velocity from the Doppler shift of echoes returned by particles moving with the surrounding flow. It produces depth-resolved velocity profiles that can be examined along a transect or through time. Depending on the instrument configuration and survey design, bottom tracking, echo intensity, and repeated observations may also contribute information on discharge, suspended material, sediment transport, or bedform migration[27].

These additional uses should be separated from the instrument's primary function. Water-column velocity and current structure are the direct ADCP products. Bed elevation or bedform movement inferred from bottom tracking and repeated acoustic records is an extended product that depends on further processing. Such information may be useful for change analysis, but it does not normally provide the terrain detail expected from an MBES survey.

USV motion forms part of the measured velocity and must be removed during processing. The survey also requires reliable position and heading, a known transducer orientation, an appropriate vehicle speed, and sufficient acoustic range for the selected water depth. Blanking distance, depth-cell size, beam geometry, and track layout determine which part of the water column is sampled and at what resolution. With these conditions controlled, a USV-mounted ADCP can map cross-sectional flow, velocity gradients, discharge, and spatial or temporal hydrodynamic variability.

Water-Level Sensors

Water-level observations provide a temporal reference that complements bathymetric and current measurements. They may be obtained from pressure sensors, radar or ultrasonic ranging devices, optical instruments, or other contact and noncontact systems[28]. Depending on the mission, their records can support tidal or river-stage monitoring, depth reduction, discharge estimation, and the interpretation of changing hydrological boundary conditions.

Measurements collected onboard a USV are useful for documenting local water-level changes during a survey, but they rarely define the full vertical datum on their own. Final hydrographic products may still be referenced to a shore-based tide gauge, a fixed monitoring station, GNSS-derived water levels, or an established geodetic datum. The onboard sensor is therefore most often used as a local reference, an auxiliary correction source, or a record of short-term variation along the mission route.

These instruments usually impose modest power and data demands and can be operated during extended missions. Their accuracy nevertheless depends on installation height or immersion depth, platform motion, pressure and temperature correction, waterproofing, corrosion protection, and continuous data logging. Water-level records are consequently most useful when they are synchronized with positioning, bathymetry, and current measurements rather than interpreted as an isolated survey product.

Taken together, MBES, side-scan sonar, ADCPs, and water-level sensors describe different aspects of the same hydrographic environment: terrain geometry, acoustic appearance, water-column motion, and temporal reference level. The combination selected for a mission should reflect whether the main objective is detailed bathymetry, target screening, hydrodynamic characterization, or correction for changing water level. In every case, the usefulness of the final product depends on more than payload choice; positioning, motion correction, survey control, interference management, calibration, and post-processing must be coordinated across the complete measurement system.

2.2.2 Air-Sea Observation Payloads

Air-sea studies require atmospheric, radiative, and upper-ocean measurements to be collected at approximately the same location and time. By following planned routes, USVs can obtain continuous records of these variables and complement observations from fixed buoys, satellites, and crewed vessels. A typical payload suite combines meteorological instruments, radiometers, and temperature and salinity sensors, while some platforms also carry current meters and biogeochemical sensors [2,22]. For discussion, the principal payloads are divided into meteorological sensors, radiation sensors, and upper-ocean physical sensors.

Meteorological Sensors

Meteorological payloads usually record wind speed

and direction, air temperature, relative humidity, and atmospheric pressure. Rain gauges may also be included when precipitation is relevant to the mission. The resulting time series describe the near-surface atmospheric state and provide inputs for estimating momentum, sensible heat, and latent heat fluxes, although the instruments do not generally measure turbulent fluxes directly.

Figure 5 presents a representative arrangement of meteorological and oceanographic sensors on a Saildrone. Wind instruments are mounted at elevated and relatively unobstructed locations to limit flow distortion. Temperature and humidity probes require ventilation and protection from direct solar heating, whereas pressure measurements depend on a stable enclosure and reliable data logging. The arrangement shows that sensor placement should follow exposure and measurement requirements rather than simply the availability of mounting space.

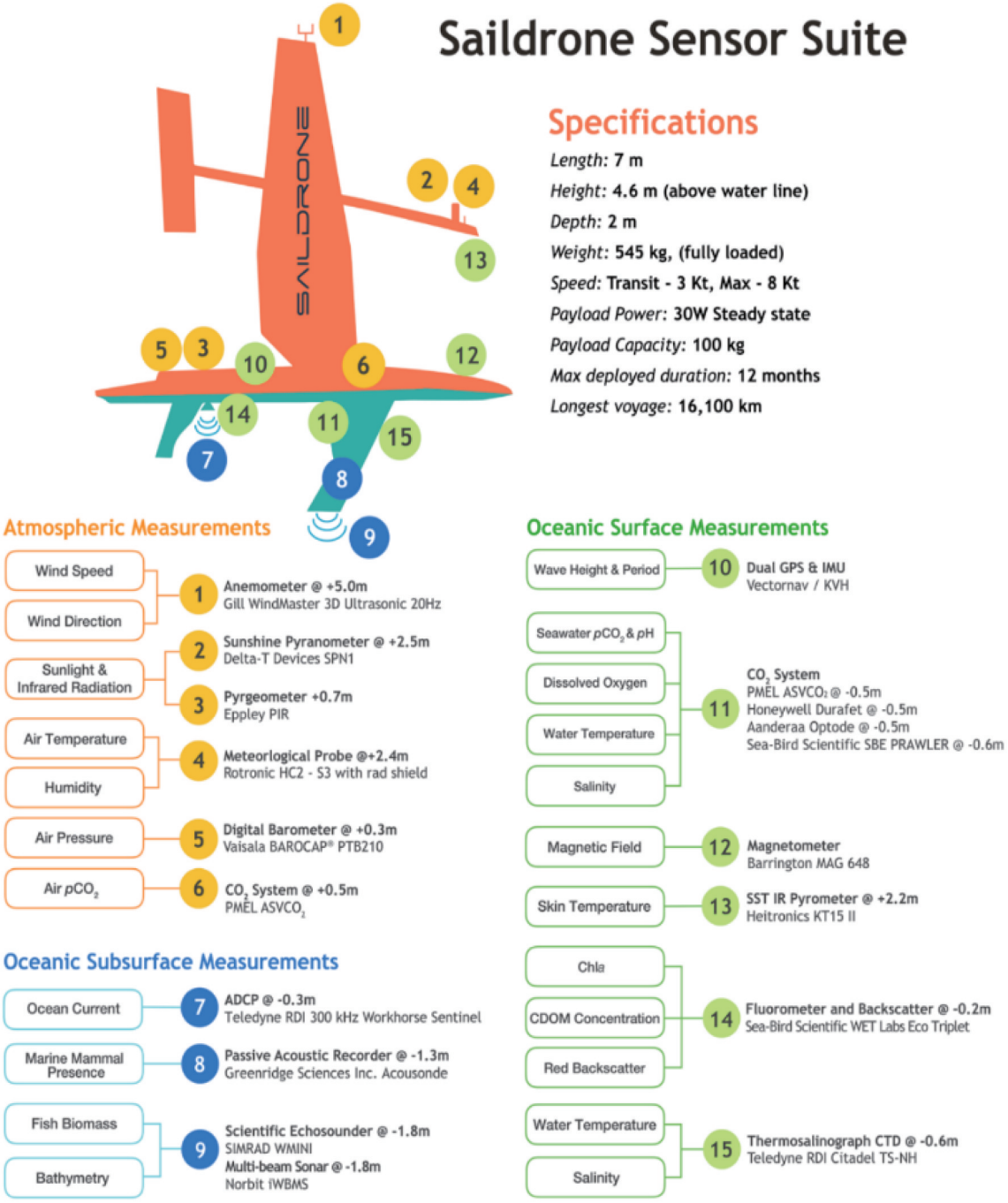


Fig.5 Representative arrangement of meteorological and oceanographic sensors on a Saildrone platform, redrawn from[29].

Measurement height and vehicle motion need to be accounted for during data processing. Wind, temperature, and humidity vary with height near the sea surface, and observations may therefore need to be adjusted to standard reference levels. The wind measured onboard also contains contributions from vehicle translation and rotation. Correcting these effects requires platform velocity and attitude records in addition to the raw wind

measurements[29].

Amador et al. assessed mast-mounted meteorological instruments on a Wave Glider. After motion compensation, wind-speed and wind-direction errors were reduced by 45% and 16%, respectively. Biases of 0.11 hPa in sea-level pressure and 0.09 ℃ in air temperature were also reported. The results suggest that meteorological observations from a carefully integrated USV can approach operational measurement requirements[30].

The relatively small size and modest power demand of most meteorological instruments make them suitable for persistent missions. Their accuracy, however, remains sensitive to mounting position, ventilation, motion information, reference-height adjustment, calibration, and quality-control procedures.

Radiation Sensors

Radiation payloads record downward shortwave and longwave irradiance at the sea surface. These measurements are used in surface energy-budget studies, heat-flux estimation, investigations of cloud effects, and the validation of satellite radiation products. Some instrument packages further separate direct and diffuse components of shortwave radiation.

Platform attitude and structural obstruction are particularly important for radiometers. Roll and pitch change the angle between the sensing surface and the incoming solar radiation, producing a departure from the desired horizontal reference. Shortwave measurements may therefore require high-frequency attitude observations, tilt correction, and suitable temporal averaging. Radiometers also need a clear hemispheric field of view, with as little shading as possible from masts, antennas, and other equipment. Sea spray, reflections from nearby structures, and local thermal effects can introduce additional errors[31].

Instrument choice reflects a balance between measurement performance and ease of installation. Thermopile radiometers generally cover a broader spectral range, while photodiode instruments are smaller, lighter, and more readily accommodated on compact USVs. Lightweight shortwave radiometers have been operated on solar-powered vessels, showing that useful irradiance records can be obtained when motion, shading, and quality-control issues are properly addressed[31,32].

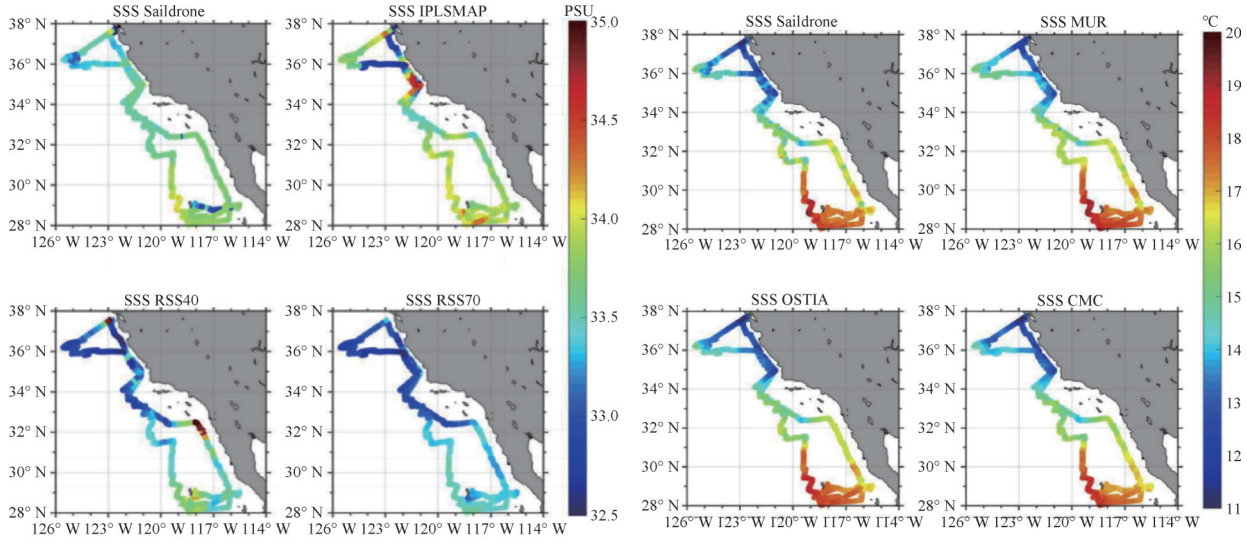
Radiation observations should therefore be treated as the product of both the radiometer and its installation. Appropriate mounting geometry, reliable attitude information, unobstructed exposure, and consistent quality control are all needed before the measurements can be interpreted as dependable irradiance records.

Upper-Ocean Physical Sensors

Upper-ocean physical payloads mainly measure temperature and salinity. Typical instruments include CTD sensors, conductivity and temperature probes, and thermistor chains. Some platforms also carry separate instruments for skin and bulk temperature. Their outputs include georeferenced time series, along-track sections, and spatial fields describing the thermal and salinity structure of the upper ocean.

Measurements collected from a moving USV can resolve fronts, upwelling zones, freshwater plumes, coastal gradients, and other relatively small-scale ocean features. They also provide in situ references for satellite sea-surface temperature and salinity products. In one Saildrone configuration, for example, a CTD was installed at a depth of approximately 0.6 m and sampled at intervals of about 1 min. Such measurements represent bulk near-surface water conditions rather than the micrometer-scale skin temperature sensed by infrared satellite instruments.

Figure 6 shows representative comparisons between USV observations and satellite temperature and salinity products.



(a) Near-surface temperature (b) Near-surface salinity

Fig.6 Comparison of USV observations with satellite products for (a) near-surface temperature and (b) near-surface salinity, redrawn from[33].

During a 60 d mission along the California-Baja California coast, Saildrone temperature observations showed close agreement with several GHRSST Level 4 products. Agreement between in situ salinity measurements and SMAP products was less consistent. The correspondence became weaker when spatial gradients and frontal intensity were compared instead of the measured temperature and salinity values themselves[34]. Continuous transects from a USV may therefore retain fine-scale variability that is partly smoothed in gridded satellite products.

Interpretation also depends on measurement depth and local environmental conditions. Differences between satellite skin temperature and submerged observations may become larger during diurnal warming, rainfall, weak vertical mixing, or strong stratification. Salinity records can be affected by freshwater inputs, vertical gradients, small-scale spatial variability, biofouling, and sensor drift. Extended missions consequently require stable sensor immersion, accurate position and time records, calibration checks, and appropriate fouling control[33,34].

Meteorological, radiation, and upper-ocean physical sensors describe different but closely related components of the air-sea system. When operated together, they support process studies and comparisons with satellite products. The reliability of these records depends not only on nominal sensor performance, but also on vehicle motion, sensor placement, synchronization, calibration, and the quality-control procedures applied during and after deployment.

2.2.3 Water Quality and Biogeochemical Payloads

Water quality and biogeochemical payloads measure aquatic conditions, pollution-related anomalies, and ecological processes. Routine water quality sensors record physicochemical variables such as temperature, pH, dissolved oxygen (DO), conductivity, turbidity, salinity, total dissolved solids (TDS), and oxidation-reduction potential (ORP). More specialized instruments measure chlorophyll fluorescence, pCO_2, nitrate, phosphate, and related variables associated with primary production, carbon cycling, and nutrient dynamics. When integrated with positioning and data-logging systems, these payloads allow USVs to convert isolated measurements into continuous, georeferenced observations[35,36].

This review distinguishes between conventional water quality sensors, which mainly describe the physicochemical state of a water body, and biogeochemical instruments, which provide information on ecological and material-cycle processes.

Conventional Water Quality Sensors

Conventional water quality sensors are widely used for environmental assessment, pollution screening, and the detection of spatial variability. Jo et al. equipped SMARTBoat 3 with pH, turbidity, and temperature sensors for monitoring ponds, reservoirs, and lakes[37]. Other small USVs have carried turbidity, TDS, pH, or multiparameter probes for continuous monitoring and remote data transmission[35,38]. USV measurements have also been used to reconstruct the spatial distribution of pollution plumes[39].

Figure 7 shows a representative water quality monitoring system. Sensor measurements are associated with position and time records, allowing environmental conditions to be mapped along the vehicle trajectory.

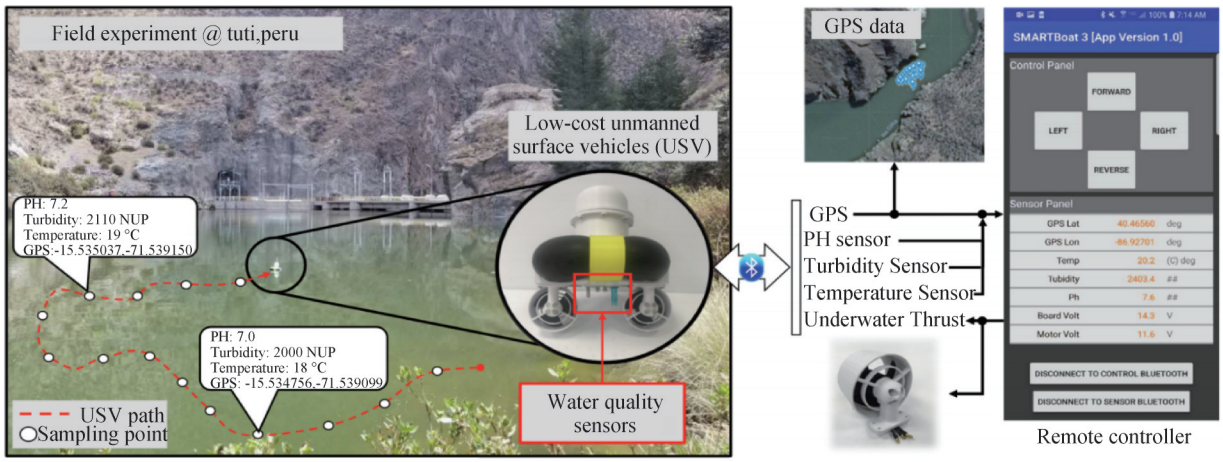


Fig.7 Water quality monitoring with SMARTBoat 3 in natural water bodies (redrawn from[37])

The main advantage of a USV is not the measurement of new variables, but the ability to collect them at higher spatial resolution than conventional grab sampling. AquaBOT, for example, achieved approximately ten times the spatial resolution of manual sampling and identified local water quality hotspots downstream of outfalls[38]. Similar systems can provide near-real-time maps of physicochemical conditions and guide subsequent sampling or investigation[41].

These variables should generally be interpreted as indicators of environmental condition rather than direct identifiers of specific pollutants. Temperature, pH, DO, conductivity, and turbidity can reveal gradients, anomalous water masses, or possible pollution inputs, but

chemical confirmation may still require grab samples or dedicated analytical instruments[40,41].

Reliable operation depends on sensor placement and maintenance. Sensors should remain at a representative and reasonably stable depth while avoiding bubbles, wake, hull contamination, and local flow disturbance. Position and time synchronization are required to create valid spatial distributions. Calibration, cleaning, drift correction, corrosion protection, and fouling control become increasingly important during extended deployments. Biofouling can degrade marine sensor performance within short deployment periods and may introduce variable-specific biases[40,19]. Conventional water quality payloads are therefore relatively easy to integrate, but their usefulness depends on stable sampling, accurate georeferencing, and regular quality control.

Biogeochemical Payloads

Biogeochemical payloads measure variables associated with phytoplankton dynamics, carbonate chemistry, and nutrient cycling. Representative instruments include chlorophyll fluorometers, pCO_2 sensors, pH sensors used in carbonate-system analysis, and nitrate or phosphate analyzers[36,42].

Chlorophyll fluorescence is commonly used as a proxy for changes in phytoplankton abundance or activity. However, fluorescence is affected by community composition, pigment properties, light history, and fluorescence yield and should not be treated as a direct measurement of absolute biomass without appropriate calibration[43]. Measurements of pCO_2, particularly when combined with pH or other carbonate-system variables, support the analysis of water-air carbon exchange and acidification processes[42,44]. Nutrient sensors provide information on nitrate, phosphate, and other compounds that constrain primary production and eutrophication, although interpretation must also consider transport, biological uptake, and regeneration[35,45].

Continuous USV transects can reveal process-related spatial patterns that are difficult to resolve through discrete sampling. AquaBOT combined a nitrate sensor with a multiparameter probe containing a chlorophyll channel and detected strong nitrate variability and local hotspots along a river[38]. Other surface platforms have measured carbonate-system variables, DO, salinity, chlorophyll fluorescence, and nutrients together to investigate the origin and development of low-pH and high-pCO2 waters[44].

Figure 8 illustrates how continuous USV observations can resolve coordinated variations among several variables between conventional sampling locations.

The value of these measurements lies in their combined interpretation. Covariation among pH, pCO_2, DO, salinity, chlorophyll fluorescence, and nutrients may help distinguish biological metabolism, freshwater influence, water-mass transport, or other controls on local

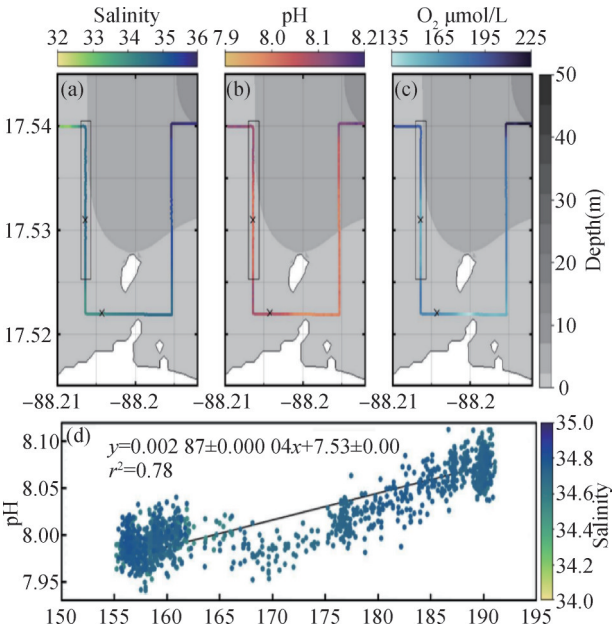


Fig.8 High-resolution USV observations showing local variations in pH, dissolved oxygen, and salinity (redrawn from[44])

environmental change. USVs can therefore support a transition from mapping individual variables to examining interactions among ecological and chemical processes.

Biogeochemical instruments generally place greater demands on the platform than conventional probes. pCO_2, carbonate-system, and nutrient measurements may require a stable water intake, controlled flow paths, temperature correction, sustained power, and continuous data logging[44,46]. Wet-chemical nutrient analyzers may also require reagents, standards, pumps, and waste storage. Microfluidic and lab-on-chip systems reduce fluid and power consumption but do not eliminate the need for calibration and flow management[45].

Long deployments must also address sensor drift, fouling, reagent consumption, calibration stability, and differences in response time among instruments. Accurate position and time records are necessary when variables from several sensors are combined. Biogeochemical payload integration therefore requires coordinated sampling, power management, data acquisition, and quality control rather than the physical installation of individual instruments alone.

Conventional water quality sensors provide broad and continuous descriptions of physicochemical conditions, whereas biogeochemical instruments support more specific interpretation of ecological, nutrient, and carbon-cycle processes. Together, they allow USVs to identify environmental anomalies, map spatial gradients, guide targeted sampling, and investigate the processes responsible for observed changes.

2.2.4 Ecological Survey Payloads

Ecological survey payloads enable USVs to investigate organisms in the water column, benthic

habitats, animal movements, and biological acoustic activity. The main payload groups considered here are scientific echosounders for water-column surveys, optical sensors for benthic mapping, and acoustic telemetry or passive acoustic systems for animal tracking and monitoring. Compared with crewed vessels or fixed stations, USVs can provide repeated transects and persistent observations in shallow, coastal, or disturbance-sensitive environments[6].

Ecological Acoustic Payloads

Ecological acoustic payloads commonly include scientific echosounders, fish-finding echosounders, and multifrequency acoustic systems. Their direct products are georeferenced records of water-column backscatter, from which biological scattering layers, fish schools, zooplankton distributions, and relative abundance patterns can be identified[6]. Unlike hydrographic sonar, which primarily characterizes the seabed, ecological acoustic systems focus on biological targets within the water column.

Backscatter does not identify species or biomass by itself. Interpretation usually requires calibration and supporting information from trawl sampling, optical observations, historical surveys, or prior knowledge of species composition. De Robertis et al., for example, deployed three echosounder-equipped USVs to continue surveys of walleye pollock in the Bering Sea when conventional ship operations were constrained. The study demonstrated that USVs could extend observations of fish distribution and relative abundance, while also showing the limitations of estimating species and size composition without simultaneous biological sampling.

Figure 9 shows representative products from such surveys. Echograms provide the direct acoustic observations, whereas biomass or abundance estimates require an additional interpretation step based on calibration and biological information.

Ecological acoustic surveys place substantial demands on platform integration. Transducers require appropriate immersion and low acoustic interference, while stable speed and attitude improve the consistency of repeated transects. Propulsion noise, bubbles, vibration, and platform motion can degrade acoustic measurements. Reliable surveys therefore require careful transducer installation, calibration, motion information, speed control, and data-quality assessment[6,47].

Optical Ecological Payloads

Optical ecological payloads are mainly used to map shallow benthic habitats and visually characterize organisms or substrate features. Typical instruments include underwater cameras and stereo cameras, with multispectral or hyperspectral systems used when spectral differences among habitat classes are important.

Continuous imagery collected along planned USV tracks can be processed into orthomosaics, three-dimensional surface models, and habitat-classification maps. Raber et al., for example, used stereo imagery from

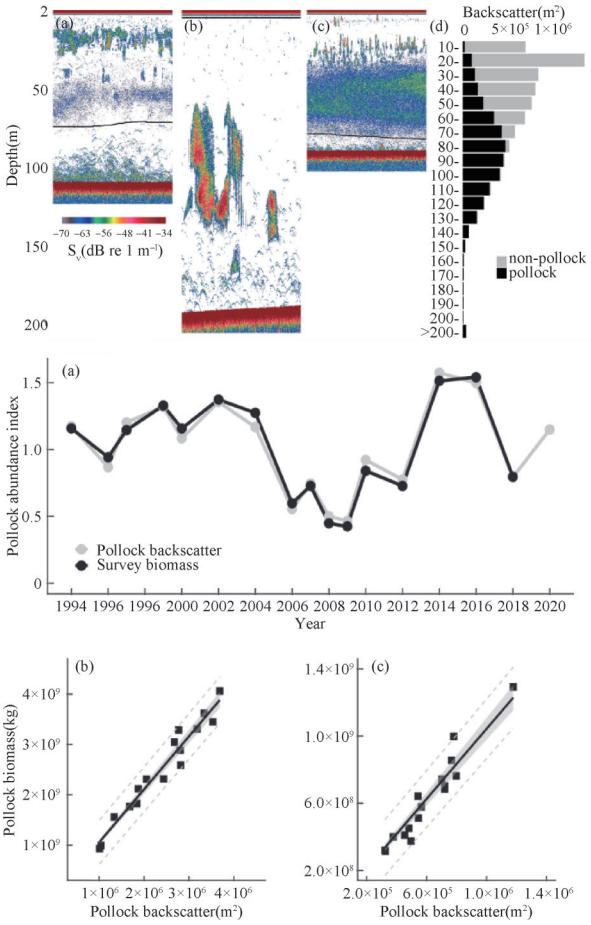


Fig.9 Representative products from USV-based ecological acoustic surveys: water-column echograms and the relationship between pollock backscatter and biomass estimates (redrawn from[47])

Reef Rover to generate high-resolution orthomosaics and digital surface models through structure-from-motion processing. Related UAV-USV workflows have been used to distinguish benthic classes such as seagrass, hard bottom, and macroalgae. Representative benthic survey products generated using Reef Rover are shown in Figure 10.

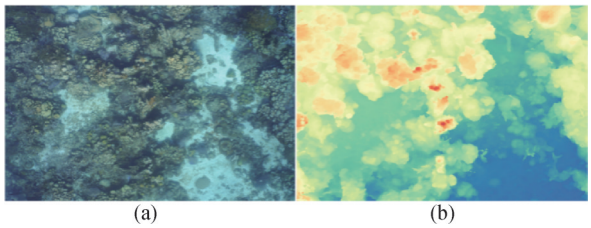


Fig.10 Representative benthic survey products generated from underwater imagery collected by Reef Rover, including an orthomosaic and a digital surface model (redrawn from[48])

The value of optical payloads therefore lies in converting repeated imagery into measurable spatial products rather than in collecting individual photographs. USVs are particularly useful in shallow water because they can maintain preplanned tracks and acquire imagery close to the target area without relying on divers. Data quality nevertheless depends on water clarity, illumi-

nation, camera immersion, vehicle speed, image overlap, and platform attitude. Stable motion and repeatable track geometry are especially important for photogrammetric reconstruction and temporal comparison[48,49].

Animal Tracking and Passive Acoustic Payloads

Acoustic telemetry and passive acoustic monitoring extend USV ecological surveys from habitat and group-level observations to individual animals and biological sound sources. Acoustic telemetry receivers detect signals transmitted by tagged animals and can be used to study movement, occurrence, and habitat use. Hydrophones and hydrophone arrays record biological sounds and can support detection, localization, and long-duration monitoring of vocalizing species[50,51].

Mobile USVs can complement fixed receiver networks by surveying areas between stationary stations or following spatially separated habitats. Reyier et al. showed that Wave Gliders equipped with acoustic telemetry receivers could extend the spatial coverage of fixed arrays during long-duration surveys. Passive acoustic systems have also been integrated with Wave Gliders using towed hydrophone arrays and onboard signal processing for marine-mammal monitoring, as illustrated in Figure 11[51].

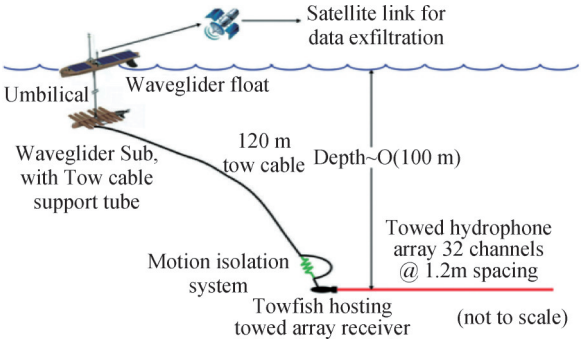


Fig.11 Wave Glider system equipped with a towed hydrophone array, onboard signal processing, and satellite communication for passive acoustic monitoring (redrawn from[51])

These missions require low platform self-noise, suitable receiver or hydrophone depth, vibration isolation, sufficient storage and power, and reliable position and time records. Towed arrays also introduce additional requirements for tow geometry and vehicle-speed control. When onboard processing and communication are available, selected detections or acoustic products can be transmitted during the mission rather than waiting for full post-recovery analysis.

Autonomous eDNA sampling represents a related but functionally different ecological capability. In contrast to acoustic or optical payloads that directly generate observation products onboard, eDNA systems require physical sample acquisition, filtration, preservation, and subsequent molecular analysis. The USV mainly provides the sampling trajectory, environmental context, and operational support rather than directly producing the final biodiversity measurement. Therefore, autonomous eDNA sampling is treated as an emerging mission workflow in Section 3 rather than as a conventional ecological sensing payload.

Overall, ecological payloads address three complementary observation targets. Scientific echosounders characterize biological scattering in the water column, optical systems map shallow benthic habitats, and telemetry or passive acoustic systems record animal occurrence, movement, and sound production. In all three cases, sensor outputs require ecological interpretation and often benefit from supporting biological observations or environmental data. The role of the USV is therefore not only to carry the sensors, but also to provide repeatable trajectories, accurate georeferencing, sufficient endurance, stable measurement conditions, and low-interference operation.

2.2.5 Emergency Search Support Payloads

Emergency search payloads are used to locate submerged targets and generate spatial cues for subsequent verification or recovery. The search function should be distinguished from rescue or recovery operations, which require physical intervention capabilities and are therefore considered mission-execution functions rather than sensing payloads in this review. Side-scan sonar supports broad-area screening, whereas forward-looking and imaging sonar can assist with target approach and close-range examination in turbid or low-visibility water. This review focuses on underwater search rather than the visual detection of floating objects[52,53].

Underwater Target Search

Emergency underwater searches may involve submerged persons, physical evidence, hazardous objects, or other anomalies. Conventional diver searches are slow and expose personnel to poor visibility, obstacles, currents, and other hazards. A USV equipped with side-scan sonar can first survey the area and direct divers or recovery teams toward selected locations.

The PRIME system demonstrates this workflow. The USV follows planned survey lines, records side-scan sonar data, generates coverage and anomaly maps, and transmits selected results to a shore station. The output is therefore not simply a sonar image, but a georeferenced set of search cues that can be reviewed and used to prioritize subsequent operations[53].

Survey-track quality directly affects the sonar data. As shown in Figure 12, turning and inconsistent speed can result in uneven acoustic coverage and image distortion, reducing the quality of sonar data. Broad-area searches therefore require stable, low-speed motion along approximately straight and parallel tracks.

Raw sonar records may also be processed into more direct decision products. Figure 13 illustrates how filtering and image-complexity analysis can highlight suspicious regions and generate an anomaly heatmap. Such products reduce the amount of raw imagery that

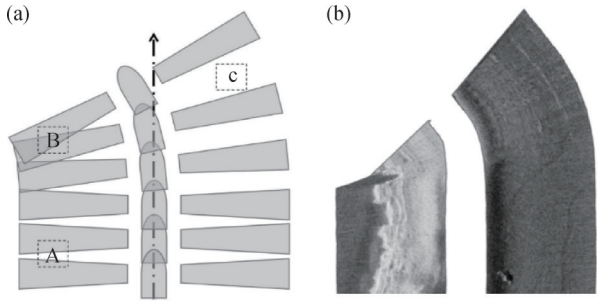


Fig.12 Effect of USV track linearity on side-scan sonar image quality (redrawn from[53])

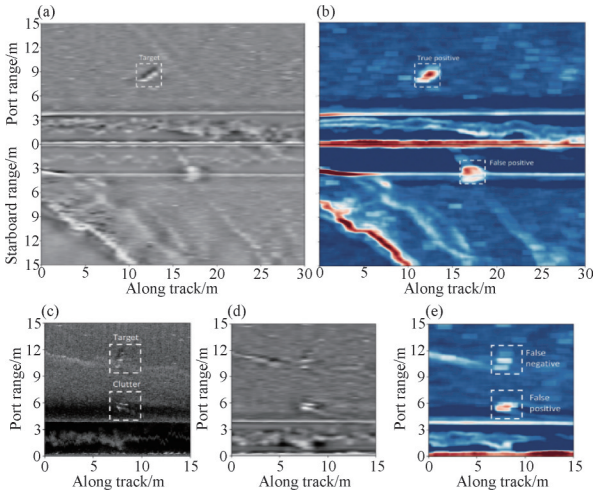


Fig.13 Generation of an anomaly heatmap from side-scan sonar imagery (redrawn from[53])

must be inspected manually and help define priority verification areas.

Reliable search products require accurate position, heading, and time records, together with known sonar geometry and stable vehicle motion. Communication links are also useful for transmitting platform status, coverage information, and selected detections to shore-based teams. Forward-looking or imaging sonar may then support closer inspection while the vehicle approaches a suspected target.

The available literature mainly supports USV use for area screening, anomaly localization, and diver support. Mechanical recovery and rescue devices perform physical actions after target confirmation and are treated here as mission-execution units rather than observation payloads.

2.2.6 Infrastructure Inspection Payloads

Infrastructure inspection payloads assess underwater structures and linear assets such as bridge piers, piles, quay walls, dams, pipelines, submarine cables, and subsea facilities. Their products may reveal surface damage, scour, burial changes, route deviation, free spans, foreign objects, or other anomalies. Unlike general seabed surveys, these missions interpret acoustic, optical, magnetic, or electromagnetic observations in relation to a known engineering asset. The resulting products primarily provide inspection evidence and anomaly localization rather than complete engineering diagnosis, which usually requires additional measurements, historical information, and expert assessment.

Underwater Structure Inspection

Imaging and scanning sonar are widely used to inspect submerged structures in turbid water, where optical visibility may be poor. They can record structural outlines, surface irregularities, attached material, local damage, and scour around bridge piers, piles, gates, and quay walls. Forward-looking sonar can provide additional information during approach and localized inspection[54,55].

Figure 14 shows sonar observations of an underwater bridge pier and corresponding numerical mappings. Irregular reflections and surface variations can provide features for damage assessment, although interpretation remains sensitive to sonar resolution, viewing geometry, speckle noise, and the condition of the structure.

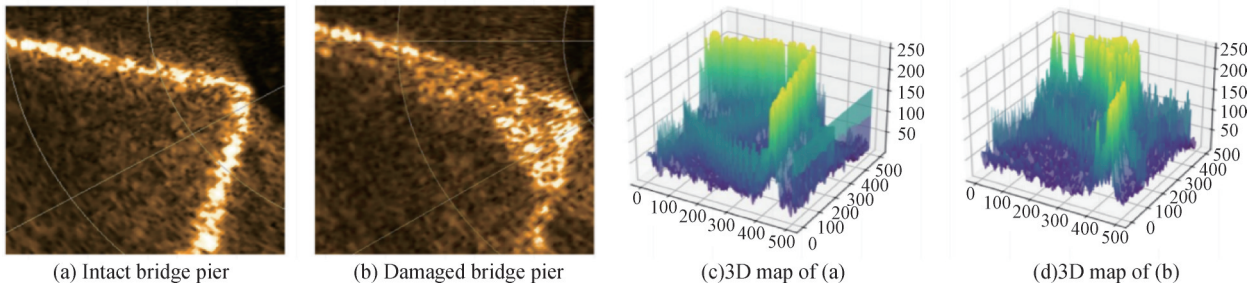


Fig.14 Sonar observations of an underwater bridge pier and corresponding three-dimensional numerical mappings (from[55])

Different sonar types provide complementary inspection products. Multibeam echosounders are suitable for mapping the seabed around foundations and identifying scour holes, sediment accumulation, exposed foundations, and changes in local terrain. Imaging or scanning sonar provides closer views of structural surfaces and localized defects. Side-scan sonar can screen the surrounding area for collapsed components, riprap, debris, or other objects, but it is less suitable than real-time imaging sonar for stationary or very slow inspection close to a structure.

Inspection data must be associated with specific structural locations. Position and attitude measurements, sensor-offset calibration, time synchronization, and

motion compensation therefore support both navigation and defect localization. These requirements become more important near bridges and quay walls, where currents, vessel wakes, GNSS obstruction, and metallic structures may affect vehicle control and navigation sensors.

Automated interpretation may further convert sonar imagery into inspection evidence. For example, three-dimensional texture features and learning-based methods have been used to distinguish damaged and intact bridge-pier observations. Such methods can reduce manual interpretation effort, but their performance depends on representative training data and consistent survey geometry.

Pipeline, Cable, and Subsea Facility Inspection

Pipeline and cable inspections commonly address route position, exposure, burial condition, free spans, adjacent scour, foreign objects, and evidence of external interference. These missions may be conducted directly by a survey USV or through cooperation with an AUV, ROV, or towed platform.

In surface-based surveys, the USV may carry multibeam and side-scan sonar. Side-scan sonar is effective for screening exposed linear targets, debris, anchor scars, and trawl marks. Multibeam data provide terrain and geometric information around the route and can reveal trenches, scour holes, exposed sections, and free spans. In cooperative operations, the USV may provide communication relay, acoustic positioning, mission supervision, and deployment or recovery support, while the underwater vehicle carries near-bottom sonar, cameras, laser scanners, sub-bottom profilers, or magnetic sensors[57].

Figure 15 shows a free-span section identified in multibeam data. The elevation difference between the pipeline and the surrounding seabed provides geometric evidence for estimating the extent of unsupported pipeline and assessing nearby scour.

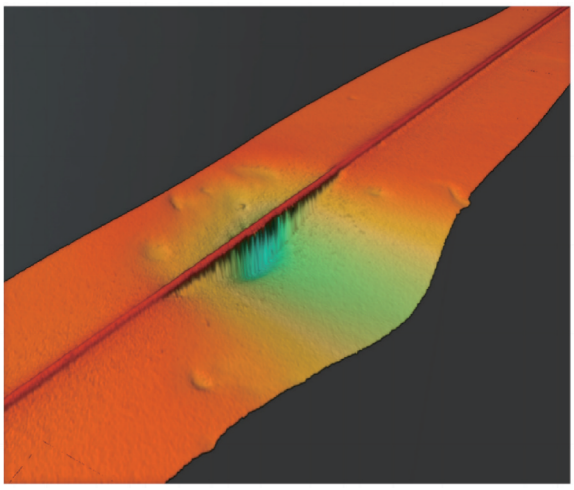


Fig.15 Free-span section of a subsea pipeline identified in multibeam data (from[57])

Surface acoustic imagery alone may be insufficient for buried or shallow-buried assets. Subbottom profilers can identify shallow subsurface structure and trench conditions, while magnetometers, magnetic gradiometers, and electromagnetic sensors can support the detection and tracking of metallic pipelines or armored cables. These sensors are commonly carried by an AUV, ROV, or towed body operating closer to the seabed. Their measurements can support route tracking, offset estimation, and burial assessment when combined with vehicle altitude and position information[58].

Inspection of manifolds, valves, wellheads, protective structures, and other localized facilities may require imaging sonar, forward-looking sonar, optical cameras, or laser scanners. Passive acoustic sensors may also screen for leakage, impacts, or unusual underwater sound sources, although confirmation generally requires additional measurements or close inspection[56].

Infrastructure inspection therefore combines several sensing scales. Surface-mounted sonar provides corridor-scale screening and terrain context, while underwater platforms provide close-range or subsurface observations. Reliable comparison across repeated inspections requires consistent positioning, calibrated sensor geometry, documented routes, and standardized data products.

Overall, mission payloads should be distinguished by the observations they directly produce. Hydrographic sensors measure terrain, imagery, currents, and water level; environmental and ecological sensors measure atmospheric, oceanic, chemical, and biological variables; and search or inspection sensors convert underwater anomalies and asset conditions into spatially referenced evidence. Their effective use depends on platform support for power, communications, positioning, motion measurement, integration, and environmental protection. The following section examines how these payloads are combined into complete mission workflows and application products.

3 Typical Application Scenarios

This section compares how USVs are used within complete operational workflows rather than whether individual sensors can be carried. The comparison focuses on mission objects, data products, the role of the USV, evidence status, and major constraints across the six application groups introduced above. The evidence categories used in this section follow the maturity criteria defined in Section 1.2. Accordingly, the assessment considers the repeatability of the reported workflow, the clarity of the resulting data product, the extent of field validation, and the dependence on specific platforms or operating conditions. Individual tasks within the same application group may nevertheless differ in maturity and validation coverage. Table 4 summarizes the cross-scenario comparison of typical USV applications, evidence maturity, and major constraints.

The following subsections examine how these roles, outputs, and constraints are expressed in representative applications.

Table 4 Cross-scenario comparison of typical USV applications

Application scenario	Mission objects	Typical products	Role of the USV	Evidence maturity	Main constraints
Hydrographic surveying and mapping	Nearshore bathymetry, coastal transition zones, river and reservoir flow fields, and bedforms	Bathymetric surfaces, contours, topo-bathymetric models, velocity sections, and bedform-change products	Direct survey platform and surface node in multi-source mapping	Operationally established for bathymetry; field-demonstrated for process-oriented surveys	Sound-speed correction, positioning and attitude accuracy, vertical datums, survey-line design, and data fusion
Air-sea and environmental observation	Near-surface atmospheric and upper-ocean states, radiative forcing, and extreme events	Co-located time series, along-track gradients, validation datasets, and event records	Long-endurance mobile ob-servation and validation platform	field-demonstrated, with strongest evidence for long-endurance platforms	Motion correction, sensor exposure, energy and communications, and differences among platform types
Water-quality, pollution, and biogeochemical monitoring	Physicochemical conditions, pollution anomalies, algal blooms, carbonate chemistry, and greenhouse-gas-related variables	Georeferenced time series, surface-distribution maps, hotspot detections, and process-related datasets	High-Resolution survey and hotspot-screening platform	Field-Demonstrated for routine monitoring; emerging for source attribution and flux estimation	Calibration, sampling representativeness, vehicle-speed effects, auxiliary variables, and quality control
Ecological surveys, fisheries, and acoustic monitoring	Benthic habitats, fish and plankton distributions, biological sound sources, and tagged animals	Orthomosaics, sur-face models, habitat maps, echograms, abundance indices, acoustic records, and telemetry detections	Shallow-water survey platform and mobile acoustic monitoring node	Field-demonstrated for benthic and acoustic surveys; emerging for autonomous eDNA sampling	Water clarity, biological validation, platform noise, detection probability, and sample handling
Infrastructure inspection	Bridges and near-water structures, pipelines, submarine cables, and other underwater assets	Structural imagery, scour and anomaly maps, route-resurvey products, and candidate exposed or unsupported sections	Direct inspection and reinspection platform and surface-support node for AUV/ ROV operations	Operationally established for selected preliminary bridge inspections, linear-asset resurveys, and cooperative USV-AUV inspection	GNSS obstruction, near-structure positioning, station keeping, sensor geometry, validation, and expert interpretation
Emergency search support	Search areas, suspected submerged targets, physical evidence, and hazardous underwater environments	Search-coverage maps, candidate target locations, anomaly heatmaps, and response priorities	Search-and-reconnaissance platform and surface-support node	field-demonstrated for underwater target search and hazardous-area reconnaissance; emerging for complete rescue and recovery	Sea state, communication interruptions, acoustic interference, positioning errors, target confirmation, and incomplete recovery capability

Note: Evidence maturity follows the criteria defined in Section 1.2. Individual subtasks within the same application scenario may differ in maturity and validation coverage.

3.1 Hydrographic Surveying and Mapping

Hydrographic applications of USVs are mainly found in three areas: bathymetric surveying in shallow or confined waters, multisource mapping across coastal transition zones, and river or reservoir surveys that combine flow measurements with observations of bedforms. Nearshore bathymetry now follows relatively well-established workflows, while surveys concerned with flow, sediment, and morphological change remain more dependent on the local environment and mission design[15,23,27].

Mission Organization and Products

Nearshore bathymetry is among the most established applications of USVs. Their shallow draft, ease of deployment, and ability to follow repeatable tracks make small platforms useful in beach zones, harbor basins, estuarine margins, reservoirs, and waters close to the shoreline, where conventional survey vessels may be difficult or unsafe to operate. In practice, USVs are commonly used to extend deeper-water surveys into shallow areas, fill gaps near the coast, and conduct rapid resurveys rather than replace crewed platforms under all operating conditions.

The division of work is illustrated in Figure 16. In this case, the conventional vessel covered the broader and deeper offshore region, whereas the USV surveyed the narrow shallow-water zone adjacent to the shore.

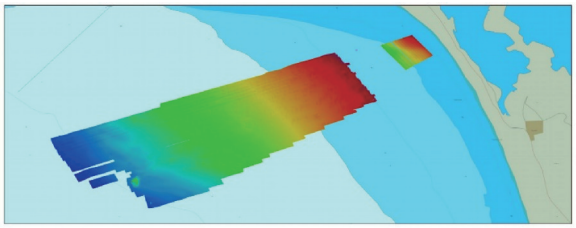


Fig.16 Complementary survey coverage provided by a conventional vessel and a USV during a nearshore hydrographic survey. Adapted from[23].

Common bathymetric products include georeferenced soundings, digital underwater terrain models, and depth contours. Their reliability is determined by the complete measurement workflow, including survey-line control, position and attitude observations, sound-speed correction, sensor calibration, and post-processing quality assessment. Faster deployment does not remove the need for sound-speed measurements, outlier screening, and expert review[23]. Jin et al. demonstrated a USV bathymetric workflow combining RTK positioning with a single-beam echosounder and explicitly accounting for wave and tidal effects in the derivation of chart depth, further illustrating the importance of vertical-reference treatment in operational bathymetric products[59].

Side-scan sonar adds information on seabed texture, obstacles, and localized anomalies. Before its records can be used as mapped products, the nadir region, slant-range effects, platform motion, and overlap between adjacent swaths must be addressed. Side-scan imagery therefore complements bathymetric surfaces rather than acting as an equivalent depth-measurement product[25].

In rivers and reservoirs, the addition of ADCP measurements can extend a survey beyond static mapping toward hydrodynamic and geomorphic observation. Repeated transects may yield velocity sections, discharge estimates, information on suspended sediment, and indicators of bedform movement. The usefulness of these products depends strongly on track geometry, data density, motion correction, and interpolation, and they do not generally provide a substitute for high-density multibeam bathymetry[27].

Mapping across the coastal transition zone usually requires more than one observation platform because neither a surface vehicle nor an aerial system can measure the complete land-water boundary without interruption. USV bathymetry may therefore be combined with UAV photogrammetry, LiDAR, and ground observations within a shared horizontal and vertical reference framework[15].

Figure 17 shows how underwater bathymetry can be connected with shoreline and terrestrial topography. In the reported study, the interpolated digital terrain model achieved an RMSE of 0.089 m, an MAE of 0.055 m, and an R_{95} of 0.187 m[15]. The USV supplied the shallow-water component of the mapping system rather than serving as the only source of data.

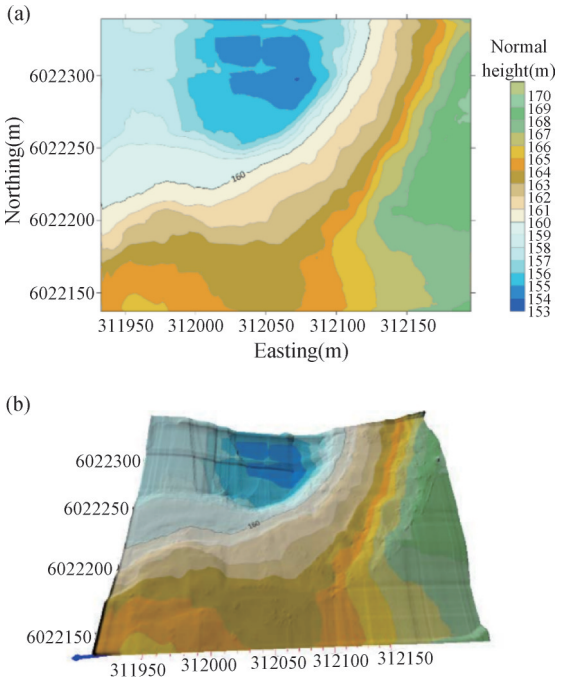


Fig.17 Continuous topo-bathymetric surface generated through multisource data fusion. Adapted from[15].

The resulting hydrographic products can be considered at three levels. The first consists of basic bathymetric surfaces and contours. The second adds seabed imagery and anomaly layers. The third combines several data sources into products such as continuous topo-bathymetric models, velocity sections, and datasets describing bedform change.

Applicability and Limitations

The main practical advantages of USVs are access to shallow water, rapid deployment, repeatable track following, and reduced exposure of personnel. These characteristics make them especially useful for filling nearshore survey gaps, surveying harbors and reservoirs, assessing dredging areas, inspecting sites after disruptive events, and repeating measurements over time[23].

Many limitations arise from the small size of the platform and from the difficulty of maintaining a consistent measurement geometry. Waves, heading changes, equipment faults, bubbles, and short-term variations in sound speed can affect data collected by compact USVs. Product accuracy also remains dependent on position and attitude quality, datum control, installation calibration, and manual review. Automated processing may reduce the amount of routine work, but it does not remove the need for quality assessment[22].

Multisource mapping introduces further requirements

for consistent datums, coordinate systems, acquisition times, and uncertainty estimates. The very shallow zone immediately beside the shoreline may remain inaccessible even to a USV and may need to be measured using UAVs or ground-based methods. Side-scan sonar and ADCP products are likewise sensitive to survey-line design and to assumptions made during processing[15,24,27].

USVs can therefore be regarded as operationally established for many nearshore bathymetric and coastal-mapping tasks. Integrated observations of flow, sediment, and bedform change are better viewed as field-demonstrated extensions whose performance remains more scenario dependent. Their main contribution is flexible and repeatable coverage within a broader survey system. Producing high-quality results still requires careful error control, common spatial and temporal references, appropriate survey design, and coordination with complementary platforms and datasets.

3.2 Air-Sea and Environmental Observation

USVs can acquire co-located measurements of the near-surface atmosphere, radiative forcing, and upper ocean while following planned or adaptive routes. Combined meteorological, radiation, and temperature-salinity observations support air-sea flux estimation, environmental-gradient analysis, cross-platform validation, and extreme-event studies[2,29,30]. Current applications are field-demonstrated, although much of the evidence comes from long-endurance platforms such as Saildrone. Their applicability to smaller, nearshore, or short-endurance USVs should therefore be assessed cautiously[20,60].

At the application level, the payload groups discussed in Section 2.2 operate as an integrated observing system. Meteorological sensors characterize atmospheric conditions and provide inputs for bulk-flux algorithms, radiometers constrain surface energy inputs, and upper-ocean instruments measure temperature, salinity, and their spatial variability. Their value lies in synchronized observations rather than in the independent collection of individual variables.

Mission Organization and Products

USV-based air-sea observation can be organized into three main operational modes. The first is long-duration observation of background conditions and environmental gradients. A USV follows preplanned or adaptively modified routes while recording wind, pressure, air temperature, humidity, radiation, and upper-ocean properties. Continuous transects can resolve fronts, upwelling boundaries, nearshore-offshore transitions, and mesoscale variability that are difficult to characterize using fixed stations alone[2,60].

Figure 18 illustrates a long-endurance Saildrone mission organized around regional sea-surface temperature structures. The platform combines persistent sampling with broader spatial coverage than a fixed observing station.

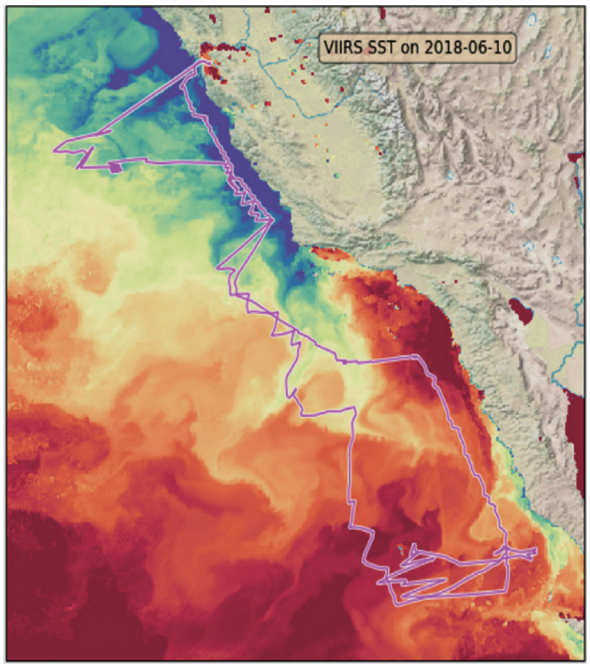


Fig.18 Long-duration Saildrone track used to sample regional sea-surface temperature variability. Adapted from[60].

The second mode is cooperative observation and cross-platform validation. USVs may operate near moored buoys, research vessels, or other in situ platforms to produce matched datasets for evaluating measurement consistency and analyzing air-sea exchange. During the SPURS-2 experiment, Saildrones conducted repeated sampling near ship and buoy observations, allowing their meteorological and upper-ocean measurements to be compared with established observing systems[29]. Related assessments indicate that autonomous surface platforms can provide research-quality observations when installation geometry, motion compensation, calibration, and quality control are properly addressed[30].

Figure 19 shows that the USV operated as part of a broader observing system rather than as an isolated platform. Repeated measurements near reference observations supported consistency assessment, flux-related analysis, and the identification of platform-dependent biases.

The third mode is event-driven observation under severe weather and hazardous sea states. These missions target rapidly evolving processes such as storms, strong winds and waves, and tropical cyclones. Their objective is to maintain measurements during event development and record atmospheric and oceanic responses that are difficult or unsafe to observe continuously from crewed platforms[20].

Typical products include co-located time series of atmospheric and upper-ocean conditions, along-track records of fronts and gradients, matched datasets for flux estimation and platform validation, and process records collected during extreme events. These outputs integrate several measured variables into datasets suitable for environmental-process analysis.

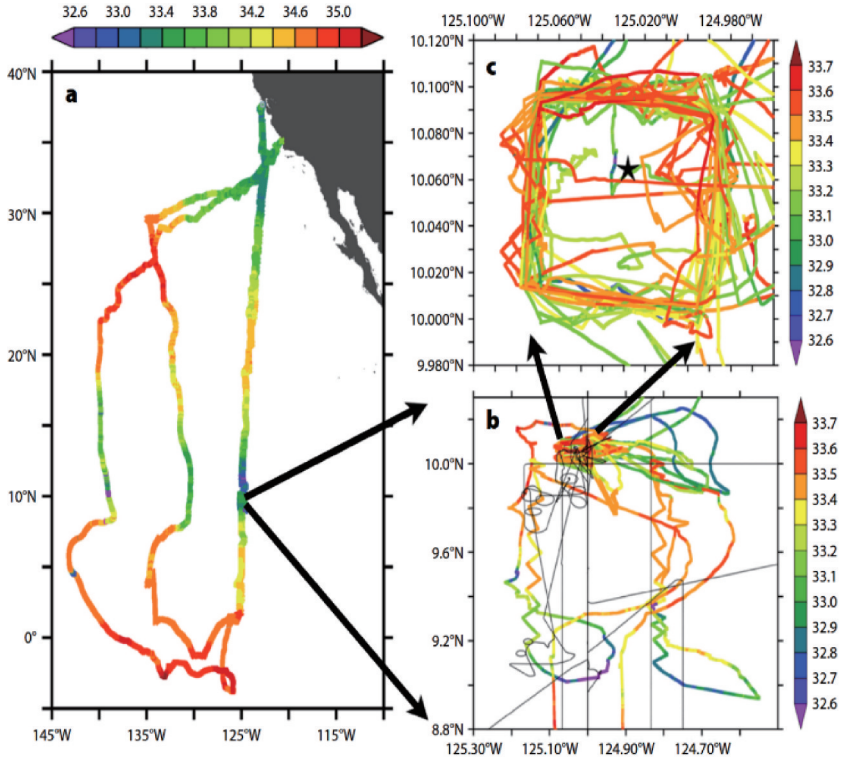


Fig.19 Saildrone tracks during the SPURS-2 experiment, showing regional coverage and repeated sampling near ship and buoy observations. Adapted from[29].

The principal advantages of USVs are persistent operation, repeated or adaptive sampling, reduced personnel exposure, and direct access to the air-sea interface. They are therefore particularly useful for regional gradient surveys, observations around fixed reference stations, and data collection during hazardous events[2,41,60].

Data quality nevertheless depends strongly on platform integration. Wind observations require correction for vehicle translation and rotation, while radiometers are sensitive to tilt, obstruction, reflections, and spray. Temperature and salinity measurements depend on sensor depth, immersion stability, fouling, and differences between submerged bulk measurements and satellite-retrieved surface properties. Accurate position, attitude, and time records are therefore required to combine observations from different instruments [29,30].

Applicability and Limitations

Long deployments also increase demands on energy management, communications, sensor stability, and remote quality control. Severe sea states may reduce track accuracy, alter sensor exposure, interrupt communications, or create data gaps even when the platform remains operational[2,20]. However, the reviewed evidence does not establish broad validation across storm or high-sea-state conditions for all payload classes. Consequently, successful severe-weather demonstrations on selected long-endurance platforms should not be generalized to other USV configurations without additional validation. Moreover, the performance demonstrated by large renewable-energy platforms cannot be assumed for smaller USVs with lower stability, endurance, payload capacity, or sensor mounting height.

USVs are therefore field-demonstrated for long-duration environmental transects, cooperative validation, and selected extreme-event observations. Their contribution lies in combining mobility, persistence, and synchronized atmospheric and oceanic measurements within a wider observing system. Reliable products depend on mission design, motion correction, calibration, and quality control rather than on endurance or sensor quantity alone. For example, Zhou et al. applied range and spike checks together with model-based correction to meteorological observations collected by a Wave Glider, demonstrating a practical quality-control workflow for autonomous surface observations[61].

3.3 Water-Quality, Pollution, and Biogeochemical Monitoring

USVs are increasingly used to map water-quality conditions, pollution anomalies, algal blooms, and surface biogeochemical variability in lakes, rivers, estuaries, wetlands, and coastal waters. Their principal advantage is the ability to collect synchronized measurements continuously along a route, thereby resolving spatial gradients and local hotspots that may be missed by fixed stations or discrete sampling[62,63].

The evidence level differs among applications. Routine water-quality surveys and harmful algal-bloom monitoring are field-demonstrated in multiple environments. High-resolution mapping of carbonate chemistry, nutrients, and dissolved gases has also been

demonstrated, although interpretation often depends on auxiliary environmental variables. Heavy-metal detection, pollution-source attribution, and direct flux estimation remain emerging applications because they require more demanding calibration, sampling, and analytical procedures [41,44,64].

Mission Organization and Products

The first common mode is continuous mapping of conventional water-quality conditions and algal blooms. USVs may record chlorophyll fluorescence, colored dissolved organic matter (CDOM), turbidity, dissolved oxygen, pH, conductivity, and temperature along predefined or adaptively modified routes. These measurements support the identification of bloom patches, transition zones, and local water-quality anomalies at a higher spatial resolution than fixed monitoring alone[41,62]. Li et al. demonstrated a water-color remote-sensing-oriented USV integrating optical reflectance measurements, automated water-sample collection, water-quality sensors, and meteorological instruments, illustrating how sensing and physical sampling can be combined within a single mission workflow[65].

Figure 20 illustrates the use of a USV during short-response and extended regional surveys of Florida red tides. Satellite imagery provided the regional background, discrete cell counts supplied biological validation, and the USV collected continuous observations within and around suspected bloom areas.

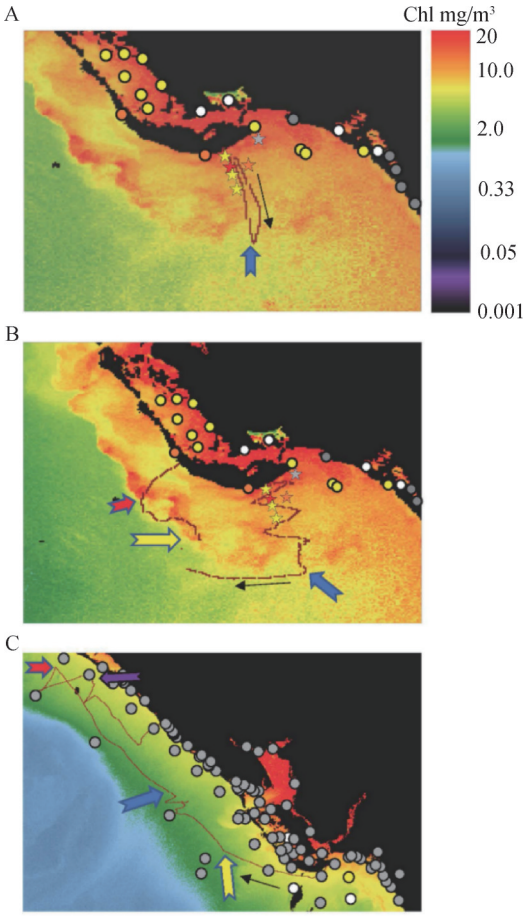


Fig.20 Nav2 survey tracks during short-response and extended regional monitoring of Florida red tides, shown with satellite imagery and discrete *Karenia brevis* cell counts. Adapted from[62].

This workflow positions the USV between remote sensing and discrete sampling. Satellite products provide broad spatial coverage, laboratory or field samples confirm biological conditions, and the USV resolves local variability along the survey track. The platform therefore supplements rather than replaces the other observing methods. Beyond continuous sensing, USVs can also integrate physical sampling as part of the mission workflow. Yuan et al. developed a USV system combining water-quality monitoring with autonomous waypoint operation and quantitative water-sample collection, illustrating the distinction between sensing payloads and mission-execution functions[66].

The second mode is targeted investigation of pollution anomalies. USVs can survey waters affected by wastewater discharge, agricultural runoff, industrial activity, or episodic overflow events and identify spatial gradients, hotspots, and possible dispersion boundaries. Routine physicochemical sensors can screen for anomalies, but they do not usually determine pollutant identity or source without dedicated chemical sensors and sample analysis. In situ heavy-metal monitoring has been explored, but current systems remain limited by sensor sensitivity, calibration requirements, and environmental interference[41].

The third mode is high-resolution biogeochemical mapping. Platforms such as ChemYak have measured surface pCO_2, CH_4, oxygen, nitrate, and salinity during rapid estuarine surveys, while other USVs have mapped low-pH and high-pCO_2 coastal waters[44,63]. These observations reveal spatial covariation among gases, nutrients, salinity, and oxygen and can support preliminary interpretation of freshwater influence, mixing, biological activity, and local source regions.

Figure 21 represents a characteristic USV product: co-located two-dimensional maps of several chemical and physical variables rather than isolated measurements at individual stations. Such products help locate anomalous water masses and compare their spatial boundaries with mixing and nutrient indicators. They describe surface structure directly, but do not by themselves establish complete source or process mechanisms.

USV observations may also be integrated with fixed stations, remote sensing, discrete sampling, and laboratory analysis. Mobile observations can guide targeted sampling and provide validation data for satellite products[41,62]. At a more advanced level, simultaneous measurements of atmospheric and seawater CO_2 , wind, and other variables may support estimates of air-sea CO_2 flux. Such products are model dependent and remain sensitive to wind products, temporal resolution, and parameterization choices[64].

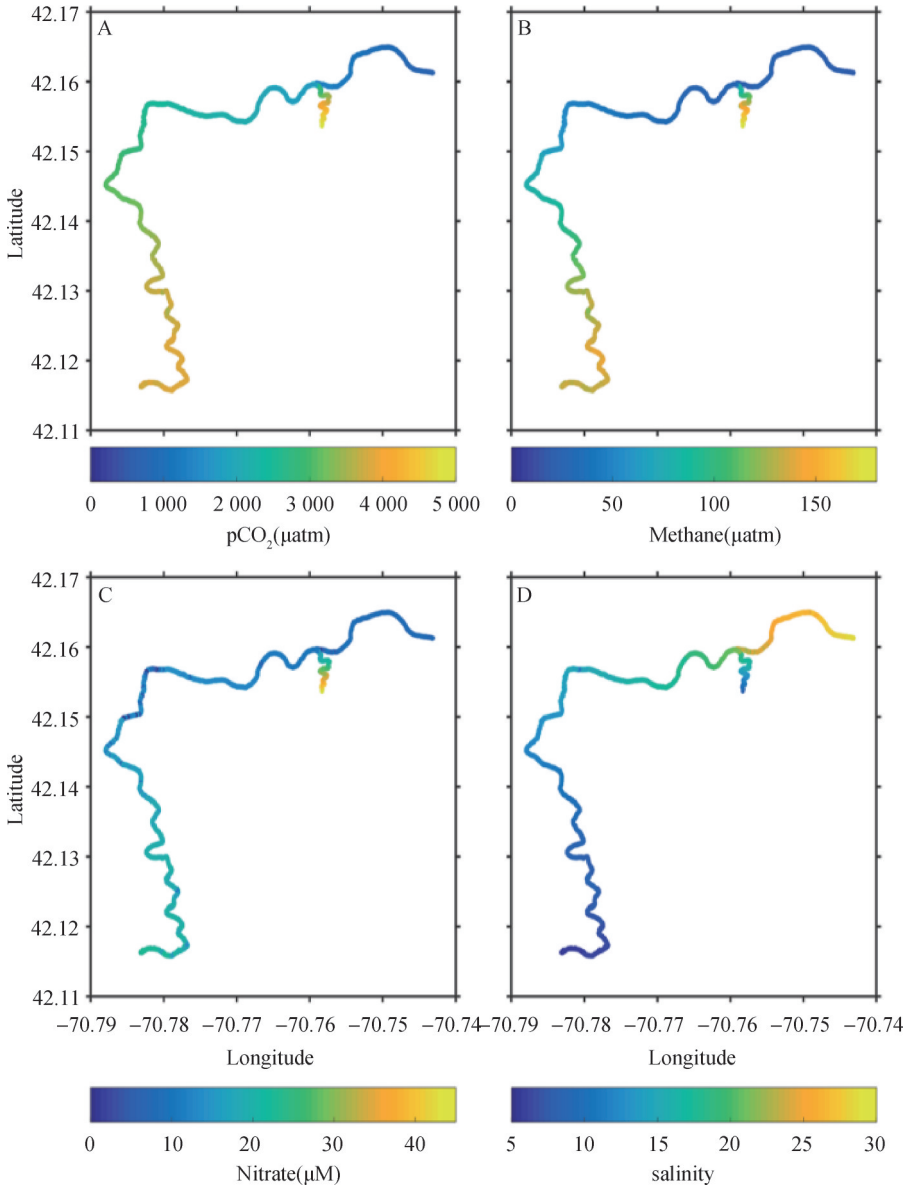


Fig.21 Continuous surface mapping of pCO_2, CH_4 , nitrate, and salinity by ChemYak in the North River. Adapted from[63].

The principal outputs of these missions are therefore georeferenced time series, two-dimensional surface-distribution maps, hotspot and anomaly detections, and matched datasets for process or flux analysis. The first three are relatively direct observational products, whereas source attribution and flux estimates require additional variables, models, and quality control.

Applicability and Limitations

USVs are particularly useful in spatially heterogeneous environments and in shallow or confined waters that are difficult for conventional vessels to survey repeatedly. They can rapidly intensify sampling around algal blooms, outfalls, estuarine plumes, low-pH waters, or greenhouse-gas hotspots. Their ability to measure several variables at the same location also improves the interpretation of environmental gradients[44,62,63].

Measurement quality remains strongly dependent on sensor calibration and maintenance. Chemical and biogeochemical instruments may require stable water intake, controlled flow, temperature correction, reagents, cleaning, and frequent calibration. Heavy-metal sensors remain particularly sensitive to accuracy and detection-limit constraints[41].

Platform operation can also affect the observations. Vehicle speed may alter sensor response or residence time, while bubbles and wake can interrupt flow-through measurements. Cryer et al. reported speed-related effects on pH measurements, and Nicholson et al. identified data gaps associated with bubbles near the sensor intake. Constant-speed routes, suitable intake placement, and coordinated response-time correction are therefore important.

Most reported systems measure water at a fixed near-surface depth. Their products should consequently be interpreted as high-resolution surface maps rather than complete descriptions of the water column. Strong stratification, tidal variability, freshwater input, and vertical gradients may limit the representativeness of

surface observations. Profiling systems, discrete depth samples, or supporting hydrodynamic measurements may be required when vertical structure is important.

The available evidence also spans highly different platforms, from small inland-water vehicles to coastal chemical-survey systems and open-ocean Saildrones. Results obtained with one platform class cannot automatically be transferred to another because payload capacity, endurance, sampling design, and environmental exposure differ substantially.

USVs are therefore field-demonstrated for conventional water-quality mapping, algal-bloom surveys, and selected surface biogeochemical observations. Heavy-metal monitoring, detailed source attribution, and greenhouse-gas flux estimation remain emerging extensions. Reliable products depend on calibration, stable sampling, route and speed control, vertical representativeness, auxiliary measurements, and post-processing quality control rather than on increasing the number of measured variables alone.

3.4 Ecological Surveys, Fisheries, and Acoustic Monitoring

USVs support shallow-water habitat mapping, fisheries acoustic surveys, passive acoustic monitoring, acoustic telemetry, and emerging molecular sampling. Evidence is strongest for benthic imaging in clear shallow waters, supplementary fisheries acoustic surveys, and mobile acoustic monitoring. Autonomous environmental DNA (eDNA) sampling remains an emerging application because it requires additional sampling, preservation, and laboratory-analysis procedures[6,47-51,67].

USVs are well suited to these tasks because they can follow repeatable tracks in shallow or hazardous environments and support persistent observations with limited personnel exposure. Their typical role is to complement UAVs, research vessels, fixed acoustic arrays, and manual biological surveys rather than replace them.

Mission Organization and Products

The first application mode is shallow-water benthic habitat mapping. Underwater cameras or stereo cameras collect continuous imagery along low-speed USV tracks. Structure-from-motion (SfM) processing can then generate orthomosaics and three-dimensional surface models, which may be further classified into habitat or benthic-cover maps[48,49]. These products support repeated assessment of coral reefs, seagrass beds, rocky habitats, erosion, deposition, and local ecological change.

USVs can also operate with UAVs in a multi-scale mapping workflow. UAV imagery provides broad regional context, whereas close-range USV imagery resolves finer underwater habitat boundaries and community structure.

Figure 22 illustrates the scale complementarity of the two platforms. The USV provides detailed underwater observations within the broader spatial framework supplied by the UAV.

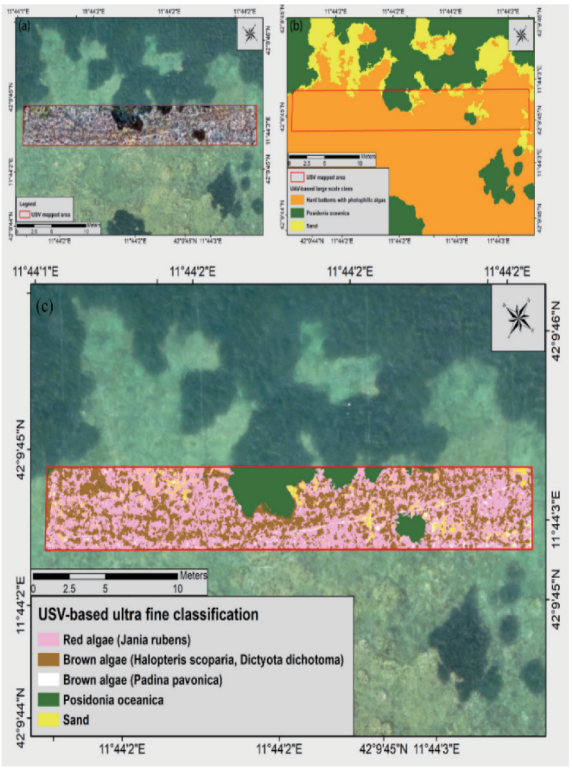


Fig.22 Complementary products from UAV-USV surveys of shallow benthic habitats, showing regional aerial coverage and higher-resolution underwater classification. Adapted from[49].

The second mode is fisheries and plankton acoustic surveying. Scientific echosounders mounted on USVs collect georeferenced water-column backscatter along predefined transects. These observations can reveal fish schools, plankton layers, and relative spatial patterns and can extend survey coverage when research-vessel operations are constrained[6].

During the 2020 eastern Bering Sea pollock survey, three echosounder-equipped USVs helped reduce the observation gap created by the cancellation of a conventional acoustic-trawl survey[47]. However, acoustic backscatter does not independently determine species composition, size structure, or biomass. These interpretations generally require trawl samples, optical observations, historical relationships, or other biological information. USVs therefore supplement rather than replace complete stock-assessment surveys.

The third mode comprises passive acoustic monitoring and acoustic telemetry. Passive acoustic systems record natural vocalizations and soundscapes, particularly from marine mammals, and may provide detections, bearing estimates, and continuous acoustic records[51]. Acoustic telemetry receivers instead detect transmissions from tagged animals and support studies of occurrence, movement, and habitat use[50].

Mobile receivers can survey gaps between fixed stations and move among spatially separated habitats. Figure 23 compares detections from a Wave Glider with those from a fixed receiver array and demonstrates that the two observing approaches provide complementary coverage.

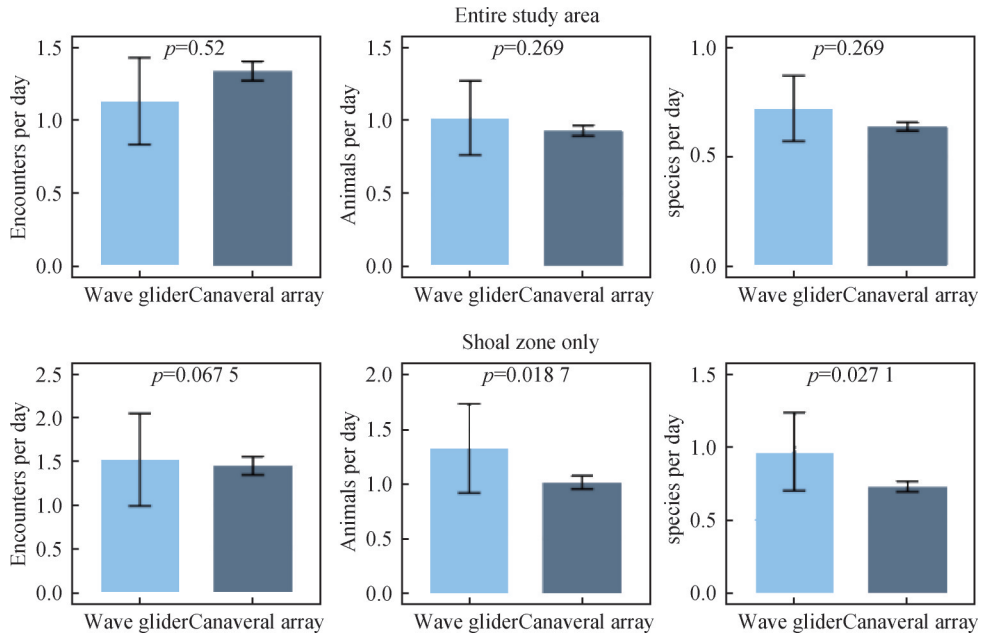


Fig.23 Per-receiver comparison of acoustic telemetry detections from a Wave Glider and the fixed Canaveral Array across the study area and within the Shoal Zone. Adapted from[50].

A mobile platform is not necessarily superior to a fixed array in detection rate or residence-time estimation. Its main contribution is flexible spatial coverage, particularly in remote areas, gaps between receivers, and disconnected habitat patches. Performance remains dependent on vehicle tracks, detection range, tag orientation, water depth, and environmental conditions.

A fourth and less established mode is autonomous eDNA sampling. A USV equipped with an environmental sample processor can filter and preserve surface-water samples along a planned route for subsequent quantitative polymerase chain reaction or metabarcoding analysis [67]. This extends USV ecological missions from imaging and acoustic detection to physical sample acquisition. However, current evidence remains platform specific, and the resulting biodiversity information still depends on sample preservation, contamination control, laboratory processing, and interpretation of eDNA transport.

Typical outputs across these applications include orthomosaics, three-dimensional habitat models, classification maps, acoustic transects, relative abundance indices, passive acoustic records, telemetry detections, and preserved samples for molecular analysis. Some outputs, such as imagery and detection records, are obtained relatively directly. Biomass estimates, animal residence patterns, and biodiversity interpretations require additional biological information or analytical processing.

Applicability and Limitations

The main advantages of USVs are access to shallow or disturbance-sensitive habitats, repeatable survey geometry, persistent operation, and reduced personnel exposure. Their mobility also allows them to connect observations made by platforms with different coverage scales. UAVs provide regional habitat context, research vessels provide biological sampling, and fixed acoustic arrays provide long-term local records, while USVs supply mobile and spatially continuous observations.

The limitations vary by task. Optical habitat mapping depends strongly on water clarity, illumination, camera immersion, image overlap, and platform stability. Turbidity, surface reflections, waves, and motion blur can reduce photogrammetric reconstruction and classification quality[48,49].

Fisheries acoustic products are sensitive to propulsion noise, bubbles, transducer attitude, platform motion, and calibration. More importantly, the absence of synchronous trawling limits species identification and biomass interpretation[6,47]. Passive acoustic observations similarly require low self-noise, vibration isolation, suitable hydrophone depth, and stable towing geometry[51].

Telemetry detections depend on range, environmental propagation, vehicle trajectory, and the time spent near each habitat. Detection density from a mobile receiver should therefore not be interpreted as equivalent to long-term residence measured by a fixed array[50]. Autonomous eDNA sampling introduces additional uncertainty associated with sample depth, preservation temperature, contamination, transport, and delayed laboratory analysis[67].

USVs are therefore field-demonstrated for shallow-water benthic mapping, supplementary fisheries acoustic surveys, passive acoustic monitoring, and selected telemetry applications. Autonomous eDNA sampling remains emerging. Across these tasks, their principal value lies in providing repeatable and mobile observations within a wider ecological observing system. Reliable ecological interpretation still requires appropriate environmental measurements, biological

validation, and task-specific quality control.

3.5 Infrastructure Inspection

USVs are used for preliminary inspection of bridges and near-water structures and for repeated surveys of pipelines, submarine cables, and other underwater assets. Infrastructure inspection is operationally established for selected tasks, particularly anomaly localization, condition resurveying, and cooperative inspection involving surface and underwater platforms[54,57]. In these applications, the USV may directly collect inspection data or serve as a surface-support node for an AUV, ROV, or towed system. The resulting observations generally support preliminary assessment, anomaly localization, and targeted reinspection rather than independent completion of engineering diagnosis.

Mission Organization and Products

The first application mode is inspection of bridges and other near-water structures, including piers, piles, quay walls, gates, docks, and coastal foundations. These missions focus on structural surfaces, scour, attached material, local damage, and nearby hazards rather than general seabed morphology. Imaging or forward-looking sonar can collect structural observations during low-speed approaches or station keeping, while positioning and attitude data associate anomalies with specific locations.

USVs are particularly useful for preliminary inspection and targeted reinspection. Von Ellenrieder et al. integrated sonar observation, waypoint-based navigation, station keeping, and inspection procedures into a bridge-survey workflow [54]. Sonar products may also support automated damage classification, although engineering conclusions still depend on image quality, survey geometry, validation data, and expert interpretation[55]. Typical products include structural images, scour observations, localized anomaly areas, and priorities for closer inspection.

The second application mode is inspection of pipelines, submarine cables, and other linear subsea facilities. Surface-mounted multibeam or side-scan sonar may be used to resurvey routes, exposed sections, free spans, adjacent scour, and foreign objects. For detailed near-bottom inspection, the USV more commonly serves as a surface-support platform for an AUV, ROV, or towed system.

In the pipeline-inspection system reported by Rumson, the USV supported deployment and recovery, communication relay, acoustic positioning, mission monitoring, and replanning, while the AUV performed detailed inspection along the asset route[57]. The resulting products included route-resurvey data, candidate free spans or exposed sections, local seabed conditions, anomaly locations, and mission records for subsequent comparison. Consistent positioning and survey geometry are particularly important because these inspections often rely on multitemporal assessment of known assets.

The principal products of USV-based infrastructure inspection therefore include structural inspection imagery, scour and anomaly locations, asset-route resurvey data, candidate exposed or unsupported sections, and priorities for targeted reinspection. These products primarily describe the condition of known assets and support the identification of locations requiring closer investigation or professional engineering assessment.

Applicability and Limitations

The main advantages of USVs in infrastructure inspection are reduced personnel exposure, access to shallow or difficult-to-reach areas, repeatable survey tracks, and integration with underwater and shore-based systems. They can enter bridge-underwater zones, confined waters, and potentially unstable sites before personnel are deployed. Repeated routes also support comparison among successive inspections and systematic resurvey of known assets.

Their role nevertheless remains limited by the stage of the inspection workflow. Many applications provide preliminary assessment, anomaly localization, and reinspection support rather than complete engineering diagnosis or lifetime evaluation. Structural significance usually requires additional measurements, historical records, close-range inspection, or professional assessment.

Near-structure operation also presents navigation and measurement challenges. Bridges, quay walls, and confined waters can obstruct GNSS signals and introduce currents, acoustic reflections, vessel wakes, and collision hazards. Reliable inspection may therefore require accurate local positioning, station keeping, obstacle avoidance, stable sensor geometry, and continuous operator supervision. Sea state, turbidity, acoustic interference, positioning errors, and equipment failures can further affect the consistency of inspection data, particularly when repeated surveys are used to assess changes in known structures or subsea assets[54,57].

USVs can therefore be regarded as operationally established for selected preliminary bridge inspections, linear-asset resurveys, and USV-AUV cooperative inspection workflows. Their principal strength lies in repeatable anomaly localization and condition resurveying while reducing personnel exposure. However, the resulting observations should generally be interpreted as inspection evidence rather than complete engineering diagnosis, because structural assessment still depends on positioning quality, sensor geometry, historical information, close-range verification, and professional interpretation.

3.6 Emergency Search Support

USVs are increasingly used for underwater target search and reconnaissance in hazardous or difficult-to-access environments. Current applications are field-demonstrated mainly for search-area coverage, target screening, anomaly localization, and the generation of

spatial cues for subsequent verification[52,53]. In these missions, the USV primarily serves as a search-and-reconnaissance platform that reduces personnel exposure and narrows the area requiring closer investigation. Evidence for complete rescue, transport, or recovery operations remains limited, and such tasks should therefore be distinguished from the search function itself [52,68].

Mission Organization and Products

Emergency underwater searches may involve submerged persons, physical evidence, hazardous objects, or other suspected targets. Current USV applications concentrate on defining search areas, following systematic coverage patterns, detecting candidate targets, and transmitting results to response teams[52]. Side-scan sonar can screen relatively large areas, while forward-looking or imaging sonar may assist with localized verification. The resulting information reduces the search area and identifies locations requiring closer examination, but it does not replace physical confirmation or recovery.

The PRIME system demonstrates this workflow in an underwater forensic and emergency-search setting. A side-scan-sonar-equipped USV followed planned survey tracks, georeferenced the observations, and combined multiple survey lines into anomaly heatmaps that could be interpreted by dive teams[53]. The resulting product was therefore not simply a set of individual sonar images, but a spatially referenced representation of candidate areas requiring further investigation.

Figure 24 shows how multi-track fusion can convert complex sonar records into georeferenced priority areas.

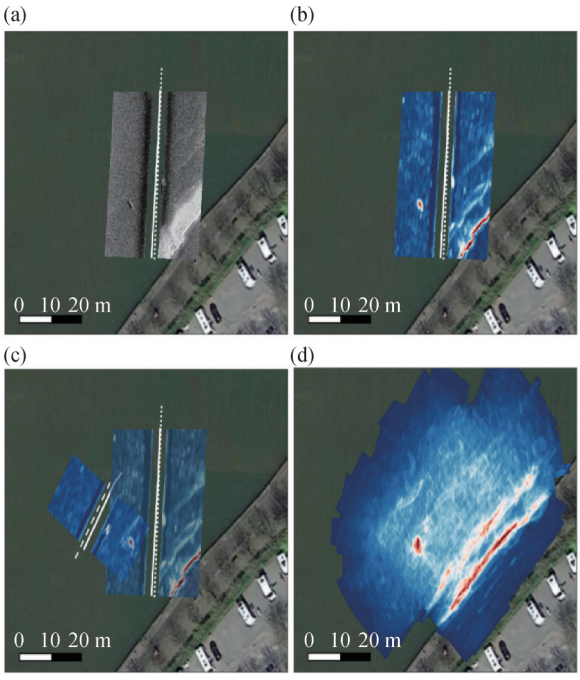


Fig.24 PRIME workflow from individual sonar acquisition to georeferenced products and anomaly prioritization: (a) sonar imagery acquired along an individual survey track; (b) the corresponding georeferenced sonar image; (c) fused sonar imagery generated by combining multiple survey tracks; and (d) the final anomaly heatmap for target prioritization. Adapted from[53].

Divers, ROVs, or forensic teams can then focus verification on selected locations rather than conducting a broad blind search.

The principal products of USV-based emergency search include search-coverage maps, candidate target locations, georeferenced sonar records, anomaly heatmaps, and response priorities. Unlike infrastructure-inspection products, which describe the condition of known assets, emergency-search products are generally produced under greater uncertainty and are intended primarily to guide subsequent verification or intervention. Their practical value therefore depends not only on target detection but also on whether the resulting search cues can be transferred rapidly and accurately to divers, ROVs, forensic teams, or other response units.

Applicability and Limitations

The main advantages of USVs in emergency search are reduced personnel exposure, systematic coverage of suspected areas, repeatable survey tracks, and the ability to operate before divers or other personnel are deployed. This is particularly useful in turbid, hazardous, or poorly characterized waters where direct human entry may be inefficient or unsafe. Systematic survey routes can also provide a documented record of the areas that have been searched and help response teams prioritize subsequent investigation[52,53].

The available evidence, however, is considerably stronger for search organization and target localization than for rescue, transport, or recovery. Reviews of maritime unmanned search systems emphasize coverage planning, cooperative platforms, and target discovery, while real disaster deployments demonstrating complete autonomous response workflows remain comparatively limited[52,68]. A detected sonar anomaly may indicate a candidate target, but additional confirmation is normally required before its identity or operational significance can be established. USVs should therefore be described primarily as search-and-reconnaissance support platforms unless a study demonstrates the physical intervention needed to complete the response.

Search performance is also sensitive to operating conditions and platform support. Sea state, turbidity, acoustic interference, positioning errors, communication interruptions, and equipment failures can reduce survey consistency or delay the transmission of results to response teams. Reliable products require accurate position and heading information, stable sonar geometry, suitable vehicle motion, and sufficient communication or onboard storage to preserve search records. These requirements become particularly important when candidate detections must be revisited rapidly or transferred to another platform or response team.

USVs can therefore be regarded as field-demonstrated for underwater target search, hazardous-area reconnaissance, and the generation of georeferenced search cues. Complete rescue and recovery remain emerging because target detection and localization do not

by themselves provide physical confirmation, transport, manipulation, or recovery capability. The principal contribution of the USV at the current stage is consequently to reduce the search area, prioritize subsequent intervention, and reduce personnel exposure rather than independently complete the full emergency-response workflow.

Section Summary

Across the six application scenarios considered in this section, USVs serve three main roles: direct survey platforms, cooperative nodes within multi-platform systems, and preliminary-entry platforms for hazardous or difficult-to-access environments. Hydrographic surveying and selected infrastructure inspections have the most stable workflows and products. Air-sea, water-quality, and ecological applications are field-demonstrated but depend more strongly on synchronized measurements, biological or environmental validation, and platform-specific quality control. Pollution-source attribution, biogeochemical flux estimation, autonomous eDNA sampling, and complete emergency-response operations remain emerging. The value of USVs therefore lies less in replacing existing platforms than in extending spatial coverage, increasing observation continuity, reducing personnel risk, and linking complementary measurements within a coordinated operational workflow.

Representative quantitative findings further illustrate the different forms of mission-level performance evidence, although they cannot be compared on a common scale. Motion compensation reduced reported wind-speed and wind-direction errors by 45% and 16%, respectively[30]; a multisource topo-bathymetric terrain model achieved RMSE, MAE, and R95 values of 0.089, 0.055, and 0.187 m, respectively[15]; and AquaBOT achieved approximately ten times the spatial sampling resolution of conventional manual sampling [38]. Because these results describe different mission products and validation procedures, they are interpreted within their respective workflows rather than pooled into a single cross-domain performance measure.

4 Common Issues, Challenges, and Trends

The preceding sections show that USV mission capability depends on the combined performance of mission payloads, platform-support capabilities, and operational workflows. Although the six application scenarios differ in their observation targets, operating environments, and final data products, several limitations recur across domains. A recurring challenge is moving beyond the demonstration that a payload can be carried by a USV toward showing that the complete system can produce traceable, quality-controlled, and interpretable data over the required spatial and temporal scales[2,6,30]. These limitations can be considered from three related perspectives: the quality and traceability of the observations, the reliability of the system over the required mission duration, and the ability of the USV to operate as part of a broader multi-platform and data-management framework.

4.1 Common Issues and Major Challenges

Observation Quality and Measurement Traceability

Across the reviewed applications, obtaining a measurement is only the first step toward producing a useful mission product. Sensor output may be affected by platform motion, installation geometry, environmental exposure, synchronization accuracy, calibration status, and subsequent processing. Reliable products therefore require not only suitable sensors, but also documented offsets and mounting angles, synchronized position and attitude records, appropriate calibration procedures, and consistent quality-control methods.

These requirements occur in both environmental and geometric observations. Air-sea measurements may require corrections for vehicle translation, rotation, tilt, structural obstruction, and sensor exposure, together with comparison against established observing platforms[2,30]. Hydrographic and infrastructure-inspection products similarly depend on positioning, attitude determination, time synchronization, installation calibration, and common coordinate references for spatial registration and repeated surveys[7]. Water-quality, biogeochemical, and ecological applications introduce additional concerns related to sensor drift, fouling, sampling depth, response time, biological validation, and the interpretation of indirect or proxy measurements.

The common issue is therefore measurement traceability rather than sensor integration alone. A useful data product should retain sufficient information to reconstruct how the observation was generated, corrected, and validated. Calibration records, sensor configuration, coordinate definitions, sampling conditions, processing history, quality flags, and uncertainty information become particularly important when observations from different platforms or deployment periods are compared.

Current studies do not always provide a consistent link between nominal sensor accuracy and uncertainty in the final mission product. Greater attention is therefore needed to the complete measurement chain, including positioning, platform motion, installation geometry, environmental exposure, processing, and validation. This is especially important when methods are transferred between different platform classes, because performance demonstrated on a large or relatively stable vehicle cannot automatically be assumed for smaller USVs with different motion characteristics, payload capacity, or installation constraints.

Energy, Communications, and Long-Duration Reliability

Long-endurance USVs have enabled persistent

observations in undersampled regions and during selected hazardous-weather conditions[2,20]. However, effective endurance depends on the requirements of the complete mission system rather than on propulsion or battery capacity alone. Navigation, communications, onboard computing, data storage, thermal management, and mission payloads all compete for limited energy. Continuous operation is consequently more difficult for high-power acoustic instruments, active sampling systems, and high-data-rate payloads than for low-power environmental sensors.

Communication capacity creates a related constraint. Low-rate environmental measurements and platform-health information can often be transmitted during the mission, whereas raw multibeam records, side-scan sonar imagery, optical images, and ecological acoustic datasets are generally too large for continuous transmission. These products are commonly stored onboard while selected telemetry, compressed information, quality indicators, or detected events are transmitted to shore. Onboard compression, preliminary quality control, and event detection can reduce communication demand, but these functions also consume computing resources and energy and do not remove the need for detailed post-mission processing[6].

Long-duration measurement quality can further deteriorate because of biofouling, sensor drift, corrosion, water ingress, mechanical wear, actuator failure, and communication interruption. Recovery allows equipment to be cleaned, repaired, and recalibrated, but extended autonomous missions still require health monitoring, fault detection, fouling mitigation, and practical recovery procedures. These issues are particularly important for environmental and biogeochemical observations, where slow sensor drift or progressive fouling may alter the quality of an otherwise continuous record.

The relevant objective is therefore not simply to maximize mission duration, but to maintain useful measurement capability throughout the deployment. Energy management, payload duty cycles, sensor-health assessment, data preservation, and fault recovery need to be considered together. A platform that remains physically operational but can no longer maintain reliable measurements or preserve essential data provides limited value as a long-duration observing system.

Interoperability, Adaptive Autonomy, and Standardization

Many of the applications reviewed in this paper involve cooperation among USVs, UAVs, AUVs, ROVs, crewed vessels, fixed stations, and shore-based systems. Within these workflows, a USV may act as a direct sensing platform, communication relay, acoustic-positioning node, mission supervisor, or surface-support platform. Cooperation broadens the range of tasks that can be performed, but it also introduces requirements for communication interfaces, task allocation, timing, state exchange, coordinate consistency, and data integration.

Autonomous operation in these missions also extends beyond following predefined waypoints. Depending on the application, a platform may need to intensify sampling around an environmental feature, repeat an inadequate survey line, approach a detected anomaly, modify its route after a communication interruption, or adjust payload operation when energy becomes limited. These decisions can improve mission efficiency, but they should remain compatible with the measurement requirements of the payload. For example, improved target coverage is of limited value if route changes produce unsuitable vehicle speeds, unstable sampling depth, or inconsistent survey geometry.

Adaptive operation also needs to remain interpretable after the mission. Changes in routes, sampling rates, or payload states should therefore be recorded together with relevant platform conditions, quality indicators, and operator interventions. Such records are necessary when observations are reviewed, compared with other datasets, or used to reconstruct the circumstances under which a measurement was obtained.

Interoperability of the resulting datasets presents a parallel problem. Differences in variable names, measurement units, coordinate conventions, file formats, quality flags, calibration records, sampling-depth definitions, and metadata can make observations difficult to compare across platforms or reuse outside the original project. Incomplete reporting also makes it more difficult to determine whether a method demonstrated on one platform can be transferred to another.

Future development should therefore consider platform cooperation and data interoperability together. Mechanical and electrical payload interfaces are important, but consistent timing, positioning references, communication protocols, metadata, calibration records, and decision logs are also required. Without such integration, improvements in individual sensors or autonomy algorithms may remain difficult to transfer among platforms and application domains.

4.2 Development Trends

The challenges identified above suggest that future USV development will depend less on isolated improvements in individual sensors or vehicle functions and more on the integration of payloads, platform support, autonomous operation, and data management. Two developments are particularly relevant across the application areas reviewed here: modular and cooperative system architectures, and improved reliability and data handling during extended autonomous operation.

Modular Architectures and Multi-Platform Operations

Future USV systems are likely to place greater emphasis on standardized and modular payload interfaces. Mechanical, electrical, power, timing, and data connections that accommodate interchangeable instruments can reduce the effort required to configure a

platform for different missions. Modularity can also simplify calibration, maintenance, fault isolation, and replacement of individual components.

The same principle applies at the system level. A single USV does not need to carry every instrument or perform every stage of a complex mission. UAVs can provide regional imagery, USVs can supply mobile surface observations and communications, AUVs or ROVs can obtain near-bottom measurements, fixed stations can provide long-term reference records, and crewed platforms can conduct biological sampling or physical intervention. In such systems, individual platforms can be assigned tasks according to their operating advantages rather than forcing one vehicle to provide all required capabilities[2,6].

This approach is already evident in hydrographic mapping, ecological observation, infrastructure inspection, and emergency search, where surface, aerial, underwater, fixed, and crewed components may contribute different parts of the final workflow. Further work is needed to make these cooperative operations more repeatable, particularly by resolving task-allocation conflicts, improving target-coordinate transfer and time synchronization, managing communication latency and loss, coordinating deployment and recovery, and ensuring consistency of data products between platforms.

Long-Duration Reliability, Onboard Processing, and Data Standardization

Long-duration USV development should distinguish physical endurance from the duration over which useful measurements can be maintained. Increasing deployment time is valuable only when sensor quality, platform state, timing, storage, and communication remain sufficiently reliable throughout the mission. Energy management, fouling control, sensor-health monitoring, fault diagnosis, and safe recovery should therefore be treated as part of the observing system rather than as separate engineering issues.

Onboard processing can support this objective by identifying abnormal sensor responses, unstable measurement geometry, missing data, or degraded observations before the mission is complete. Compression and event detection can reduce communication demand, while onboard analysis may also support adaptive sampling, targeted reinspection, or repetition of inadequate survey lines[6]. The practical value of these functions depends on whether they improve mission efficiency without reducing the reproducibility or interpretability of the resulting data. This direction is consistent with the U.S. IOOS QARTOD framework, which promotes variable- and instrument-specific real-time quality-control procedures and identifies autonomous field instrumentation as an important area for further implementation of embedded quality control[69].

Adaptive mission planning should therefore take measurement quality into account in addition to navigation and coverage. Vehicle speed, sampling frequency, route selection, payload duty cycles, and communication strategy may need to change according to mission objectives, data-quality indicators, platform condition, and remaining energy. At the same time, automated changes should be recorded so that the operational history of the mission can be reconstructed during subsequent analysis.

Data management will become increasingly important as deployments become longer and observations from different platforms are combined. Near-real-time telemetry and delayed-mode products should use consistent variable definitions, measurement units, coordinate references, time standards, quality flags, calibration records, and uncertainty descriptions[2]. Metadata should also document platform type, sensor installation, sampling depth, processing procedures, and relevant changes in payload configuration during deployment.

These practices are important because the same environmental or structural variable may be measured by different USV classes under different operating conditions. Without sufficient metadata and validation information, differences caused by platform motion, sensor configuration, sampling depth, or processing may be mistaken for real environmental or structural change. More consistent reporting would also improve comparisons among field studies and make it easier to distinguish broadly transferable methods from results that remain specific to a particular platform or deployment.

Taken together, these issues define the main research priorities identified from the reviewed literature. Further progress depends on improving complete mission systems rather than individual components in isolation. Reliable calibration and validation, sustained measurement quality, adaptive but traceable operation, modular cooperation among platforms, and consistent data and metadata practices are closely related requirements. Addressing them together would support the transition from successful individual demonstrations toward more repeatable and scalable USV-based observing, inspection, and operational systems.

5 Conclusion

This review examined USV applications through the relationships among mission objectives, mission payloads, platform-support capabilities, operational workflows, validation evidence, and final data products across six application scenarios. The reviewed evidence shows that mission capability cannot be inferred from the presence or nominal performance of a sensor alone. Reliable observations depend on how the payload is positioned, powered, synchronized, mounted, protected, calibrated, and operated within the complete mission system. Distinguishing mission payloads from platform-

support modules and mission-execution units therefore provides a practical basis for comparing USV applications with different sensing targets, operating conditions, and workflow requirements.

The six application groups do not show the same level of evidence maturity. Nearshore hydrographic surveying and selected infrastructure-inspection tasks have the clearest repeatable workflows and most clearly defined products. Air-sea observation, conventional water-quality mapping, shallow-water ecological surveys, fisheries and passive acoustic monitoring, acoustic telemetry, and underwater target search have been demonstrated successfully in the field, although their performance remains dependent on platform characteristics, environmental conditions, supporting measurements, and validation procedures. Pollution-source attribution, biogeochemical flux estimation, autonomous eDNA sampling, and complete rescue or recovery operations remain less mature because important limitations in validation, sampling, interpretation, physical intervention, or system reliability have not yet been fully resolved. Across these applications, USVs are therefore most effective as complements to crewed vessels, fixed stations, UAVs, AUVs, ROVs, and manual surveys rather than as universal replacements.

Further progress will depend on the reliability of the complete mission system rather than on increases in payload number or vehicle autonomy alone. Particular attention is needed to measurement traceability and validation, sustained measurement quality during long deployments, adaptive operation that remains interpretable after the mission, modular cooperation among heterogeneous platforms, and consistent data and metadata practices. These requirements are closely connected: longer endurance has limited value if sensor quality cannot be maintained, adaptive autonomy is difficult to evaluate if operational decisions cannot be reconstructed, and multi-platform observations are difficult to compare without common spatial, temporal, calibration, and metadata references. Addressing these issues would help move USV applications from successful individual demonstrations toward more repeatable and scalable components of aquatic observing, inspection, and operational systems.

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Ethics Statement

Not applicable

Use of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used ChatGPT (OpenAI, GPT-5.5) for language polishing and grammar checking. The authors reviewed and revised all AI-assisted outputs and take full responsibility for the content of the manuscript.

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