

Review Article

Uncrewed marine vehicle recovery: present technologies and future challenges

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ABSTRACT: Uncrewed marine vehicles (UMVs) are essential platforms for marine science, offshore engineering, and defense applications. This review provides a comprehensive overview of UMV recovery technologies including surface and subsea recovery, with particular emphasis on the evolution from single-mode recovery towards integrated surface-subsea recovery. The recovery process is broadly divided into the approaching, engagement phase, and recovery completion phases. The corresponding key technologies, including path planning, obstacle avoidance, acoustic-based guidance, vision-based guidance, capture-based guidance, motion control, and motion compensation, are reviewed in detail, along with emerging development trends.

In addition to sea–sea domain recovery, this review highlights air–sea domain recovery as an emerging cross-domain research area extending beyond traditional UUV recovery, which has received very limited systematic attention in the existing literature.

KEYWORDS: uncrewed marine vehicles; surface recovery; subsea recovery; integrated surface-subsea recovery; cross-domain recovery.

Abbreviation

Abbreviation	Description
AUV	Autonomous Underwater Vehicle
DDQN	Double Deep Q-Network
DRL	Deep Reinforcement Learning
DUSBL	Digital Ultra-Short Baseline
LBL	Long Baseline
LDUUV	Large Displacement Unmanned Underwater Vehicle
MASS	Maritime Autonomous Surface Ship
MPC	Model Predictive Control
PID	Proportional-Integral-Derivative
RATS	Relative Acoustic Tracking System
ROV	Remotely Operated Vehicle
SBL	Short Baseline
SSBL	Super-Short Baseline
TD3	Twin Delayed Deep Deterministic Policy Gradient
ULV	Uncrewed Launch Vehicle
UMV	Uncrewed Marine Vehicle
USBL	Ultra-Short Baseline
USV	Uncrewed Surface Vehicle

UUV	Unmanned Underwater Vehicle
UAV	Unmanned Aerial Vehicle
XLUUV	Extra-Large Uncrewed Underwater Vehicle

1. Introduction

In recent years, the rapid advancement of marine exploration, anti-submarine warfare, seafloor resource investigation, and autonomous robotic technologies has significantly intensified the operational role of autonomous and uncrewed marine vehicles in deployment, inspection, surveying, and recovery missions [1-3]. Notably, there is no universally accepted terminology for autonomous and uncrewed marine vehicles in the existing literature. Depending on the operational domain, control mode, and application context, relevant systems reported in the literature may be referred to by different terms, including maritime autonomous surface ships (MASS), uncrewed marine vehicles, unmanned marine vehicles, unmanned underwater vehicles (UUVs), and uncrewed surface vehicles (USVs). Underwater systems can be further classified into autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), large-displacement unmanned underwater vehicles (LDUUVs), and extra-large uncrewed underwater vehicles (XLUUVs), based on their autonomy level, operational mode, and system scale. For consistency and clarity, this review collectively refers to these systems as uncrewed marine vehicles (UMVs), unless otherwise specified. Correspondingly, platforms or systems responsible for retrieving UMVs are referred to as recovery platforms.

In the conservation and exploitation of marine resources, UMVs, which function as autonomous, tether-less robotic platforms capable of performing tasks such as resource assessment, oil and gas pipeline inspection, and underwater search operations, have been widely employed in deep-sea exploration. Although UMVs offer notable advantages, including reduced deck space

requirements and ease of operation and maintenance, their operational endurance remains inherently constrained by onboard energy storage [4-6]. Once a mission is completed, recovery operations become essential for tasks such as energy replenishment, data retrieval, maintenance and inspection, and uploading new mission profiles [7].

Among the wide variety of UMVs, some systems have matured into commercially available platforms supporting offshore industry and marine survey missions, while others have been primarily developed for defense-related applications. However, a larger portion, however, has not yet reached commercialization and remains at the stage of academic or laboratory-based development, serving primarily as platforms for scientific research and technology verification [8, 9]. These designs often include conceptually novel and unconventional approaches. In principle, most commercial UMVs can be adapted for military applications by integrating appropriate mission payloads and functional modules [10]. Nevertheless, if military requirements are not sufficiently considered during the initial system design, the operational capabilities of the modified UMV are often substantially constrained. Successful UMV platforms are often designed from the outset to accommodate demanding operational requirements, which also contribute significantly to their technical maturity and commercial viability.

The technology for UMVs recovery largely depends on the classification scheme. At present, there is no universally accepted nomenclature or classification scheme for UMVs. Existing naming conventions vary widely across the literature and industry, often reflecting manufacturer preferences [1], application contexts, or specific performance indicators [11] rather than a technical standard. As a result, product names alone provide limited insight into a vehicle's overall capability or system scale, which motivates the adoption of more engineering-oriented classification criteria in research and practice. In contrast, military UMVs are commonly categorized according to the four-tier system adopted by the U.S. Navy in its UMV Master Plan,

which distinguishes between large, medium, lightweight, and micro classes [12]. In recent years, even larger vehicles have emerged and are generally referred to as “extra-large” UMVs [13, 14]. Analogous to the conceptual significance of displacement tonnage in naval vessel classification, the tonnage of a UMV provides a concise yet informative indicator of its overall capability. Consequently, mass-based classification is not only more practical but also aligns with long-standing operational conventions of naval forces worldwide.

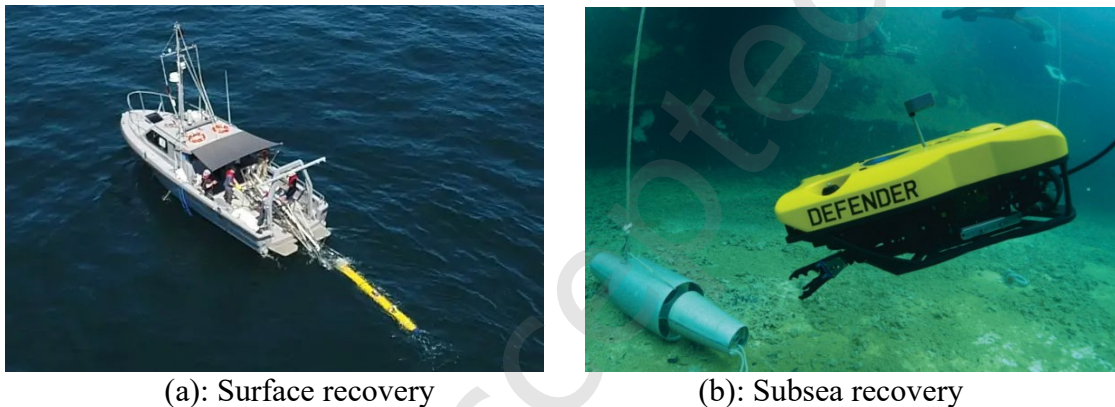


Fig. 1 Typical UMV recovery methods: (a) Surface recovery, (b) Subsea recovery

UMV recovery methods can be broadly categorized into surface and subsea recovery methods, as illustrated in Fig. 1. Surface recovery refers to the process in which a UMV returns to a designated sea area after completing its mission and approaches the mother ship, where it is lifted out of the water and recovered on board using deck-mounted lifting equipment such as cranes [15]. Surface recovery is operationally straightforward; however, it is highly susceptible to wave and wind disturbances, imposing significant limitations under adverse sea states. In contrast, subsea recovery methods eliminate the influence of surface conditions and provide superior concealment, rendering them particularly valuable for military and civilian applications [16]. Table 1-1 summarizes the principal characteristics and classification categories of representative UMV products [1, 17-21]. In general research practice, UMVs with a mass below 500 kg and a diameter (or height) of less than 400 mm are classified as lightweight UMVs. Vehicles with a mass ranging

from approximately 0.5 t to 20 t are typically designated as medium or large UMVs, depending on their specific dimensions and mission capabilities. UMVs exceeding 20 t in mass and possessing a diameter (or height) greater than 1000 mm are commonly referred to as extra-large UMVs. In the present review, UMVs are classified following this four-tier system and the recovery technology is divided based on this classification.

Table 1-1. Representative UMVs: System scale, classification, and typical recovery Approaches

UMV Name	Length/m	Mass/Kg	Classification	Typical recovery tiers	Type
Iver4	2.5	90.7	Light	Surface	AUV
SUBROV	3.1	300	Light	Surface	ROV
REMUS 600	5.5	385	Light	Surface	AUV
Osprey	5.0	400	Light	Surface	AUV
Marlin MK1	1.5	454	Light	Surface	AUV
Bluefin-21	4.93	750	Medium	Surface	AUV
Artemis	5.38	800	Medium	Surface	AUV
AUV 62F	6.5	1000	Medium	Hybrid	AUV
NMRS-UUV	5.0	1000	Medium	Subsea	UUV
SeaRaptor	5.5	1200	Medium	Hybrid	AUV
Qianlong-1	4.6	1500	Medium	Surface	AUV
Qianlong-2	4.6	1500	Medium	Surface	AUV
HUGIN Superior	6.6	2200	Large	Hybrid	AUV
Klavesin-1R	5.8	2500	Large	Subsea	UUV
Giant Key Qin	6.5	3700	Large	Subsea	UUV
Echo Seeker	9.75	13608	Large	Subsea	LDUUV
Manta	11.0	14000	Large	Subsea	LDUUV
Bopaidong	24.0	20000	Large	Subsea	LDUUV
Echo Voyager	15.5	50000	Extra-large	Subsea	XLUUV
Orca	24.0	63000	Extra-large	Subsea	XLUUV

As summarized in Table 1-1, the recovery approaches of UMVs exhibit a clear evolution with increasing vehicle scale and system mass. Lightweight and medium-weight UMVs are predominantly recovered at the surface using shipboard and recovery systems, owing to their limited size, manageable handling loads, and relatively low sensitivity to surface disturbances. As the vehicle dimensions and mass increase, the surface recovery is progressively constrained by hydrodynamic loads, sea-state limitations, and safety considerations. Large and extra-large UMVs

increasingly rely on subsea recovery concepts, that offer improved stability, concealment, and operational robustness. Notably, for the transitional range of medium-to-large UMV, hybrid recovery strategies have emerged, in which both surface recovery and subsea docking are feasible depending on mission requirements and deployment conditions. This gradual shift from single-mode surface recovery to integrated and flexible recovery architectures reflects the growing system complexity and operational demands associated with large-scale UMV platforms.

Existing UMV recovery methods can be broadly divided into surface recovery, subsea recovery, and hybrid surface–subsea recovery approaches as summarized in Table 1-2. Surface recovery methods are generally characterized by structural simplicity, low infrastructure requirements, and ease of maintenance, making them particularly suitable for lightweight and medium-scale UMVs operating under favorable sea states. However, their strong dependence on surface environmental conditions and limited stealth restrict their applicability in harsh or covert operational scenarios. Subsea recovery methods rely on fixed or mobile underwater docking infrastructure and emphasize stealth, environmental robustness, and long-term residency capabilities. These approaches are increasingly adopted for large and extra-large UMVs, despite their higher system complexity and deployment costs. For a transitional class of medium-to-large UMVs, hybrid recovery strategies that integrate surface guidance with subsea docking or capture mechanisms have been developed. Such systems provide enhanced operational flexibility by allowing recovery modes to be selected based on mission requirements, sea state, and logistical constraints.

Table 1-2. Typical surface and subsea recovery methods for UMVs

Recovery tiers	Recovery method
Surface	Crane lifting
	Net capture
	Stern ramp recovery
	Cocoon recovery

	Moonpool recovery
	Fixed seabed docking station
	Suspended docking station
Subsea	Capture-based docking
	Soft / compliant docking
	Moonpool recovery
Hybrid	Surface / Subsea

In recent years, several review studies have investigated recovery-related technologies for UMVs from different perspectives [3, 22-28]. Existing surveys have primarily focused on underwater docking mechanisms, homing and guidance strategies, navigation and control methods, and energy replenishment and resident operation concepts. These studies have provided valuable summaries of surface recovery systems, subsea docking infrastructures, acoustic-visual guidance techniques, and autonomous control frameworks, thereby establishing a solid foundation for the development of UMV recovery technologies.

However, most existing reviews tend to treat surface and subsea recovery as independent and mutually exclusive approaches, with limited attention paid to their combined or complementary use within a unified operational framework. As UMVs continue to increase in size, endurance, and mission complexity, recovery strategies are no longer confined to a single mode. Instead, there is a growing trend toward integrated recovery architectures, in which surface-based recovery and subsea recoveries coexist and are selectively employed according to vehicle scale, mission requirements, and environmental conditions. This evolution from single-mode to multiple-mode recovery, in which traditional surface-only or subsea-only recovery schemes are progressively replaced by systems capable of both surface and subsea recovery, has not yet been systematically reviewed in the literature. Motivated by this observation, the present review aims to provide a comprehensive overview of UMV recovery technologies with particular emphasis on the evolution and integration of surface and subsea recovery approaches, highlighting their respective roles, technical challenges, and integrated methodology trends across different vehicle scales. It should

be emphasized that the recovery reviewed in the existing literature is almost exclusively developed for sea-sea recovery scenarios, in which both the UMV and the recovery platform operate within the same hydrodynamic environment. Under this assumption, recovery dynamics, sensing strategies, and capture mechanisms are generally designed for continuous underwater or surface domains, where UMV-platform interactions are dominated by hydrodynamic effects. In contrast, cross-domain recovery problems involving transitions across the air-sea interface introduce fundamentally different physical characteristics to the problem. Despite the increasing operational relevance, recovery strategies for air-sea cross-domain uncrewed systems have received very limited systematic investigation compared with traditional sea-sea UMV recovery.

This study proposes a systematic decomposition of the UMV recovery process into three sequential phases: approaching, engagement, and recovery completion. Unlike existing reviews that focus on isolated technologies, this phase-based framework provides a unified perspective to organize and analyze recovery-related technologies according to their functional roles at different stages, enabling a more structured understanding of the design and operation of recovery systems. This review extends beyond conventional sea-sea recovery scenarios and, for the first time, establishes a conceptual linkage between marine recovery systems and cross-domain recovery problems, including unmanned aerial vehicle (UAV) and uncrewed launch vehicle recovery on marine platforms. By connecting aerial and space vehicle recovery with ocean-based recovery infrastructures, this work identifies air-sea cross-domain recovery as an emerging and important research direction, thereby broadening the scope of traditional UMV recovery studies.

2. UMV Recovery Key Technology

In earlier stages, most UMV focused on compact, small-scale vehicles that could be launched and recovered from small boats and served mainly as experimental platforms. These small UMVs are widely employed for shallow-water mine reconnaissance, hydrographic and coastal surveys in

support of naval operations, coastal oceanography, environmental monitoring, and other forms of scientific data collection, typically carrying side-scan sonar and a limited suite of oceanographic sensors [29-31]. Because of their restricted hull volume and battery capacity, such systems generally have short endurance (on the order of only a few hours), modest payload capability and are therefore confined to short-range, near-shore missions [32, 33].

The UMV recovery operation as illustrated in Fig. 2 for surface, subsea and hybrid recoveries can be systematically divided into three sequential phases according to the relative distance and interaction level between the vehicle and the recovery system. Phase I Approaching Phase corresponds to the far-field stage, in which the UMV navigates from its mission endpoint to a predefined recovery initiation position. During this phase, the vehicle maintains a safe separation distance from the recovery platform while aligning its heading and trajectory to satisfy the geometric and operational constraints required for subsequent recovery. Phase II Engagement Phase begins when the UMV enters the recovery region and active recovery operations are initiated. In this stage, the vehicle interacts functionally with the recovery system, following guidance cues and alignment constraints, while the relative motion between the UMV and recovery structure becomes critical. Phase III Recovery Completion Phase represents the terminal stage of the recovery process, in which the UMV is physically constrained, secured, or accommodated by the recovery mechanism, marking the completion of recovery. This phase is characterized by close-proximity interactions and requires high robustness to residual positioning errors and environmental disturbances.

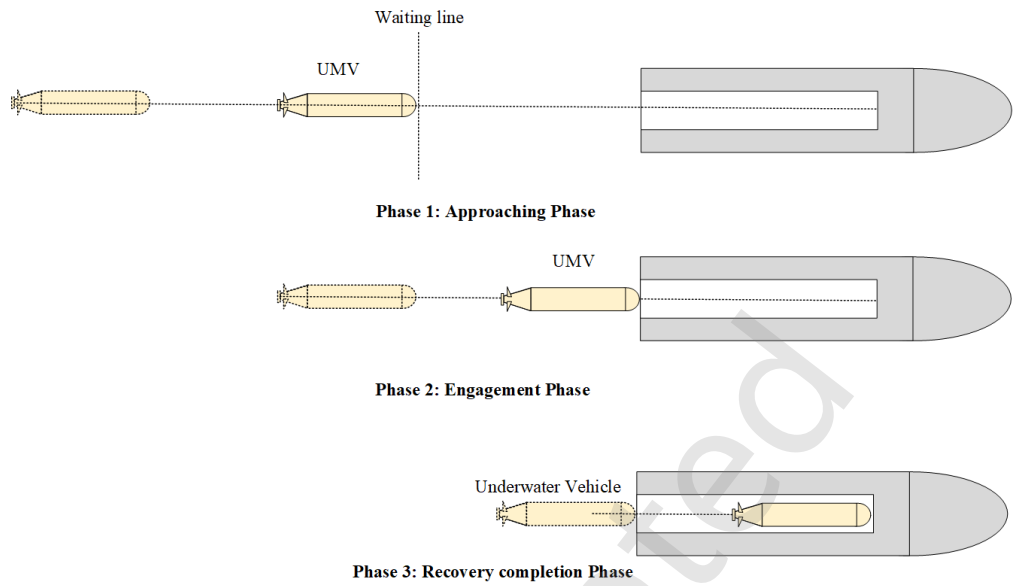


Fig. 2 Schematic illustration of the three-phase UMV recovery process

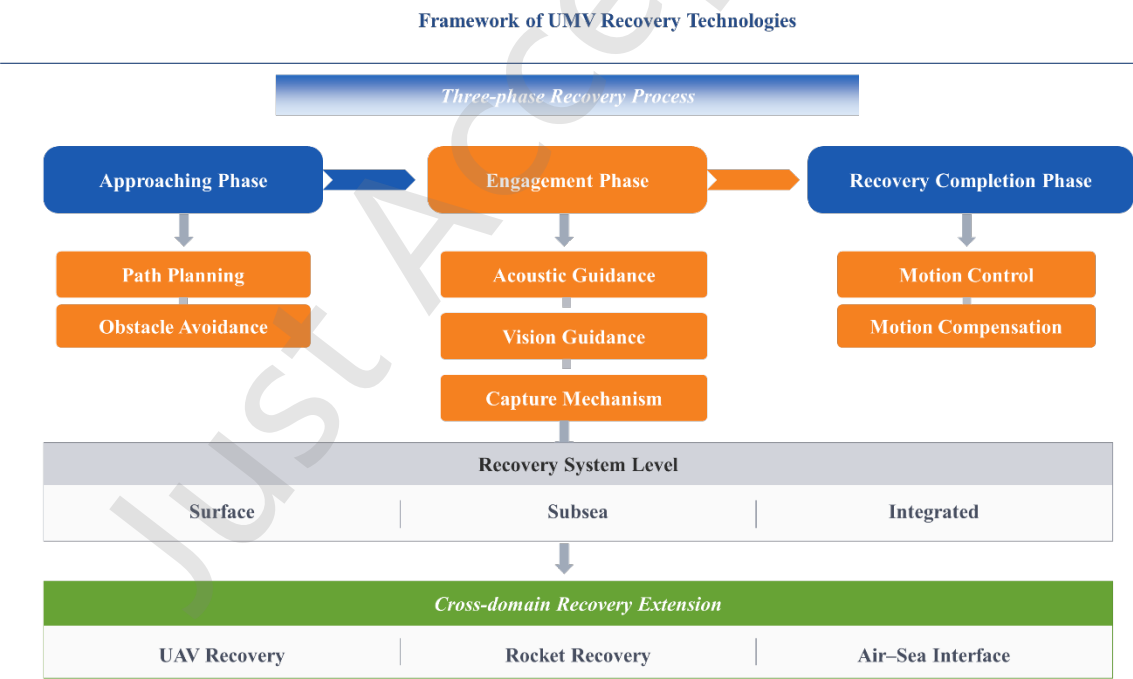


Fig. 3. Systematic framework of UMV recovery technologies and cross-domain extension.

To provide a clear overview of the logical structure of this review, the framework of UMV recovery technologies is shown in Fig. 3. The recovery process is structured into three sequential phases—approaching, engagement, and recovery completion—each associated with distinct

enabling technologies. At the system level, recovery configurations include surface, subsea, and integrated surface–subsea modes. The framework further is further extended to emerging cross-domain recovery scenarios, linking marine recovery systems with aerial and space vehicle recovery.

2.1 Approaching Phase Navigation and Path Planning

The approaching phase mainly concerns recovery-oriented navigation before close interaction with the recovery interface. As a result, the approaching phase mainly involves technology in path planning [34-40] and obstacle avoidance [41-47], which together form the foundation of recovery-oriented navigation. Path planning aims to compute a safe and energy-efficient route that guides the UMV toward the recovery region while satisfying kinematic constraints and mission requirements. Obstacle avoidance, on the other hand, enables vehicles to react to static and dynamic hazards, such as the recovery platform, support vessels, and environmental obstacles, thereby ensuring robust navigation in complex marine environments.

From a recovery-oriented perspective, both path planning and obstacle avoidance play fundamental and complementary roles in ensuring safe and reliable navigation during the approaching phase. Path planning primarily focuses on generating a feasible and efficient trajectory that guides the UMV toward the recovery region while satisfying mission constraints, vehicle kinematics, and environmental disturbances such as ocean currents. Existing methods can be broadly categorized into model-based approaches, which explicitly incorporate kinematic and dynamic constraints to ensure trajectory feasibility, and learning-based approaches, which leverage data-driven strategies to enhance adaptability in uncertain and dynamic environments.

Obstacle avoidance, on the other hand, emphasizes real-time safety during trajectory execution by enabling the UMV to respond to unexpected obstacles, dynamic hazards, and environmental uncertainties. Compared with path planning, which is typically formulated at a

global or semi-global level, obstacle avoidance operates at a more local and reactive level and often requires fast decision-making and tight integration with motion control. Modern approaches increasingly combine environmental perception, prediction, and control constraints to ensure that avoidance maneuvers remain both safe and dynamically feasible, particularly in close-proximity recovery scenarios, where the interaction between the UMV and recovery platform becomes critical.

Therefore, the integration of path planning and obstacle avoidance forms the foundation of recovery-oriented navigation, in which global optimality and local safety must be jointly considered to achieve robust performance under complex marine conditions.

2.1.1 Path Planning for Recovery-Oriented Navigation

Path planning aims to generate a feasible and safe trajectory that guides the UMV from its mission endpoint to the recovery initiation region while progressively satisfying recovery-specific constraints. Compared with general-purpose navigation, recovery-oriented planning places stronger emphasis on terminal approaching geometry, constrained maneuvering space near the recovery interface, and robustness against environmental disturbances. Therefore, existing studies generally focus on improving the feasibility, adaptivity, and energy efficiency under uncertain environments and dynamic currents.

From a methodological perspective, recovery-oriented path planning can be broadly categorized into two representative paradigms. In this work, the representative algorithms include Twin Delayed Deep Deterministic Policy Gradient (TD3), Double Deep Q-Network (DDQN), and Deep Reinforcement Learning (DRL). As shown in Fig.4, the first paradigm relies on learning-based decision-making, where deep reinforcement learning is employed to achieve online motion planning and adaptive trajectory optimization in unknown environments [48-52]. Typical efforts formulate UMV motion planning as a continuous control problem, enabling the vehicle to learn

collision-free and dynamically feasible maneuvers through reward shaping that jointly considers goal convergence, obstacle avoidance, energy consumption, and motion smoothness. Such methods are advantageous in handling uncertainty and dynamic obstacles without explicit environment models and have demonstrated promising adaptability under strong current disturbances.

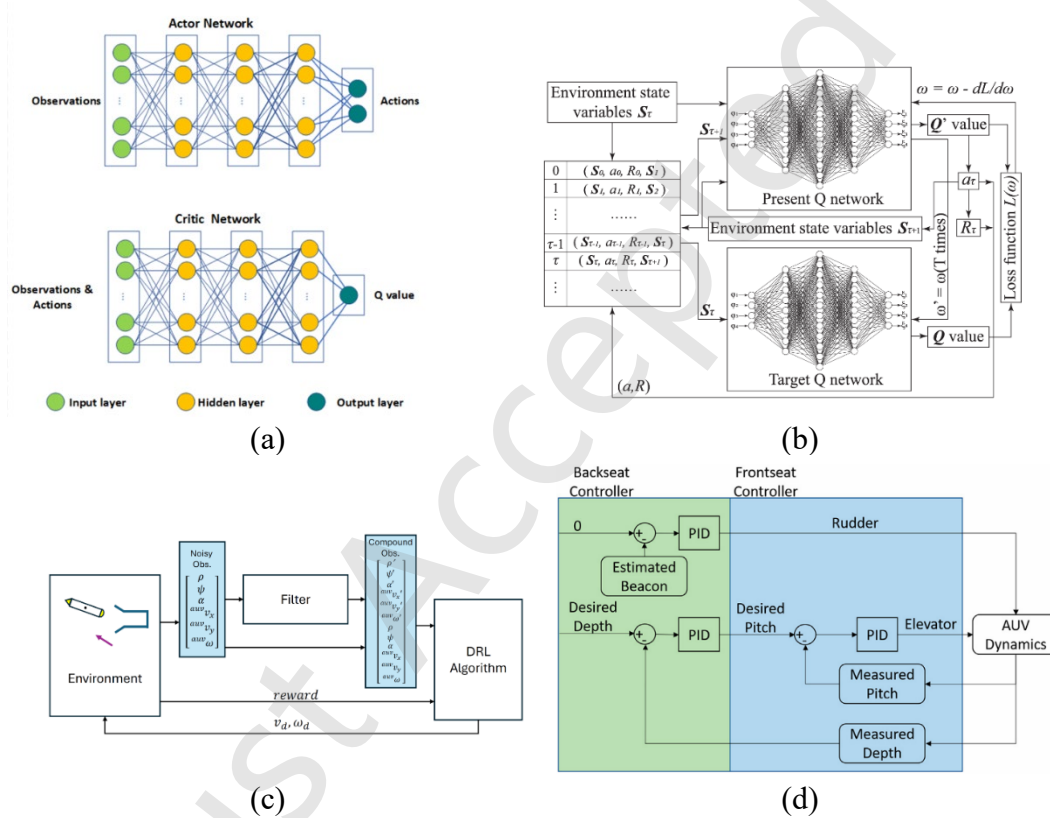
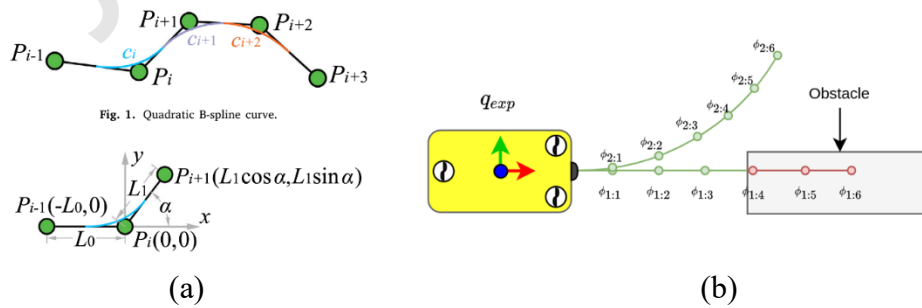


Fig. 4 Representative learning-based and controller-assisted frameworks for (a) TD3 [48], (b) DDQN [49], (c) DRL [50], and (d) PID [51] algorithms.

Despite the differences in network structure and implementation, these approaches share a common optimization philosophy. They all formulate recovery-oriented navigation as an iterative improvement process driven by a task-specific performance measure, typically encoded through a reward or value function. During training, candidate trajectories or actions that achieve higher cumulative rewards than previous solutions are reinforced and used to update the policy, whereas

suboptimal behaviors are gradually suppressed through repeated trial-and-error interactions. By continuously evaluating the navigation performance and maximizing the long-term return, the learned policy progressively converges toward a locally or globally optimal recovery path under the defined constraints.

However, it should be noted that an “optimal” solution obtained purely through reward–penalty mechanisms does not necessarily guarantee a trajectory that is suitable for practical recovery execution. In many cases, reward-driven policies may yield paths with strong uncertainty, limited smoothness, and insufficient maneuverability, particularly when the learned behavior is sensitive to observation noise or environmental disturbances. Such trajectories may further exhibit abrupt heading changes or aggressive maneuvers, which compromise the feasibility of low-level control and make it difficult to track reliably in real AUV systems. Therefore, the second paradigm places greater emphasis on generating trajectories that are explicitly smooth, controllable, and dynamically feasible [53-56] as shown in Fig.5. Instead of relying solely on implicit constraint learning, these approaches incorporate explicit kinematic and dynamic constraints, such as maximum curvature or turning-rate limits, velocity bounds, collision-distance thresholds, and feasibility regions defined by the vehicle’s motion model. By enforcing such hard constraints, the planner is able to produce strictly feasible solutions that better match real-world recovery requirements, improving both tracking robustness and operational safety.



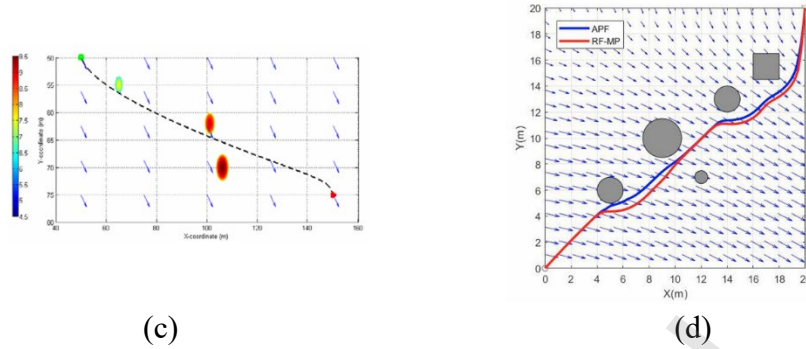


Fig. 5 Representative curvature-constrained trajectory generation from (a) [53], (b) [54], (c) [55] and (d) [56] using spline-based smoothing.

This line of research explicitly accounts for hydrodynamic effects, such as cross-current resistance and underactuated maneuvering limits, and enforces practical turning-radius constraints via smoothing tools to generate executable trajectories. By integrating environment perception with motion feasibility, these approaches improve both real-time performance and trajectory smoothness, highlighting an important direction toward deployable recovery navigation in realistic conditions. Overall, existing studies demonstrate that recovery-oriented path planning is evolving from static waypoint-based navigation to adaptive and constraint-aware planning frameworks. Future efforts are expected to further integrate disturbance prediction, uncertainty-aware decision-making, and hierarchical planning–control coupling, in order to achieve higher reliability when approaching complex recovery interfaces.

2.1.2 Obstacle Avoidance and Reactive Guidance

Although path planning provides nominal routes toward the recovery platform, safe execution of these plans in real marine environments requires effective obstacle avoidance and reactive motion control capabilities. During recovery operations, UUVs often operate in close proximity to support vessels, docking structures, and other environmental hazards, where unexpected obstacles, relative motion, and environmental disturbances can rapidly invalidate preplanned paths. As a result, obstacle avoidance cannot be treated as a purely offline planning problem and must be

addressed using real-time, feedback-driven control strategies. From a technological evolution perspective, obstacle avoidance in recovery-oriented navigation can be broadly categorized into three progressive stages: early-stage with geometric reactive methods, intermediate environment-aware refinements, and final-stage with control-aware reactive motion frameworks.

Early studies on underwater obstacle avoidance primarily focused on geometric or rule-based strategies under the assumption of static obstacles and simplified vehicle motion models. In this stage, obstacle avoidance is typically treated as a local, instantaneous reaction problem, where collision-free motion is achieved by directly mapping the obstacle geometry or relative velocity into steering or velocity adjustment commands. As shown in Fig.6, representative methods include artificial potential field approaches [57, 58], which generate repulsive forces around obstacles and attractive forces toward the goal, as well as velocity-based collision avoidance schemes that modify the vehicle's heading or speed to prevent predicted intersections [59-61]. Despite differences in implementation, these methods share a common advantage in the context of early underwater systems with limited onboard computational capabilities. By relying on simple geometric relationships and rule-based mappings, such approaches impose minimal computational burden and enable fast real-time responses using lightweight onboard processing, making these methods particularly suitable for early autonomous platforms.

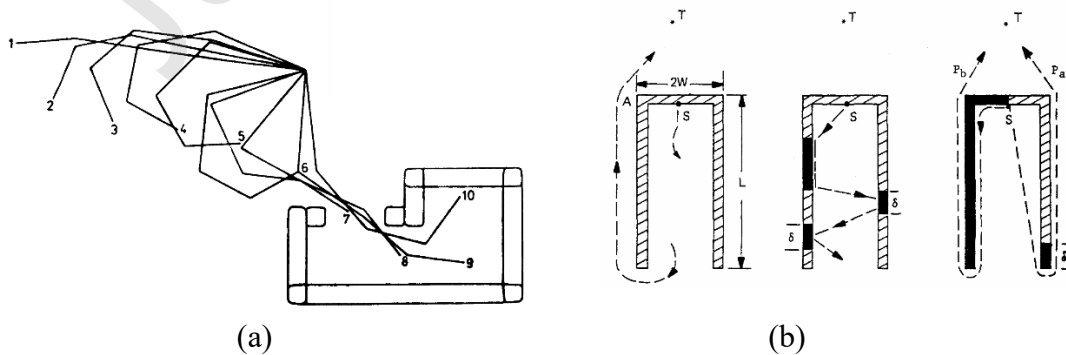


Fig. 6 Typical early-stage geometric obstacle avoidance methods for (a): Artificial potential field approaches [57] and (b): Velocity-based collision avoidance schemes [59].

However, owing to their purely reactive nature and lack of global awareness, such approaches are prone to oscillatory motion, and degraded performance in cluttered or densely constrained environments. As underwater operations expand toward more complex and dynamic scenarios, obstacle avoidance incorporates additional sources of uncertainty, including ambient flow fields, sensor noise, and moving obstacles. Under these conditions, the avoidance problem evolved from instantaneous collision prevention to maintaining a safe separation margin under persistent disturbance.

To address these challenges, intermediate-stage methods shown in Fig.7 introduce environment-aware refinements that enhance robustness beyond purely geometric reactions [62-66]. For artificial potential field-based methods, the main focus of improvement lies in overcoming the issues of oscillatory motion. Adaptive repulsive force modulation, dynamic weighting strategies, and auxiliary escape mechanisms are introduced to reshape the potential landscape in response to obstacle distribution and environmental disturbances, thereby enhancing convergence reliability [62, 63]. Velocity-based collision avoidance schemes have also been extended beyond static or simplified assumptions to accommodate dynamic obstacles and uncertainties in relative motion. By incorporating disturbance compensation, motion prediction, and collision risk evaluation metrics, these approaches transform instantaneous velocity selection into a forward-looking safety assessment problem, allowing safer and earlier evasive maneuvers in dynamic scenarios [64-66].

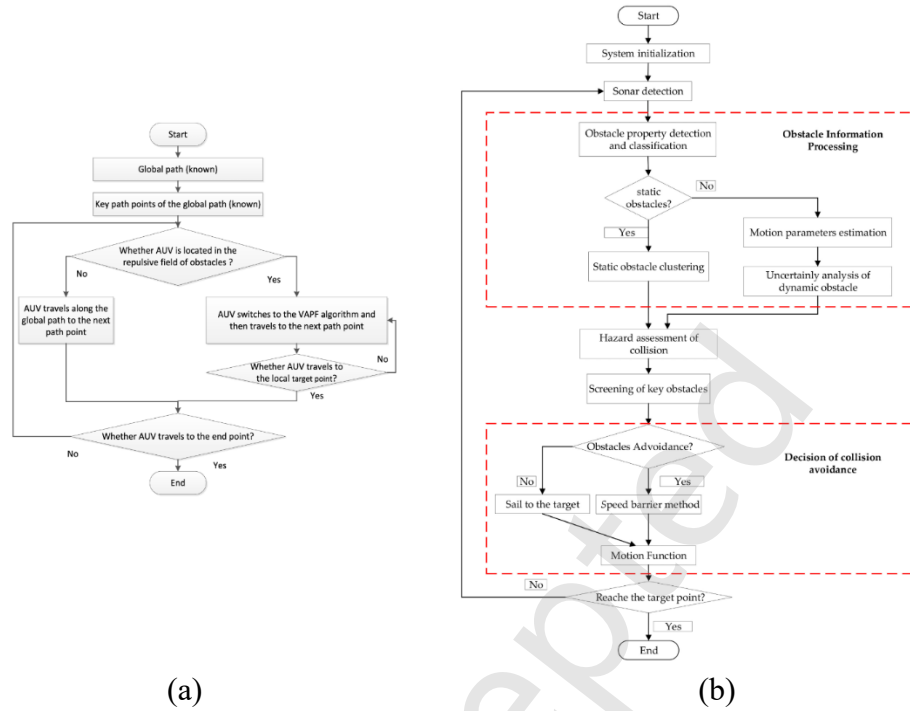


Fig. 7 Representative intermediate-stage reactive obstacle avoidance frameworks for (a) improved artificial potential field [62] and (b) velocity-based collision avoidance schemes [64].

Despite these advancements, intermediate-stage obstacle avoidance methods still exhibit several common limitations that restrict their applicability in recovery-oriented scenarios. Although environmental disturbances and dynamic obstacles are increasingly considered, avoidance decisions are predominantly generated at the guidance or planning level, with limited awareness of vehicle-level dynamics and actuation constraints. These limitations highlight the need for tighter integration between obstacle avoidance and motion control, motivating the development of control-aware reactive motion control frameworks that explicitly incorporate dynamic feasibility, control constraints, and tracking stability into the avoidance decision process. The final stage of obstacle avoidance and reactive motion control addresses these limitations by explicitly integrating avoidance decision-making with vehicle-level dynamics and control constraints [67-70]. In this stage, as shown in Fig.8, vehicle maneuverability, actuator limits, tracking stability, and motion smoothness are incorporated directly into the avoidance formulation,

ensuring that generated commands remain executable under real-world operating conditions. Typical frameworks achieve this integration by embedding collision-distance constraints, velocity and acceleration bounds, and stability considerations into predictive or feedback control structures, enabling consistent safety enforcement even in close-proximity and highly constrained recovery scenarios. As a result, obstacle avoidance evolves from a reactive correction mechanism into a coordinated motion-control process, significantly improving reliability, robustness, and safety during terminal recovery operations.

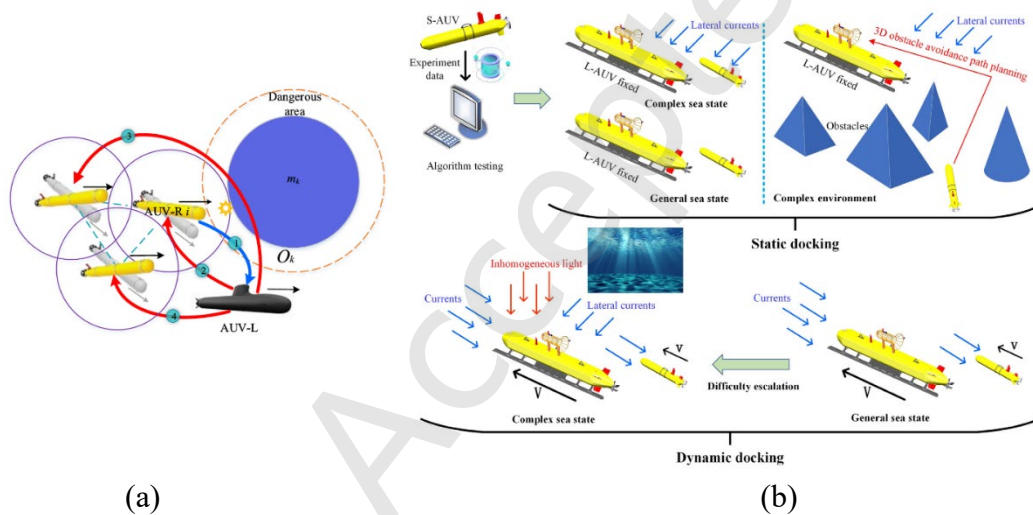


Fig. 8 Final-stage control-aware reactive motion control strategies for recovery operations: (a) safety-constrained reactive motion [67] and (b) docking-oriented reactive motion control [68].

From a critical perspective, existing path planning and obstacle avoidance methods exhibit complementary strengths and inherent limitations when applied to recovery-oriented scenarios. Learning-based path planning approaches demonstrate strong adaptability to uncertain and dynamic environments; however, they often suffer from limited interpretability and may generate trajectories that are difficult to execute under strict dynamic and safety constraints. In contrast, model-based approaches explicitly incorporate kinematic and dynamic constraints, thereby

ensuring trajectory feasibility and smoothness; however, their performance is often sensitive to environmental uncertainty and modeling inaccuracies.

For obstacle avoidance, early stage geometric methods such as artificial potential fields offer low computational complexity and strong real-time performance, but they are prone to local minima and oscillatory behavior in complex environments. More advanced velocity-based and control-aware reactive methods improve robustness and safety by incorporating motion prediction and control constraints; however, these approaches typically involve higher computational costs and require more accurate system modeling.

Overall, as shown in Table 2-1, a key challenge is achieving a balance between adaptability, robustness, and dynamic feasibility, particularly in close-proximity recovery scenarios where both global planning and local reactive control must be tightly integrated.

Table 2-1. Comparative assessment of representative path planning and obstacle avoidance methods for recovery-oriented navigation.

Method Type	Computational Complexity	Smoothness	Real-time Capability	Robustness	Implementation Feasibility
Learning-based Planning	High	Medium	Medium	High	Low
Model-based Planning	Medium	High	High	Medium	High
Artificial Potential Field	Low	Low	High	Low	High
Velocity Obstacle Methods	Medium	Medium	High	Medium	Medium
Control-aware Reactive Methods	High	High	Medium	High	Medium

To provide a clearer comparison of representative navigation and obstacle avoidance strategies, Table 2-2 summarizes the key characteristics of different methodological paradigms. As shown in the table, learning-based approaches demonstrate strong adaptability in dynamic and uncertain environments but often suffer from limited interpretability and training dependencies. In contrast, optimization-based methods generate smoother and more feasible

trajectories but rely on accurate environment modeling. Geometric and velocity-based methods offer high computational efficiency and real-time performance, making them suitable for early-stage or resource-constrained systems, although their robustness in complex environments is limited. More recently, control-aware methods have integrated dynamic feasibility and safety constraints, providing improved stability and reliability in close-proximity recovery scenarios, at the expense of increased computational costs. This comparison highlights the trade-offs between adaptability, computational efficiency, and trajectory quality, which must be carefully balanced in practical UMV recovery applications to ensure optimal performance.

Table 2-2. Comparison of representative path planning and obstacle avoidance methods for UMV recovery.

Method Type	Representative Approaches	Computational Complexity	Adaptability	Trajectory Smoothness	Real-time Performance
Learning-based	DRL (TD3, DDQN, PPO)	High	High	Medium-Low	Medium
Optimization-based	RRT, Hybrid A, spline smoothing	High-Medium	Medium	High	Medium
Geometric methods	Artificial potential field	Low	Medium-Low	Low	High
Velocity-based methods	Velocity obstacle (VO)	Medium-Low	Medium	Medium	High
Control-aware methods	MPC-based avoidance	High	High	High	Medium-Low

2.2 Engagement Phase Perception-Driven and Capture Preparation

The engagement phase focuses on close-range guidance, alignment, and capture preparations. During the engagement phase, recovery systems typically adopt a hierarchical guidance framework in which the sensing modality is selected based on environmental visibility. When visibility is limited due to turbidity or low illumination, acoustic-based guidance is employed to provide robust homing and alignment under adverse conditions. When visibility is sufficient, vision-based guidance can be adopted to deliver high-resolution relative pose information and

enable precise alignment. Once adequate proximity and alignment are achieved through either acoustic or vision guidance, capture-based technologies are applied to physically constrain and secure the UMV, completing the transition toward final recovery.

2.2.1 Acoustic-Based Guidance for Engagement-Phase Homing

As underwater recovery and docking tasks become increasingly complex, achieving reliable guidance in low-visibility and highly dynamic ocean environments is a central challenge for UMVs. Acoustic sensing provides superior propagation characteristics in the marine environment and remains the most practical modality for mid- to long-distance underwater navigation and terminal docking [71-75]. Acoustic-guided methods have emerged as a dominant approach, enabling UMVs to accurately localize, approach, and align with docking stations even under uncertain environmental disturbances.

Early research on acoustic guidance and positioning for underwater recovery was primarily driven by the need for reliable mid-range homing under limited visibility. The United States initiated related studies at an early stage, with the Woods Hole Oceanographic Institution proposing a Relative Acoustic Tracking System (RATS) in 1997. As shown in Fig.9, RATS is based on a super-short baseline (SSBL) configuration and represents one of the earliest practical acoustic guidance schemes for underwater recovery operations. In early experimental deployments, SSBL-based systems such as RATS were widely applied because of their compact hardware configuration and ability to provide relative range and bearing information for homing tasks.

underwater environments and close-range guidance scenarios [79-81]. The positioning accuracy is strongly influenced by environmental factors, including variations in the sound speed profile, acoustic multipath propagation, and ambient noise, which degrade bearing estimation performance and reduce reliability in complex underwater environments [82]. In addition, the relatively simple signal processing architectures of conventional acoustic systems limit robustness against interference and restrict achievable update rates and measurement precision [83]. Furthermore, as the relative distance decreases, small angular measurement errors can translate into large position uncertainties, making SSBL approaches unsuitable for precise terminal guidance and docking.

To address these challenges, research gradually shifted toward fully digital acoustic positioning systems [84]. Digital Ultra Short Baseline (DUSBL) architectures introduce coded acoustic waveforms, digital signal acquisition, and advanced estimation algorithms, enabling correlation-based detection, phase-difference estimation, and spatial beamforming on compact hydrophone arrays [85-88]. Compared with analog systems, DUSBL significantly improves robustness to multipath and ambient noise, increases effective update rates, and enhances range-and-bearing accuracy. As shown in Fig.11, these advances make DUSBL particularly well suited for close-range homing and docking tasks, and the approach has been successfully demonstrated on several autonomous platforms, including REMUS-class AUVs [89].

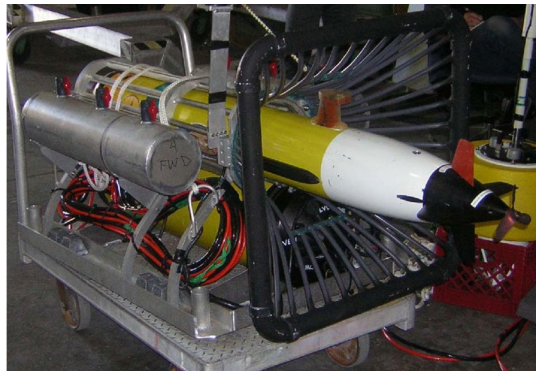


Fig. 11 DUSBL-enabled acoustic homing and docking of a REMUS-100 UUV [89].

More recent developments have further integrated digital acoustic positioning with recovery-oriented system design and control architectures [90]. Compact, vehicle-integrated acoustic arrays and docking structures are combined with centralized controllers to support coordinated homing, alignment, power transfer, and data exchange. In parallel, hybrid sensing strategies have emerged to extend acoustic guidance for terminal recovery under challenging conditions [91, 92]. By combining acoustic positioning with visual sensing, probabilistic state estimation, and current-compensating control strategies, modern systems achieve higher robustness against environmental uncertainty and enable reliable docking even under low visibility and strong currents.

2.2.2 Vision-Based Guidance for Close-Range Alignment

Although acoustic-based sensing provides robust long-range and mid-range localization capabilities in underwater environments, its accuracy and update rate are often insufficient for the terminal recovery phase, where precise relative positioning and orientation estimation are required. In particular, acoustic sensing is limited in resolving the full six-degree-of-freedom relative pose between the vehicle and recovery structure, which is critical for safe and reliable final alignment. Vision-based sensing has therefore been widely adopted as a complementary modality, offering high-resolution spatial information and fast update rates at short distances [93, 94]. By exploiting optical cues such as artificial landmarks, light beacons, or visual markers, vision-based methods enable accurate relative pose estimation in the terminal homing stage, effectively bridging the precision gap left by acoustic sensing.

Early vision-based guidance for close-range alignment was primarily based on the assumption that reliable visual contact with the recovery structure could be established. In this paradigm, artificial visual landmarks are deliberately deployed on the docking or recovery interface to facilitate detection and alignment. As shown in Fig.12, typical designs rely on active light sources arranged in predefined spatial patterns, where the relative positions of individual LEDs are

identified to infer the vessel's relative pose with respect to the recovery structure [81, 95-98]. By exploiting the known geometry of these landmarks, relative pose information can be extracted directly from camera observations, enabling accurate alignment during the terminal approach. Under favorable optical conditions, this class of methods offers several notable advantages. The use of artificial markers simplifies visual perception and reduces algorithmic complexity, allowing efficient and reliable pose estimation with modest computational resources. Moreover, the high contrast and geometric regularity of the landmarks support precise localization and alignment, yielding high accuracy in controlled environments.

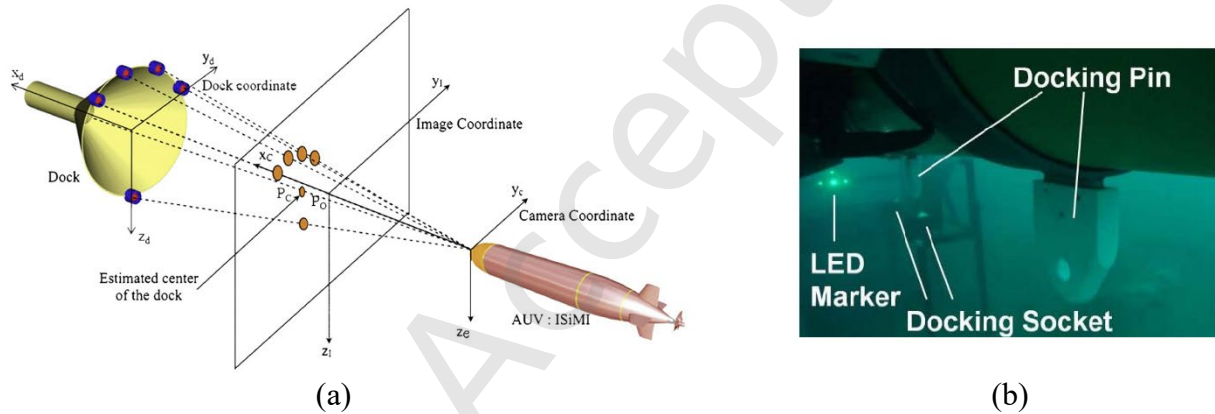


Fig. 12 Vision-based docking using LED marker configurations for (a) geometric matching of predefined LED arrangements [98], and (b): experimental example of LED markers [92].

However, the performance of early vision-based guidance is highly dependent on optical visibility, illumination conditions, and water turbidity, which can vary significantly across operational scenarios. Furthermore, reliable operation typically requires continuous visibility of the visual markers throughout the alignment process, imposing strict constraints on UUV approach geometry and limiting practical applicability in cluttered or dynamically changing environments. To address these limitations, vision-based guidance methods were developed with an emphasis on improving robustness under degraded optical conditions [99-103] as shown in Fig.13. Rather than relying solely on visual information, many studies have proposed coupling vision-based perception

with acoustic measurements to enhance robustness and accuracy [91, 104, 105]. By fusing acoustic positioning for coarse localization with visual sensing for fine alignment, these hybrid approaches have been shown to significantly reduce ambiguity in relative pose estimation and to achieve centimeter-level docking accuracy during recovery operations.

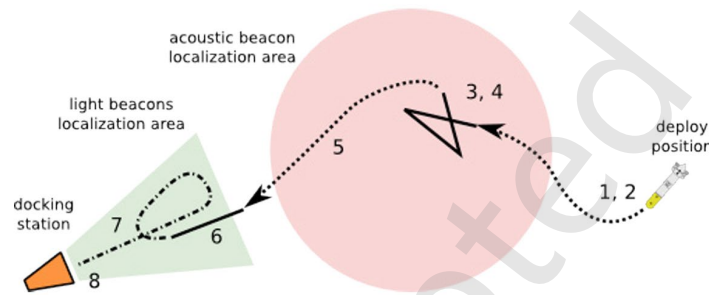


Fig. 13 Hybrid acoustic-vision guidance framework for underwater vehicle recovery [104].

2.2.3 Capture-Based Recovery for Engagement-to-Capture Transition

Although perception-driven technologies enable UMVs to detect, localize, and accurately approach the recovery platform, successful recovery ultimately requires a reliable physical interaction between the vehicle and recovery system. Even with high-precision acoustic and vision-based sensing, environmental disturbances such as waves, currents, and relative motion between the UMV and recovery platform can significantly degrade positioning accuracy in the final stage. As a result, perception alone is insufficient to guarantee safe and repeatable recovery.

Capture-based recovery addresses this challenge by providing mechanical tolerance and physical constraints that compensate for residual perception errors and dynamic uncertainties [106-112]. Through appropriate capture mechanisms, the relative motion between the UMV and recovery system can be constrained, absorbed, or guided, thereby ensuring secure engagement. Unlike acoustic- or vision-guided systems that depend heavily on active sensing and high-precision localization, capture-based approaches primarily rely on mechanical guidance structures to physically constrain UMVs and guide them into a stable docking posture.

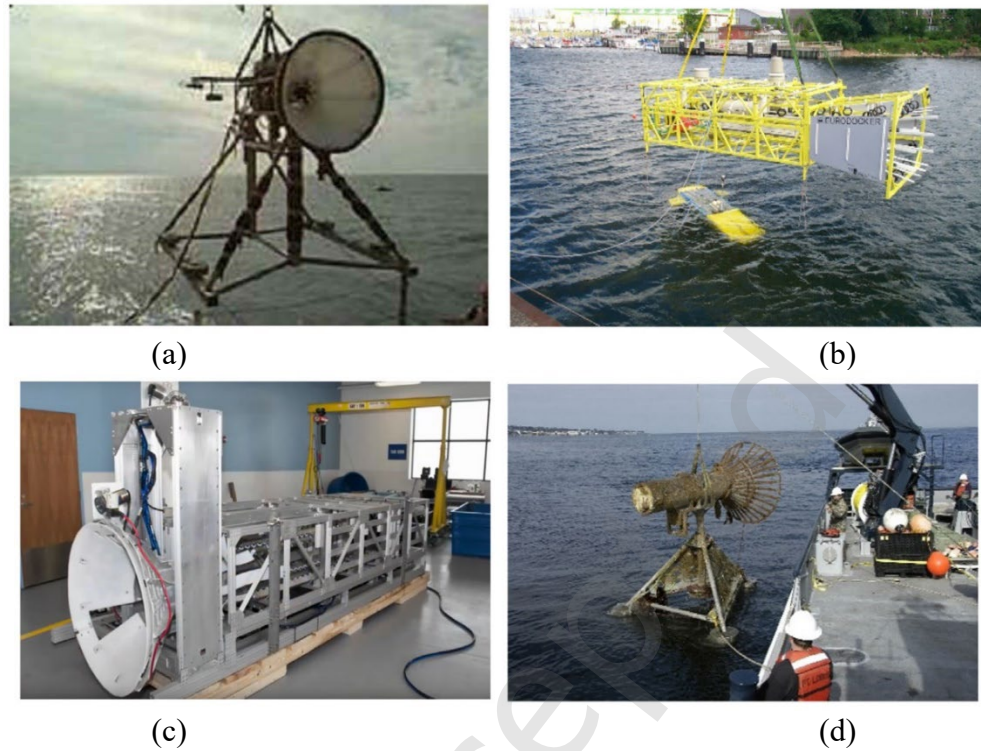


Fig. 14 Funnel-shaped capture mechanisms conducted by Yazdani et al. [109]. (a) REMUS docking system; (b) Eurodocking system (c) Bluefin docking system; (d) Dorado docking system.

However, one primary concern lies in accommodating residual misalignment during the capture process, as UMVs often approach the recovery interface with non-negligible lateral and angular errors. As shown in Fig.14, to mitigate this issue, many capture mechanisms employ funnel-shaped entrances, compliant guiding structures, or self-aligning geometries that passively correct approach errors and enlarge the effective capture envelope. Another critical challenge arises from relative motion and impact loads during engagement, particularly under wave- and current-induced disturbances. Excessive impact forces can compromise structural integrity and increase failure risks. Consequently, capture systems frequently incorporate passive energy-absorbing elements, such as springs, dampers, or compliant clamping mechanisms, to attenuate impact loads and accommodate transient relative motion between the UMV and the recovery platform.

In addition, practical recovery operations must account for the possibility of failed capture attempts. Modern capture-based designs therefore emphasize open or re-entrant structures that allow repeated approach attempts, along with mechanical release or reset mechanisms that prevent jamming or entrapment. For long-term or resident UMV deployments, further considerations include mechanical durability, corrosion resistance, and biofouling tolerance, favoring simple, passive, and low-maintenance capture solutions over complex active mechanisms.

From a critical perspective, the three representative approaches in the engagement phase—acoustic-based guidance, vision-based guidance, and capture-based recovery—exhibit complementary advantages as well as inherent limitations under different operational conditions. Acoustic-based guidance provides robust long-range and mid-range localization capabilities and performs reliably under low-visibility environments; however, its positioning accuracy and update rate are generally insufficient for precise terminal alignment. In contrast, vision-based guidance offers high-resolution spatial information and enables accurate pose estimation during close-range operations; however, its performance is highly dependent on environmental conditions such as water turbidity, illumination, and visibility.

Capture-based recovery mechanisms address the limitations of perception-driven methods by introducing mechanical tolerance and physical constraints, thereby reducing dependence on high-precision localization. These approaches improve robustness against residual positioning errors and environmental disturbances; however, they often require careful structural design and may introduce additional system complexity and mechanical constraints.

Overall, as shown in Table 2-3, an effective recovery system typically relies on the integration of these approaches, where acoustic sensing provides coarse guidance, vision-based methods enable fine alignment, and capture mechanisms ensure reliable physical interaction. Achieving

optimal coordination among these components remains a key challenge for future recovery systems.

Table 2-3. Comparative assessment of representative engagement-phase technologies for UMV recovery.

Method Type	Sensing Range	Accuracy	Environmental Dependency	Real-time Capability	Robustness	System Complexity
Acoustic-based Guidance	Long	Medium	Low	Medium	High	Medium
Vision-based Guidance	Short	High	High	High	Medium	Medium
Capture-based Recovery	Very Short	High	Low	High	High	High

Table 2-4 provides a comparative overview of representative guidance and sensing methods used in UMV recovery. Acoustic-based approaches, such as SSBL, USBL, and LBL systems, offer strong environmental robustness and effective long-range operation but are generally limited in positioning accuracy and update rate, particularly in close-range scenarios. In contrast, vision-based methods provide high-resolution pose estimation and fast update rates, making them well suited for terminal alignment, although their performance is strongly affected by visibility conditions. Digital acoustic systems, such as DUSBL, improve accuracy and robustness through advanced signal processing, whereas hybrid acoustic–vision approaches combine the advantages of both modalities to achieve reliable multi-stage guidance. This comparison highlights that no single sensing modality is sufficient across all recovery phases, and multi-sensor fusion is essential for robust and high-precision UMV recovery.

Table 2-4. Comparison of representative guidance and sensing methods for UMV recovery.

Method Type	Representative Systems	Effective Range	Positioning Accuracy	Computational Cost	Environmental Robustness
SSBL	Early acoustic tracking (RATS)	Medium	Low–Medium	Low	High
USBL	Modern acoustic positioning	Medium–Long	Medium	Medium	High

LBL/SBL	Baseline array systems	Long	High	Medium-High	High
DUSBL	Digital acoustic systems	Short–Medium	High	Medium-High	High
Vision-based	LED markers / camera systems	Short	Very High	Medium-High	Low–Medium
Hybrid (Acoustic + Vision)	Fusion-based docking	Short–Medium	Very High	High	High

2.3 Recovery Completion Phase: Motion Control and Compensation

The recovery completion phase addresses stabilization and safe handling after capture. In this phase, the primary technical challenge shifts from guidance and capture to the stabilization and safe handling of the UMV within the recovery system under wave- and current-induced disturbances. Although physical capture marks the nominal completion of recovery, relative motion between the UMV and recovery platform may persist due to platform dynamics and environmental loads.

Platform seakeeping enhancement and station-keeping strategies play critical roles in improving recovery success by reducing the relative motion between the UMV and the recovery platform at the system level [113, 114]. Therefore, enhancing the seakeeping capability of both the UMV and recovery platform is essential to enlarge the operational envelope and ensure reliable recovery under adverse sea conditions, particularly for small UMVs that are more sensitive to wave-frequency motions [115, 116].

Seakeeping enhancement for UMV recovery primarily focuses on mitigating wave-induced motion and enlarging the operational envelope under adverse sea states. One line of research emphasizes passive seakeeping improvement for UMV, where structural and geometric design modifications are employed to reduce the vehicle's sensitivity to wave excitation. Typical approaches include the optimization of the hull form, mass distribution, and damping characteristics to attenuate heave, roll, and pitch responses during recovery operations. By

reducing the intrinsic motion amplitude of the UMV without relying on active control, these passive strategies provide a robust and low-complexity means of improving recovery feasibility, particularly in scenarios where control authority or sensing availability is limited [117, 118].

Beyond passive modifications to the UMV, another research direction investigates active motion mitigation strategies applied to the recovery platform. In these approaches, wave-induced platform motion is measured or estimated in real time and actively compensated through dedicated control mechanisms [119, 120]. As shown in Fig.15, representative solutions include anti-roll tanks, actively controlled ballast systems, heave-compensation devices, and coordinated thruster-based stabilization. By actively suppressing platform oscillations induced by waves, these methods aim to reduce relative motion between the UMV and recovery structure during the recovery completion phase. As a result, the relative velocity and misalignment risk are significantly reduced, thereby improving capture safety and overall recovery success probability.

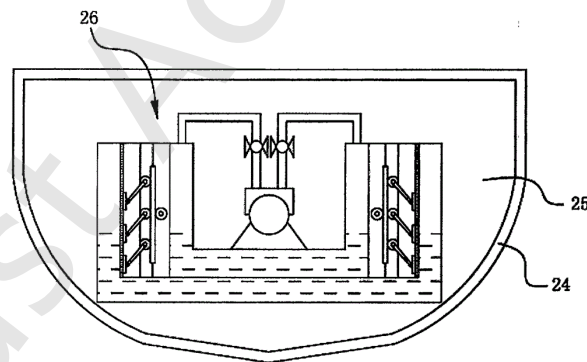


Fig. 15 Schematic illustration of a typical antiroll tank for passive roll stabilization.

More recent studies have extended seakeeping enhancement to a system-level perspective, where both the recovery platform and UMV are considered as a coupled dynamic system [119, 121-124]. Rather than solely stabilizing the platform, coordinated control strategies are designed to regulate relative motion by exploiting the maneuverability of the UMV in conjunction with platform motion characteristics. This coupled approach provides greater flexibility in handling

complex sea states and forms a natural bridge toward station-keeping and dynamic positioning strategies.

3. Recovery System Configurations and Operational Modalities

Beyond individual technologies, autonomous UMV recovery is ultimately realized through integrated recovery system configurations tailored to specific operational environments and mission requirements. Existing recovery systems can be broadly categorized into three configuration classes according to the location of the recovery interface and operational mode: surface recovery systems, subsea recovery systems, and integrated surface–subsea recovery systems. Each class corresponds to distinct UMV scale, recovery tier, and system-level design consideration.

3.1 Surface Recovery Methods

In the early stages of UMV development, the applications were primarily confined to limited missions such as scientific surveys, environmental monitoring, and tactical reconnaissance in nearshore and shallow waters. At that time, UMVs were relatively small in size, with limited endurance and payload capacity, and mission complexity was low, leading to simpler requirements for recovery systems. Consequently, surface recovery emerged as the most prevalent method due to its operational simplicity and lack of need for complex underwater infrastructure. As shown in Fig.16, this method typically involves the UMV surfacing after mission completion and being retrieved from the water onto the deck of a recovery platform using deck machinery such as cranes or recovery nets. The earliest water-surface recovery often relied on primitive methods such as manual hook, grapnel, or towline capture, where personnel directly hooked a floating UMV or dragged it alongside recovery platform, which process was inefficient, risky, and highly susceptible to sea state [106, 116, 125-126].

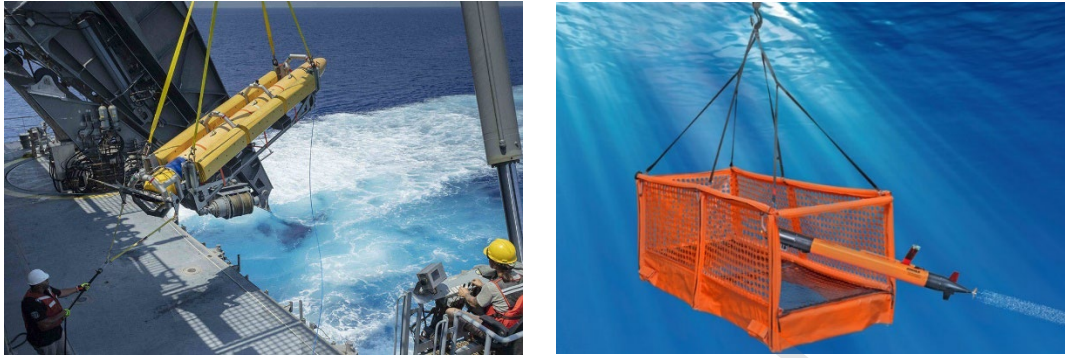


Fig. 16 Early representative surface recovery methods for UMVs: (a) crane lifting [125]; (b) net capture [126].

A representative early advancement in surface recovery systems was the introduction of mechanically guided and structurally protected recovery architecture. Two typical examples within the surface recovery tier summarized in Table 1-2 are stern ramp recovery and cocoon-based recovery [127, 128]. As shown in Fig.17, in stern ramp recovery, the UMV is guided onto an inclined ramp at the stern of the support vessel and gradually retrieved using winches or rollers, allowing controlled alignment and reduced relative motion during recovery. Cocoon-based recovery systems further enhance environmental robustness by towing the UMV into a floating cylindrical or semi-enclosed shell, which shields the vehicle from wave-induced lateral loads. A similar load-mitigation principle is embodied in moonpool-based recovery. Together, these mechanically guided surface recovery approaches mark a key transition from direct grappling to buffered, safety-oriented surface recovery configurations.

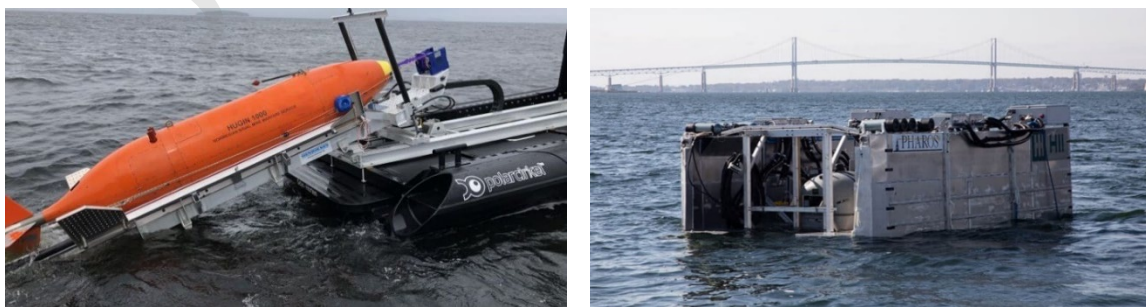


Fig. 17 Representative early advancements in surface recovery systems: (a) stern ramp recovery [127], and (b) cocoon-based recovery [128].

More recent efforts have focused on fully autonomous surface recovery architectures, in which perception, guidance, and mechanical capture are tightly integrated. Autonomous launch and recovery systems based on uncrewed surface vehicles exemplify this trend by combining multi-sensor perception, robotic clamping mechanisms, and coordinated motion control to enable human-free recovery operations [129]. These systems emphasize end-to-end automation, adaptability to varying sea states, and minimal modification of the recovered UMV, reflecting the current trend of surface recovery toward higher autonomy, safety, and operational flexibility.

3.2 Subsea Recovery Methods

The limitations of surface recovery, particularly its poor stealth and high vulnerability to surface conditions, have driven the need for more covert and reliable recovery solutions. As UMV missions increasingly demand extended endurance, persistent presence, and operational security in contested environments, the research focus has shifted decisively towards subsea recovery methods [51, 69, 104, 130-133]. As summarized in Table 1-1, medium-, large-, and extra-large UMVs increasingly adopt subsea recovery as their primary recovery mode as vehicle mass, operational depth, and mission duration increase. Correspondingly, subsea recovery systems, classified under the subsea recovery tier in Table 1-2, represent a fundamental departure from surface-based recovery configuration.

The most infrastructure-intensive subsea recovery configuration is the fixed seabed docking station, in which the recovery interface is permanently installed on the seafloor. These systems are typically designed to support long-term UMV residency, enabling repeated docking for battery recharging, data transfer, and maintenance without requiring surface intervention. Due to the high structural stability and complete isolation from surface wave effects, fixed seabed docking stations are particularly suited to large and extra-large UMVs operating in deep-water or long-duration missions.

To improve deployment flexibility while retaining the benefits of subsea recovery, suspended docking stations, as shown in Fig.18, have been proposed as an intermediate configuration between fixed seabed docks and surface recovery systems. In this architecture, the docking interface is suspended below a surface platform via cables or tethers, allowing recovery operations to be conducted below the wave-affected zone while avoiding permanent seabed installation [134, 135].

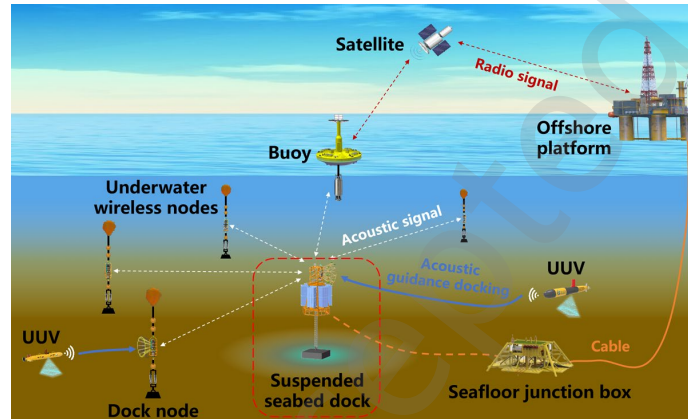


Fig. 18 Representative subsea recovery systems: suspended seabed docking station [134].

As subsea recovery systems must accommodate residual positioning errors and relative motion under currents, capture-based and soft or compliant docking configurations have emerged to enhance mechanical tolerance during engagement. Capture-based docking relies on funnel-shaped or guiding structures to physically constrain the UMV during approach, whereas soft or compliant docking further incorporates energy-absorbing or flexible elements to mitigate impact loads and accommodate misalignment, as shown in Fig.19. Together, these configurations reflect a shift from precision-dependent docking to mechanically tolerant and robust subsea recovery architectures.

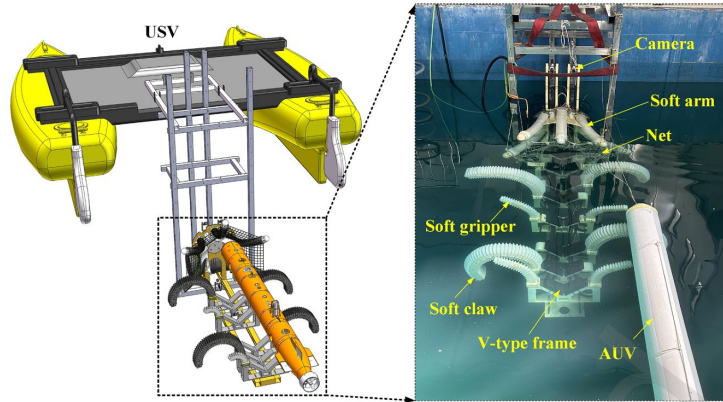


Fig. 19 Soft dock subsea recovery systems [136].

In addition to fully external subsea docking stations, moonpool-based recovery can be regarded as a specialized subsea recovery configuration in which the recovery interface is located within a sheltered vertical shaft of the support vessel. By positioning the docking operation below the free surface while maintaining direct access to onboard systems, moonpool recovery, as shown in Fig.20, combines subsea environmental isolation with surface-level logistical convenience.

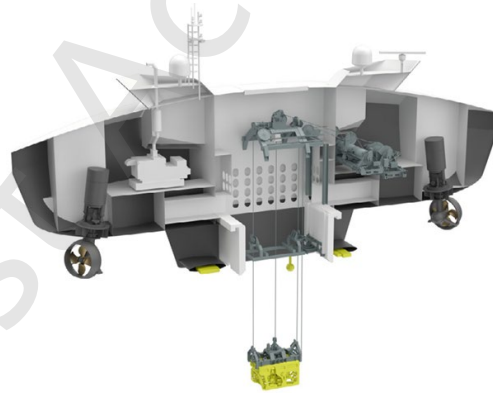


Fig. 20 Representative subsea recovery systems: moonpool recovery system [137].

Overall, these developments illustrate a clear evolution in subsea recovery technology: from fixed and rigid docking infrastructures to mobile, compliant, and perception-robust systems that explicitly account for environmental disturbance, relative motion, and long-term operational flexibility. Rather than pursuing isolated improvements in docking accuracy, recent research has

increasingly emphasized integrated recovery architectures that jointly consider mechanical tolerance, sensing robustness, and system-level adaptability.

3.3 Integrated Surface-Subsea Recovery Systems

With the continuous advancement of recovery system autonomy, sensing capability, and mechanical tolerance, the traditional distinction between surface and subsea recovery has become increasingly blurred. Rather than being confined to a single operational domain, modern recovery systems are increasingly designed to operate across the surface–subsea interface, enabling flexible transitions between surface-assisted and underwater recovery modes. This convergence has given rise to integrated surface–subsea recovery systems that combine the logistical accessibility of surface platforms with the environmental isolation and stability of subsea recovery.

A representative manifestation of this blurred boundary is the use of dock- or channel-based recovery architectures, in which the recovery interface is realized as an enclosed or semie-closed internal structure, as shown in Fig.21. Depending on the operational requirements and environmental conditions, such systems can perform recovery either at the sea surface or below the surface, without a fundamental change in the system configuration.

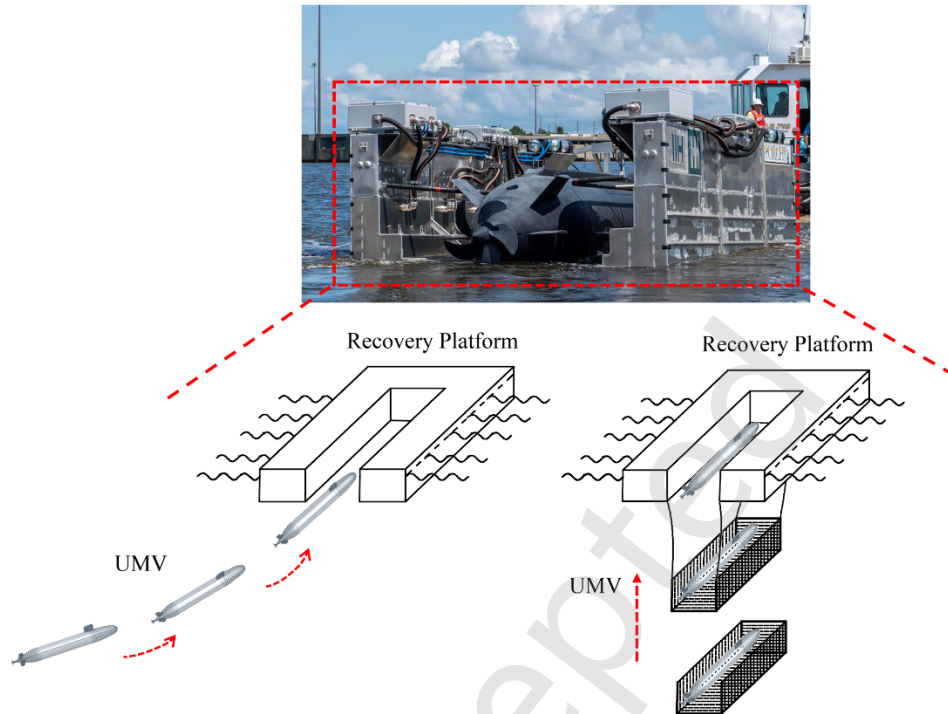


Fig. 21 Representative integrated recovery system.

When operated near the surface, these recovery architectures function as surface recovery systems by allowing the UMV to enter a sheltered internal space while remaining accessible for handling and maintenance. When submerged or partially submerged, these structures enable recovery below the wave-affected zone, effectively performing subsea recovery with enhanced environmental isolation and reduced hydrodynamic loading. As a result, the recovery mode can be adaptively selected-surface-assisted or fully subsea-based on sea state, mission urgency, and platform capability, without altering the fundamental recovery mechanism.

Overall, integrated surface-subsea recovery systems reflect a broader evolution in UMV recovery philosophy from domain-specific solutions toward flexible, adaptive, and system-integrated recovery architectures. By dissolving the rigid boundary between surface and subsea recovery, these systems provide enhanced operational robustness, extended environmental adaptability, and greater resilience under uncertain sea conditions. Such convergence-oriented

recovery designs are expected to play an increasingly important role as UMVs continue to grow in scale, autonomy, and mission complexity.

From a system-level perspective, surface, subsea, and integrated surface–subsea recovery represent three fundamentally different yet complementary recovery paradigms. Surface recovery systems are characterized by their structural simplicity, low cost, and operational convenience, making them suitable for small- to medium-scale UMVs operating under favorable sea conditions. However, their performance is highly sensitive to environmental disturbances, and they generally lack stealth capabilities.

In contrast, subsea recovery systems provide enhanced environmental robustness and concealment by avoiding direct exposure to surface waves and wind, thereby enabling reliable recovery of large-scale and long-endurance UMVs. Nevertheless, these systems typically require complex infrastructure and high deployment costs.

Integrated surface–subsea recovery systems combine the advantages of both approaches by enabling flexible switching between surface-assisted and subsea recovery modes. Such systems offer improved adaptability to varying operational conditions and represent a key development trend in modern UMV recovery architecture. However, they also introduce increased system complexity and design challenges associated with multi-mode coordination.

Overall, as shown in Table 3-1, the selection of the recovery configuration depends on multiple factors, including vehicle scale, mission requirements, environmental conditions, and operational constraints, highlighting the need for adaptive and system-level recovery strategies.

Table 3-1. Comparative assessment of surface, subsea, and integrated recovery systems for UMVs.

Recovery Mode	Operational Environment	Complexity	Environmental Robustness	Stealth Capability	Suitable UMV Scale
Surface Recovery	Surface	Low	Low	Low	Small–Medium

Subsea Recovery	Subsea	High	High	High	Medium–Extra Large
Integrated Recovery	Surface/Subsea	Very High	High	High	Medium–Large

4. Challenges in UMV Recovery

Despite significant advances in perception, capture mechanisms, navigation, and seakeeping-oriented motion mitigation, reliable UMV recovery in real-world marine environments remains highly challenging. Beyond laboratory demonstrations, operational recovery must contend with strong environmental disturbances, sensing uncertainties, limited onboard resources, and strict safety requirements. From a system-level perspective, the remaining challenges can be broadly summarized into five interconnected aspects: structural robustness and mechanical reliability, perception and localization uncertainty, control stability under environmental disturbances, energy constraints during terminal recovery, and environmental harshness affecting operational reliability. Addressing these challenges requires integrated solutions rather than isolated technical optimizations.

UMV recovery inevitably involves physical interactions under relative motion, impact loads, and misalignment, making structural robustness a critical concern, particularly for large-scale or long-endurance vehicles. Existing solutions rely on mechanically tolerant designs, such as funnel-shaped docking interfaces, compliant capture mechanisms, and passive guidance structures, to enlarge capture envelopes and absorb residual errors. Although these designs improve robustness through simplicity and passive tolerance, many remain platform-specific and lack adaptability across different UMV configurations and long-term deployments. Future progress will depend on modular, scalable, and self-adaptive mechanical designs that balance robustness, simplicity, and long-term reliability.

Accurate perception and localization are fundamental to recovery; however, underwater sensing remains severely constrained by acoustic latency, noise, limited resolution, optical turbidity, and illumination variability. Hybrid acoustic–vision frameworks and hierarchical sensing strategies have improved robustness across different ranges; however, most existing systems rely on predefined thresholds and switching logic, which are vulnerable to rapid environmental changes. Uncertainty is often insufficiently quantified or propagated in decision-making. Future recovery systems should emphasize uncertainty-aware perception and probabilistic fusion frameworks that explicitly account for sensing confidence and degradation in real time.

Terminal recovery represents a disturbance-intensive control problem involving nonlinear dynamics, wave- and current-induced disturbances, and tight spatial constraints. Robust, model predictive, and reactive motion control strategies have been proposed to maintain stability and ensure safe engagement. However, model-based methods often require conservative tuning, while learning-based approaches raise concerns regarding stability guarantees and safe deployment. A key challenge lies in unifying perception, planning, and control under formal safety constraints. Hybrid control architectures that combine model-based guarantees with adaptive learning remain a promising but largely unresolved area.

Recovery operations are typically performed at the end of a mission when UMV energy reserves are limited. High sensing and computation loads, repeated recovery attempts, and active control strategies can rapidly deplete the remaining energy. Although resident UMV concepts and subsea docking stations enable underwater recharging and data transfer, energy consumption is still often treated as a secondary consideration in recovery planning. Future systems should integrate energy awareness as a primary decision variable, balancing recovery success probability against energy expenditure and system longevity.

Environmental conditions, such as sea state, currents, and visibility, strongly influence recovery success by shrinking safe capture windows and increasing collision risk. Seakeeping enhancement, station-keeping strategies, and motion compensation systems mitigate these effects within nominal operating envelopes; however, most recovery systems lack resilience under extreme or rapidly changing conditions. Robust fallback strategies, predictive environmental awareness, and autonomous abort-and-retry mechanisms remain underdeveloped. Long-term field validation and resilience-oriented design will be essential to ensure reliable recovery across diverse operational scenarios.

Overall, autonomous UMV recovery is transitioning from isolated technological solutions to integrated system-level capabilities that must operate reliably under uncertainty, disturbance, and resource constraints. Future research will increasingly emphasize holistic recovery architectures that jointly consider perception, control, mechanical design, energy management, and environmental adaptability. Therefore, advancing UMV recovery will therefore require not only incremental technical improvements, but also a shift toward robust, flexible, and mission-aware system design.

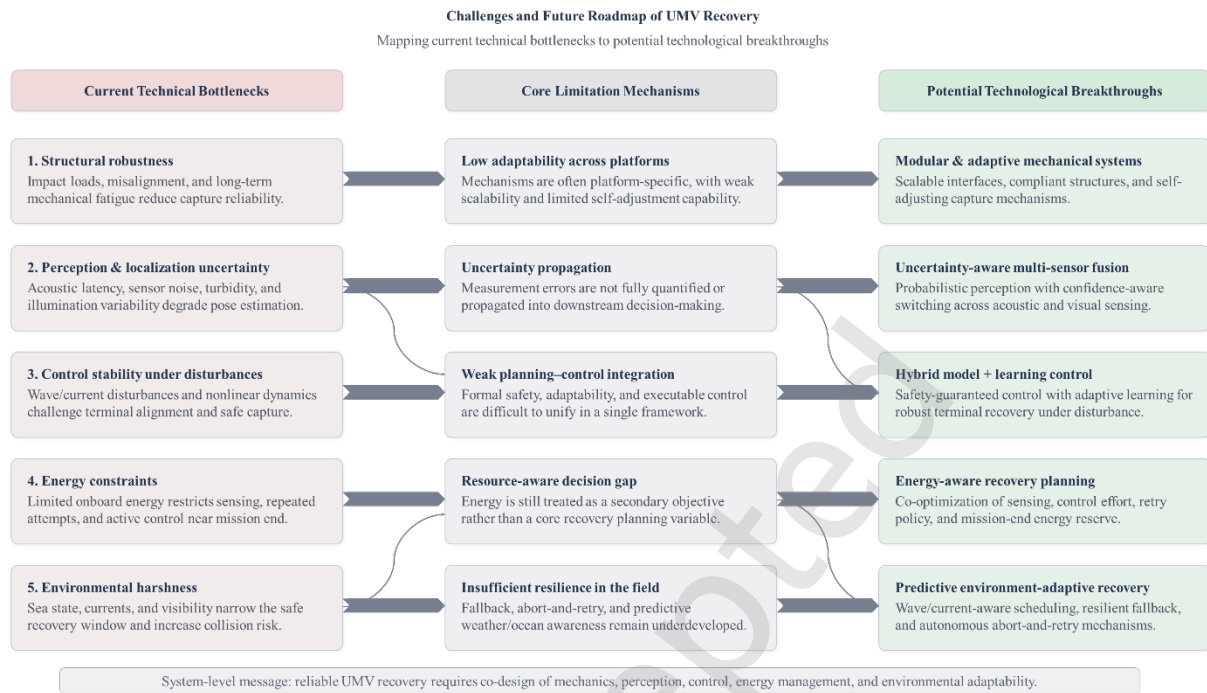


Fig. 22 Challenges and future roadmap of UMV recovery: mapping current technical bottlenecks to core limitation mechanisms and potential technological breakthroughs.

To provide a clearer and more intuitive understanding of the key challenges and their corresponding development directions, a schematic summary of the challenges and future roadmap for UMV recovery is presented in Fig. 22. The figure systematically maps the current technical bottlenecks to their underlying core limitation mechanisms and connects them to potential technological breakthroughs. Specifically, five major categories of challenges are identified, including structural robustness, perception and localization uncertainty, control stability under disturbances, energy constraints, and environmental harshness. These challenges are associated with fundamental limitations, such as low cross-platform adaptability, uncertainty propagation, weak planning-control integration, insufficient resource-aware decision-making, and limited field resilience. To address these issues, several promising research directions are highlighted, including modular and adaptive mechanical systems, uncertainty-aware multi-sensor fusion, hybrid model-learning-based control strategies, energy-aware recovery planning, and predictive environment-

adaptive recovery. This roadmap emphasizes that reliable UMV recovery requires a system-level co-design across mechanics, perception, control, energy management, and environmental adaptability.

From a system-level perspective, as shown in Table 4-1, the challenges in UMV recovery are inherently interconnected rather than isolated technical issues. Structural robustness, perception uncertainty, control stability, energy constraints, and environmental disturbances jointly influence the reliability and success rate of recovery operations. In particular, perception and control are tightly coupled under environmental disturbances, while energy limitations further constrain sensing and control performance during terminal recovery.

Moreover, most existing solutions address these challenges individually, whereas integrated approaches that simultaneously consider perception, control, mechanical design, and energy management remain limited. This highlights the necessity of developing holistic and system-level recovery strategies capable of operating reliably under uncertainty, disturbance, and resource constraints. Table 4-1 summarizes the key challenges and their characteristics to provide a clearer overview of the current limitations and research gaps in UMV recovery.

Table 4-1. Summary of key challenges in UMV recovery.

Challenge Category	Key Issues	Impact on Recovery	Current Limitations	Future Direction
Structural Robustness	Impact loads, misalignment, mechanical fatigue	Reduced reliability, failure risk	Platform-specific designs, limited adaptability	Modular and adaptive mechanical structures
Perception & Localization	Sensor noise, limited visibility, acoustic uncertainty	Positioning errors, alignment failure	Limited robustness under dynamic environments	Multi-sensor fusion and uncertainty-aware perception
Control Stability	Nonlinear dynamics, wave/current disturbances	Instability, collision risk	Conservative control or limited guarantees	Hybrid model-based and learning-based control

Energy Constraints	Limited onboard energy, high sensing/control cost	Reduced operation time, failed recovery attempts	Energy not integrated in planning/control	Energy-aware recovery strategies
Environmental Disturbances	Waves, currents, turbidity	Shrinking safe operation window	Poor performance under extreme conditions	Predictive environment-aware recovery and adaptive strategies

5. Beyond UMV Recovery: Emerging Recovery Challenges for Cross-Domain Uncrewed Systems

Although this review is primarily focused on recovery technologies for sea-sea UMVs, it is worth noting that recovery itself remains a critical and largely underexplored challenge when viewed from a broader system perspective. As maritime operations increasingly incorporate cross-domain uncrewed systems, recovery is no longer confined to a single physical domain but involves complex transitions across heterogeneous environments. In particular, the recovery of uncrewed aerial vehicles (UAVs) operating from ships exemplifies this emerging challenge.



Fig. 23 Shipborne UAV recovery based on flexible net capture [138-139].

Shipborne UAV recovery systems as illustrated in Fig. 23 predominantly rely on flexible materials, such as nets or compliant frame structures, to intercept and decelerate the vehicle during recovery. These systems were originally designed to minimize structural damage to UAVs by providing a compliant contact interface rather than rigid mechanical capture. However, such recovery methods inevitably impose rapid deceleration on the UAV during the capture process.

The rapid velocity reduction generates significant transient loads that are transmitted through the airframe and concentrated on structurally sensitive components. Given the inherently lightweight and slender structural design of UAVs, the localized loads can easily lead to material fatigue, deformation, or even structural failure. Consequently, flexible net-based recovery, while conceptually damage-mitigating, cannot fundamentally eliminate the risk of mechanical damage to UAVs during maritime recovery operations.



Fig. 24 UAV recovery via robotic retrieval [140].

Building on the limitations of flexible net capture, a clear emerging trend in maritime UAV operations is the integration of recovery capability into the ship itself, particularly through the use of internal moonpool-like structures or sheltered waterborne recovery zones. In this paradigm, UAVs are no longer required to achieve precise deck landings under harsh wind and wave conditions; instead, they descend into a protected internal water area or deliberately land on the sea surface adjacent to the vessel, followed by mechanical retrieval, as illustrated in Fig. 24. Despite its practical relevance and increasing operational appeal, the problem of UAV recovery from the sea surface has received very limited research attention to date. Systematic recovery strategies that address the coupled challenges of air–sea transition dynamics, water-impact loads, vehicle stability on the surface, and subsequent mechanical capture remain largely absent from the existing literature.



Fig.25 Air-sea recovery of ULV on an autonomous recovery platform [141].

Another, and arguably more disruptive, class of cross-domain uncrewed system recovery involves uncrewed launch vehicles (ULVs) as illustrated in Fig. 25. ULV recovery entails a direct transition across the air-sea interface under extreme dynamic conditions. This transition is characterized by orders-of-magnitude differences in the mass, velocity, and energy between the recovered vehicles and conventional maritime uncrewed systems. As a result, the descending ULV introduces substantial momentum transfer, impact loads, and transient disturbances that fundamentally alter the recovery environment. Consequently, ULV recovery represents a tightly coupled vehicle–platform interaction problem rather than a vehicle-centric recovery task. In this cross-domain scenario, the recovery platform itself becomes an active and performance-critical component of the system. Platform stability, structural strength, motion response, energy absorption capability, and real-time positioning accuracy collectively determine the feasibility and safety of recovery. This paradigm fundamentally challenges traditional recovery design philosophies developed for sea–sea systems and underscores the necessity of platform-aware, system-level recovery strategies, in which recovery performance must be evaluated from the perspective of coupled dynamics across heterogeneous physical domains.

To the best of the authors’ knowledge, systematic investigation of cross-domain recovery for uncrewed systems operating across air-sea interfaces remain largely unexplored. This emerging

problem represents a promising and open research direction that extends beyond vehicle-centric recovery paradigms to system-level recovery architectures. By naturally inheriting and generalizing concepts developed for UUV recovery, future cross-domain recovery systems may achieve reliable, scalable, and resilient recovery performance across fundamentally different energy, mass, and dynamic regimes.

From an ocean engineering perspective, cross-domain recovery involving UAVs and ULVs should not be viewed solely as a vehicle-centric problem, but rather as a platform-dominated system challenge. Unlike conventional sea–sea recovery, the success of cross-domain recovery is critically governed by the dynamic response and operational capability of the surface recovery platform.

In particular, platform seakeeping performance plays a fundamental role in maintaining a stable recovery interface under wave-induced motions. Dynamic Positioning (DP) systems are required to ensure precise station-keeping and alignment between the recovery platform and incoming vehicle under environmental disturbances. In addition, the structural design of the recovery platform must be capable of withstanding significant transient impact loads during landing or capture, especially in the case of high-mass and high-velocity ULV recovery. Active motion compensation technologies further contribute to reducing relative motion and expanding the operational window under adverse sea states.

These considerations indicate that cross-domain recovery is inherently a coupled ocean–aerospace system problem, in which ocean engineering constraints and platform-level performance ultimately determine the feasibility, safety, and scalability of recovery operations.

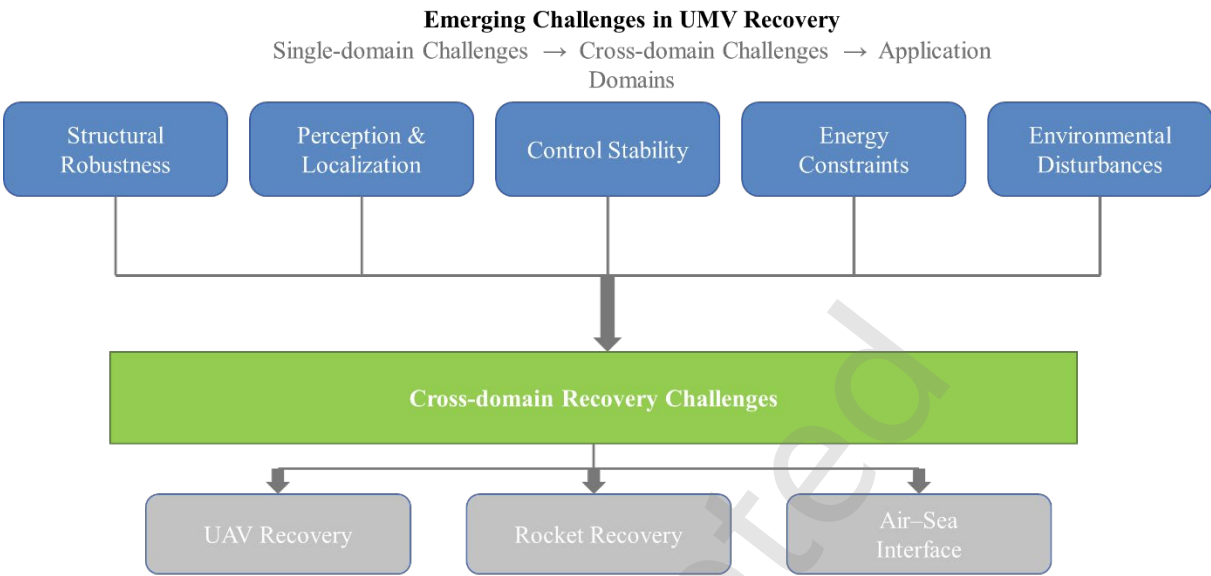


Fig. 26 Framework of emerging challenges in UMV recovery from single-domain to cross-domain perspectives.

To provide a clearer and more structured understanding of the challenges discussed in Sections 4 and 5, a systematic framework is illustrated in Fig. 26. As shown in the figure, the challenges in UMV recovery are divided into two hierarchical levels. The first level corresponds to conventional challenges in sea-sea recovery, including structural robustness, perception and localization uncertainty, control stability under disturbances, energy constraints, and environmental effects. The second level extends to emerging cross-domain recovery scenarios, which introduce additional complexities associated with air-sea interface dynamics, UAV recovery, and uncrewed launch vehicle recovery on marine platforms. This hierarchical representation highlights the evolution of recovery challenges from traditional single-domain problems to more complex cross-domain and system-level challenges.

Table 5-1. Comparison of integrated surface-subsea and air-sea cross-domain recoveries.

Category	Integrated Surface-Subsea Recovery	Air-Sea Cross-Domain Recovery
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System Architecture	Dock/channel-based systems; hybrid surface-subsea interface; moonpool-like structures	Net-based capture; water-surface landing + retrieval; platform-assisted recovery
Operational Mode	Switchable surface/subsea recovery; environment-adaptive	Cross-medium transition (air-sea); high-speed descent / impact
Control Strategies	Coordinated guidance + docking control; mode switching; relative motion control	Impact-aware control; trajectory shaping; platform-vehicle coordination
Key Challenges	Mode transition stability; sensing continuity; hydrodynamic coupling	Air-sea interface dynamics; impact loads; vehicle stability on water
Representative Systems	Docking channels, submerged recovery bays	UAV net recovery, sea-surface retrieval, rocket landing platforms
Technology Maturity	Medium (emerging integration)	Low (early-stage / conceptual)

To provide a clearer and more structured comparison between integrated surface-subsea recovery and air-sea cross-domain recovery, Table 5-1 summarizes their key characteristics from multiple perspectives, including system architecture, operational mode, control strategies, key challenges, representative systems, and technological maturity.

As shown in Table 5-1, integrated surface-subsea recovery systems are primarily characterized by hybrid system architectures that enable flexible transitions between surface-assisted and subsea recovery modes. These systems emphasize coordinated guidance, docking control, and relative motion regulation under varying environmental conditions. In contrast, air-sea cross-domain recovery involves fundamentally different physical processes associated with transitions across heterogeneous media, where high-speed impact, multi-domain dynamics, and platform-vehicle coupling become dominant factors.

From a control perspective, integrated recovery focuses on mode switching and precise docking under hydrodynamic disturbances, whereas cross-domain recovery requires impact-aware control, trajectory shaping, and coupled system coordination. In addition, the two paradigms differ significantly in their technological maturity: integrated recovery has reached a moderate level of

development with emerging practical implementations, whereas cross-domain recovery remains largely at an early or conceptual stage with limited systematic validation.

Overall, this comparison highlights that while both approaches aim to enhance recovery flexibility and operational capability, they differ substantially in underlying physical mechanisms, system design principles, and research maturity, indicating distinct directions for future development.

6. Conclusion

This review provides a comprehensive overview of uncrewed marine vehicle (UMV) recovery technologies from both system- and technology-level perspectives. By decomposing the recovery process into three sequential phases—approaching, engagement, and recovery completion—a unified framework was established to systematically organize the key enabling technologies, including navigation and path planning, perception-driven guidance, capture mechanisms, and motion control with seakeeping compensation.

From a technological evolution perspective, UMV recovery has progressed from simple surface-based methods to more advanced subsea recovery systems, driven by increasing vehicle scale, mission complexity, and operational requirements. More recently, integrated surface–subsea recovery architectures have emerged, enabling flexible transitions between recovery modes and improving adaptability under varying environmental conditions. This evolution reflects a shift from single-mode, platform-dependent solutions to more flexible and system-integrated recovery paradigms.

Despite these advances, several fundamental challenges remain. These include achieving robust perception and localization under uncertainty, ensuring stable control under strong environmental disturbances, improving mechanical reliability and tolerance during capture, and addressing energy constraints during terminal recovery. In addition, environmental variability

continues to impose strict limitations on the safety and operability of recovery, particularly in high sea states and dynamic ocean conditions.

Future research is expected to move toward more integrated and intelligent recovery systems. Key directions include the development of uncertainty-aware perception and decision-making frameworks, hybrid control architectures that combine model-based safety with learning-based adaptability, and modular, scalable recovery mechanisms capable of handling diverse UMV configurations. Furthermore, the emerging problem of air–sea cross-domain recovery introduces fundamentally new challenges associated with multi-domain dynamics, impact loads, and platform–vehicle coupling, which require new system-level design approaches beyond traditional marine recovery paradigms.

Overall, advancing UMV recovery will require a shift from isolated technological improvements to holistic system-level integration, where perception, control, mechanical design, energy management, and environmental adaptability are jointly considered to achieve reliable and scalable recovery in complex marine environments.

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Author contribution statement

Wei Wang is responsible for methodology, investigation, formal analysis, and data curation. Yuhang Zhang is responsible for writing – review & editing. Zhiming Yuan is responsible for writing – review & editing. Aichun Feng is responsible for writing – review & editing, supervision, resources, and project administration. All the authors have approved the final manuscript.

Data availability

Not applicable.

Declaration of competing interest

All the contributing authors report no conflicts of interest in this work.

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Use of AI statement

None.

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