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**Review**

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# Modular reconfigurable underwater robots (MRUR): a comprehensive review of structure, perception and control

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**Abstract:** Modular reconfigurable underwater robots (MRURs) have attracted increasing attention due to their potential to overcome the limitations of conventional underwater robots with fixed structures and single-task capabilities. This review summarizes recent progress in MRUR from three perspectives: modular structural design, sensing and perception, and control strategies. For structural design, this review examines module division, housing, and connectors, highlighting composite pressure-resistant structures and magnetic docking mechanisms as feasible solutions. For perception, MRURs require not only multisensor fusion but also topology awareness, docking perception, and distributed perception to handle changes in reconfiguration. For control, MRUR reconfiguration alters topology, dynamics and actuation; therefore, key issues include topology recognition, docking and separation control, propulsion redundancy, distributed coordination, and the transition toward self-reconfiguration. Finally, representative application scenarios, key technical challenges, and future research directions of MRURs are discussed. With continued technological progress, MRURs are expected to evolve toward self-reconfiguration and self-adaptation, achieving intelligent control and cooperative autonomy.

**Key words:** Modular robotics; Underwater robotics; Modular reconfigurable underwater robots (MRURs); AUV

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## 1 Introduction

### 1.1 Research Background and Significance

Underwater robots enable us to explore the vast underwater world and even reach the deepest parts of the ocean. Conventional underwater robots are mainly remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). These platforms typically feature rigid structural configurations and can be further classified according to their operational requirements and geometric characteristics into torpedo-shaped AUVs, spherical designs, disc-shaped configurations, and bioinspired platforms (Cui et al., 2023; Eldred et al., 2021; Neira et al., 2021; Wang et al., 2019). As research continues to advance, the limitations of such systems have become increasingly apparent. A single-structure platform is inherently constrained in its ability to accommodate diverse operational environments and task requirements, often necessitating task-specific designs, which become a significant barrier to both academic research and commercial deployment (Zheng et al., 2025).

To address these limitations, underwater robotic systems have increasingly incorporated the concepts of modularity and reconfigurability. By reconfiguring the physical connections among modules, such systems can reorganize their structures and extend their functional capabilities according to specific mission requirements (Hildebrandt et al., 2020). This review draws on definitions of modular and reconfigurable robots from previous studies and proposes a systematic definition of modular and reconfigurable underwater robots (MRURs): C1, which is composed of two or more physically separable hardware modules connected through explicit mechanical, electrical, or communication interfaces; C2, whose module arrangement or intermodule topology can be reconfigured to change

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morphology, actuation layout, sensing layout, or functional capability; and C3, whose design explicitly considers underwater constraints such as sealing, pressure tolerance, buoyancy balance, hydrodynamic coupling, underwater actuation, underwater sensing, or deployment limitations (Yim et al., 2007; Stoy et al., 2010; Seo et al., 2019; Liang et al., 2025).

Compared with traditional AUVs and ROVs, MRURs can simplify manufacturing and maintenance processes while reducing overall system costs. They exhibit significant technical relevance and broad application potential in subsea equipment maintenance, environmental monitoring, ocean exploration, and data acquisition (Meng et al., 2025), and have emerged as one of the major directions in underwater robotics research.

## 1.2 Current Research Status and Literature Review

Research on MRURs can be traced back to the development of modular and reconfigurable robots (MRRs). Since the introduction of the first MRR system, CEBOT (Fukuda et al., 1989; Fukuda and Kawauchi, 1990), in the 1980s, the field has undergone nearly four decades of advancement. It has evolved from early two-dimensional planar motion systems to sophisticated platforms capable of three-dimensional self-reconfiguration, self-assembly, and rapid docking. The core mechanisms and design principles of MRRs have provided essential theoretical foundations and technical references for MRUR research.

Building on MRUR research, modular self-reconfigurable underwater robots (MSRUR) represent a further progression. Its defining characteristic is the ability to autonomously and dynamically reconfigure its physical topology and functional morphology without external intervention (Salemi et al., 2006; Yim et al., 2007).

The lineage of MRURs can be traced from general modular reconfigurable robotics to underwater-specific embodiments. At the conceptual stage, HYDRON/HYDRA explored self-organizing modular artifacts inspired by cell adhesion, while AMOUR investigated underwater docking, optical ranging, and the feasibility of autonomous modular underwater robots (Østergaard et al., 2005; Vasilescu et al., 2005). Subsequent studies made the MRUR concept more concrete in underwater platforms. Researchers at Nanyang Technological University (NTU) developed a modular biomimetic robotic fish platform in which undulating-fin/body components could be rearranged or extended to support different bioinspired locomotion modes (Low and Yu, 2007). The bioinspired electric-sense robot developed by Mintchev further advanced this direction by using nine rigid modules that could separate, navigate, and reassemble underwater (Mintchev et al., 2012). SeaDrone demonstrated task-oriented physical reconfiguration among different underwater layouts (Moreno and Chung, 2014), while REMORA-related work developed docking, energy-aware planning, and multimodule coordination for underwater self-reconfiguration (Furno et al., 2017). More recently, ASRR extended MRUR research toward multienvironment adaptability by using modular self-reconfigurable units to alter morphology for locomotion and task execution in aquatic and other operating environments (Yang et al., 2024b).

Since then, research on MRURs has diversified toward bioinspired, compact, and task-adaptive architectures. Bioinspired platforms such as MMBAUV employ magnetically coupled body modules for morphology adaptation and fish-like locomotion (Wright et al., 2023), while compact systems, including synthetic-jet miniature MRURs and chain-like micro underwater robots, target confined-space operation through configuration switching and task-oriented morphology changes (Bauschmann et al., 2023; Wang et al., 2024). Alternative actuation strategies, such as hinge-connected piezoelectric-jet modules and modular hydraulic propulsion, further expand the design space by enabling capture-oriented motion and fluid-routing-based locomotion(Doyle et al., 2016; Zhang et al., 2025a).

More recent studies have moved toward collective and standardized-module systems, including magnetically docking robotic fish swarms and cubic modular marine robots for scalable underwater assembly and morphology formation (Zhou et al., 2024; Zheng et al., 2025; Si et al., 2026).

The representative evolutionary timeline and corresponding Sankey diagram of MRUR development are presented in Fig. 1.

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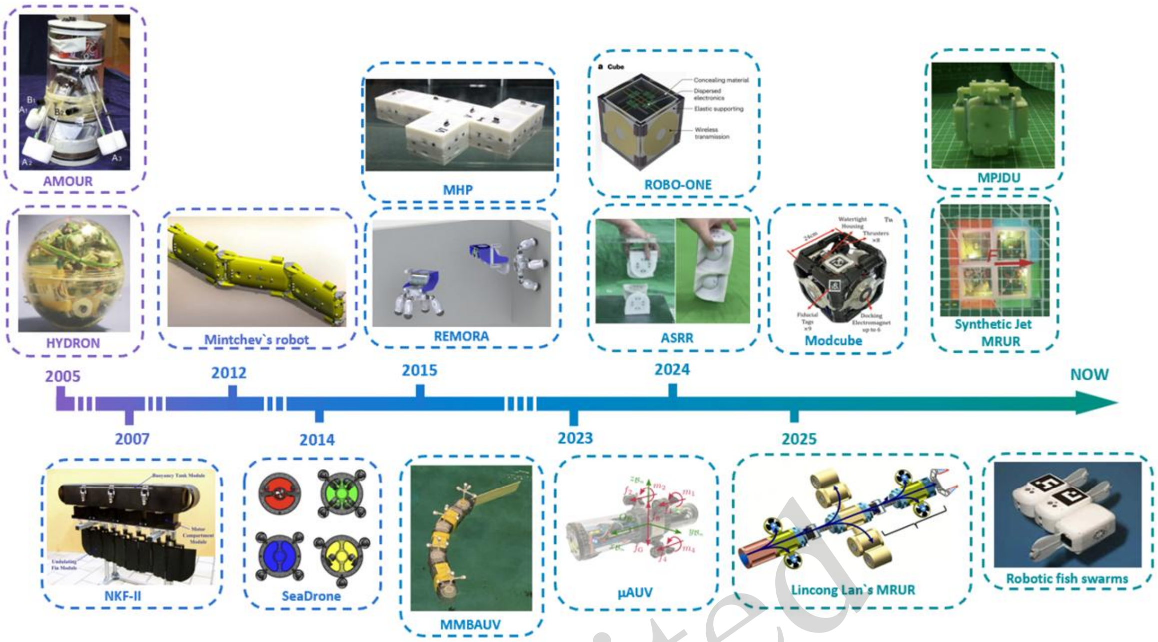
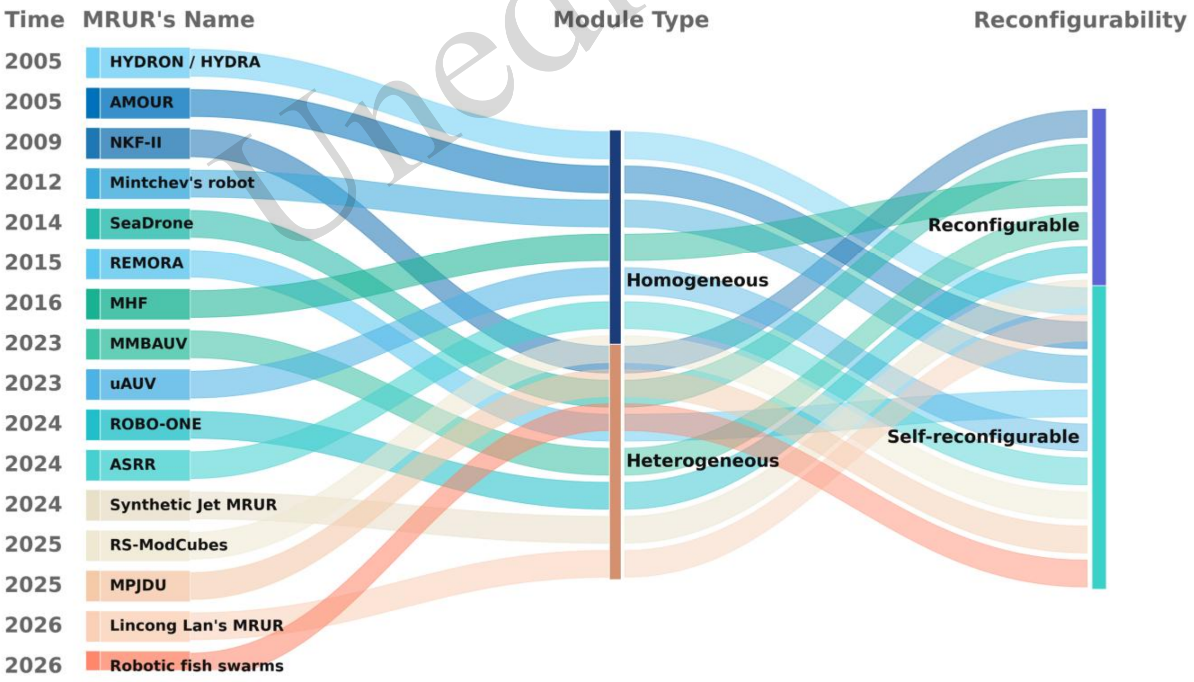


(a) The project development timeline of MRUR



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(b) Sankey diagram of MRUR project characteristics

**Fig. 1 The timeline of the MRUR project (a) and the Sankey diagram illustrating the project characteristics (b)**

With the progressive advancement of research, the development trajectory of MRUR has formed a comprehensive technological landscape. To systematically examine its core technologies, this study investigates three fundamental aspects—structural design, sensing systems, and control strategies—and further analyzes the associated application potential and technical challenges.

### 1.3 Review Scope and Methodology

This review is positioned as a methodologically transparent narrative review rather than a PRISMA-style systematic review. This choice is motivated by the current state of the MRUR literature, which remains relatively small, technically heterogeneous, and distributed across journals, conference proceedings, preprints, project reports, and neighboring research areas, including modular robotics, underwater vehicles, soft robotics, and autonomous systems.

A structured literature search was conducted using Web of Science, Scopus, IEEE Xplore, Google Scholar, publisher databases, and relevant project pages. The search strategy combined modular-robotics terms, including "modular", "self-reconfigurable", "reconfigurable", "docking", "module graph", and "topology", with underwater-domain terms, including "underwater robot", "AUV", "ROV", "aquatic", "subsea", and "marine".

Studies were included when they described, analyzed, or experimentally demonstrated robotic systems satisfying the operational definition of MRURs adopted in this review. Additional studies were included when they provided the necessary background on modular robotics, underwater docking, sensing and perception, soft-body modeling, or control methods directly relevant to reconfiguration. Studies were not classified within the MRUR development line when they only addressed payload modularity, generic AUV hardware or software accessibility, adjustable thruster orientation without physically separable modules, or conventional underwater sensing and control without an explicit connection to topology or configuration change.

Therefore, the objective of this review is to establish a reproducible inclusion boundary and an analytically structured account of MRUR development. The reporting approach follows the transparency-oriented rationale of PRISMA 2020 while avoiding a full PRISMA claim because the current MRUR evidence base is not yet sufficiently mature or homogeneous for reliable quantitative synthesis (Page et al., 2021).

## 2 Modular Structural Design of MRURs

### 2.1 Principles for Modular Unit Division

MRUR architectures can be broadly classified into two types: highly integrated modularity and function-separated modularity. These two types exhibit significant differences in system design concepts, module functional boundaries, and reconfiguration methods.

In highly integrated modular architectures, each module typically incorporates key subsystems, including propulsion, control, power supply, communication, and structural interfaces, enabling it to operate as an independent minimal robotic unit. A representative example of this approach is RS-ModCubes, whose modules encapsulate thrusters, drive circuits, sensors, and onboard power systems, achieving a high level of integration at the module level (Zheng et al., 2025). The advantage of such systems lies in their reconfiguration flexibility and module-level autonomy. However, this comes at the cost of higher manufacturing complexity and increased module cost, while functional expansion typically depends on adding more modules rather than replacing module types.

In contrast, function-separated modular architectures follow the design principle of one module, one function, where propulsion, power supply, and main control are distributed across separate modules(Zhou et al., 2024). This configuration enables the system to construct diverse mission profiles through different combinations of functional modules, with ROBO-ONE serving as a representative example. The advantages of this approach include clear functional division, strong replaceability, and high system scalability. However, its drawbacks lie in the strong interdependence among modules, with overall system reliability being highly dependent on the quality of intermodule connections.

Regardless of the architectural approach, the core objective of structural design is to achieve hardware-level reliability, scalability, and maintainability through robust physical encapsulation and reliable intermodule connections(Hildebrandt et al., 2020).

### 2.2 Pressure Hull Design

Pressure hull design constitutes the fundamental structural unit of an MRUR system. One of the key requirements in hull design is to provide reliable

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protection for internal electronic components (Wang et al., 2024) while also accommodating buoyancy distribution and module standardization requirements. The pressure hull design has evolved from traditional rigid pressure-resistant housings to biomimetically optimized hydrodynamic structures and further toward the integration of advanced functional materials.

Traditionally, pressure housings have predominantly adopted cylindrical or spherical geometries(Hildebrandt et al., 2020), similar to conventional torpedo-shaped AUVs, as illustrated in Fig. 2. Owing to their axisymmetric configurations, cylindrical and spherical pressure hulls exhibit a relatively uniform stress distribution and can effectively reduce local stress concentrations under external hydrostatic pressure (Meschini et al., 2019), and their internal structure is shown in Fig. 3a.

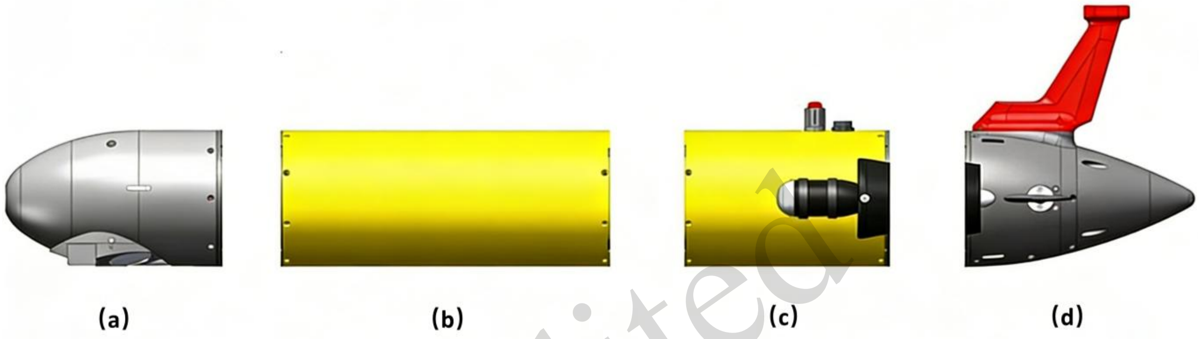

**Fig. 2 Hull modularization of a torpedo-shaped AUV**

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The increasing demand for modular reconfiguration in underwater robotics has led to the gradual abandonment of traditional pressure hull designs lacking structural extensibility. Inspired by cellular structures (Fukuda and Kawauchi, 1990), polygonal modular underwater robots have subsequently been developed. Compared with conventional cylindrical or spherical pressure hulls, cubic and polyhedral structures are more susceptible to stress concentration at edges and vertices under external hydrostatic pressure. This reduces their overall pressure resistance and imposes more stringent requirements on sealing design.

In response, existing studies typically adopt various engineering compensation strategies. First, local pressure housings or pressure-balanced oil-filled sealing structures are incorporated within polyhedral modules(Hildebrandt et al., 2020). Second, chamfered edges, rounded transitions, or encapsulating outer shells are introduced in module geometry design (Zheng et al., 2025) to reduce stress concentration and improve hydrodynamic performance. Third, metal frame structures are employed to ensure the strength and toughness of the core structure(Zheng et al., 2025).

For shallow-water experimental scenarios with depths less than 30 m, physical housings are commonly fabricated using 3D printing techniques. The primary materials employed are ultraviolet curable resins (Bianchi et al., 2024; Lan et al., 2026; Wang et al., 2024) and ABS (Bianchi et al., 2024), with waterproof adhesives and epoxy resins applied at joints and seams for sealing (Bianchi et al., 2024). This approach enables rapid fabrication at low cost while satisfying the basic structural strength and pressure-resistance requirements under shallow-water conditions. Fig. 3b illustrates the ultraviolet curing 3D printing process.

However, in deep-sea environments, as external hydrostatic pressure increases, UV-curable resins are limited by insufficient fracture toughness and fatigue resistance, making it difficult to maintain structural integrity and sealing reliability under prolonged high-pressure conditions. Based on this, recent studies have begun to explore the potential of flexible materials for deep-sea sealing and structural adaptability.

The successful descent of a self-powered soft underwater robot to the Mariana Trench demonstrated that flexible structures based on soft gel materials can achieve reliable pressure adaptation and sealing performance in extreme deep-sea environments (Li et al., 2021).

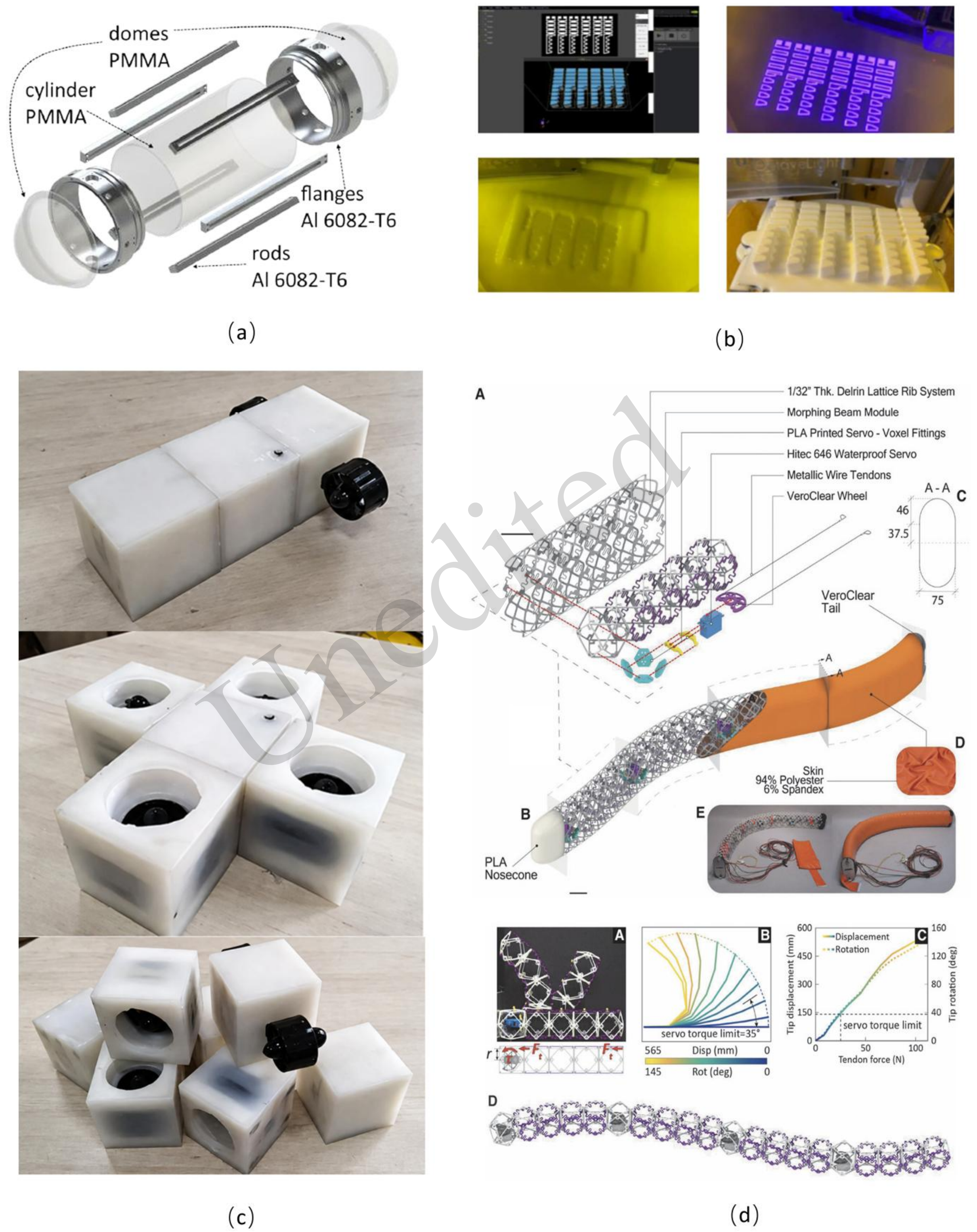

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**Fig. 3 Illustrations of different underwater robot hull designs: (a) conventional rigid pressure hull exemplified by the FeelHippo AUV (Meschini et al., 2019); (b) UV-curable 3D printing process for hull fabrication (using DLP as an example)(Sun et al., 2023); (c) gel-based soft cubic modules in ROBO-ONE; (d) deformable mechanical metamaterial structure: cross-sectional view, surface texture and deformation testing(Parra Rubio et al., 2023)**

In ROBO-ONE at Zhejiang University, a series of interchangeable gel-based cubic modules were constructed using soft gel materials(Zhou et al., 2024), as shown in Fig. 3c. In the study by Parra Rubio et al., a deformable mechanical metamaterial structure, discretely assembled from rigid and soft voxel units, was applied to the field of modular underwater robotics (Parra Rubio et al., 2023), as shown in Fig. 3d.

Compared with conventional rigid pressure housings, composite systems based on flexible materials and supporting structures can maintain underwater sealing while achieving load redistribution and deformation coordination through structural compliance, offering a new research avenue for highly reliable and lightweight underwater robotic systems.

### 2.3 Connection mechanism

In MRRs, connectors determine how modules attach, detach, align, and exchange power or data (Liu et al., 2018). Typically, MRRs can be categorized into four types: mechanical connectors(Murata et al., 2002; Yim et al., 2000), magnetic connectors (Murata et al., 2002; Wright et al., 2023; Zheng et al., 2025), electrostatic force connectors (Karagozler et al., 2007), and nylon connectors (Moeckel et al., 2006).

In MRUR systems, constrained by the comprehensive requirements for rapid assembly, repeated disassembly and hermetic reliability of modules in the underwater environment, the connection schemes between current modules include magnetic connectors(Lan et al., 2026; Wang et al., 2024; Zhou et al., 2024)and hybrid magnetic-mechanical connectors (Lan et al., 2026). Pure mechanical connections are only adopted in a limited number of scenarios due to adaptability constraints (Bianchi et al., 2024). Fig. 4 successively illustrates the three common underwater connection methods: pure mechanical connection, permanent magnet attraction and alignment combined with bolt connection, and pure magnetic connection.

In the future, magnetic and hybrid magnetic-mechanical interfaces are likely to remain important because they support rapid alignment and repeated attachment while reducing assembly complexity. Rapid and robust modular docking can be achieved via electropermanent magnet technology (Zhu and El Baz, 2019), optimized magnetic pole arrangement (Jiao et al., 2022), and integration with mechanical structures(Lan et al., 2026; Zhang et al., 2025b). Recent robotic fish swarms also show that magnetic docking can support collective aquatic reconfiguration when the modules include communication and distributed control functions (Si et al., 2026).

## 3 Sensing and Perception of MRURs

In underwater robotic systems, sensors serve as core components for acquiring environmental information and system states, and they form the critical foundation for achieving autonomous perception, precise control, and safe operation(Merveille et al., 2024; Xu et al., 2025). As shown in Fig. 5a, due to the impacts of underwater environmental factors such as severe optical attenuation, limited electromagnetic wave propagation, and complex fluid disturbances(Yang et al., 2024a), underwater robots typically rely on the collaborative operation of multiple heterogeneous sensors (Kaveti et al., 2025)to realize comprehensive perception of the environment(Huy et al., 2023), pose (Huang et al., 2026), position and mission targets (Qin et al., 2023), as well as a variety of underwater functions including navigation and positioning (Jalal and Nasir, 2021), planning and control (Guo et al., 2021), obstacle avoidance(Cheng et al., 2021)and target tracking(Kumar and Mondal, 2021). Fig. 5b illustrates the common types of underwater sensors and a schematic diagram of multisensor cooperation in an MRUR system.

However, MRURs inherit the perception, communication, buoyancy, and energy constraints of conventional underwater robots, but reconfiguration introduces additional uncertainty because docking, separation, and morphology changes may alter the module connectivity, sensor graph, sensor-to-body extrinsics, actuator–sensor layout, and the set of active sensing nodes (Yim et al., 2007; Hasan, 2012; Parra Rubio et al., 2023). Therefore, MRUR perception should be viewed not only as multisensor fusion but also as the problem of maintaining state-estimation consistency under changing physical topology and sensing configuration (Castano and Will, 2001; Salemi et al., 2004; Mathews et al., 2017).

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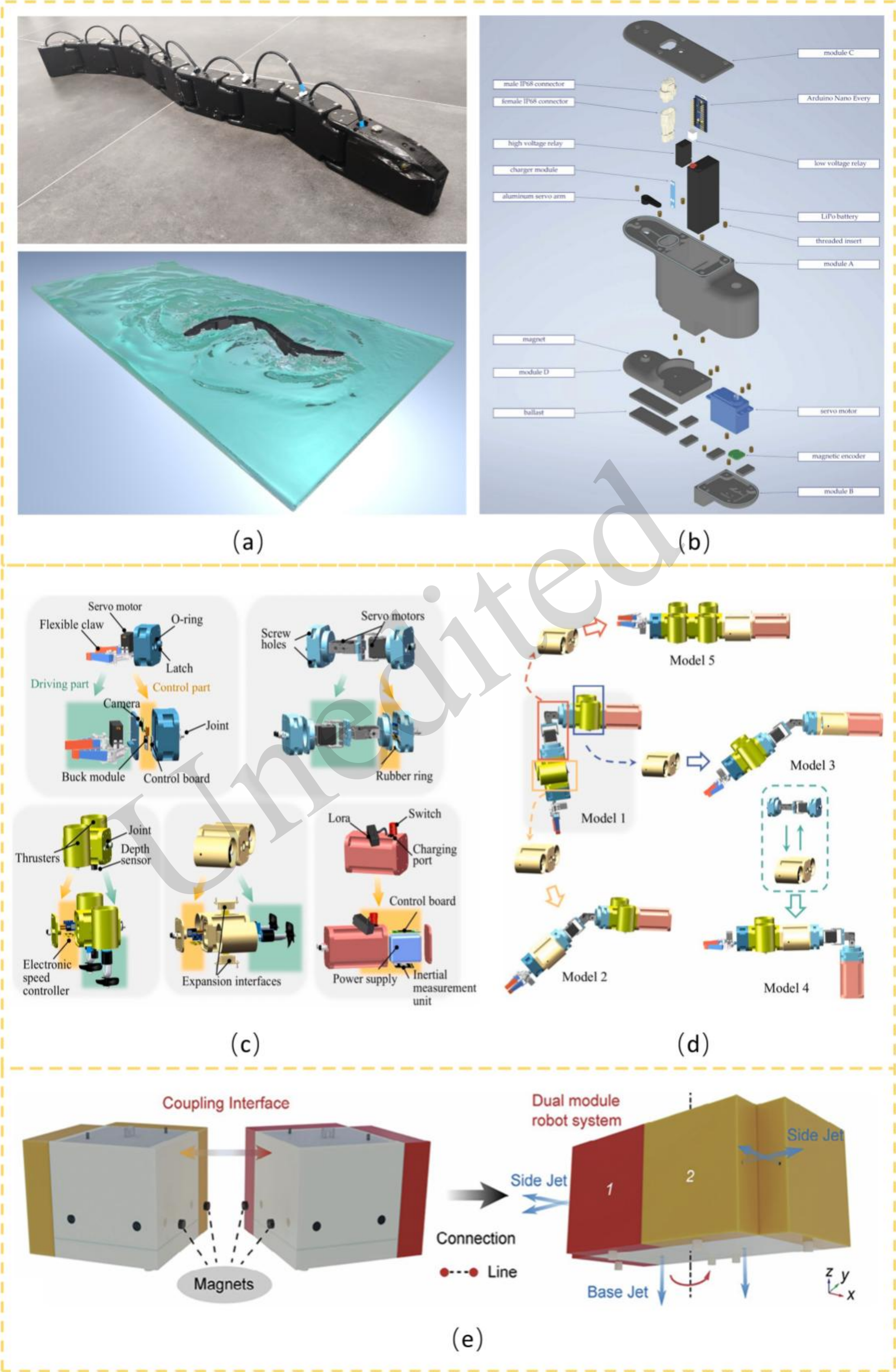

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**Fig. 4** Various connection methods of the modules of MRUR systems: (a) Physical and simulation schematics of the assembled modular snake robot(Bianchi et al., 2024); (b) Module cross-sectional view of the modular snake robot; the steering gear shaft, mechanical structural components and screws are clearly visible, making it a typical representative of mechanical connection; (c) Schematic of the MRUR module structure designed by Lincong Lan et al.(Lan et al., 2026); (d) Schematic of several connection modes of the MRUR; the permanent magnet adsorption and alignment combined with bolt connection is adopted in this project; (e) Detailed diagram of the magnetic connection process of the MRUR; this project enables the rapid realization of various configurations including linear, diagonal and annular arrangements(Wang et al., 2024)

**Fig. 5 Different classifications of underwater sensors: (a) Overview of sensor classification and configuration architecture for MRURs; (b) Sensor configuration architectures for modular systems, distinguishing between fully distributed and master-slave topologies**

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Centered on state-estimation consistency, perception in MRURs involves several interrelated challenges, including maintaining sensor-fusion continuity and adaptive updating under topology changes, handling perception uncertainty during docking and separation, managing redundant sensing across multiple modules, and coordinating distributed perception to preserve global consistency. The following sections discuss these four aspects in detail.

## 3.1 Topology-Aware Fusion

Traditional multisensor fusion frameworks usually rely on a static, predefined sensor suite and fixed topological constraints. In contrast, MRURs face additional challenges caused by topology variation, including abrupt changes in the dimensionality of the state space, invalidation of precalibrated sensor extrinsics, and changes in the observable state variables(Huang et al., 2025). Therefore, maintaining stable perception under newly formed configurations is a key problem that must be addressed in MRUR systems.

To handle topology changes, modular robotics studies such as those by Conro and Park commonly use a graph ($G_k = (V_k, E_k)$) to describe the current physical configuration or connection topology of the robot. In this representation, $V_k$ contains active modules and sensor nodes, while $E_k$ represents mechanical, electrical, communication, and calibration relationships(Castano and Will, 2001; Park et al., 2008). In EKF-based estimation schemes, changes in $G_k$ require corresponding updates to the state vector and measurement functions. Automatic configuration recognition can then be regarded as the process of determining whether the current configuration graph is isomorphic to a known configuration in a predefined library.

However, when conventional EKF-based underwater multisensor fusion methods are applied to changing configurations, the estimator must modify the state vector, update the observation models, rederive the measurement Jacobians, and handle covariance augmentation or marginalization. These operations increase the implementation difficulty and computational complexity. The MaRS modular fusion framework uses covariance segmentation to separate core navigation states from sensor-specific extrinsic or calibration states. The filter then uses the measurement residual to jointly correct both the robot core state and the corresponding sensor extrinsics, enabling runtime self-initialization and online extrinsic calibration(Brommer et al., 2021). Thus, MaRS forms a complete dynamic plug-and-play sensor-fusion framework. Although originally developed for unmanned aerial vehicle (UAV) applications, its treatment of modular sensor fusion provides a useful reference for perception and fusion under MRUR topology changes.

Factor-graph methods provide another promising solution (Dahal et al., 2023). In such frameworks, heterogeneous measurements, intermodule pose relationships, and docking constraints can be uniformly formulated as factors, thereby reducing the difficulty of repeatedly modifying state and observation structures in EKF-based implementations (Kaess et al., 2012; Indelman et al., 2013). In addition, studies on decentralized cooperative acoustic navigation have shown that robots can exchange compact pose-graph constraints or relative navigation information to achieve cooperative localization under bandwidth-limited, lossy, or faulty underwater communication. The communication robustness and redundant-constraint utilization demonstrated by these methods provide important references for maintaining state-estimation consistency during MRUR topology reconfiguration(Walls and Eustice, 2013; Webster et al., 2013; Chaves et al., 2017).

Existing MRUR projects rarely delve deeply into topologically aware perception technologies. The research conducted by Modularis has begun to explore this direction. By using standardized sensor boards and ROS-based node abstractions, it separates the sensor drivers and fusion nodes from the specific hardware implementation, providing a software-level reference(Herrin et al., 2023).

## 3.2 Perception for Docking

Docking and separation require the perception of spatial and temporal scales. For MRURs, module docking perception generally requires relative pose estimation, attitude alignment, capture-state recognition, and verification of mechanical or magnetic contact. In AUV docking studies, docking

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perception is typically formulated as a multistage process: acoustic or inertial information supports the approach phase, vision or imaging sonar supports mid-range alignment, and optical markers, magnetic fields, electric fields, tactile cues, or connector-state sensors support final capture (Peng et al., 2019; Lv et al., 2022; Parra Rubio et al., 2023; Zhang et al., 2024).

Existing solutions address MRUR docking perception in a partial but technically meaningful way. Early work on AMOUR demonstrated the feasibility of using optical sensing for underwater modular docking, showing that relative detection and optical ranging can support the approach and alignment of modular underwater units (Vasilescu et al., 2005). The bioinspired electric-sense robot further expanded this idea by using nonvisual near-field sensing for underwater module localization and reassembly, providing an alternative perception mechanism when optical sensing is degraded by turbidity or poor illumination (Mintchev et al., 2012). REMORA-related studies shifted the focus from sensing alone to the coupling between perception, rendezvous control, docking execution, and reconfiguration planning. In particular, Nielsen's work on modular underwater robots and Furno et al.'s energy-heuristic self-reconfiguration study show that docking should be treated as part of a larger control and planning loop rather than as an isolated terminal maneuver (Furno et al., 2017). More recently, RS-ModCubes demonstrated underwater hovering docking with magnetic connectors. In this system, magnetic capture and passive self-alignment partially reduce the requirement for extremely precise terminal pose estimation, thereby mitigating the conflict between pose estimation accuracy and flow-induced disturbances during the final docking phase (Zheng et al., 2025).

Beyond MRUR-specific systems, the broader AUV docking literature provides useful perception primitives that can be transferred to MRUR module docking. Vision-based docking guidance can estimate the relative position and attitude during the terminal approach, while enhanced target detection improves robustness in visually degraded underwater environments(Lv et al., 2022; Ni et al., 2025; Zhang et al., 2024). Acoustic or sonar-based guidance provides an alternative when optical visibility is poor, and electromagnetic or magnetic-dipole guidance can provide robust near-field cues during final capture (Peng et al., 2019; Lin et al., 2022; Wang et al., 2025b). However, most of these AUV docking methods assume docking between the vehicle and a fixed station. In contrast, MRUR docking typically involves two relatively moving small modules. Docking perception in MRURs requires further processing of issues such as relative motion and attitude disturbances based on this foundation.

### 3.3 Sensor Redundancy

When MRUR modules are rearranged, docked, or separated, the number, type, and spatial distribution of active sensors may change. Some configurations may provide redundant inertial, pressure, or visual measurements. Therefore, MRUR sensing performance should be evaluated not only by the sensor suite installed on each module but also by the sensing coverage, observability, and fault tolerance of each possible configuration.

Redundant sensing can improve the robustness of MRUR perception. Multiple IMUs, pressure sensors, or local proprioceptive sensors can be used to cross-check state estimates, detect abnormal module behavior, and maintain partial observability after docking, separation, or module failure. This principle is consistent with broader AUV navigation practice, where redundant sensors are used to compensate for inertial drift and the absence of GPS underwater (Paull et al., 2014).

However, this benefit depends on how redundant measurements are organized and managed. On the one hand, MRURs require an additional layer of configuration awareness: after reconfiguration, the fusion system must identify which sensors remain active and where they are located in the current topology. On the other hand, the perception architecture also affects the availability and use of redundant sensing information.

In fully distributed architectures, redundant measurements can be locally processed and shared among modules, improving fault tolerance under topology changes. RS-ModCubes exemplify this direction: each cubic module integrates sensing, computation, propulsion, and magnetic docking interfaces, allowing the assembled robot to retain distributed sensing capability across different morphologies (Zheng et al., 2025). In master-slave

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architectures, redundant sensor data are usually aggregated by a central module, which simplifies fusion but increases dependence on communication reliability and the master node. Lan et al.'s modular reconfigurable underwater robot reflects this pattern (Lan et al., 2026).

In addition, redundancy can also lead to inconsistencies. After the connection is completed, the relative external parameters of different sensors may no longer match the precalibrated values due to vibrations and other factors. If these uncertainties are not taken into account when fusing the redundant measurements, the estimator may become overly confident or deviate. When the intermodule correlations are unknown, conservative decentralized fusion methods can be considered (Julier and Uhlmann, 2001).

The redundant sensors in MRURs should be regarded as schedulable sensing resources, and reliable fusion can be achieved through efficient sensor management and organizational structure.

### 3.4 Distributed Perception Coordination

Unlike conventional AUVs, where most sensors are fixed to a single rigid body, an MRUR may contain several modules that each carry local sensors, processors, and communication interfaces. When the robot changes configuration, the relative positions of these modules and the communication paths among them may also change. Therefore, MRUR perception should coordinate local estimates, global communication, and global state consistency under changing topology.

Communication is the foundation of global perception. In MRURs, communication uncertainty is amplified by modularity and reconfiguration. The communication graph may change together with the mechanical topology, causing variations in link quality, transmission delay, packet availability, and clock synchronization among sensor-bearing modules. This issue is already implied in existing modular underwater systems: Lan et al. emphasized shared communication and power interfaces for multimodule underwater configurations, while RS-ModCubes and self-reconfigurable robotic fish swarms rely on module-level communication for docking, state exchange, and coordinated morphology formation (Zheng et al., 2025; Si et al., 2026; Lan et al., 2026). Related Bluetooth/BLE modular and sensor-network studies further show that timing consistency and low-latency communication are important for reliable distributed coordination (Moeckel et al., 2006; Bideaux et al., 2015). Consequently, measurements from different modules may reach the fusion center or neighboring estimators with inconsistent timestamps, outdated topology information, or incorrect spatial associations. Therefore, MRUR perception requires estimation methods that can tolerate delayed, asynchronous, and topology-dependent information exchange. Distributed Kalman filtering, consensus-based estimation, and decentralized pose-graph fusion provide useful algorithmic foundations for this problem because they allow individual modules to maintain local estimates while exchanging compact state or information summaries to preserve system-level consistency under changing module configurations (Olfati-Saber, 2006; Walls and Eustice, 2013; Ji et al., 2017).

Overall, distributed perception for MRURs remains at an early stage. A better distributed perception system can be established by defining unified sensing and communication standards at the module-interface level and integrating them with distributed optimization algorithms.

## 4 Control Strategy for MRURs

Before deriving the dynamic model of an MRUR system, the reference frames are defined, including the earth-fixed frame, the body-fixed frame, and the module-fixed frames, as illustrated in Fig. 6a. Following the standard underwater vehicle modeling framework proposed by Fossen (Fossen, 2011), the six-degree-of-freedom dynamics can be written as:

$$M(\theta)\dot{\nu} + C(\theta,\nu)\nu + D(\theta,\nu)\nu + g(\eta,\theta) = \tau_{act} + \tau_{env}$$

where $\theta$ denotes the current modular configuration and $\nu$ and $\dot{\nu}$ are the generalized velocity and acceleration, respectively. $M(\theta)$, $C(\theta,\nu)$, $D(\theta,\nu)$, and $g(\eta,\theta)$ represent the inertia matrix, Coriolis and centripetal matrix, hydrodynamic damping matrix, and restoring force vector, respectively. The terms $\tau_{act}$ and $\tau_{env}$ denote the actuator-generated control input and environmental disturbance induced by currents.

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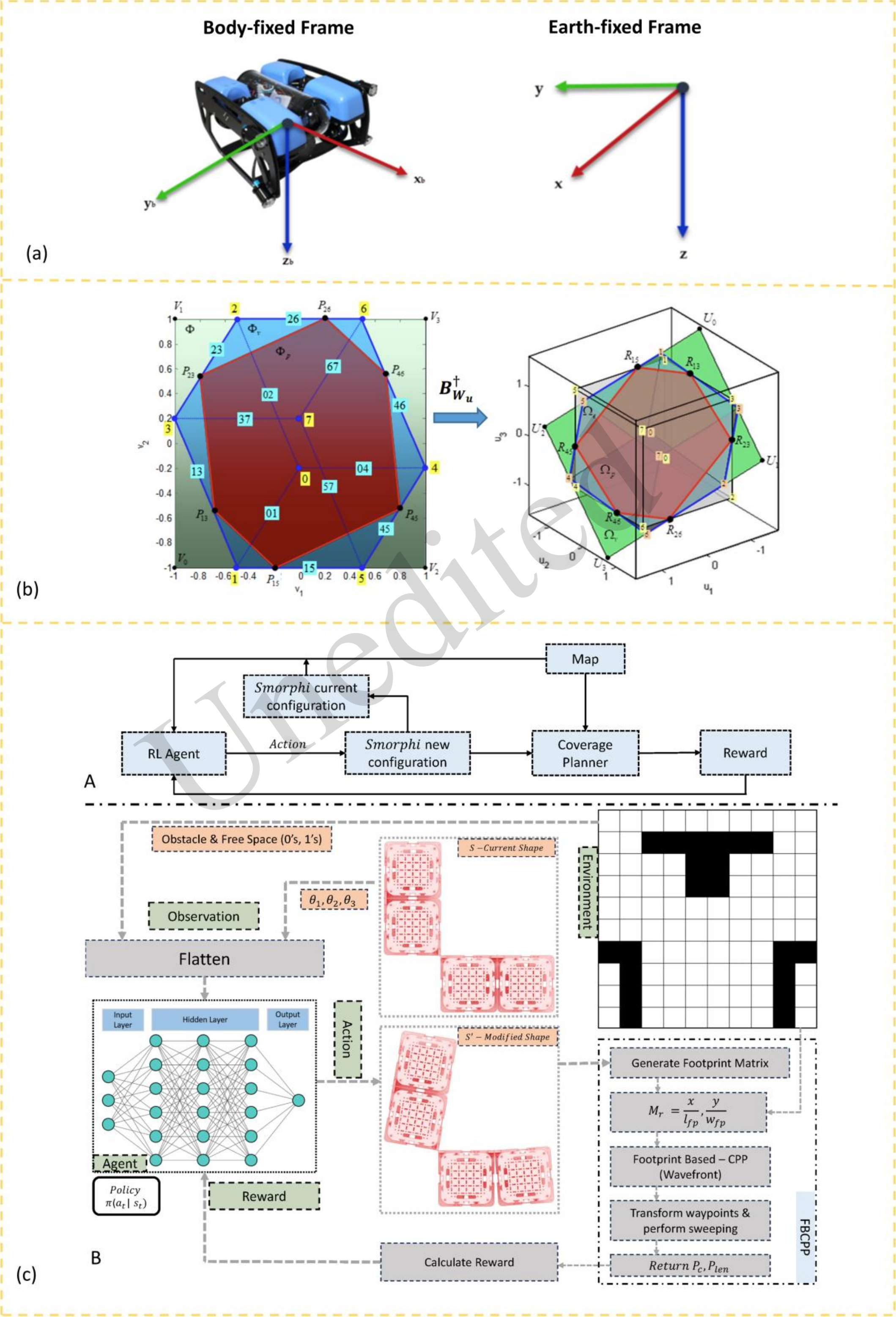

**Fig. 6 MRUR modeling and control techniques: (a) Coordinate definition: body-fixed and earth-fixed frames (González-García et al., 2022); (b) Thruster configuration and control allocation: mapping from virtual control space to actual control space via weighted pseudoinverse (Omerdic et al., 2020); (c) Simplified framework and detailed workflow of the reinforcement learning-based morphology generation method for reconfigurable robots (Kalimuthu et al., 2023a)**

Unlike fixed-geometry underwater vehicles, MRURs experience configuration-dependent changes in inertia, hydrodynamic parameters, buoyancy distribution, actuator layout, and sensing arrangement during docking, detaching, or rearrangement. These changes alter both the dynamic model and the control effectiveness of the system, making purely analytical hydrodynamic modeling difficult and configuration specific. Although simplified parametric models are useful for reducing computational complexity, they inevitably neglect part of the detailed hydrodynamic coupling, module-interaction effects, and configuration-dependent disturbances introduced by reconfiguration. Therefore, such models usually need to be combined with data-driven identification or online calibration to compensate for configuration-induced uncertainties (Zhang and Katzschmann, 2022; Parra Rubio et al., 2023). On this basis, MRUR controllers must explicitly account for topology variation, docking uncertainty, actuation redundancy, and multimodule coordination rather than relying on a fixed-geometry control model (Johansen and Fossen, 2013; Dang et al., 2022, 2023; Zheng et al., 2025; Lan et al., 2026).

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### 4.1 Topology Structure Control Strategy

Control of MRURs should not be treated as the control of a fixed rigid-body underwater vehicle. The defining difficulty is that the physical topology of the robot can change when modules are added, removed, docked, separated, or rearranged. Therefore, MRUR topology-structure control should be designed as a configuration-aware framework coupled with the topology-aware perception architecture described in Section 3.1. By representing the current configuration as a graph $G_k = (V_k, E_k)$, the system can first identify the active module topology and then update the corresponding dynamic parameters, thrust-allocation matrix, control constraints, and feedback gains according to the current morphology.

Existing MRUR studies provide several representative solutions. SeaDrone introduced a task-oriented reconfigurable thruster layout, where different geometric arrangements were used to optimize task-space control capability and actuator redundancy (Moreno and Chung, 2014). Lan et al. developed an MRUR with five assembly modes and used an integral sliding-mode controller to maintain robust trajectory tracking across different configurations, showing that robust control can reduce the need to redesign a separate controller for every morphology (Lan et al., 2026). RS-ModCubes further demonstrates that standardized cubic modules can form scalable underwater morphologies, which requires the control framework to update the mapping between module-level actuation and global motion after assembly (Zheng et al., 2025). In miniature MRURs, synthetic-jet modules form different motion configurations with corresponding motion schemes, illustrating that topology control can also be expressed as the selection of propulsion layouts and module functions at small scales (Wang et al., 2024).

From a control-design perspective, topology-structure control can be formulated as a two-layer problem. The upper layer selects or recognizes the robot configuration according to task requirements, environmental constraints, energy cost, and available modules. The lower layer performs configuration-dependent motion control and control allocation. For overactuated or redundantly actuated underwater systems, control allocation methods are especially important because the same desired wrench can be produced by different actuator combinations. Energy-efficient configuration and control allocation for dynamically reconfigurable underwater robots has been studied using constrained optimization, where mechanical limits, actuator saturation, dead zones, and energy-like objectives are considered simultaneously (Dang et al., 2023). Although not every dynamically reconfigurable underwater vehicle is a strict MRUR, this optimization-based idea is highly relevant because MRUR topology changes similarly require the control allocator to update actuator mappings and constraints. More generally, constrained underwater control allocation and ROV allocation studies provide useful tools for MRURs with redundant thrusters or module-level actuation (Kou et al., 2021; Omerdic et al., 2020).

### 4.2 Docking, Separation, and Reconfiguration Control

Docking, separation, and reconfiguration control in MRURs should be understood along a spectrum from manual reconfiguration to autonomous self-reconfiguration. Currently, many MRUR platforms are manually assembled or reconfigured

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before deployment. In these systems, the main control problem is not autonomous docking but configuration recognition, controller switching, and recalculation of the thrust-allocation matrix after the physical topology has changed. SeaDrone and Lan et al.'s MRUR are representative examples: their module or thruster layouts can be changed to support different task requirements, but the controller mainly operates after the target configuration has been established (Moreno and Chung, 2014; Lan et al., 2026).

Autonomous docking and self-reconfiguration represent a more demanding stage. In this case, modules must approach, align, connect, and verify the new topology and then switch from independent module control to coupled-body control. Early work, such as AMOUR, demonstrated the feasibility of underwater modular docking, while Mintchev et al. showed that separated modules could navigate and reassemble underwater (Vasilescu et al., 2005; Mintchev et al., 2012). REMORA-related studies further treated reconfiguration as a planning and control problem: Furno et al. used an energy heuristic and Basic Theta* search to plan transitions between module morphologies, and Nielsen developed modeling and docking-control methods for modular underwater robots with arbitrary interconnections(Furno et al., 2017; Nielsen, 2018).

Recent platforms continue to show that docking control must be coupled with connector mechanics. RS-ModCubes uses electromagnets and hovering docking to support underwater assembly, but stable connection still depends on relative-motion regulation, capture tolerance, and postdocking stabilization (Zheng et al., 2025). Joint-level studies on underwater autonomous docking and separation also indicate that alignment tolerance, locking reliability, and separation force must be considered together with the control sequence (Zhang et al., 2025b). For compact systems such as synthetic-jet MRURs, different assembled morphologies correspond to different motion primitives, so the controller must update its available action set after reconfiguration (Wang et al., 2024).

In summary, reconfiguration control in MRURs includes two levels: for manually reconfigured systems, the key issue is configuration-dependent controller switching; for autonomous self-reconfiguring systems, the key issue is hybrid control across approach, connection, topology verification, and postdocking stabilization.

### 4.3 Propulsion Unit Allocation and Redundancy Control

Since an MRUR system typically exhibits a redundant structure characterized by multiple thrusters and fewer degrees of freedom (Fossen, 2002), a critical issue in its control architecture is how to map high-level decision commands to low-level actuation. Specifically, the accurate mapping of the desired 6-DOF forces and moments to individual thrusters under actuation redundancy is essential for achieving stable motion control of MRUR (Dang et al., 2023).

Lincong Lan et al. solved the problem of thruster allocation and redundant control by using the ISMC algorithm combined with pseudoinverse allocation to compute the required thrust for each thruster (Lan et al., 2026). RS-Modcubes adopts a similar thrust allocation scheme, mapping the desired 6-DOF forces and moments to thrust outputs of eight thrusters (Zheng et al., 2025).

To further improve reconfigurability and robustness, various optimization algorithms can be introduced on the basis of the pseudoinverse method, including weighted pseudoinverse (Omerdic et al., 2020; Vu et al., 2021), null-space redundancy optimization (Tohidi et al., 2016), and thruster saturation constraints (Kou et al., 2021), as shown in Fig. 6b. These approaches achieve thruster allocation with minimum energy consumption, load balancing, and fault tolerance from different perspectives. This enables the MRUR to maintain stable and efficient omnidirectional motion even under complex hydrodynamic environments and frequent module reconfiguration.

Overall, thruster redundancy is a key bridge between MRUR topology reconfiguration and motion control. Current MRURs mainly rely on pseudoinverse allocation to map desired 6-DOF forces and moments to individual thrusters, but future systems should move toward configuration-aware optimal allocation. By updating the allocation matrix, actuator weights, and constraints after each topology change, MRURs can use redundant thrusters not only for motion generation but also for energy optimization, load balancing, saturation handling, and fault-tolerant control (Corradini and Cristofaro, 2016; Lan et al., 2026; Omerdic et al., 2020; dos Santos et al., 2016; Tohidi et al., 2016; Zheng et al., 2025).

### 4.4 Distributed Coordination Control

Distributed coordination control in MRURs concerns how multiple module-level controllers are organized to generate coherent system-level motion. The main issue is not only communication among modules but also how control authority, actuator commands, and module roles are redistributed after each topology change.

Existing MRUR platforms show different levels of coordination. In centralized architectures, a main controller computes the desired motion and sends commands to distributed actuation modules. Lan et al.'s MRUR follows this pattern: sensing and control computations are concentrated in the main module, while actuation commands and power are transmitted to other modules through a bus-based architecture (Lan et al., 2026). This design is simple and suitable for small module numbers, but it relies on the reliability of the central controller and the communication/power bus. In more integrated architectures, each module contains local sensing, computation, propulsion, and docking interfaces. RS-ModCubes represent this direction because each cube can operate as a functional robotic unit and then participate in larger assembled morphologies (Zheng et al., 2025). Synthetic-jet MRURs and self-reconfigurable robotic fish swarms further show that compact modules may require local control logic for different motion primitives, docking states, and collective morphologies (Wang et al., 2024; Si et al., 2026).

Although MRUR-specific distributed control is still limited, multi-AUV coordination studies provide useful algorithmic foundations. Formation-control methods with alterable communication topology and time-varying delay show how coordinated controllers can maintain stability when the communication graph changes (Yu et al., 2022). Distributed model predictive control provides another useful direction: ADMM-based distributed MPC decomposes the formation-control problem into local optimization subproblems coupled by formation constraints, while distributed dual closed-loop MPC incorporates disturbance observation and collision avoidance for multi-AUV systems (Zhao et al., 2022; Zhang et al., 2023). These methods are not MRUR specific, but they are relevant because MRURs also require local controllers to satisfy global motion constraints under limited communication, hydrodynamic disturbances, and changing intermodule topology.

In summary, MRURs should adopt a configuration-aware hierarchical control architecture. The global layer updates the topology graph, module roles, and control-allocation structure, while local module controllers execute constrained motion commands and coordinate with neighboring modules. This architecture enables module-level autonomy while preserving system-level motion stability after docking, separation, and reconfiguration.

### 4.5 Control execution architecture

Motion control in MRURs essentially coordinates the thrust output of each thruster according to high-level decisions to achieve ideal control of the system's six-degree-of-freedom motion state. Most MRUR projects follow the execution architecture shown in Fig. 7.

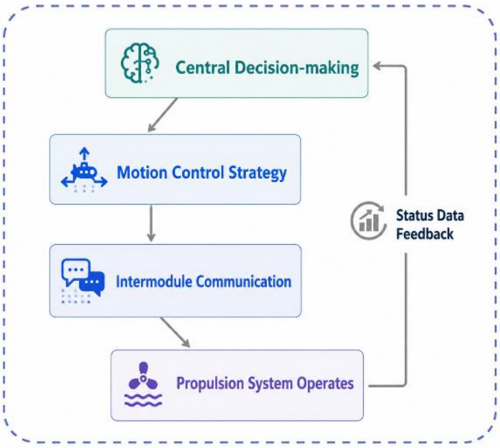

**Fig. 7 Overall control framework diagram for MRUR systems**

The deployment of the central decision-making module can generally be summarized into two typical architectures: centralized control architecture and distributed control architecture.

In the former, the system undertakes global task planning and decision-making through one core module; each functional module reports status to the center via a communication link and executes the control commands issued by it. For example, the

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Raspberry Pi used by Lincong Lan and the Nvidia Jetson NX used in RS-Modcubes serve as the brain core of the entire system.

In the latter, the MCU control unit is directly integrated inside each module. The system no longer relies on a unified central brain but achieves cooperative control through lightweight or wireless communication. For instance, each module in the Synthetic Jet MRUR platform integrates an MCU and BLE (Wang et al., 2024).

Regardless of the architecture, pose solving and navigation path planning are accomplished using the received perception data and system-set targets.

According to the selected motion control strategy, the central decision-making module converts behavioral objectives into desired force vectors for each thruster and sends commands to each thruster module via CAN/UART. The MCU inside the thruster module converts the received commands into high-frequency PWM signals to drive the ESC, thereby completing the closed-loop conversion from logical commands to physical rotational speed.

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### 4.6 From Reconfigurable to Self Reconfigurable

The evolution from reconfigurable MRURs to MSRURs represents a shift from configuration-dependent control to autonomous reconfiguration decision making. In reconfigurable MRURs, the topology is usually selected before deployment or manually adjusted according to task requirements, as shown in Fig. 8a. In MSRURs, by contrast, the system must autonomously determine whether a topology change is needed, which morphology should be selected, and what sequence of module transitions should be executed.

Self-reconfiguration requires algorithmic support at three levels. First, reconfiguration planning is needed to determine feasible intermediate morphologies and module-motion sequences. Graph-search methods, such as Basic Theta* and other energy-aware planning strategies, can reduce unnecessary module motion and avoid unstable intermediate configurations (Furno et al., 2017). Second, transition control is required to execute docking, separation, and topology switching under hydrodynamic disturbances. Predictive control is suitable for this stage because it can explicitly handle state constraints, actuator limits, energy costs, and time-varying model parameters during reconfiguration(García et al., 1989; Yan et al., 2020; Walker et al., 2025). Third, adaptive and learning-based model updating is needed after reconfiguration because each new topology changes the hydrodynamic parameters and control-effectiveness matrix. Adaptive control and data-driven identification can therefore provide online compensation for configuration-induced uncertainty (Åström, 1991; Fossen and Sagatun, 1991; Feczko et al., 2015; Faria et al., 2024; Liu et al., 2024). The robotic fish swarms shown in Fig. 8 illustrate the process of module docking and the formation of various topological structures through self-reconfiguration.

Beyond these model-based and planning-based methods, artificial intelligence algorithms provide an additional route for MSRURs to achieve higher autonomy under complex and uncertain reconfiguration conditions. Reinforcement learning has been used to automatically design adaptive controllers for modular robots and to enable morphology-independent locomotion strategies that can adapt to different module arrangements and module faults (Varshavskaya et al., 2008; Christensen et al., 2013). Graph neural networks and modular policy architectures further provide a natural way to encode the robot topology as a graph, allowing the control policy to change with the hardware configuration rather than being redesigned for each morphology (Whitman et al., 2023). Deep reinforcement learning has also been explored for autonomous reconfiguration planning and task-oriented morphology generation, while multiagent reinforcement learning offers a distributed decision-making framework in which individual modules learn coordinated reconfiguration behaviors under local interaction constraints (Song et al., 2021; Kalimuthu et al., 2023; Wu et al., 2023). Although these AI-based methods have not yet been widely validated in underwater MSRURs, they provide promising algorithmic foundations for future systems that must combine structural awareness, autonomous topology selection, and adaptive cooperative control.

Therefore, self-reconfigurable control should be understood as an integrated framework that combines topology planning, hybrid transition control, configuration-aware model updating, and distributed coordination while enabling a higher level of autonomy. In the future, MRUR control systems are expected to integrate artificial intelligence algorithms with structural awareness to support task-driven autonomous decision-making and adaptive cooperative control, thereby driving MRURs toward higher intelligence and autonomy.

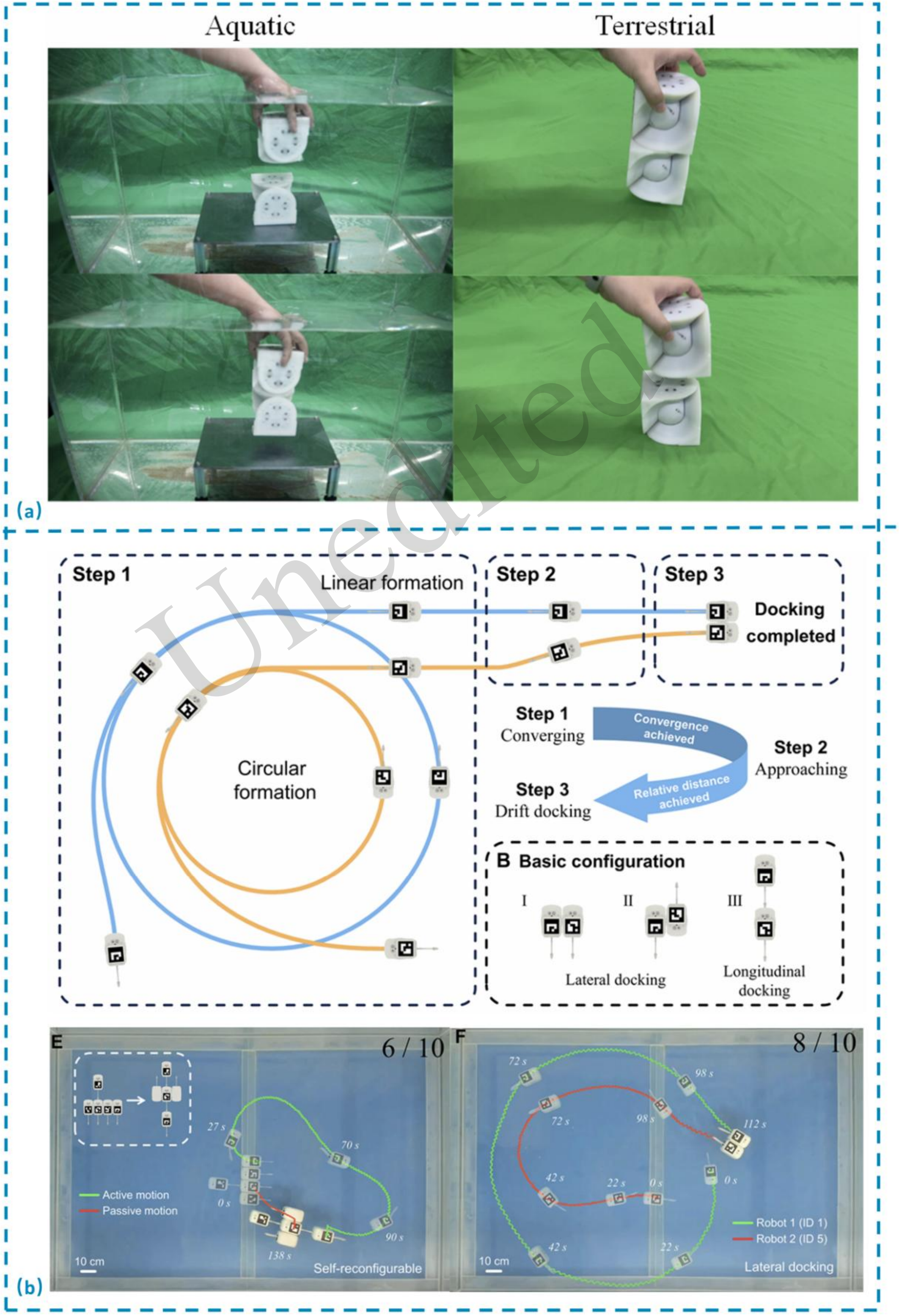

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**Fig. 8 Representative examples of manual reconfiguration and self-reconfiguration: (a) ASRR demonstrates the process of**

**manual module reconfiguration (Yang et al., 2024b); (b) whereas robotic fish swarms illustrate module docking and the formation of multiple topological structures through self-reconfiguration (Si et al., 2026).**

## 5 Application Scenarios and Main Challenges of MRURs

### 5.1. Application Scenarios

### 1) narrow underwater area

Traditional AUVs are difficult to operate in shallow water, rocky areas, or narrow confined spaces due to their large size and complex propulsion systems (Wang et al., 2024). In contrast, MRURs can reduce volume through modularization and reconfigure underwater to adapt to various underwater environments.

Karst caves are a typical application scenario forMRUR. They are characterized by narrow, tortuous, and irregular terrain, accompanied by strong currents and rapidly changing hydrodynamic conditions (Williams, 2008), which pose great challenges to the size and operational stability of underwater robots (Abdullah et al., 2025). MRURs can adapt to various underwater requirements through topological transformation. In the umbrella robot, the robot dynamically switches configurations by adjusting thruster angles $\alpha F$ and $\alpha B$. In the 45° torpedo-like configuration, thrusters are aligned in the same direction to form a slender profile, enabling efficient passage through narrow channels and resistance to strong current impacts. When switched to the 90° fully actuated configuration, 6-DOF motion control is achieved, allowing terrain mapping, current monitoring, and sample collection (Dang et al., 2022), as shown in Fig. 9. Moreover, it achieves both energy efficiency and actuation redundancy in practical applications. The redundant thruster configuration provides fault tolerance, and the configuration matrix can be optimized according to tasks to minimize energy consumption (Dang et al., 2023).

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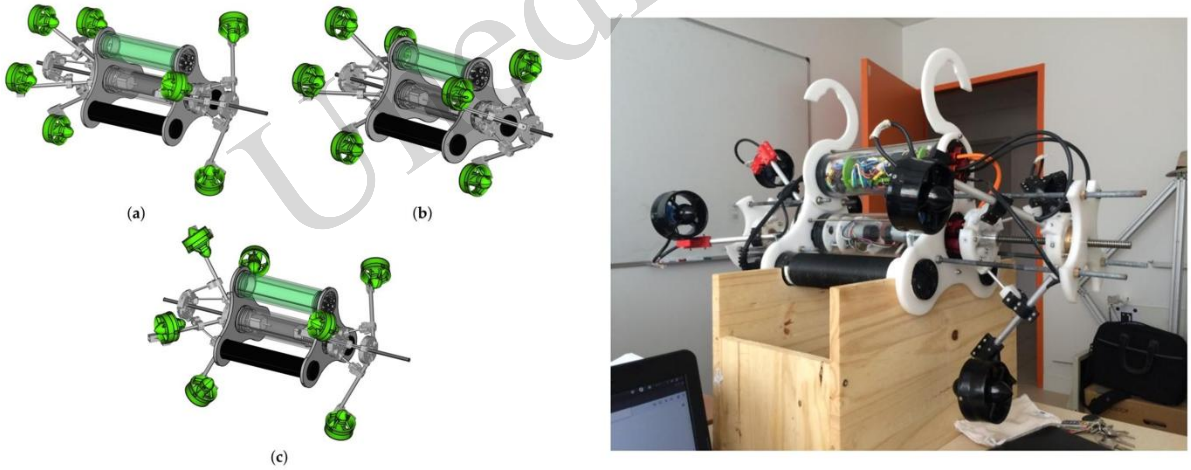

**Fig. 9 3D layout diagram and physical image of the propulsion system for each mode of the umbrella robot**

MRURs also exhibit outstanding advantages in pipeline operations. RS-Modcubes have undergone detailed experimental testing in pipelines. Before entering narrow pipe sections, RS-Modcubes can be split into individual modules to reduce the cross-sectional area. When transportation or stable operation is needed, they can be reassembled into dual-module or multimodule structures. The paper demonstrates that the dual-module combination of ModCubes successfully lifts a metal pipeline and passes through narrow sections (Zheng et al., 2025). Furthermore, each module is equipped with eight obliquely arranged thrusters to provide redundant thrust, enabling precise attitude adjustment and small-displacement control inside narrow pipelines.

In addition, the reconfigurable structure and distributed propulsion systems of MRUR enable adaptive morphological adjustment and cooperative operation in constrained and complex environments such as shipwreck salvage and underwater archaeology (Xu et al., 2005; Hotta et al., 2023), demonstrating superior spatial adaptability and operational flexibility over conventional AUVs.

### 2) Applicable to common underwater scenarios

In addition to their special advantages in constrained environments, MRURs also inherit the basic functions of conventional underwater vehicles as underwater robotic systems.

An MRUR system integrates navigation and attitude control modules. Based on multisensor fusion algorithms, it can achieve basic underwater motion functions, including autonomous navigation (Leonard and Bahr, 2016), constant-speed cruising (Gao et al., 2021), depth keeping (Patil et al., 2022), and trajectory tracking (Li and Du, 2021).

Equipped with devices such as side-scan sonars, multibeam echo sounders, water quality sensors, and high-resolution imaging systems, MRURs can perform scientific sampling missions, including seabed terrain reconstruction (Campbell et al., 2015; Specht, 2023), water parameter measurement and quality monitoring (Eichhorn et al., 2013; Amran et al., 2021), marine ecological surveys (Barrett et al., 2010; Kondo et al., 2014), offshore oil and gas exploration and development (Niu et al., 2009; Zagatti et al., 2018), and underwater pipeline safety monitoring (Kasparavičiūtė et al., 2025; Waldner and Sadhu, 2024). Furthermore, the modular design allows flexible replacement of perception payloads according to mission requirements, enabling a single platform to switch quickly among various detection modes without redesigning an entirely new platform for different tasks, which greatly improves mission versatility and execution efficiency. Fig. 10a - Fig. 10d presents various common underwater applications.

As shown in Fig. 10e, when an MRUR system is equipped with manipulator arms, samplers, or capture tool modules, it can also perform complex operational functions, such as underwater target grasping(Huang et al., 2020; Bian et al., 2022), sediment sampling (Pierdomenico et al., 2015; Hwang et al., 2019), and other deep-sea operation tasks. Compared with traditional large-scale AUVs, MRUR can achieve precise attitude adjustment through coordinated control among modules.

In emergency rescue and maritime accident response, the inherent redundancy of the modular design further improves system reliability in search and rescue operations (Venkatesan, 2016). In various hazardous and sudden situations, the loss of a single propulsion unit does not compromise the integrity of the entire mission. In addition, MRURs with amphibious capability can achieve cross-medium maneuvering under complex conditions (Yang et al., 2024b). Integrated with communication, multiple MRURs can collaboratively perform tasks such as search grid scanning, target positioning, and obstacle removal (Cai et al., 2023; Zhou et al., 2025), improving the efficiency and coverage of search and rescue. Fig. 10e illustrates the collaborative work of multiple MRURs.

## 5.2 Main Challenges

### 1) Connection Stability

Physical reconfiguration, as the core feature of MRURs, brings structural advantages while also introducing more technical challenges. As discussed in Section 2.3 on connection mechanisms, MRURs commonly rely on magnetic adsorption and mechanical latches for module coupling. However, fluid disturbances, collisions, pressure variations, and attitude coupling in underwater environments can significantly degrade connection stability (Zheng et al., 2025). Magnetic coupling facilitates structural assembly and self-reconfiguration but is prone to slippage under external loads. In addition, contact-based electrical connections suffer from issues such as corrosion (Mroczkowski, 1985), increased contact resistance (Bryant, 1994), and fretting wear (Siddaiah et al., 2019) during long-term underwater operation, leading to communication interruptions or unstable power supply. Balancing fast reconfigurability with improved connection strength and durability remains a major challenge for the practical deployment of MRUR.

### 2) Perception Fusion and Communication Reliability

Multisensor fusion in underwater environments is affected by uncertainties such as varying turbidity, increased sonar noise, and long-term drift of inertial navigation (Heshmat et al., 2025). Although fusion algorithms can improve the robustness of localization and perception through information complementarity, they also complicate data synchronization, time alignment, and error modeling (Zhang et al., 2020; Wang et al., 2025a), imposing higher requirements on on-board computing resources.

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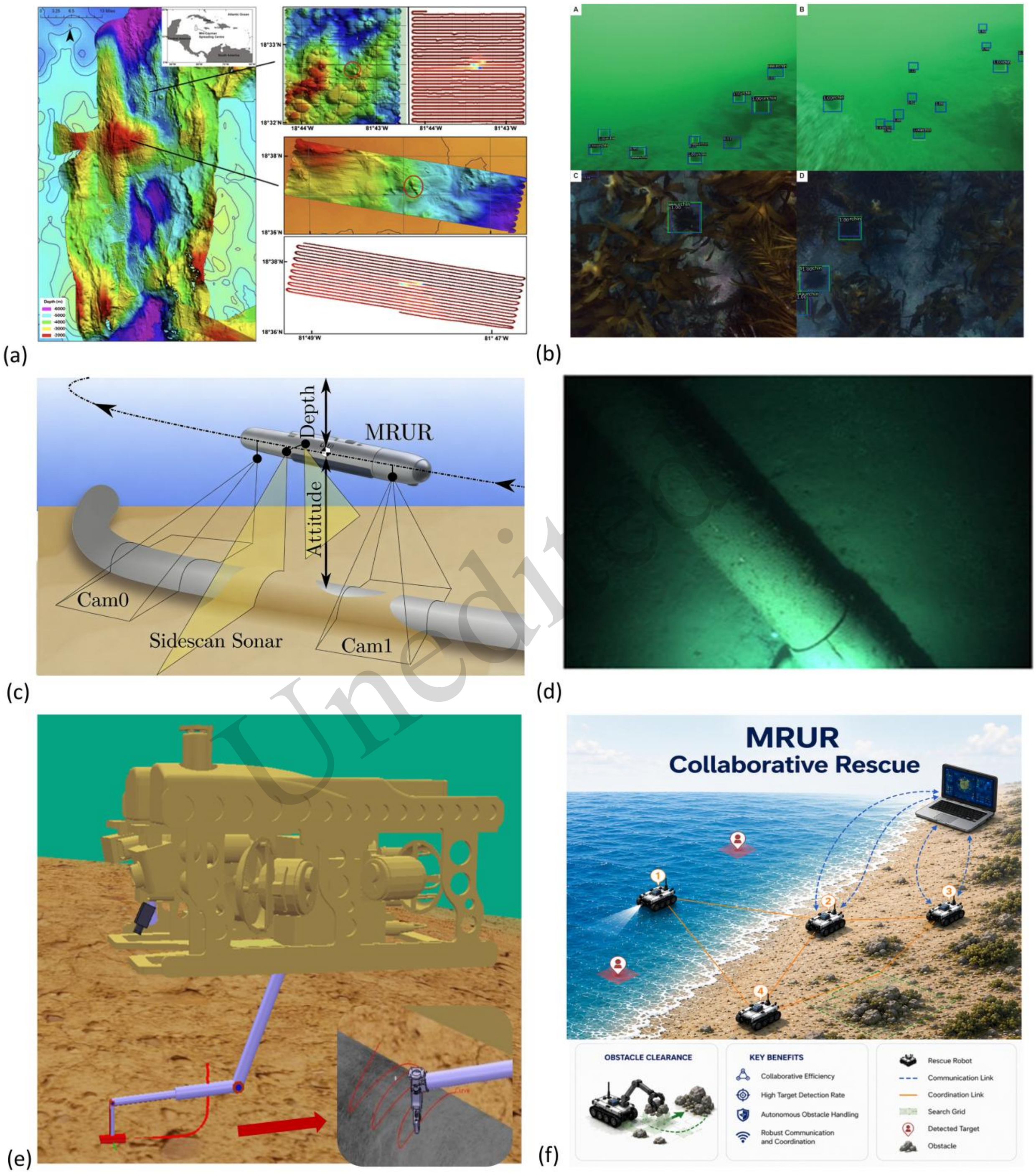

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**Fig. 10 Application scenarios of MRURs: (a) Seabed terrain reconstruction using multibeam sonar (map of the Mid-Cayman Spreading Centre) (Wynn et al., 2014); (b) Underwater robot with R-CNN pretraining can accurately identify objects in complex underwater environments (sea urchin identification is used as an example) (Doig et al., 2025); (c)(d) Schematic diagram of underwater pipeline monitoring using a vision camera and the actual image obtained in application (Bobkov et al., 2023); (e) A soil sampling scene in the CoppeliaSim simulator (Konoplin et al., 2024); (f) Schematic diagram of collaborative search and rescue operations of MRUR in cross-medium marine emergency scenarios**

Most current projects use CAN, UART, or BLE communication methods with limited bandwidth, which is insufficient to support high-frequency sensor synchronization and data sharing (Fitch and Lal, 2009;

Hollinger et al., 2011; Walls and Eustice, 2013; Bideaux et al., 2015). The RS-ModCubes paper notes that intermodule communication relies on CAN-bus converters, but bandwidth bottlenecks, delay accumulation, and data packet collisions occur under multimodule coordination. Underwater wireless communication such as BLE exhibits obvious attenuation, short communication range, and high packet loss in Synthetic Jet MRUR, making high-precision cooperative control difficult to achieve in distributed architectures(Wang et al., 2024).

### 3) Configuration-Aware Control and Robustness

Underwater currents, modeling errors, actuator faults, and hydrodynamic coupling among adjacent modules can reduce control accuracy. Robust control, model predictive control, and adaptive control have been widely studied for underwater vehicles (Li and Du, 2021; Yan et al., 2020), but their application to MRURs requires additional consideration of topology variation and modular redundancy. In future MRUR systems, control strategies should integrate topology-aware perception, online model updating, fault-tolerant allocation, and energy-aware optimization (Corradini and Cristofaro, 2016; Johansen and Fossen, 2013; Liu et al., 2024). Learning-based methods, such as physics-informed neural networks, graph neural networks, and reinforcement learning, may further improve configuration adaptation, but their stability, safety, and real-world underwater validation remain open challenges (Whitman et al., 2023; Wu et al., 2023; Zhao et al., 2024).

### 4) Energy supply issues

The modular structure of MRURs enables two energy supply modes: an independent power supply for each module and a centralized power supply. A centralized power supply requires high-current transmission through magnetic contact points, which brings risks such as contact heating, voltage drop, corrosion, and safety issues. A distributed power supply, on the other hand, leads to unbalanced power levels among modules. RS-ModCubes, Aquabot, and MARES all mention that the modular structure significantly increases the complexity of power management, power distribution, and energy consumption optimization. In addition, the high energy consumption caused by redundant thrusters results in insufficient endurance for MRURs in long-endurance tasks. How to achieve efficient energy management and a low-loss power supply under a modular architecture is an important factor restricting the engineering application of MRURs.

### 5) industrial implementation challenges

Despite the significant advantages of MRUR in flexibility and adaptability, its engineering cost remains relatively high. Compared with conventional AUVs, the modular and reconfigurable design requires additional docking mechanisms, sealing structures, and an MCU for each module, making the overall system more expensive than the monolithic structure of traditional AUVs. SeaDrone notes that modular systems exhibit a remarkable increase in manufacturing complexity, maintenance cost, and reliability verification cost (Moreno and Chung, 2014). Furthermore, industrial scenarios impose extremely high requirements on reliability, while the reconfigurable nature of MRURs leads to longer verification cycles and greater certification difficulties. Therefore, the conflict between cost and reliability presents a major obstacle to the commercialization of MRUR.

Nevertheless, ModCubes has achieved pioneering progress in this regard. By adopting a standardized unified architecture, multifunctional reuse, and a mature civilian supply chain during the design phase, the cost of each ModCube module (excluding the on-board computer) is approximately 800 US dollars, which is lower than that of conventional AUVs. The cost comparison is shown in Table 1.

**Table 1 Comparison of prices between Modcubes and common AUVs**

| Robot Model | Cost per Unit/Module (USD) | Core Differences |
|---|---|---|
| RS-ModCubes | 800 | Modular design, reconfigurable and splittable |
| Chasing M2 | 2500 | Traditional compact ROV, fixed configuration |
| BlueROV2 Heavy | 4500 | Traditional heavy-duty ROV, multithruster configuration |
| BlueROV2 | 6000 | Classic commercial small |

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| | | |
|---|---|---|
| | | AUV, fixed configuration |
| Girona 500 | 7000+ | Medium-to-large AUV, long-range design |

## 6 Conclusion and Future Development

### 6.1. Summary

With the increasing complexity of marine missions and diversity of operating environments, MRURs, as a new type of underwater system with both structural reconfigurability and task adaptability, are becoming an important development direction of intelligent marine equipment. This paper focuses on the research and discussion of three core technologies: modular structure design, perception systems, and control strategies.

1)Structure design: MRUR modules can be functionally classified into highly integrated modularity and function-separated modularity. Regardless of the classification method, the structural design can generally be divided into two aspects: the pressure hull and the module connection structure. The physical hull has evolved from traditional tubular rigid hulls to polygonal stress structures using flexible materials. The module connection mechanisms fall into three categories: pure mechanical constraint, pure magnetic adsorption, and hybrid magnetomechanical actuation

2)Perception system: The sensors used in MRURs can be classified according to their type, sensing targets, and configuration architecture. After years of development in multisensor fusion, underwater robots are now capable of performing high-precision mapping, autonomous obstacle avoidance, and target recognition in complex environments. Compared with traditional underwater robots, MRUR faces additional challenges due to frequent configuration changes. To address this issue, existing studies have gradually evolved from integration schemes that rely on fixed physical spatial layouts toward logically decoupled layered architectures, where standardized hardware and software modules enable improved maintainability, scalability, and rapid sensor reconfiguration.

3)Control strategy: Compared with conventional underwater robots, the dynamic modeling of MRURs is more challenging due to configuration changes that lead to variations in hydrodynamic parameters. To address this issue, many existing studies adopt simplified hydrodynamic models or establish dynamic models based on experimental data. The motion control of MRURs essentially coordinates the thrust outputs of multiple thrusters according to high-level decisions, and stable motion control is typically achieved through methods such as PID regulation, robust control, and redundant thruster allocation. In recent years, MRUR control systems have evolved from static control strategies based on predefined offline configurations toward task-driven approaches that support online configuration evolution and dynamic reconfiguration.

### 6.2. Future development

Looking ahead, MRURs are expected to achieve deeper integration and coordinated development among structural design, perception, and control.

1)Structural design: A composite structure composed of flexible shell materials and supporting frameworks provides a promising solution for ensuring structural stability and sealing reliability under high-pressure environments. In the future, such design schemes are expected to become a key approach for enabling MRURs to overcome the challenges of high-stress operations in extreme deep-sea environments. For intermodule connection mechanisms, achieving both rapid and robust connections remains a critical issue for future modular self-reconfiguration. Magnetic connection is expected to become a mainstream technical direction. In particular, approaches such as optimizing magnetic flux control using electropermanent magnet technology, improving magnetic pole arrangements, and integrating mechanical limiters and guiding structures can ensure rapid docking while maintaining high-strength and stable connections, thereby providing a reliable structural foundation for self-reconfiguration operations.

2)Perception system: Although SLAM techniques have been extensively studied in the AUV domain, their application in modular systems with reconfigurable configurations remains relatively limited. In the future, SLAM-based computation is expected to be more widely adopted in MRUR platforms. To address deviations and uncertainties introduced by modular reconfiguration, multisensor fusion methods are likely to evolve toward more adaptive, self-calibrating, and learning-driven

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approaches. By incorporating lightweight neural networks and self-supervised learning algorithms, the system can automatically adjust fusion strategies and weighting according to configuration changes, thereby maintaining stable perception performance while coping with sensing noise, drift, and environmental uncertainties.

3)Control strategy: In the future, the development of control systems will be more tightly integrated with perception systems, forming a perception–control cooperative framework. With the support of perception modules, a multilayer collaborative control architecture based on state estimation, environment understanding, and task planning can be established to enable task-oriented self-reconfiguration control. At the algorithmic level, more artificial intelligence and learning-based mechanisms are expected to be introduced. On the one hand, MPC combined with deep learning is likely to become an important research direction, where physics-informed neural networks can adaptively compensate for unknown terms in traditional dynamic models. On the other hand, techniques such as adaptive reinforcement learning and neural-network-based self-tuning controllers will be applied to enhance the system`s ability to respond rapidly to unknown environmental disturbances and to achieve optimized control performance.

MRURs have broad application prospects in underwater exploration, ecological monitoring, energy infrastructure inspection, disaster response, and scientific investigation. With continued technological advancements, MRUR is expected to overcome the limitations of conventional underwater robots characterized by fixed configurations and single-task operations, thereby providing stronger support for deep-sea scientific research and marine resource utilization.

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## Author contributions

Ling HE conducted the literature review and drafted the manuscript. Jing ZHOU, the corresponding author, provided supervision and revised the manuscript. Xi GAO, provided robot application background and article revision suggestions.

## Conflict of interest

Ling HE, Jing ZHOU, and Xi GAO declare that they have no conflict of interest.

## Declaration on the use of generative AI tools

During the preparation of this work the authors used ChatGPT in order to improve language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

## Data availability

No datasets were generated or analyzed during the current study.

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## 中文概要

**题　目：模块化可重构水下机器人（MRUR）：结构、感知与控制**

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**目　的：**传统水下机器人通常采用固定结构，任务适应性和环境适应能力有限，难以满足复杂、受限和多变水下作业场景的需求。模块化可重构水下机器人通过模块重组等方式提升水下机器人系统的任务适应性、扩展性和协同作业能力。本文旨在系统梳理模块化可重构水下机器人在结构设计、感知系统和控制策略方面的研究进展，总结其关键技术特点与发展趋势，为后续 MRUR 系统设计与工程应用提供参考。

**创新点：**1. 从结构设计、感知系统和控制策略三个层面对模块化可重构水下机器人研究进行系统归纳，构建了面向 MRUR 系统发展的技术分析框架；2. 总结了多个关键技术在 MRUR 中的作用机制与适用场景；3.分析了 MRUR 相较于传统固定构型水下机器人的潜在优势，并进一步指出其向自重构、自适应和深度协同方向发展的关键挑战。

**方　法：**1. 本文采用方法透明的叙述性综述方法，而非 PRISMA 式系统综述，以适应当前 MRUR 研究数量有限、技术路径多样且文献来源分散的特点；2. 根据检索获得的文献与相关研究工作，从结构设计、感知系统和控制策略三个方面对已有 MRUR 研究进行分类梳理，并总结各类系统的技术特点与关键问题；3. 对 MRUR 在复杂水下环境的应用进行归纳分析，并总结其工程化应用面临的重要挑战。

**结　论：**1. 模块化可重构水下机器人能够通过结构重组和功能扩展提升系统对复杂水下任务的适应能力，是突破传统固定构型水下机器人局限

的重要发展方向；2. 可靠的耐压密封结构和稳定的水下连接机制是MRUR实现工程化应用的基础；3. MRUR感知系统需要适应拓扑变化、模块对接、传感冗余和分布式协同需求；4. MRUR控制策略应面向拓扑变化下的推进冗余与协调控制问题，实现从构型规划到自重构执行的全过程控制；5. 未来，MRUR有望向自重构、自适应和深度协同方向演进，在复杂水下环境中发挥更高的应用价值。

**关键词：** 模块化机器人技术；水下机器人技术；模块化可重构水下机器人（MRUR）；自主水下航行器（AUV）

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