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Development of Multibody Marine Robots: A Review

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ABSTRACT Multibody marine robots, representing a promising research and development area, have gained acute attention and response from civil and military fields. A multibody marine robot is a multibody system composed of multiple single-body marine robots (defined as a unit) in a certain topology. Such a system is generally characterized by underactuation, hyperredundancy, power distribution, modularization and so on. Compared with traditional single-body marine robots, multibody marine robots can carry greater loads and have more forms of motion, so they can meet more specialized functional requirements. At the same time, they also have more complex hydrodynamic characteristics due to their unique structures and motion forms. In this paper, the types, features, and hydrodynamic characteristics of typical multibody marine robots are reviewed and summarized based on the connection structures between units. In addition, the development trends of multibody marine robots are analyzed and discussed. This review work anticipates positive attention from future readers regarding multibody marine robots, which represent an important subarea of marine robots.

INDEX TERMS Multibody marine robot, underwater vehicle, hydrodynamic characteristic, topology, connection structure.

I. INTRODUCTION

With the rapid development of science and technology, unmanned marine robots have been widely used in civil fields such as marine environment observation [1], deep sea mineral resource exploitation [2], and seabed geomorphology [3]. In addition, as powerful equipment for anti-mine, anti-submarine, reconnaissance, and submarine rescue operations, marine robots have also played an important role in the military [4]. Marine robots can be divided into single-body and multibody marine robots. The single-body autonomous underwater vehicle (AUV) is widely used because of its high speed and wide detection range [5]. It can perform analysis, decision-making and collaboration tasks autonomously by carrying different sensors. A multibody underwater manipulator equipped on a remotely operated vehicle (ROV) has strong and long-lasting operational abilities. It is currently the most effective and reliable underwater platform for the development and utilization of marine resources and deep-sea rescue salvage [6], [7].

Single-body marine robots sometimes do not work well in applications with specific requirements due to their limited operational abilities, even if they can be used in a clustered way [8]. To meet specific requirements and provide an effective means to solve problems, increasingly more multibody marine robots have been developed in recent years. For example, multibody observation AUVs have been developed to meet the requirements of high stability and good maneuverability [9], [10]; marine snake-like robots are developed to meet the requirements of detection and maintenance in confined spaces [11]; wave gliders have been developed to meet the requirements of long-range and real-time communications [12]. According to incomplete statistics from the Autonomous Underwater Vehicles Application Center (AUVAC), 237 AUVs have been archived worldwide as of November 2019. Among them, multibody configuration

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platforms account for 12.7%. In addition, only 2 multibody AUVs were archived in 1990. However, in 2000 and 2010, the number of multibody AUVs archived increased to 12 and 30, respectively. This shows that multibody AUVs are getting more and more attention from researchers.

Multibody marine robots, composed of multiple isomorphic or heterogeneous single-body marine robots in a certain topology, are multibody systems [14]. They can be categorized as rigid multibody systems, flexible multibody systems and rigid-flexible hybrid multibody systems according to the type of units. They can be further segregated into body wave propulsion systems, distributed propulsion systems, wave energy propulsion systems, and body-propeller hybrid propulsion systems according to their propulsion mechanisms. In addition, multibody marine robots can also be divided into serial-like multibody systems, tree-like multibody systems, closed-loop multibody systems, and hybrid multibody systems according to their topology [15]. They generally exhibit characteristics of underactuation, hyper-redundancy, distributed propulsion, and modular structure. The connection structure between units can use rigid rods, joints, and cables, which play different roles in the degrees of freedom(DOFs) for a multibody marine robot. In addition, the form of the relative motion between units can be active or passive. An active motion is driven by the actuator, and a passive motion is usually caused by adjacent units. At the same time, the motion of a multibody marine robot can exhibit more complex hydrodynamic characteristics and flow fields because of its features, such as connection form and propulsion mechanism. Major studies of the hydrodynamics of multibody marine robots have included the calculation and estimation of viscous hydrodynamics and inertial hydrodynamics in equations of motion, the analysis and prediction of resistance components for the optimizing of body shape and configuration, and flow field features such as vortex street characteristics and wake flow features for the study of propulsion mechanisms. Therefore, the multibody marine robots have more complex classification systems, features and hydrodynamic characteristics than the single-body marine robots, which presents challenges for their mechanical design, hydrodynamic analysis, and control.

The specific operational advantages of multibody marine robots have made them a research topic of interest in recent years. The in-depth study of multibody marine robots is of great significance. In this paper, the development of multibody marine robots is reviewed. The types, features, hydrodynamic characteristics, and future development trends are summarized after analyzing the relevant research results. This paper will provide researchers with more detailed information on the current state of technological development of multibody marine robots.

II. TYPES AND FEATURES OF MULTIBODY MARINE ROBOTS

Multibody observation AUVs, marine robots equipped with underwater manipulators, marine snake-like robots, robotic fishes, underwater self-reconfigurable robots, multilegged marine bionic robots, wave gliders and so on are typical representatives of multibody marine robots. Classification according to their topology can distinguish their shape differences but cannot effectively distinguish the interaction characteristics between the internal units. To better reflect the differences of interaction form between units and better analyze the differences in hydrodynamic characteristics, multibody marine robots are divided into rigidly connected, joint connected and cable connected robots according to the connection structure between units in this paper, as shown in Fig. 1.

A. RIGIDLY CONNECTED MULTIBODY MARINE ROBOTS

There is no relative motion between units in a rigidly connected multibody marine robot. This connection structure is designed to increase stability and maneuverability or meet specific functional requirements, such as landing, docking, expansion and so on.

1) OBSERVATION AUVs WITH INCREASED STABILITY AND MANEUVERABILITY

The SeaBED [9] and ABE [10] multibody observation AUVs are typical representatives designed to increase stability and maneuverability, as shown in Fig. 2. They are composed of several single-body AUVs connected by a rigid structure, and both were developed by the Woods Hole Oceanographic Institution (WHOI). These single-body AUVs are placed in the upper or lower part. The upper unit provides positive buoyancy, and the lower unit provides negative buoyancy. This configuration increases the whole navigation stability of the robot, which allows it to perform tasks better on a rugged sea floor.

The SeaBED AUV, developed in 2004, is composed of two single-body AUVs in parallel configuration, as shown in Fig. 2a. It is mainly used in high-resolution bathymetric mapping. The control system and certain electronic devices are inside the upper unit, which provides a large positive buoyancy. The battery and sensors are inside the lower unit, which has a large negative buoyancy. The SeaBED AUV is approximately 2 m long, 1.5 m high, and weighs nearly 200 kg in air. Its maximum operating depth, speed, energy carrying capacity, and endurance are 2000 m, 1.5 m/s, 2 kWh and 10 h, respectively. Its propulsion system consists of 4 propellers. The maximum forward propulsion, vertical propulsion and lateral propulsion are 100 N, 50 N, and 50 N, respectively. It is also equipped with a 1200 kHz ADCP for navigation, a 300 kHz side-scan sonar, a 675 kHz mechanically scanned pencil beam sonar, a 12-bit camera system with high dynamic range, and a Seabird CTD sensors.

The ABE AUV adopts a three-body and open frame configuration for performing complex seafloor topography measurements and resource exploration, as shown in Fig. 2b. Its maximum operating depth, range, endurance, and cruising speed are 4500 m, 30 km, 24 h, and 0.6 m/s, respectively.

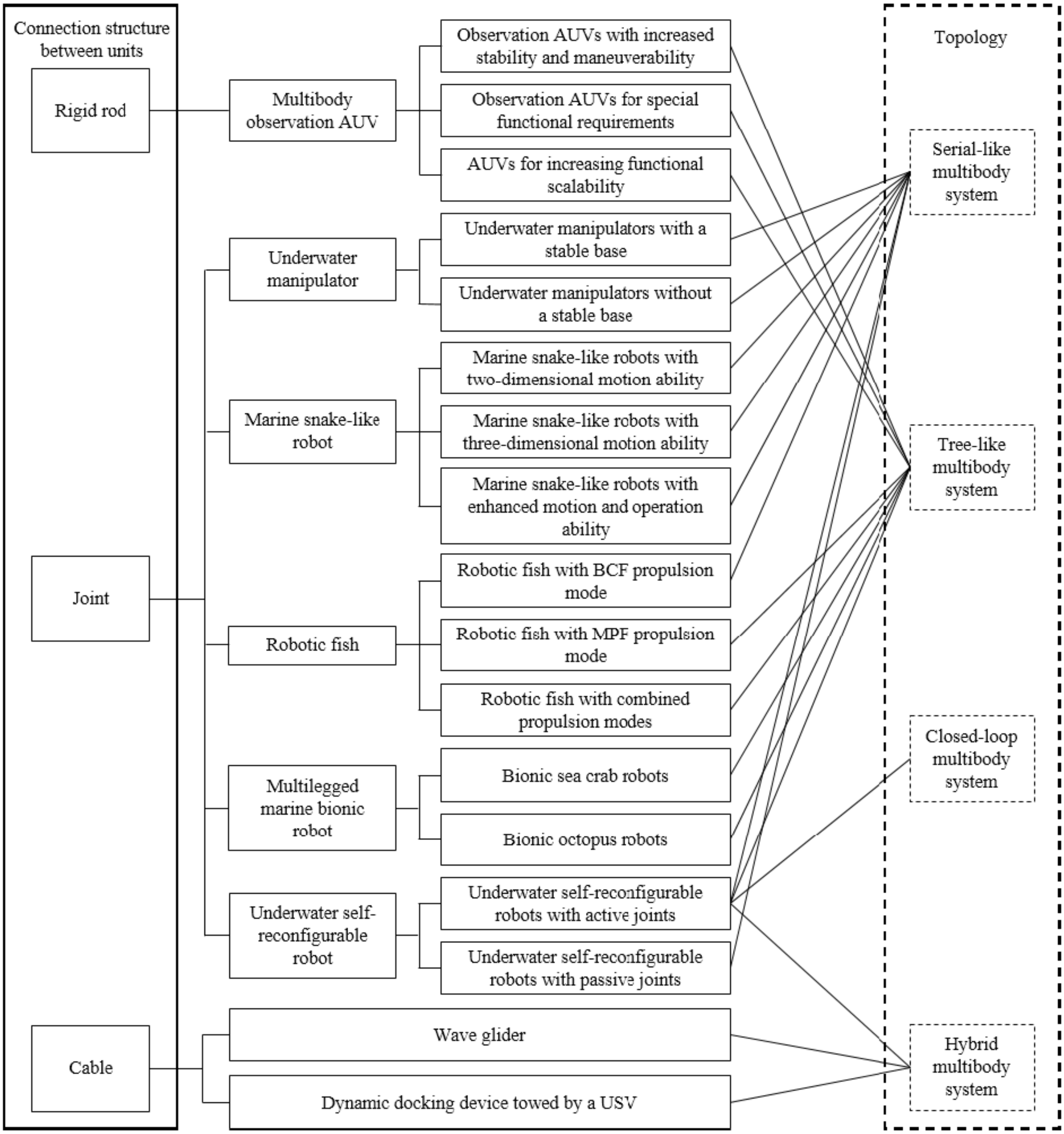


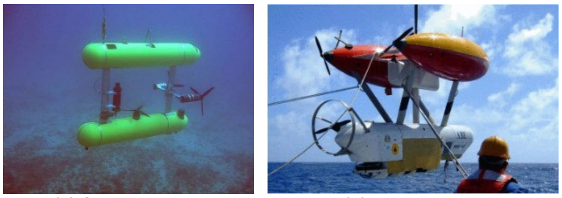
FIGURE 1. The classification of multibody marine robots according to the connection structure between units.

It can achieve 6 DOFs of movement by using 5 propellers. The navigation stability of the ABE AUV is increased by a rigidly connected structure. Hovering and in situ rotation abilities reflect its good maneuverability.

2) OBSERVATION AUVs FOR SPECIAL FUNCTIONAL REQUIREMENTS

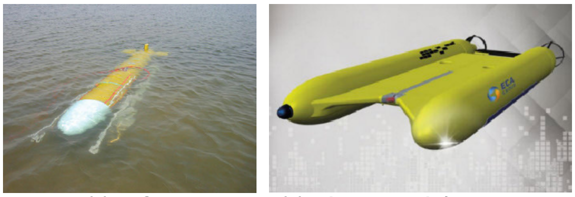
To meet the special functional requirements of landing, docking and other functions, some rigidly connected multibody observation AUVs have been developed.

The VBS landing-type multibody AUV was developed for long-term ocean measurement tasks by Zhang *et al.* [16], [17] in 2007. The VBS consists of a central body and two ballast tanks, which are rigidly connected, as shown in Fig. 3a. The ballast tanks are used for landing and bottom-sitting. The buoyancy of the ballast tank is adjusted by water injection and abandonment. The VBS AUV is approximately 3 m long, and 0.33 m in diameter, and weighs 195 kg in air. Its maximum operating depth, speed, range, and endurance are 120 m, 4 knots, 50 km, and 3 months, respectively.



(a) SeaBED AUV (b) ABE AUV

FIGURE 2. Multibody observation AUVs with increased stability and maneuverability.



(a) VBS AUV (b) Alister 18 Twin/A18-TD AUV

FIGURE 3. Multibody observation AUVs for special functional requirements.

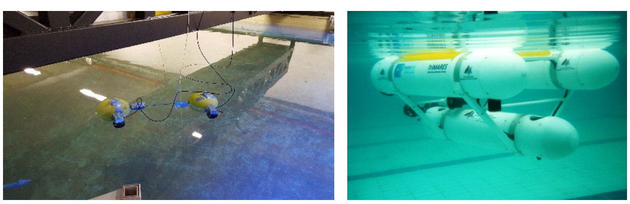
The two-body AUV Alister 18 Twin/A18-TD [18] was developed by the French ECA Group in 2010, as shown in Fig. 3b. It adopts a parallel structure that is primarily used for stable positioning on a platform to facilitate underwater docking. It is approximately 4.7 m long, 1.8 m wide, and weighs 1.2 t in air. Its maximum operating depth, speed, energy carrying capacity, and endurance are 3000 m, 6 knots, 22 kWh, and 24 h, respectively. The configuration of the two propulsion devices also increases its maneuverability.

3) AUVs FOR STUDYING DYNAMIC CHARACTERISTICS OR INCREASING FUNCTIONAL SCALABILITY

In addition to the robots mentioned above, there are some rigidly connected multibody marine robots that have been developed to study dynamic characteristics or increase functional scalability.

A simple reconfigurable underwater robot was developed for studying the dynamic characteristics of multibody underwater robots by Nielsen *et al.* [19] in 2016, as shown in Fig. 4a. It adopts a configuration where two spherical single-body AUVs are connected by a 596-mm long metal rod.

Ferreira *et al.* [20], [21] developed a three-body AUV named TriMARES in 2012, as shown in Fig. 4b. The body and the propeller configuration are a result of careful customization to typical maneuvers that can be performed by the AUV, such as station keeping, hovering, lateral or frontal scan. Based on this configuration, there is more space to equip some extended modules to increase functional scalability.



(a) A reconfigurable underwater robot (b) TriMARES AUV

FIGURE 4. Multibody marine robots for studying the dynamic characteristics or increasing functional scalability.

4) HYDRODYNAMIC CHARACTERISTICS

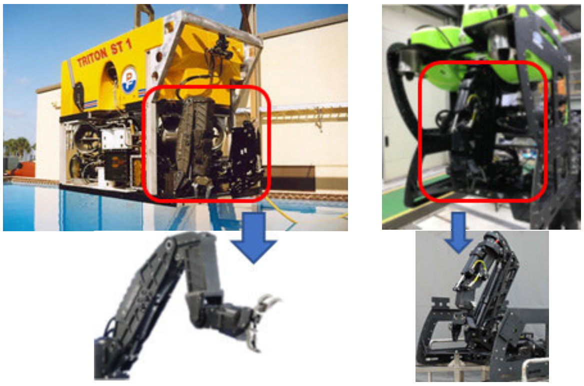
The interaction form between units of rigidly connected multibody marine robots can be characterized as having connection constraints. The analysis method of their hydrodynamic characteristics is the same as that of single-body marine robots with complex shapes. Therefore, the process of analyzing their hydrodynamics is divided into viscous hydrodynamics and inertial hydrodynamics. Viscous hydrodynamics are related to speed, and inertial hydrodynamics are related to acceleration [22]. There are usually four methods used for calculating viscous hydrodynamics, including the maternal estimation method [23], the restraint model test method [24], the CFD numerical calculation method [25], and the parameter identification method [26]. There are usually three methods used for calculating inertial hydrodynamics, including the plane motion mechanism method, the panel method [27], and the CFD numerical calculation method.

The maternal estimation method is based on a regression analysis of the hydrodynamic model test data of a similar shape. It can only provide a reference for the initial design of a robot. The restraint model test method obtains a viscous hydrodynamic coefficient of a robot by using a test facility such as a tow pool or a plane motion mechanism. It is the most reliable and accurate method. However, there are still some limitations, such as a long test period and high cost. The CFD numerical calculation method offers higher accuracy than the main maternal estimation method and a shorter test period and lower cost than the restraint model test method. However, the solution results are influenced by some factors, such as the selection of a turbulence model and the division of the grid. The parameter identification method is mostly used to evaluate the hydrodynamic performance of a robot and verify the accuracy of the test results of a restraint model. The panel method uses potential flow theory to calculate the inertia hydrodynamics. It is suitable for a robot with a simple shape.

At times, multiple calculation methods of a hydrodynamic model can be used simultaneously in one design cycle of a marine robot. For example, the hydrodynamics of the TriMARES AUV were modeled by the maternal estimation method at the beginning of the design phase and corrected by the parameter identification method at a later development phase. Therefore, the method selected for calculating the hydrodynamic model of a rigidly connected multibody marine robot should be based on the scope and characteristics.

B. JOINT CONNECTED MULTIBODY MARINE ROBOTS

Joint connected multibody marine robots are composed of several units and joints. This connection structure can realize hyperredundant motions, modular structures and distributed propulsion forces. The hyperredundant motion can



(a) The Triton ST ROV (b) The KRISO ROV

FIGURE 5. **Underwater manipulators with a stable base.**

achieve better operational ability, the modular structure can achieve convenient assembly, and the distributed propulsion forces can achieve multiple forms of motion. The typical representatives of joint connected multibody marine robots include underwater manipulators, marine snake-like robots, robotic fishes, multilegged marine robots, and underwater self-reconfigurable robots.

1) UNDERWATER MANIPULATORS

The underwater manipulator plays an important role in marine engineering. It is a common mechanical tool for underwater vehicles. Its irreplaceable operational advantages have made it a research topic of interest in recent years, especially in the fields of lightweight structure design, high-precision control algorithms, and autonomous operation modes. The underwater manipulator is typically equipped on other mobile platforms to extend operating range. It can be categorized as a root system or a rootless system according to there is a stable base or not.

a: UNDERWATER MANIPULATORS WITH A STABLE BASE

The underwater manipulators equipped on an ROV are usually regarded as a root multibody system with a stable base. A detailed overview of underwater manipulators equipped on ROVs was done by Sivčev *et al.* [7]. The mass of 12 typical ROVs from lightweight to the heavyweight is listed. The average mass ratio of an underwater manipulator in an ROV is 3.63% in [7]. Therefore, the mass and volume of an underwater manipulator with a stable base are usually much smaller than the base. Therefore, the maneuverability of the underwater manipulator on a stable base (such as the ROV) is little affected by the base.

The Triton ST ROV, developed by the Helix Energy Solutions Group, meets the requirements of most offshore operations, as shown in Fig. 5a. It is approximately 1.3 m wide, 2.6 m long, 2.1 m high, and weighs 2.95 t in air. The Kraft Raptor manipulator, a 6 DOFs multibody marine robot, is equipped on the Triton ST ROV. It is the top-level hydraulic driven underwater manipulator in the world and was developed by Kraft Telerobotics in 2017. Its weight in air, maximum operating depth, maximum lifting capacity, maximum torque, maximum clamping force, and main material are 75 kg, 6500 m, 227 kg, 135 Nm, 135 kgf, and structural steel and aluminum alloy, respectively.

The KRISO ROV [28], developed by the Korea Research Institute of Ship & Ocean Engineering, is used to verify the effectiveness of autonomous intervention algorithms for underwater manipulators, as shown in Fig. 5b. It is approximately 0.9 m wide, 1.1 m long, 1.2 m high, and weighs 230 kg in air. It consists of an upper part and a lower part. Buoyancy blocks and propellers are installed on the upper part. Manipulators and oil compensation devices are installed on the lower part. The ECA Robotics 7E mini manipulator, a 6 DOFs multibody marine robot, is equipped on the KRISO ROV. It is the top-level electric driven underwater manipulator in the world. Its weight in air, maximum operating depth, maximum lifting capacity, maximum jaw rotating torque, and main material are 51 kg, 300 m, 25 kg, 25 Nm, and aluminum alloy 6082 T6, respectively.

b: UNDERWATER MANIPULATORS WITHOUT A STABLE BASE

The underwater manipulators equipped on an underwater vehicle-manipulator system (UVMS) or invention-autonomous underwater vehicle (I-AUV) are usually regarded as rootless multibody systems. The inertia of an underwater manipulator is generally not negligible for a UVMS/I-AUV.

UVMSs/I-AUVs have been increasingly developed due to their good autonomous operational abilities. The ALIVE I-AUV [29]–[31] is a milestone robot in autonomous underwater interventions, as shown in Fig. 6a. It has been reported as the first AUV able to autonomously carry out manipulation actions, including opening/closing a valve in a subsea panel. The ALIVE I-AUV is approximately 4 m long, 2.2 m wide, and 1.6 m high; and weighs 3.5 t in air. Two 5 DOFs manipulators with hydraulic claws are installed on it for operation.

(a) ALIVE I-AUV (b) Type-R ARV (c) Girona 500 I-AUV

FIGURE 6. **UVMSs/I-AUVs that have been developed.**

The type-R ARV was developed by Zhang [32] in 2007, as shown in Fig. 6b. It is suitable for underwater operations in nonstructured environments and has the feature of good flexility and high efficiency. It has been verified in lake and sea trials. It is equipped with a 2 DOFs electric manipulator. The manipulator is composed of two links, two swing joints, and a mechanical claw. It weighs 5 kg in air and 2 kg in water. Its maximum lift capacity is 5 kg.

The Girona 500 I-AUV was developed by Ridao *et al.* [33], [34] in 2012, as shown in Fig. 6c. It is composed of three torpedo-type single-body AUVs and can be equipped with underwater manipulators in different configurations according to different requirements. Its length, width, height, weight, and maximum working depth are 1.5 m, 1 m, 1 m, 150 kg, and 500 m, respectively. The project plan of the TRIDENT was completed with the cooperation of the Girona 500 I-AUV and another underwater vehicle. The collaborative mapping abilities of the two vehicles and operational abilities of the I-AUV were verified in this project. The manipulator installed on the I-AUV determines the operational capability. In Fig. 6c, it is a 6 DOFs manipulator with 3-fingers at the end and has strong grasping and valve management abilities.

In addition, there are a number of new UVMSs/I-AUVs being developed. For example, the Kawasaki AUV has been planned for release in 2020 [5], as shown in Fig. 7a. It will be equipped with a manipulator as an inspection tool module for the maintenance and repair of submarine natural gas or oil pipelines. The ROBUST AUV [35], [36] has been planned for development by the ROBUST project supported by the EU in 2020, as shown in Fig. 7b. It includes three Folaga AUVs [37] and a rigid frame. A manipulator is equipped on the bottom of the AUV for operation.

(a) Kawasaki AUV (b) ROBUST robotic platform

FIGURE 7. UVMSs/I-AUVs that are being developed.

As more and more subsea resources need to be developed and the existing submarine infrastructure needs to be inspected, maintained and repaired (IMR) [38], marine robots equipped with underwater manipulators will play a more important role.

c: HYDRODYNAMIC CHARACTERISTICS

The hydrodynamic characteristics of a manipulator can be analyzed separately in a system of underwater manipulators with a stable base. The main analysis methods include the maternal estimation method, the parameter identification method, and the CFD method. A method combining the maternal estimation method and the CFD method is typically used [39]. Lv [40] used this method to analyze the hydrodynamic effects of an underwater manipulator equipped on an ROV. The hydrodynamics of the manipulator are modeled by the maternal estimation method, and the value of the resistance coefficient is calculated by the CFD method.

The influence of the base on the hydrodynamic characteristics of the manipulator should be considered in a system of underwater manipulators without a stable base. The main analysis methods include the maternal estimation method, the parameter identification method, and the CFD method. A method combining the maternal estimation method and the parameter identification method, which has been shown to be the most feasible, is typically used [32]. The maternal estimation method is used to build a model with unknown hydrodynamic coefficients. The parameter identification method is used to obtain the approximate value of the hydrodynamic coefficient through experiments on different influencing factors, such as flow velocity and section area. In this way, a model with known coefficients can be obtained by combining the two methods. Mclain *et al.* [41], [42] used this method to analyze the hydrodynamic effects of a circular cross-section underwater manipulator in a UVMS. However, the accuracy of the hydrodynamic model built by this method is greatly affected by the parameter identification experiments.

2) MARINE SNAKE-LIKE ROBOTS

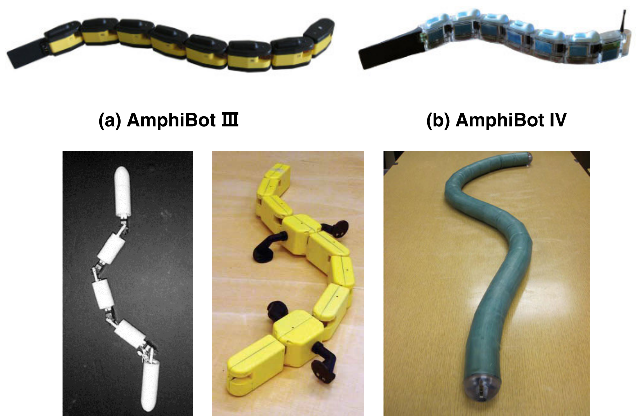
A marine snake-like robot consists of several single units in a series. It is characterized by a body wave propulsion system. This is a research topic of interest in serial-like multibody systems because of its advantages in flexibility and autonomous operation ability [38]. It needs to have different motion abilities according to different task requirements. Its adjacent units are connected by joints. Different joint structures will lead to different motion abilities.

a: MARINE SNAKE-LIKE ROBOTS WITH TWO-DIMENSIONAL MOTION ABILITY

A marine snake-like robot with a joint that adopts a plane hinge structure can only perform two-dimensional motions. However, the motion is more stable, and its control method is simpler.

The AmphiBot series robots, developed by the French Nantes Communication and Network Research Institute, are typical representatives of two-dimensional motion. The AmphiBot III [43] (Fig. 8a), developed in 2014, consists of 8 body units and 1 tail unit. The conventional unit is 97 mm long, 40 mm wide and 57 mm high. The tail unit is 103 mm long, 30 mm wide and 57 mm high. The AmphiBot IV, known as the Envirobot, was developed in 2016 [44]. It has a larger flexible tail fin than the AmphiBot III, as shown in Fig. 8b. There is a larger flexible tail fin than the AmphiBot III, as shown in Fig. 8b. It has a great advantage in performing pollutant composition tracking tasks because, unlike a propeller-driven robot, it does not affect the measurement of chemical composition by agitating mud or disturbing aquatic organisms.

In addition, there are other typical marine snake-like robots with two-dimensional motion, such as the Reel [45], the salamander robot [46] and the Neelbot-1.1 [47]–[49]. The bionic amphibious robot Reel (Fig. 8c) includes 5 units.



(a) AmphiBot III (b) AmphiBot IV

(c) Reel (d) Salamander robot (e) Neelbot-1.1

FIGURE 8. Marine snake-like robots with two-dimensional motion ability.

It is used as a platform to test various locomotive gaits. The salamander robot (Fig. 8d) includes 9 units. It can not only move on the ground through 4 limbs but also swim in the water through the lateral undulations of a spine generated by 6 actuated hinge joints. The Neelbot-1.1 marine snake-like robot (Fig. 8e) includes 20 units and 19 servo-actuators. It is used to study the hydrodynamics of an eel swimming motion by analyzing its propulsive wake.

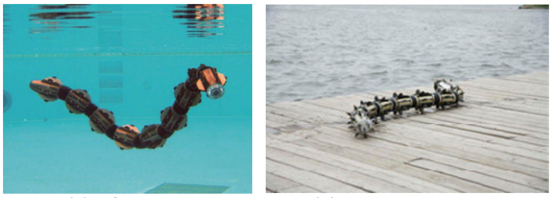
b: MARINE SNAKE-LIKE ROBOTS WITH THREE-DIMENSIONAL MOTION ABILITY

A marine snake-like robot with joints that adopt a universal joint structure can perform three-dimensional motion. This structure type gives the robot higher motion redundancy and more complex control methods relative to the plane hinge structure.

The ACM [50] and Perambulator [51]–[53] series robots are typical representatives of performing three-dimensional motion. The ACM-R5, developed in 2009, is 1.75 m long and weighs 7.95 kg in air, as shown in Fig. 9a. Its diameter and length are 80 mm and 170 mm, respectively. Each unit is equipped with 6 fins with passive wheels. Its joints adopt a universal joint structure that can realize 2 DOFs motion of yaw and pitch. The ACM-R5 snake-like robot can not only move on a flat or rough surface but also swim in water. It has excellent three-dimensional motion ability, and its maximum swimming speed is 0.4 m/s. The Perambulator 3, developed by the Shenyang Institute of Automation, Chinese Academy of Sciences, is composed of 9 units, as shown in Fig. 9b. It is used for environmental detection and underwater rescue. It has a three-dimensional motion ability, and its maximum swimming speed is 0.3 m/s.

c: MARINE SNAKE-LIKE ROBOTS WITH ENHANCED MOTION AND OPERATION ABILITY

The motion ability of a marine snake-like robot can be enhanced by adding additional propulsion devices. The Eelume series robots [54], [55], which have been developed



(a) ACM-R5 (b) Perambulator 3

FIGURE 9. Marine snake-like robots with three-dimensional motion ability.

since 2016, have added additional propellers on both sides of the body to enhance their motion ability. They can move not only by swimming but also by propeller propulsion in three-dimensional space. This configuration increases their maneuverability so that the Eelume series robots can perform tasks in a narrow space. The Eelume 2 marine snake-like robot can perform tasks such as marine environment observation and pipeline exploration, as shown in Fig. 10a. Its joints adopt a structure that can realize two DOFs motion (yaw and pitch). Its diameter, weight in air, maximum operating depth, and maximum power are 180 mm, 75 kg, 150 m, and 2 kW, respectively.

(a) Eelume 2 (b) EELY500

FIGURE 10. Marine snake-like robots with enhanced motion and operational ability.

In addition, with the increasing demands of IMR, additional claw devices have been added to marine snake-like robots to increase their operational ability. This kind of robot is also called an underwater swimming manipulator (USM). The latest generation of EELY500, presented in February 2019, is a typical representative. Its main body diameter, maximum diameter (including the propeller), length, weight in air, maximum operating depth, and maximum speed are 200 mm, 490 mm, 2.5 m, 70 kg, 500 m, and 4 knots, respectively, as shown in Fig. 10b.

d: HYDRODYNAMIC CHARACTERISTICS

There are two main ideas for modeling the hydrodynamics of a marine snake-like robot. The first is to treat the robot as a discontinuous system with multiple links, and the second is to treat the robot as a continuous system.

Khalil *et al.* [56], Kelasidi *et al.* [57]–[59], and Pettersen [11] treated the marine snake-like robot as a discontinuous system and made assumptions that the unit is a link and the connection structure is a joint. In these works, the hydrodynamic influence on the link was considered, while the hydrodynamic influence on the joint was ignored. In addition, the hydrodynamics were divided into viscous hydrodynamics and inertial hydrodynamics (including the Coriolis force generated by the noninertial system). The viscous hydrodynamics based on the Morison equation are divided into the frictional resistance and differential pressure resistance. The inertia hydrodynamics are represented by an additional linear angle coupled inertia matrix and an additional angular inertia matrix. Boyer and Porez [60] treated the marine snake-like robot as a continuous system and built a hydrodynamic model of the AmphiBot III marine snake-like robot. They solved the hydrodynamic model using the Newton Euler method, which is based on a large amplitude slender body theory proposed by Lighthill [61]–[63] and a resistance hydrodynamic model proposed by Taylor [64]. With the increase in demand for improving motion ability, the structure and motion form of marine snake-like robots have become more diverse, which presents more challenges in accurately building a hydrodynamic model.

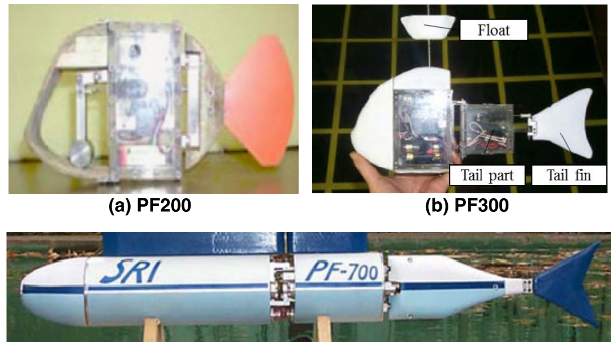
3) ROBOTIC FISH

The robotic fish is widely used in water quality monitoring, pollution source tracking and underwater detection. Its propulsion is the result of the interaction between an internal actuator and external fluid [65]. The body and/or caudal fin (BCF) and the median and/or paired fin (MPF) are two main propulsion modes of robotic fish. A robotic fish with BCF propulsion mode consists of multiple units in series. Its propulsion is generated by the swinging of a part of the body and the caudal fin, which has large instantaneous acceleration and excellent endurance [65], [66]. A robotic fish with MPF propulsion mode consists of a fish body, a pair of pectoral fins and a caudal fin. Its propulsion is generated by the swing of the fins, which offers good maneuverability and stability [67].

With the application of new flexible materials and the improvement of serial-like structures, more and more robotic fish offer high-speed, high-efficiency, and low-noise swimming characteristics.

a: ROBOTIC FISH WITH BCF PROPULSION MODE

A representative of the BCF propulsion mode is the PF series robotic fish [68], which was developed to study the optimal propulsion mode of fish, as shown in Fig. 11. The PF-200 (Fig. 11a) has a flat appearance and consists of three units. It is developed for studying the floating and diving behaviors of robotic fish. The PF-300 [68], [69] (Fig. 11b) also consists of three units. Its minimum turning radius (@2.2 Hz) and maximum speed are 300 mm and 0.2 m/s (@2.3 Hz), respectively. The PF-700 [69] robotic fish (Fig. 11c) was developed for studying the mechanism of the high-speed motion. It consists of three joints. Its length, diameter, and maximum speed are 700 mm, 80 mm, and 0.7 m/s. (@12 Hz), respectively.



(a) PF200 (b) PF300
(c) PF700

FIGURE 11. Robotic fish with BCF propulsion mode.

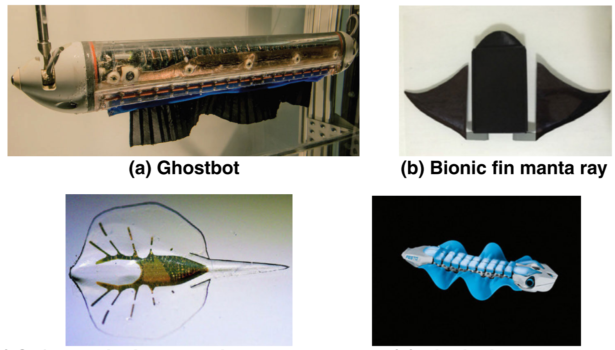

(a) Ghostbot (b) Bionic fin manta ray
(c) Soft-robotic tissue-engineered ray (d) BionicFinWave

FIGURE 12. Robotic fish with MPF propulsion mode.

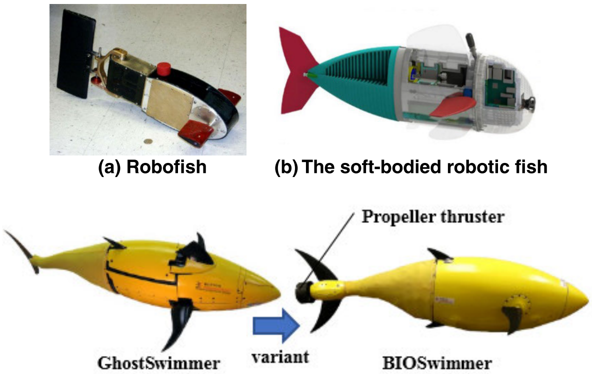
b: ROBOTIC FISH WITH MPF PROPULSION MODE

A representative of the MPF propulsion model is the Ghostbot robotic fish, which was developed by Neveln *et al.* [70], [71] in 2014, as shown in Fig. 12a. It was developed with reference to the structure of a weakly electric black ghost knifefish. Its propulsion is generated by the swing of a black ventral fin. Its maximum swimming speed is 260 mm/s.

Chew *et al.* [72] developed a robotic fish that references the structure of a manta ray, as shown in Fig. 12b. A pair of steering gears are used to achieve the swing of the pectoral fin. Its length, width, weight, and maximum swimming speed are 280 mm, 580 mm, 767.7 g, and 0.4992 m/s, respectively. It has been deeply studied in maneuvering control, system optimization and propulsion mechanism.

Park *et al.* [73], [74] of Harvard University developed a biohybrid robot in 2016 that references a stingray structure, as shown in Fig. 12c. Its body is connected to several metal skeletons with good elasticity. Isolated rat cardiomyocytes are distributed around the skeleton. Its propulsion is generated by the swing of a pectoral fin that is caused by optically stimulating the contraction of cardiomyocytes. Its length is approximately 17 mm. It can travel 250 mm at an average speed of 1.5 mm/s on a specified path. In addition, the feasibility of an autonomous, light-driven activated tissue robot has been verified by it.

The BionicFinWave [75] is another typical robotic fish with an MPF propulsion mode, as shown in Fig. 12d. It was developed with reference to the structure of marine worms



(a) Robofish (b) The soft-bodied robotic fish
(c) GhostSwimmer and BIOSwimmer

FIGURE 13. Robotic fish with combined propulsion modes.

and cuttlefish. Its propulsion is generated by the swing of two side fins. The side fins are assembled on nine small lever links and driven by servo motors.

c: ROBOTIC FISH WITH COMBINED PROPULSION MODES

To achieve large instantaneous acceleration ability and good maneuverability simultaneously, some robotic fish that combine BCF and MPF propulsion modes have been developed. Morgansen *et al.* [76], [77] developed a two-joint robotic fish in 2007, as shown in Fig. 13a. It combines both BCF and MPF propulsion modes to realize the swimming mode of trunkfish [78]. It can achieve three-dimensional motion by using its single-degree-of-freedom pectoral fins. Its maximum swimming speed, maximum steering angle, and average steering speed are 1.1 BL/s (Body length per second), 20°, and 50°/s, respectively. Trimmer *et al.* [79] of MIT developed a flexible robotic fish in 2014 for studying quick start ability, as shown in Fig. 13b. It adopts a propulsion mode similar to the carangiform undulation [65], which has good bending and stretching properties. Its main body length, flexible swingable length, width, and maximum swimming speed are 339 mm, 159 mm, 51 mm, and 0.15 m/s, respectively. It can generate more than 20 kinds of movements at different swimming speeds and angles. To achieve rapid motion and flexible turning ability simultaneously, some robotic fish have been developed that combine BCF and propeller propulsion modes. Conry *et al.* [80] develop the GhostSwimmer and BIOSwimmer robotic fish, as shown in Fig. 13c. The GhostSwimmer adopts the BCF propulsion mode. It uses the bluefin tuna as a bionic target and has the characteristics of flexible turning and efficient swimming. Its length, width, height, weight, maximum dive depth, and endurance are 1.52 m, 0.36 m, 0.46 m, 40.8 kg, 100 m, and 14 h, respectively. The GhostSwimmer was developed in order to further increase the rapid motion ability of the BIOSwimmer. It combines BCF and propeller propulsion modes. The BCF propulsion mode ensures its flexible turning ability, while the propeller propulsion mode increases its rapid motion ability. Its maximum swimming speed and maximum reverse speed are 5 knots and 3 knots, respectively. It is mainly used for security work, such as water reconnaissance and mine positioning, near a port.

d: HYDRODYNAMIC CHARACTERISTICS

Due to the different mechanisms of the BCF and MPF propulsion modes, the analysis methods of the hydrodynamic characteristics of the two types of robotic fish are also different.

The hydrodynamic characteristics of the robotic fish with the BCF propulsion mode are similar to those of the marine snake-like robot with two-dimensional motion ability. Some classic hydrodynamic characteristics analysis methods, such as the resistance hydrodynamic model [64], the large amplitude slender body theory [61]–[63], and the two-dimensional wave plate theory [81], have been proposed. To analyze the hydrodynamic characteristics of three-linkage robotic fish and obtain more vortex features and flow field details, some new methods have been proposed, such as the method for calculating dynamic coupled fluid interaction based on the viscous vortex particle method proposed by Eldredge [82], [83] and the numerical simulation method based on multibody dynamics proposed by Li *et al.* [84].

The action of the MPF propulsion mode in general includes two phases: the power stroke and the recovery stroke. From the initial position, it generates the power stroke, which generates the requisite thrust to take the fish towards its direction of motion; then, the recovery stroke brings the fins back to the initial position for the next power stroke [85]. The analysis of the hydrodynamic characteristics of robotic fish with the MPF propulsion mode mainly uses the maternal estimation method based on many assumptions. A method for analyzing the hydrodynamics of labriform locomotion through a blade-element was proposed by Blake [86]. This method assumes that the flow has been separated from the rear surface of the fin, the resistance is almost entirely caused by pressure resistance, and the surface friction can be negligible.

4) MULTILEGGED MARINE BIONIC ROBOTS

A multilegged marine bionic robot is composed of a central body and multiple legs, and the components are connected by joints. The bionic sea crab robot and the bionic octopus robot are two typical representatives of the multilegged marine bionic robot.

a: BIONIC SEA CRAB ROBOTS

A representative of the bionic sea crab robot is the seabed walking robot CR200 [87] that was developed in 2013 for operating in extreme environments with high current intensity and low visibility, as shown in Fig. 14. Its main frame is made of carbon fiber composite material. Its length, width, weight, sitting height, walking height, maximum operating depth, maximum power, and maximum speed are 2.4 m, 2.4 m, 600 kg, 1.3 m, 2.0 m, 200 m, 20 kW, and 0.5 m/s, respectively. It consists of a central body and 6 mechanical

FIGURE 14. Bionic sea crab robot CR200.

legs evenly distributed along both sides. This structure can not only walk on the seabed but also float in the water based on the propeller and 6 mechanical legs. To complete tasks effectively, it is equipped with sensors such as an acoustic camera, side-scanning sonar, ADCP, CTD, AHRS, USBL, contact force sensor, etc.

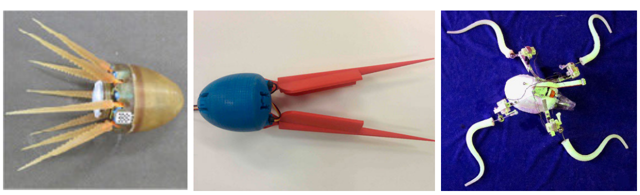
b: BIONIC OCTOPUS ROBOTS

The bionic octopus robot adopts a configuration in which the central body and multiple legs are connected by joints. It mimics the jet propulsion mechanism of an octopus by providing different opening and closing frequencies for each leg to achieve different forms of motion. Its swimming endurance is poor, but its turning ability is good [74].

An eight-legged/armed bionic octopus robot was developed in 2015 by Sfakiotakis *et al.* [88] to study the propulsion performance of multilegged marine bionic robots in different swimming forms, as shown in Fig. 15a. Its maximum swimming speed and maximum propulsion are 98.6 mm/s and 3.5 N, respectively. A two-legged bionic octopus robot was developed by Kazakidi *et al.* [89] in 2017, as shown in Fig. 15b. It consists of a central body and a pair of legs. The legs are mounted on the rear side of the body via rotating joints with 1 DOF. A soft-structured bionic octopus robot was developed by Arienti *et al.* [90] in 2013, as shown in Fig. 15c. It consists of a central body and 4 legs evenly distributed around the central body. It can grasp objects with its flexible legs.

c: HYDRODYNAMIC CHARACTERISTICS

Jet propulsion makes the nonlinear characteristics of the hydrodynamic interaction between multiple legs more significant. Therefore, the analysis method of the hydrodynamic characteristics of the multilegged marine bionic robot is usually based on some assumptions and simplifications. The maternal estimation method and the CFD method are usually used to analyze the hydrodynamic characteristics of the multilegged marine bionic robot. Sfakiotakis built a simplified resistance hydrodynamic model of an eight-legged bionic octopus robot using the maternal estimation method. The modeling process assumes that the hydrodynamic force acting on a single leg is only caused by its motion, and the inertial hydrodynamic force is mainly considered. Renda *et al.* [91] analyzed the hydrodynamic characteristics of a soft-structured bionic octopus robot using the maternal estimation method. Its hydrodynamics are calculated by the inertial hydrodynamics and the viscous hydrodynamics. The inertial hydrodynamics are calculated by the potential flow theory, and the viscous hydrodynamics are estimated by the resistance coefficient. Kazakidi et al. analyzed the hydrodynamic characteristics of a two-legged bionic octopus robot using the CFD method. The modeling process assumes that the fluid is a Newtonian fluid and is incompressible.



(a) eight-legged robot (b) two-legged robot (c) PoseiDRONE

FIGURE 15. Bionic octopus robots.

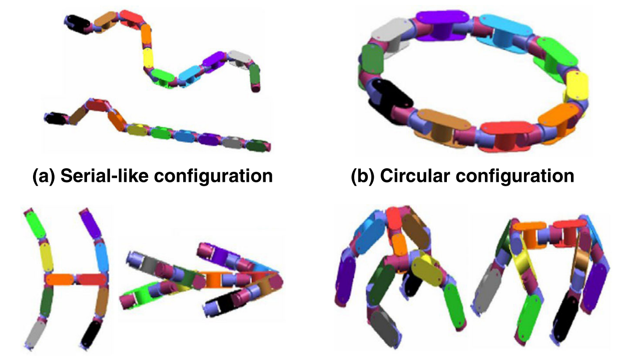
5) UNDERWATER SELF-RECONFIGURABLE ROBOTS

The underwater self-reconfigurable robot exhibits the characteristics of self-assembly and easy expansion compared with traditional multibody underwater robots. Issues such as pose perception, behavior decision-making, motion control, and reconfiguration mechanisms are current areas of research. The joints of the underwater self-reconfigurable robot can be divided into active and passive ones.

a: UNDERWATER SELF-RECONFIGURABLE ROBOTS WITH ACTIVE JOINTS

Two generations of underwater self-reconfigurable robot, USS-G1 and USS-G2, were designed by Wu *et al.* [92], [93] in 2013. The USS-G1 is used to verify the concept of an underwater self-reconfigurable robot. Each unit consists of a motion module and a carrying module. The USS-G2 is the upgrade of USS-G1 in terms of self-reconfigurable ability. It can be reconstituted into serial-like, circular, limb swimming and quadruped walking configurations according to the environmental characteristics and task requirements, as shown in Fig. 16. It can also be reconstituted into configurations for studying bionic propulsion mechanisms [94]. Each unit consists of two joint modules and a torso module. The motion of USS-G2 is generated by the active motion of the units and the interaction between the units, so its joints need to be active.

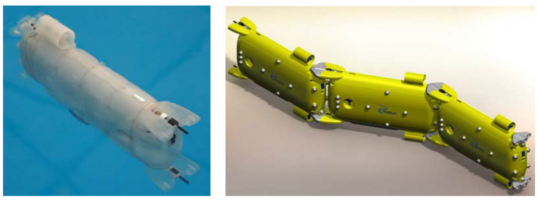
An underwater self-reconfigurable robot called the Angel was developed in 2012 by Mintchev *et al.* [95]; a unit and three units in series are shown in Fig. 17. It was developed with the support of the European project ANGELS (anguilliform robot with electric sense). Bioinspired electric sensors are equipped on it to realize the perception of the target. A long serial structure can increase the perception range of the Angel by electric field focusing. The Angel can swim like an eel, and its adjacent units are connected by active rotatable joints. Each unit consists of three distributed propellers and a



(a) Serial-like configuration (b) Circular configuration

(c) Limb swimming configuration (d) Quadruped walking configuration

FIGURE 16. Underwater self-reconfigurable robot USS-G2 with active joints.



(a) Single unit (b) Three units in series

FIGURE 17. Underwater self-reconfigurable robot Angel with active joints.

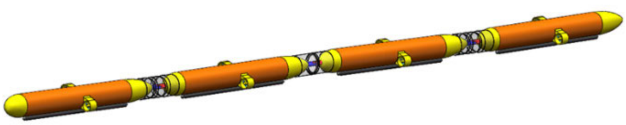


FIGURE 18. Underwater self-reconfigurable robot with passive joints.

docking system composed of a small permanent magnet and a mechanical structure. The weight, maximum working depth, and maximum forward velocity of the unit are 1.2 kg, 3 m, and 0.3 m/s, respectively.

b: UNDERWATER SELF-RECONFIGURABLE ROBOTS WITH PASSIVE JOINTS

A serial-structured underwater vehicle with distributed propulsion was designed by Kang *et al.* [96] in 2018, as shown in Fig. 18. It is a self-reconfigurable robot and consists of several AUVs in series. It can play an important role in underwater target detection. It can be reconfigured to a certain length to realize combined detection according to requirements for high-accuracy detection. It can also separate units to realize distributed detection according to requirements for wide-range detection. In addition, the serial-structured underwater vehicle can achieve efficient navigation because each unit obtains different resistance reduction effects during the propulsion process [97]. The motion of the serial-structured underwater vehicle is generated by propellers distributed along both sides of each unit. To reduce the difficulty of control and the complexity of the structure, passive joints are used between the units.

FIGURE 19. Wave-driven unmanned surface vehicle Wave-Glider.

c: HYDRODYNAMIC CHARACTERISTICS

The hydrodynamic characteristics of the self- reconfiguration process is similar to the process in which multiple single-body robots (units) are close to each other. It can be characterized as having no connection constraints and having a rapidly changing coupling relationship of the flow fields between units. There are significant nonlinearities of hydrodynamic characteristics that are varied with the parameters, such as the velocity, spacing and Reynolds number, during the process of multiple robots being close to each other. Therefore, it is difficult to analyze and predict resistance components.

An analysis of the hydrodynamic characteristics of an underwater self-reconfigurable robot typically uses a parameter sensitivity analysis based on the CFD method. Pan *et al.* [98], [99] analyzed the hydrodynamic interaction between units during underwater docking. The relationship between the hydrodynamic characteristics of an AUV and the distance from the AUV to the recovery device is obtained by the CFD method. Su *et al.* [100] analyzed the relationship between the resistance, lift and overturning moment of a microsized underwater vehicle and the relative velocity and spacing between units using the CFD method.

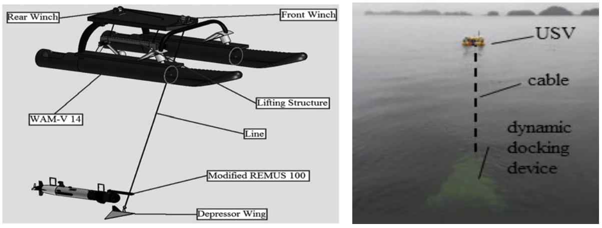
However, the CFD method is very time-consuming in simulating all the situations encountered during the reconfiguration process. To meet the needs of rapid prediction and precise control in the reconfiguration process, it is necessary to add further theoretical analysis to the original method.

C. CABLE CONNECTED MULTIBODY MARINE ROBOTS

The cable connected multibody marine robot is a robotic system where the adjacent units are connected by cables. The wave-driven unmanned surface vehicle (WUSV) and the robotic platform of a dynamic docking device towed by an unmanned surface vehicle (USV) are typical representatives. The cable can only limit the maximum distance between the units. The cable connected multibody robot can be regarded as multiple single-body robots at close range when the distance between units is nonmaximum.

1) WAVE-DRIVEN UNMANNED SURFACE VEHICLES

The WUSV is a multibody system, which consists of a surface floating body, a cable and an underwater gliding body [101].



(a) Developed by Sarda (b) Developed by Meng

FIGURE 20. Robotic platforms of a dynamic docking device towed by a USV.

It is widely used for the long-term observation of sea-air interfaces due to its excellent endurance.

The Wave-Glider [12] is a typical representative of a WUSV, as shown in Fig. 19. Its weight, speed range, average speed, maximum long-term observation time, and maximum movement distance are 75 kg, 1-3 knots, 1.5 knots (when the wave height is 0.4-1 m), more than one year, and 17371.76 km, respectively. It is equipped with solar panels with a peak power of 86 W and an average power of 5 W. It can also be equipped with matching sensors according to different application requirements. The surface floating body of the Wave-Glider is 2.1 m long and 0.6 m wide. The underwater gliding body (including 7 units) of the Wave-Glider is 0.4 m long and 1.9 m wide. The cable of the Wave-Glider is 7 m long.

2) ROBOTIC PLATFORMS OF A DYNAMIC DOCKING DEVICE TOWED BY A USV

The robotic platform of a dynamic docking device towed by a USV is a multibody system. It can complete the docking and recycling of AUV during navigation. It mainly consists of an upper part, a lower part and a cable. The upper part is a USV that operates on the surface, and the lower part is a docking device that operates under the surface. The two parts are connected by a cable.

Sarda and Dhanak [102] and Meng *et al.* [103] developed an AUV dynamic docking recovery device through the USV towing guide cover in 2017 and 2019, respectively, as shown in Fig. 20. Their recovery success rate is high due to their stability and reliability. The upper (including 2 units) and lower (including 2 units) parts in the platform, developed by Sarda *et al.*, are the WAM-V14 USV and the REMUS 100 AUV, respectively. The WAM-V14 USV is a catamaran. It is 1.25 m long, 2.13 m wide, 1.1 m high, and weighs 125 kg in air. The REMUS 100 AUV is 1.6 m long, 0.19 m in diameter, and weighs 38.5 kg in air. The USV of the platform developed by Meng *et al.* is also a catamaran. The underwater docking device in the platform developed by Meng *et al.* has two styles: a captured style and a guided style. The captured-style docking device is 0.95 m long, 1.02 m wide, 0.4 m high, and weighs 21.2 kg in air. The guided-style device is 1.47 m long, 1.04 m wide, 1.04 m high, and weighs 41.55 kg in air.

3) HYDRODYNAMIC CHARACTERISTICS

The hydrodynamic characteristics of the cable connected multibody marine robot with at least one unit operating on the surface need to take into account the effects of the waves [104], [105]. However, the effects of the waves are usually simplified, such as the waves being considered regular with a small amplitude.

The hydrodynamic characteristics of the cable connected multibody marine robot are usually analyzed by the maternal estimation method, the parameter identification method, and the CFD method. The CFD method is used to analyze the hydrodynamic characteristics of a wave glider by Yu *et al.* [106] and Chang *et al.* [107]. Some simplifications have been made in this method, such as considering the waves as regular and with small amplitude or only considering the resistance and lift components but neglecting the inertial component. The method of combining the maternal estimation method and the parameter identification method was proposed by Sarda and Dhanak [102] and Meng *et al.* [103] to analyze the hydrodynamic characteristics of the robot system of a dynamic docking device towed by a USV.

III. SUMMARY OF THE RESEARCH STATUS OF MULTIBODY MARINE ROBOTS

Multibody marine robots have received extensive attention and research due to their unique operating advantages in different application backgrounds. The current state of technology development of multibody marine robots has been introduced in detail above, which can provide important reference for researchers. It can be seen from the introduction that there are some commonalities and differences between different multibody marine robots. These commonalities and differences are helpful to summarize and review multibody marine robots.

Table 1 lists some features of typical multibody marine robots, including the topology, connection structure between units, relative motion between units, weight, number of units, propulsion mechanism, and function type. It can be seen from Table 1 that most of the multibody marine robots adopt the serial-like or the tree-like configuration because they meet the operational requirements in the simplest way. Second, most of the multibody marine robots adopt the joint connection structure between units rather than the rigid rod connection structure or the cable connection structure. The reasons are as follows. (1) The joint connection structure can provide 1-2 DOFs, and its control technology is relatively mature. In addition, a robot with this structure has more application requirements. (2) The rigid rod connection structure does not generate relative motion between units and is relatively easy to control. However, this kind of platform is suitable for operational tasks with high requirements on the stability of multibody marine robots, but at present, such operational requirements are relatively rare. (3) The cable connection structure can only limit the maximum distance between units,

TABLE 1. The features of typical multibody marine robots.

Platform type	Multibody marine robot	Topology	Connection structure between units	Relative motion between units	Weight (kg)	Number of units	Propulsion mechanism	Function type
Multibody observation AUV	Observation AUV with increased stability and maneuverability	Tree-like	Rigid rod	None	$10^{1\sim2}$	2～3	Propeller	Observation
	Observation AUV for special functional requirements							
	AUV for increasing functional scalability							
Underwater manipulator	Underwater manipulators with a stable base	Serial-like	Joint	Active	$10^{1\sim2}$	2～7	Propeller	Operation
	Underwater manipulators without a stable base							
Marine snake-like robot	Marine snake-like robots with two-dimensional motion ability	Serial-like	Joint	Active	10^{1}	5～20	Swimming / Propeller	Observation / Operation / Study
	Marine snake-like robots with three-dimensional motion ability							
	Marine snake-like robots with enhanced motion and operation ability							
Robotic fish	Robotic fish with the BCF propulsion mode	Serial-like	Joint	Active	$10^{0\sim1}$	2～8	Swimming	Observation / Study
	Robotic fish with the MPF propulsion mode	Tree-like					Swimming	
	Robotic fishes with combined propulsion mode	Tree-like					Swimming / Propeller	
Multilegged marine bionic robot	Bionic sea crab robots	Tree-like	Joint	Active	$10^{0\sim1}$	3～9	Swimming / Propeller / Crawling	Observation / Operation
	Bionic octopus robots						Swimming	Study
Underwater self-reconfigurable robot	The underwater self-reconfigurable robot with active joints	According to configuration	Joint	Active	$10^{0\sim1}$	2～9	Swimming / Propeller	Observation / Operation / Study
	The underwater self-reconfigurable robot with passive joints	Serial-like	Joint	Passive	10^{1}	2～5	Propeller	Observation
Wave glider		Hybrid	Cable	Passive	10^{1}	3～8	Wave force component	Observation / Energy collection
Dynamic docking device towed by a USV		Hybrid	Cable	Passive	10^{2}	4	Propeller	Docking recovery

and it is difficult to control. In addition, the robot with this structure is mostly used for cross-domain tasks. In addition, environmental observation is a basic function of multibody marine robots, and multibody marine robots with both environmental observation and operational abilities are becoming more popular.

Table 2 lists the hydrodynamic characteristics of typical multibody marine robots, including the object, researchers/teams, terms considered, and analysis method. It can be seen from Table 2 that the maternal estimation method, CFD method and the parameter identification method are typically used to analyze the hydrodynamic characteristics. In addition, multiple methods can be used in combination with each other for better analysis.

IV. FUTURE DEVELOPMENT TREND OF MULTIBODY MARINE ROBOTS

A. ROBOTIC STRUCTURE IS DEVELOPING TOWARDS DIVERSIFICATION AND SPECIALIZATION

The ever-increasing special requirements for a certain operational ability place higher demands on the structure of multibody marine robots. The 30 multibody marine robots archived by AUVAC can be divided into 7 structures, and the structural diversity of the archive is gradually increasing. Sometimes, in order to complete the task better, it is necessary to add other function modules that generate motion to the original multibody robot. Taking marine snake-shaped robots as an example, hybrid propulsion (swimming and the propeller) can be achieved by adding propeller function modules to

TABLE 2. The hydrodynamic characteristics of typical multibody marine robots.

Platform type	Object	Researchers	Terms considered	Analysis method
Multibody observation AUV	TriMARES AUV	Ferreira[20, 21]	Inertia terms + Viscous terms	Maternal estimation method / Parameter identification method
Underwater manipulator	Manipulator with circular cross section in UVMS	Mclain[41] / Zhang[32]	Inertia terms + Viscous terms	Maternal estimation method/ Parameter identification method
Robotic fish	long and narrow animals	Taylor[64]	Viscous terms	Resistance hydrodynamic model
	Carangiform	Lighthill[61-63]	Viscous terms	Large amplitude slender body theory
	Flat ciliate tail fish	Wu[81]	Viscous terms	Two-dimensional wave plate theory
	Labriform locomotion	Blake[86]	Viscous terms	Maternal estimation method / Blade-element approach
	The three-linkage robotic fish	Eldredge[82, 83]	Inertia terms + Viscous terms	A method for calculating dynamic coupled fluid interaction based on viscous vortex particle method
		Li[84]	Inertia terms + Viscous terms	A numerical simulation method based on multibody dynamics
Marine snake-like robot	Marine snake-like robot	Khalil[56] / Kelasidi[57] / Pettersen[11] / Zhang[51-53]	Inertia terms(including the Coriolis force of the additional mass) + Viscous terms	Maternal estimation method / Parameter identification method
	AmphiBot III marine snake-like robot	Porez[60]	Inertia terms + Viscous terms	Large amplitude slender body theory / resistance hydrodynamic model
Multilegged marine biological robot	Two-legged octopus imitating robot	Kazakidi[89]	Viscous terms	CFD method
	Four-legged soft underwater bionic robot	Renda[91]	Inertia terms + Viscous terms	Large amplitude slender body theory / Parameter identification method
Underwater self-reconfigurable robot	AUV docking process	Pan[98, 99]	Viscous terms	Maternal estimation method / CFD method
	The process of a small underwater robot near a large underwater robot or structure	Su[100] / Leong[108-110]	Viscous terms	Maternal estimation method / CFD method
Wave glider		Chen[101]	Inertia terms + Viscous terms	Maternal estimation method
Dynamic docking device towed by a USV		Sarda[102] / Meng[103]	Inertia terms + Viscous terms	Maternal estimation method/ Parameter identification method

meet the task requirements of high motion speed and limited motion attitude. The added propeller function modules not only increase the maneuverability of the marine snake-like robot but also increase its diversity. In addition, the structure of most multibody robots currently adopts a design concept where a robot can perform a variety of task types or satisfy multiple task indicators. In the future, there will be more tasks with higher operation difficulty and higher operation quality. The most simplified and specialized structure for robots to complete such tasks will be a development trend. Therefore, diversification and specialization are the future development trends of multibody marine robot structures.

B. THE STRUCTURE OF EACH UNIT IS DEVELOPING TOWARDS RECONFIGURABILITY

Large single-body AUVs not only require high research, development, and maintenance costs, but their complex workflows require more people to participate in the operation. In addition, small and medium-sized single-body AUVs have limited energy and limited functionality due to their volume limitations. Assigning reconfigurable abilities to small and medium-sized single-body AUVs will be a potential solution to the current situation. According to the statistical data of 42 multibody AUVs introduced in this paper, the typical platforms (the reconfigurable underwater robot [19], TriMARES [20], [21], Girona [33], [34], ROBUST [35], [36], Angel [95], USS-G2 [92], [93], and the serial-structured underwater vehicle [96]) with reconfigurable ability account for approximately 16.7%. Due to the limitation of maneuverability, a single-body AUV capable of performing general ocean observation tasks has difficulty meeting the mapping requirements of complex seabed terrain. However, multiple single-body AUVs with reconfigurable abilities can be reorganized into a multibody robot with good maneuverability, which not only meets the mapping requirements but also has the advantages of energy sharing. Therefore, the reconfigurability of units is the future development trend of the multibody AUV structure.

C. THE MOTION MODELING OF BIONIC ROBOTS IS DEVELOPING TOWARDS MECHANISM PERFECTION

The motion mechanism of the marine animal is the basis for building hydrodynamic models of corresponding bionic robots. The realization of fish movement in water is generally considered to be the result of vortex control. However, a relatively perfect and effectively controllable model has yet to be built. It is necessary to explore the interaction mechanism and energy consumption mechanism between the body deformation and flow response for a perfect modeling. In addition, the effect of the generated vortex on the rapid start-up and direction change also needs to be considered in motion mechanism modeling. Exploring the perfect modeling of motion mechanism to achieve efficient and highly maneuverable motion will accelerate the application of bionic multibody marine robots [65].

D. THE HYDRODYNAMIC MODEL IS DEVELOPING TOWARDS ACCURACY

The research on the hydrodynamic characteristics of multibody robots is mainly divided into analysis methods and numerical simulation methods. In the early stages, the research results have mainly focused on the theoretical analysis method, which is modified base on the N-S equations according to the object. An approximate analytical solution can be obtained by this method. Most of these results are based on assumptions that make it only applicable to specified situations and have significant errors. With the development of computer technology, numerical simulation methods are gradually being applied to the study of hydrodynamic characteristics. This method is also based on the N-S equations, but there is no modification process. It usually reduces the error by thousands of iterations to approximate an exact solution. Although this method cannot obtain an analytical solution due to the computational discretization, the results obtained are more accurate and can present rich flow field details. Numerical simulation methods based on an analytical model can be more targeted and accurate because the approximate analytical solution model can reduce the initial error of the numerical simulation. Therefore, a more accurate hydrodynamic model can be obtained by combining the two methods. Improving model accuracy through a combination method is the future development trend of hydrodynamic characteristics research of multibody marine robots.

V. CONCLUSION

In this paper, the types, features, and hydrodynamic characteristics of multibody marine robots have been reviewed. A classification method that can better reflect the difference of interaction between units and better analyze the difference of hydrodynamic characteristics was proposed. The topology, connection structure between units, relative motion between units, number of units, propulsion mechanism, and function type of different multibody marine robots were summarized and compared. The hydrodynamic characteristics and analysis methods of different multibody marine robots were summarized. Finally, the development trends were presented. Among the robots introduced above, the multibody marine robot with self-reconfigurable abilities has advantages in transportation economy, simplification of deployment and recycling, environmental adaptability, and work efficiency. It will play an important role in the future. However, there is an urgent need to solve the technical challenges brought by the complex underwater environment to the docking of two units. At the same time, the specialization of the overall structure, the simplification of the unit structure, the easy analysis of the coupled flow field, and the simplification of the control can significantly improve the operating ability of the multibody marine robot. The authors recommend that these features be considered in the design of new multibody marine robots.

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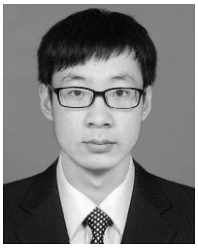

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