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Editorial
Frontiers in Deep-Sea Equipment and Technology

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1. Introduction

The conflict between population, resources, and environment in the twenty-first century made the ocean the strategic space and resource treasure of human society to realize sustainable development. In order to study the ocean environment and exploit the ocean's resources, a fundamental understanding of complex and interwoven ocean processes across a broad range of spatial and temporal observational scales is required. This is heavily relied on in various research fleet and equipment to support increasingly complex, multidisciplinary, multi-investigator research projects, including those in support of autonomous technologies, ocean observing systems, process studies, remote sensing, and modeling [1]. Various underwater submersibles such as the human occupied vehicle (HOV), remotely operated vehicle (ROV), autonomous underwater vehicle (AUV), hybrid autonomous and remotely-operated vehicle (HROV or ARV) and glider are the main working force for the research fleet and, of course, some cheap means such as the profiler and lander are also useful for deep sea research.

However, the development of deep-sea equipment involves great technological challenges; for example, how to solve the conflict between economic performance and safety requirement and in order to ensure the safety, we need to solve how to predict the future environmental loads, how to calculate the responses considering the nonlinearities of material and environments, how to predict the failure under unknown loading process, how to assess the consequence of human behavior on the system safety in the whole process of design, manufacture, operation, and decommission [2].

In response to the promotion of the deep sea technology development and to better meet the requirements for a sustainable society, the Journal of Marine Science and Technology (JMSE) launched a Special Issue on this topic and three of us, i.e., the authors, were invited to be its guest editors. Based on a combination of specific invitations to potential authors from us and free submissions from the authors, many submissions were received. Following the same reviewing process established by JMSE, 30 papers were finally published within the time period for this Special Issue. We are very grateful to all authors who made contributions to the success of this Special Issue and also pleased to know that JMSE intends to publish all these papers in a book for further promotion.

The purpose of this Editorial was to briefly introduce all these papers and, based on a superficial analysis, they were grouped into six categories: ROV and its variants, AUVs for multiple cooperation, glider and other specific equipment, pressure resisting hull, component technology, and robotic fish. In Ref. [3], the submersible technology was divided into three generations according to the main materials and their fabrication technology. The first generation was a fully manned submersible. This generation of submersibles used steel manned cabin and mainly relied on aviation gasoline to provide buoyancy. The submersible

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was very heavy and had almost no self-propulsion capability. The second generation submersibles used solid buoyancy materials to provide buoyancy, and used ultra-high strength steel or light-weight aluminum alloy or titanium alloy as pressure hulls; thus, the miniaturization of the submersible and its self-navigation ability was greatly improved. The development process of the second generation submersibles was from the miniaturization of manned submersibles to unmanned remotely operated submersibles, to unmanned autonomous submersibles, and to hybrid unmanned submersibles [1]. The intelligent bionic robot fish-type submersible was defined as the third-generation submersible [3]. Its characteristics were to replace solid metal and buoyancy materials with flexible and large deformation soft materials, replace traditional welding and forging technology with manufacturing technology based on 3D printing, replace traditional control technology with artificial intelligence technology, and replace traditional sensors with sensors designed and manufactured based on nanotechnology. Using this criterion, it was clear that while all the first five topics belonged to the second-generation submersibles, while robotic fish belonged to the third generation. In the following sections, each topic is discussed in the context of the papers that were published in this Special Issue.

2. ROV and Its Variants

In order to overcome the limitations of the risk to human beings and short time of the battery, the remotely operated vehicle (ROV) was developed since 1970s and now, people mainly focus on some specific types of ROV or specific technologies.

With the increasingly exhausted exploitation of land resources, the interest in deep-sea mining grew substantially in the last few decades for seafloor massive sulfides (SMSs) near hydrothermal vents, poly-metallic nodules on the deep sea floor, and cobalt-rich crusts on sea mounts. Xie et al. proposed a compact design of the subsea cobalt-rich crust mining vehicle with a general purpose support vessel for subsea resource exploration, sample collection, and research [4]. The prototype was tested in both tank and subsea environment and they showed that the main intended functions, such as walk, crushing, and collection, worked well in sea trials.

To better study the biology and ecology of hadal trenches for marine scientists, full-ocean-depth (FOD) manned/unmanned submersibles and FOD landers were required to obtain samples in the hadal trenches. In this paper, a novel three-body prototype design and sea trial of an 11,000 m autonomous and remotely operated vehicle “dream chaser” is presented [5]. A detailed illustration of the whole system design method is provided and the procedures and results of lake trials, South China Sea trials, and the first phase of Mariana Trench sea trials of the ARV in 2020 are also introduced. The ARV could work in both remotely-operated and autonomous-operated modes, and served large-range underwater observation, on-site sampling, surveying, mapping, etc.

In the application scenarios of underwater robots, such as search and rescue, monitoring and surveillance, petroleum exploration, deep-sea archaeological research, ship hull maintenance, they were often required to track the targets in a fast and accurate manner. In order to achieve robustness to uncertainties and external disturbances, realize finite-time convergence, attenuate chattering, and obtain the tracking error’s prescribed performance simultaneously, Guo et al. proposed a neural network-based nonsingular terminal sliding mode controller with prescribed performances for the target tracking problem of under-actuated underwater robots. Through simulation comparison with other methods, the controller proposed in this paper had better dynamic performance, steady-state performance, and chattering suppression. In particular, the steady-state error of the tracking error was lower, and the convergence time of the tracking error in the vertical distance was reduced by 19.1% [6].

3. AUVs and Its Multiple Cooperation

ROV is very effective in providing long time for underwater operation and avoiding the risk for human diving; however, its maneuverability is greatly limited due to its umbilical cable. Autonomous underwater vehicles (AUVs) are unmanned underwater robots with strong maneuverability to carry out diverse oceanographic missions autonomously, such as geological exploration, oil spill detection, bathymetry, and thermocline tracking [1]. This concept was first proposed in 1957 and now, its technology is more or less matured for practical purpose. So, it was developed towards a specific purpose and multiple cooperation for application.

In recent years, hybrid unmanned aerial underwater vehicles (HAUVs), which are capable of air–water trans-media motion, received an increasing amount of attention. Wei et al. presented the first study on the kinematic stability of the air–water trans–media motion of HAUVs [7]. A new air–water trans–media kinematic stability criterion for HAUVs was proposed and, for example, the authors showed that the proposed criterion was effective in judging the vehicle's design, including the geometry and thruster power, which are important factors in the performance of the trans–media process.

The distance, accuracy, and reliability of acoustic detection are greatly affected by the complexity of the underwater environment. A single AUV independent detection operation can no longer meet the current demand. Therefore, a multi-AUV cooperative system was produced, which showed outstanding advantages such as low cost, high efficiency, fault tolerance, and reconfigurability. To reduce the cooperative positioning error and improve the navigation accuracy, Ren et al. proposed a single master–slave AUV cooperative navigation method, which mainly focused on planning the optimal path of the master AUV by the time difference (TD) method, under the premise that the path of the slave AUV was planned [8]. Their results showed that the theoretical positioning error of the slave AUV can be controlled to about 3.2 m by planning the path of the master AUV using the TD method. This method can not only reduce the observation error and positioning error of the slave AUV during the whole cooperative navigation process, but also keep the relative measurement distance between the master AUV and the slave AUV within an appropriate range.

As ocean exploration advances, new tasks demand more stringent requirements for the cooperative operation of multiple types of submersibles. Yang et al. proposed three cooperative operational modes of manned and unmanned submersibles for a range of different deep-sea application scenarios [9]. These were pure research vessel R/V-based mode, unmanned surface vehicle-based mode, and lander-based mode. Through a comparison, they found that the time required to complete the same task was only one-third of the traditional operational mode. The cooperative operational mode improved the overall operational efficiency of scientific research work. If sea conditions permit, the cooperative operation mode based on a USV is the most suitable for underwater target detection tasks.

4. Glider and Other Specific Equipment

An underwater glider is a type of autonomous underwater vehicle (AUV) that employs variable-buoyancy propulsion instead of traditional propellers or thrusters. It employs variable buoyancy in a similar way to a profiling float, but unlike a float, which can move only up and down, an underwater glider is fitted with hydrofoils (underwater wings) that allow it to glide forward while descending through the water. At a certain depth, the glider switches to positive buoyancy to climb back up and forward, and the cycle is then repeated [1]. The sailing efficiency of an underwater glider directly affects its range and duration. The zero-angle-of-attack gliding can be achieved by adjusting the wing installation angle to minimize the drag and improve the sailing efficiency, thus improving the performance of the glider further. Tian et al. presented a study on the dynamic characteristics of a hybrid-driven underwater glider with a certain wing installation angle when it sailed at zero angle of attack in buoyancy-driven mode and hybrid-driven mode [10]. Their main focuses were on how to realize zero-angle-of-attack gliding with different driving modes, how to determine the appropriate wing installation angle to obtain a higher sailing efficiency, whether the introduction of a propulsion system will cause a reduction in economy, and how to compare the sailing efficiency of a zero-angle-of-attack glider with that of a traditional glider. Their theoretical analysis showed that the sailing efficiency of a zero-angle-of-attack glider can be higher than that of a traditional glider. Considering the requirements of different measurement tasks, a higher sailing efficiency can be achieved by setting reasonable parameters and selecting the appropriate driving mode.

In order to achieve a better motion performance, Li et al. proposed a command-filtered adaptive algorithm with a detailed system dynamic model for underwater gliders [11]. The stability of the whole system was proved through the Lyapunov theory. Comparative simulations were conducted to verify the effectiveness of the proposed controller. The results demonstrated that the proposed algorithm improved the motion control performance for underwater gliders under uncertainties and disturbances.

A profiler driven by ocean thermal energy can monitor the vertical profile of the surrounding sea area for a long time. To realize the levitation at a fixed water depth on the premise of saving energy, Xia et al. designed a new buoyancy regulation system driven by the mixture of ocean thermal energy and electric energy and a new depth control strategy for the hybrid drive [12]. Compared with the traditional profiler, the new profiler, in which the main energy required for buoyancy regulation was provided by ocean thermal energy, can reduce electrical energy consumption. Simulations of SMC (sliding mode control) and conventional PID control showed that the SMC method had advantages in terms of response speed, overshoot, and energy saving.

Sun et al. proposed a deep-sea landing vehicle (DSLV) system, in which crawler chassis and conventional underwater robots were combined [13]. DSLV consists of four major subsystems, namely chassis drive and crawling systems; energy and electronic systems; location and recovery systems; and scientific payload and communication systems. The system can complete the sites-series movement detection over a large area and the time-series precise investigation in a local area with high reliability and strong expansibility to adapt to a complex seafloor. The most challenging issue for DSLV is the method to accurately model its motion mechanism. The support vector regression (SVR) model optimized through particle swarm optimization (PSO) was used to complete the black-box motion modelling and vehicle prediction. The effectiveness of the method was verified through multi-body dynamics simulation and scaled test prototype data. Their experimental results confirmed that the proposed PSO–SVR model could establish an accurate motion model of the vehicle, and provided a high-precision motion state prediction.

5. Pressure Resisting Hull

The pressure-resisting hull is one of the most weight critical component for manned and unmanned submersibles and its weight reduction through the selection of new materials and improved the fabrication process is an eternal theme. The use of light weight composite material and ceramics as pressure hulls in addition to traditional high strength steel, aluminum and titanium alloys is a new trend. In applying composite materials to pressure resisting hulls in underwater vehicles to withstand hydrostatic pressure, the prevention of buckling failure mode for thin-walled composite cylindrical shells is the main concern of the designers. Shen et al. proposed an analytical solution for the buckling of a composite cylindrical shell subjected to hydrostatic pressure [14]. A finite element analysis and external hydrostatic pressure test were conducted to verify the proposed approach. The efficiency and accuracy of the analytical solution in predicting the critical buckling pressure and buckling mode were demonstrated. The same group continued to study the buckling and post-buckling behavior of perfect and perforated composite cylindrical shells subjected to external hydrostatic pressure [15]. Three filament wound composite cylindrical shells were fabricated from T700-12K Carbon fiber/Epoxy, two of which were perforated and reinforced. Comparative analysis was carried out based on the experimental observation and finite element prediction. Their results showed that the deformation of composite cylindrical shell under hydrostatic pressure included linear compression, buckling, and post-buckling processes. The buckling behavior was a progressive evolution process which accounted for 20% of the load history, and strain reversal phenomenon generally occurred at the trough of the buckling wave. As for the post-buckling deformation, the load carrying capacity of the shell gradually decreased while the magnitude of strain continued to increase. Both the perfect and perforated composite cylindrical shells collapsed at the trough of the buckling wave. Compared with the perfect shell, it was validated that the reinforcement design could effectively ensure the load-carrying capacity of the perforated composite cylindrical shell.

One of the weak points of using composite materials as pressure resisting hulls is its larger variation and uncertainty in manufacturing quality. Uncertainties in geometrical dimensions and mechanical properties propagate to the structural performance of composite cylindrical shells under hydrostatic pressure. Chen et al., from the same group, investigated the effect of this uncertainty on the critical buckling pressure of a composite cylindrical shell by means of sparse polynomial chaos expansion (PCE) [16]. With limited design samples, sparse PCE was built and validated for predictive accuracy. They found that the mean and standard deviation of critical buckling pressure were 3.5777 MPa and 0.3149 MPa, with a coefficient of variation of 8.801%. Global sensitivity analysis results from Sobol′ indices and the Morris method showed that the uncertainty of longitudinal modulus had a significant influence on the critical buckling pressure of composite cylindrical shell, whereas the uncertainties of transverse modulus, shear modulus, Poisson's ratio, ply thickness, and orientation angle had an insignificant influence. The study showed that the sparse PCE was effective at resolving the problem of high-dimensional uncertainty quantification of composite cylindrical shell with geometrical and material uncertainty.

Lightweight, high-strength pressure hulls are essential requirements for FOD submersibles. Due to their extremely high specific modulus and specific compressive strength compared to traditional metal materials, engineering ceramics are of increasing interest. Moreover, not only are pressure housings made of corrosion-resistant ceramics, but they also have no magnetic shielding. This means that engineering ceramics are excellent materials for fabricating pressure housings for FOD submersibles. However, due to the low tensile strength of most ceramic materials, the tensile stress generated at the contact surface of ceramic pressure housings under hydrostatic pressure may exceed the material's limits and, thus, lead to cracking failure. Currently, there are no valid calibration methods for the tensile stress caused by material discontinuities at the contact surface. Wang et al. proposed an approximate model based on contact mechanics [17]. The absolute error of the approximate model, as verified by the simulation results for nine groups of ceramic pressure housings, did not exceed 14.2%. They also concluded that the smaller the difference in Young's modulus between the ceramics and metals, the higher the tensile strength safety factor.

6. Component Technologies

In addition to the pressure resisting hulls, several papers were received with regard to the specific component technologies and they are grouped in this subsection.

Deep-sea rapid salvage is always needed in practice and its capability and efficiency greatly depends on the manipulator. Nan et al. proposed a concept prototype of the arm-claw-type manipulator with a general purpose support vessel for the rapid salvage of deep submergence vehicles, aircraft, satellites, etc. [18]. The key functions were realized, including object clamping, claw butting and locking, position and posture adjustment, awareness, positioning, and navigation. The prototype was successfully tested in a lake environment on a hollow and cylindrical object. The arm-claw-type manipulator is suitable for the rapid salvage of cylindrical objects in an underwater environment to minimize the clamping force and possible clamping damage on the object being salvaged.

A pump-jet propulsor (PJP) differs from the traditional propeller which can afford high propulsion efficiency and high speeds. In this paper, the cavitation performance over the pump-jet propulsor was investigated by Qiu et al. [19]. A hybrid deep learning model CNN-Bi-LSTM to quickly and accurately predict the bearing force of a pump-jet propulsor (PJP) was proposed, which will solve the problem of time-consuming calculations and the consumption of considerable computing resources in traditional computational fluid dynamics. The shear–stress–transport model and Reynolds-averaged Navier–Stokes equations were utilized to procure the training and testing datasets. The results showed that the propulsion efficiency decreased more obviously under higher rotating speed conditions, with a maximum decrease of up to 13.59%. The small cavitation numbers and high oblique angle significantly impacted the efficiency reduction; the maximum efficiency loss exceeded 20%.

The pump system was widely used in ocean engineering, such as ship sewage, cooling water supply, port dredging, and deep-sea water transfer, etc. The shaft tubular pump system is one of the more widely used forms of bidirectional pumping station, which can meet many engineering needs, e.g., water transmission in the deep sea. In order to study the characteristics of a bidirectional shaft tubular pump with S-type symmetric airfoil blades, a prototype model was designed, manufactured, and tested by Chen et al. [20]. Based on the basic equations of the pump and the inlet and outlet velocity triangles, combined with model tests and numerical simulations, the hydraulic performance of the pump was extensively analyzed and evaluated. Semi-empirical equations for reverse efficiency and runaway characteristics were proposed. The results revealed that the efficiency of the pump in reverse operation was greater than that of forward operation only under a very small flow rate. While the cavitation performance of the bidirectional pump in the two operating modes was almost the same, the runaway speed and backflow rate in forward operation were considerably greater than those of reverse operation. The results provided an important reference for the safe and stable operation of bidirectional shaft tubular pumps.

Subsea oil and gas pipelines are formed by connecting a large number of pipes and equipment and, thus, connectors play a critical role in subsea oil and gas pipelines. The subsea retractable connector is the latest product for the connection of subsea production facility. The core sealing component of the subsea retractable connector is the rubber packer, whose sealing performance is relatively poor. In order to improve the sealing performance of the rubber packer, an optimal study was carried out by Jiao et al. to investigate the structure of the rubber packer [21], by considering the influence of the variations of structural parameters of the rubber packer on the sealing performance. Hydrostatic pressure tests to compare the sealing performance of the rubber packer before and after optimization were conducted. Their results showed that the pipe pressure that can be sealed by the optimized rubber packer structure was 25.61% higher than that before optimization. The anti-shoulder extrusion variable and the asymmetric cross-sectional shape of the rubber packer proposed by the authors shed new light on the finite element simulation of rubber and the research on similar seals.

A deep-water bolt flange automatic connection tool plays a very important role in the process of offshore oil exploitation and transportation. In the connection process, the alignment error of bolts and nuts is the key factor to ensure the connection process is successful. In this paper, Wang et al. proposed an alignment error model of the deep-water bolt flange automatic connection tool to analyze the influence of manufacturing accuracy on the alignment error of bolts and nuts [22]. Based on the error matching design method, the manufacturing accuracy of parts were optimized with a part-size-based priority sequence to ensure the bolt–nut alignment error within the allowable limits. The land tests, pool tests, and sea tests were carried out, and the test results showed that the bolt and nut can be connected in the subsea environment reliably.

Underwater oil and gas pipelines are prone to alignment differences and angle offsets during docking, and the spherical flange connector can address this problem. Its main function is to enable compensation of the different angles of the pipeline during docking and to apply a non-standard spherical sealing structure using O-rings to the connection. In this paper, the study of a spherical sealing structure using O-rings was carried out by Liu et al. [23]. The structure of the non-standard spherical sealing groove was designed with reference to the standard sealing groove. To determine a more reasonable compression ratio in the sealing structure, the effects of different pressures and compression ratios on the O-ring sealing performance were investigated in terms of von Mises stress, contact pressure, and contact width of different contact surfaces. The theoretical analysis of the non-standard spherical sealing structure using O-rings was validated by testing, and it was proven that it could maintain a good seal under high pressure.

7. Robotic Fish

Compared with traditional underwater vehicles, bio-inspired robotic fish typed submersibles have the advantages of high efficiency, high maneuverability, low noise, and minor fluid disturbance and, thus, they will be the next generation of submersibles. In this Special Issue, 10 papers were accepted, which truly reflects the technology development trend. Sun et al. carried out a comprehensive survey on the modeling and control of bio-inspired fish robots [24]. Their focus was specifically devoted on two aspects of the problem: (1) how to identify and extract the extraordinary characteristics of fish, in order to establish effective physics models and explore the mechanisms and (2) how to imitate the structure and control characteristics of fish in engineering design, and manufacture robot fish with high-performance parameters. They first highlighted their enhanced scientific understanding of bio-inspired propulsion and sensing underwater and then, presented the research progress and performance characteristics of different bio-inspired robot fish, classified by the propulsion method. Finally, the advantages and challenges of soft robotic control and multi-phase robotics were highlighted based on their review analysis.

Unlike propeller-based robots of ROVs and AUVs, biomimetic robots have a variety of actuation methods, such as fluid actuation, smart material actuation (including shape memory alloy (SMA), electroactive polymer (EAP), piezoelectric materials (PZT)), chemical reaction actuation, biological hybrid actuation, magnetic field actuation, and a combination of these methods. A literature review of the locomotion mode, actuation method, and typical works on fluid-driven bionic aquatic robots was carried out by Bu et al. [25]. The actuator and structural material selection were discussed, followed by research directions and application prospects of fluid-driven bionic aquatic robots.

A novel vehicle that combines a gliding and flapping propulsion inspired by a manta ray was developed by Zhang et al. [26]. Its integrated maneuverable flapping propulsion was realized by two bionic flexible pectoral fins and long-range efficient gliding propulsion, which was based on a buoyancy adjustment system and a mass-adjustment system. The gliding propulsion capability and the flapping propulsion performance were verified through gliding and swimming experiments. They concluded that the designed bionic manta robot provided a platform with practical application capabilities in marine environment detection, concealed reconnaissance, and aquaculture.

Currently, most of the robotic fish work in shallow water environments and are built with purely rigid structures. This will limit the mobility and practical usability of robotic fish. Inspired by the stability of the real manta ray, a manta ray robot design with soft-material-made flapping wing based on an open-source ROV (remotely operated vehicle) was proposed by Liu et al [27]. The flapping wing structure with three different materials mimicked the wide pectoral fins of real manta rays, which have bones, muscles, and skin. Furthermore, its modular design made it easy to install and disassemble. The kinematic and hydrodynamic analysis of the manta ray robot were simulated in their paper. The actual manta ray robot was fabricated and several sets of test were performed in the pool. The robot can swim forward continually and stably with a simple rolling and pitching pattern.

To better exploit the characteristics of the bionic manta ray robot, a similarity evaluation rule was constructed by Cao et al. by a dynamic time warping (DTW) algorithm to guide the optimization of the control parameters [28]. The central pattern generator (CPG) network with time and space asymmetry oscillation characteristics was improved to generate coordinated motion control signals for the robot. To optimize similarity, the CPG network was optimized with the genetic algorithm and particle swarm optimization (GAPSO) to solve the problems of multiple parameters, high non-linearity, and uncertain parameter coupling in the CPG network. The experimental results indicated that the similarity between the forward motion pose of the optimized manta ray robot and the manta ray was improved to 88.53%.

In order to realize the motion control of robotic manta with pectoral fin flexible deformation, Cao et al. proposed a control scheme that combines the bioinspired central pattern generator (CPG) and T-S fuzzy neural network (NN)-based control [29]. Considering the unknown dynamics and the external environmental disturbances, a sensor-based classic T-S fuzzy NN controller was designed for heading and depth control. Finally, a pool test demonstrated the effectiveness and robustness of the proposed controller: the robotic manta can track the depth and heading with an error of ±6 cm and ±6°, satisfying accuracy requirements.

Oscillating pectoral fins' spanwise flexibility is a key factor influencing the forwarding propulsion performance of bionic cownose rays, including thrust and heave-pitch stability. In order to investigate the effects of the bionic pectoral fin ray's spanwise flexibility on its propulsion performance, an experimental study was carried out by He et al. [30]. The movement parameters included the following: the flapping frequency of 0.3–0.7 Hz, the flapping amplitude of 20–40°, and the phase difference of 20–40°. The experimental results showed that the stiffness of the bionic pectoral fin rays played an important role in the thrust, lift force, and pitch moment. The fin rays with high stiffness root segment and low stiffness tip segment had lower lift and pitch moment while maintaining a high thrust. This shows that the pectoral fins' flexible characteristics of the cownose ray were of great significance to the design of the bionic prototype.

In order to confirm the speculation that pectoral fins with varying spanwise and chordwise stiffness produce specific biological propulsion effects, Lu et al. compared the effects of spanwise and chordwise stiffness on thrust performance [31]. A simplified bionic pectoral fin named cross-joints fin (CJF) was first fabricated. This novel fin structure had five types of cross-joint widths that varied in the spanwise and chordwise directions. Their experimental results indicated that the magnitude of spanwise stiffness should be considered when designing the bionic oscillating pectoral fin structure.

Xing et al. proposed a novel bionic pectoral fin and experimentally studied the effects of the oscillation parameters on the hydrodynamic performance of a bionic experimental prototype [32]. The active spatial motion was realized by the space six-link mechanism driven by two motors, and the passive deformation was achieved by carbon fiber. The motion analysis of the bionic pectoral fin proved that the pectoral fin can realize an "8"-shaped spatial trajectory. An experimental prototype was developed accordingly. The experimental results indicated that the hydrodynamic performance of the pectoral fin oscillation is closely related to the motion equation parameters including the amplitude, frequency, phase difference, and initial bias. Their results shed light on the updated design and control of a bionic robot fish.

By considering that few comparative studies were conducted on the performance of different fin types, Chen et al. presented a modularized robot fish with high-fidelity biomimetic pectoral fins and novel multi-DOF propelling mechanism [33]. Through experiments comparing the performance of different fin types constructed with different materials and approaches, they found that the new soft fins made of silicon rubber showed better performance than traditional fins constructed with a flexible inner skeleton and a permeable outer skin as a result of better 3D profile preservation and hydrodynamic force interaction. The robot ray prototype also acquired a better combination of high speed and maneuverability compared to results of their previous researches.

8. Conclusions

In order to exploit the ocean resources, a fleet of various deep sea equipment to support increasingly complex, multidisciplinary, multi-investigator research projects is necessary. The development of each piece of equipment involves many technology challenges due to its extreme environmental conditions. Thus, deep sea equipment represents the frontier technology in the deep sea field. This Special Issue is timely in reporting the latest progress in this field, and we hope that the publication of the whole issue as a book could further promote the development of deep sea technology.

However, by reviewing the papers published, we feel that some regrets still exist. First, we did not receive any papers exploring HOV, although, in recent years, the full ocean depth manned submersibles "limiting factor" and "Fendouzhe" were successfully developed and put into service. FOD HOV represents the real frontier of the second generation submersible technology. Second, the papers were too heavily received from several research groups. However, a wider distribution of authors internationally would have been ideal. Third, most of the papers focused on the concrete detailed technical problems and few questioned the validity of current theory. For example, the majority of authors publishing robotic fish papers in this issue believed that bionic propulsion had advantages over traditional blade propellers in efficiency. However, when the critical question was asked (what is the actual swimming efficiency for a real living fish?), we found that the calculation method was not available. Our current understanding to life is still very limited. By experience, we know that two persons will consume very different food in doing the same work. This indicates that the efficiencies for different living creatures are quite different from each other; this is the same case for the fish. It is difficult to know the limit of the swimming efficiency of a living fish. This could be regarded as a future problem.

Due to the importance of this topic and the active response we received together with the improving aspects found, we started the second term of the Special Issue and you are welcome to submit your relevant work to Frontiers in Deep-Sea Equipment and Technology II.

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