Marine Robots: From Laboratories to the Real Underwater Adventure

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In our continuous exploration and exploitation of the ocean, marine robots are powerful tools for accessing oceanic environments that are sometimes harsh or even too dangerous for humans. Early marine robots acted under human supervision, executing preprogrammed tasks or working under the control of highly trained specialists. In recent years, with the advancements in hardware and software, marine robots have begun to possess the capability to autonomously sense and adapt to the intricate ocean environment, thus working more efficiently and intelligently. By integrating recent advances in science and technology, ranging from biomimetic technology and new materials to advanced artificial intelligence methods, marine robots have the potential to be more powerful in the exploration of the ocean environment and facilitating a broader spectrum of tasks, such as studying marine life in their natural habitats or performing inspections and dexterous manipulation in the deep sea.

Unlocking the full potential of marine robots calls for further improvement in their autonomy, intelligence, and capabilities of perception, detection, and operation. However, great challenges arise from the hydrodynamics around marine robots and the complexities of the unpredictable natural environment. While extensive research has been done on autonomous and intelligent marine robots, significant new joint efforts are crucial to expedite the transition from laboratory conditions to real-world applications.

This special issue attempts to close the gap between theoretical development in marine robotics and its widespread real-world applications. It focuses on up-to-date research in marine robots and innovative technologies with practical potential, where special attention is given to bionic marine robotics, perception and detection in underwater scenarios, and real-world applications. The following is an overview of the 10 articles accepted in this special issue.

Bionic robotics, drawing considerable attention over recent decades, continues to be a fascinating subject, particularly in the area of marine robots.

Li et al. [A1] design a platform to capture realistic morphology, kinematics, and movements from real schooling fish and create high-fidelity fish-like robots accordingly. By measuring critical parameters such as the power cost, thrust, and detailed flow fields of the robots, one can map the sensory information to the locomotory and movement responses and hydrodynamic information of real fish, which are extremely challenging to collect from real animals. This work not only offers a possibility to investigate authentic fish behavior using robots but also presents a way to improve the performance of bionic marine robots.

Wang et al. [A2] focus on the challenges arising from disturbances caused by unknown dynamics and environmental factors in controlling an underactuated bionic underwater vehicle. They propose a control approach, combining the robustness of a model predictive controller with the modeling capabilities of a learning-based observer, which realizes disturbance rejection control while ensuring real-time application, constraint satisfaction, and recursive feasibility under complicated disturbances. Simulations and real-world experiments verify the efficiency and practicality.

To promote the practical usage of marine robots, it is imperative to strengthen their perception and detection capabilities to improve their ability to sense and understand the environment effectively.

Wen et al. [A3] focus on the realm of camera vision, which remains a prevailing perceptive technology for robots operating in underwater scenarios. The authors propose a transformer-based network for underwater image enhancement, effectively leveraging the advantages of global and local features while being computationally efficient. Extensive experiments demonstrate that their method outperforms other state-of-the-art methods both qualitatively and quantitatively.

Qi et al. [A4] present a comprehensive review of detection techniques developed over the past 15 years for identifying small leaks (fewer than 1 L/s) in water distribution networks—critical infrastructures vital for sustaining daily human life. Encompassing experiments and simulations carried out using both in-pipe robots and continuous monitoring, this review provides valuable insights. It fosters a clear understanding of the strengths and limitations of existing detection techniques, thereby facilitating future research endeavors in the field of small-leak detection.

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Chen et al. [A5] concentrate on an underwater hexapod robot equipped with an inertial measurement unit, an accelerometer, six encoders, a Doppler velocity log, and a depth sensor. Leveraging these proprioceptive sensors, the authors propose a terrain-adaptive locomotion controller for the robot, perceiving the leg-terrain interaction forces using proprioceptive sensory data and employing thruster forces to effectively compensate for these interaction forces. Extensive indoor pool and outdoor lake hardware experiments validate their approach. This work unveils new possibilities for underwater legged robots, enabling them to traverse diverse and unknown underwater terrains.

In addressing the diverse demands of tasks in oceanic environments, researchers consistently pioneer innovative technologies for marine robots.

Wang et al. [A6] set out to tackle the launch and recovery demands of autonomous underwater vehicles, which are essential for ensuring the safe and continuous operations of these vehicles in marine environments. After providing a summary of various existing launch and recovery mechanisms, the authors propose a launch and recovery system for autonomous underwater vehicles. This system involves an unmanned surface vehicle as the mother ship and a manipulator-based mechanism and an auxiliary mechanism designed for clamping the autonomous underwater vehicles. Experiments show the effectiveness of their system.

Astolfi et al. [A7] develop a marine sediment sampling system tailored to the specific demands of marine biologists engaged in active investigations of microplastic pollution. The system comprises a medium-sized underwater legged robot equipped with a customized sampler, consisting of a grab mounted on an underactuated mechanism. Testing in real conditions shows the system's capability to fulfill all user requirements, including the penetration depth, the weight of the sample, the ability to collect replicas without returning to the boat or the shore, the amount of sediment perturbation introduced by the system, and the sampling accuracy.

With recent advancements in marine robot technologies, humanity accelerates exploration into the depths of the sea.

Tosello et al. [A8] present an autonomous underwater architecture designed for the long-term inspection of the deep ocean. It integrates a subsea vehicle with an advanced planning architecture, resulting in an autonomous marine robot. This robot is able to perceive its surroundings, plan a mission, and dynamically adapt to contingencies and opportunities, all without human intervention. The successful deployment of their system in the field in Norway has established substantial reliability and garnered acceptance within the oil and gas community.

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Neettiyath et al. [A9] introduce their multiyear survey of cobalt-rich manganese crust deposits utilizing multiple marine robots. Two autonomous underwater vehicles and one remotely operated vehicle conducted a combined 438 h of seafloor observation, surveying about 589 km of seafloor in different locations. Leveraging camera systems, multibeam sonar, and sub-bottom sensors, the authors create a comprehensive database of cobalt-rich manganese crust distribution estimates. This work showcases the power of autonomous marine robots in conducting prolonged and thorough deep-sea surveys.

Zuo et al. [A10] implement a soft robotic gripper composed of nitinol-embedded soft fingers and an in situ wearable mechanism that allows the soft gripper to be put on and removed from the traditional rigid gripper, adapting to the specific requirements of deep-sea tasks. The soft robotic gripper has been subjected to numerous tests during three deep-sea dive trials. When deployed on a human-crewed deep-sea submersible, the gripper can perform nondestructive sampling tasks, including picking and placing fragile porcelain and operating a precision instrument at a depth range of 1,410–3,600 m. This study provides new design insights into creating next-generation deep-sea intelligent robotic systems capable of intricate dexterous manipulation.

We express our sincere gratitude to Editor-in-Chief Prof. Yi Guo and the associate editors for their support while creating this special issue, to the numerous anonymous reviewers for their insightful evaluations, and to the authors for their outstanding contributions. We hope this special issue will inspire continued exploration and innovation within the captivating realm of marine robotics.

APPENDIX: RELATED ARTICLES

[A1] L. Li, L.-M. Chao, S. Wang, O. Deussen, and I. D. Couzin, "RoboTwin: A platform to study hydrodynamic interactions in schooling fish," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 10–17, Mar. 2024, doi: 10.1109/MRA.2023.3348303.

[A2] K. Wang et al., "Bionic underwater vehicle: A data-driven disturbance rejection control framework," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 18–28, Mar. 2024, doi: 10.1109/MRA.2023.3328460.

[A3] J. Wen et al., "WaterFormer: A global–local transformer for underwater image enhancement with environment adaptor," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 29–40, Mar. 2024, doi: 10.1109/MRA.2024.3351487.

[A4] R. Qi, M. Cao, and D. Yntema, "Recent developments of subsurface small-leak detection techniques in water distribution networks: A review," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 108–118, Mar. 2024, doi: 10.1109/MRA.2024.3351483.

[A5] L. Chen, R. Cui, W. Yan, H. Xu, S. Zhang, and H. Yu, "Terrain-adaptive locomotion control for an underwater hexapod robot: Sensing leg–terrain interaction with proprioceptive sensors," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 41–52, Mar. 2024, doi: 10.1109/MRA.2023.3341247.

[A6] Y. Wang, W. Zhou, M. Fei, and H. Yan, "An unmanned surface vehicle for the launch and recovery of autonomous underwater vehicles: A novel design," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 53–61, Mar. 2024, doi: 10.1109/MRA.2023.3348302.

[A7] A. Astolfi et al., "Marine sediment sampling with an underwater legged robot: A user-driven sampling approach for microplastic analysis," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 62–71, Mar. 2024, doi: 10.1109/MRA.2023.3341288.

[A8] E. Tosello et al., "Opportunistic (re)planning for long-term deep-ocean inspection: An autonomous underwater architecture," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 72–83, Mar. 2024, doi: 10.1109/MRA.2024.3352810.

[A9] U. Neettiyat, H. Sugimatsu, T. Koike, K. Nagano, T. Ura, and B. Thornton, "Multirobot multimodal deep sea surveys: Use in detailed estimation of manganese crust distribution," *IEEE Robot. Autom. Mag.,* vol. 31, no. 1, pp. 84–95, Mar. 2024, doi: 10.1109/MRA.2023.3348304.

[A10] Z. Zuo et al., "A nitinol-embedded wearable soft robotic gripper for deep-sea manipulation: A wearable device for deep-sea delicate operation," *IEEE Robot. Autom. Mag.*, vol. 31, no. 1, pp. 96–107, Mar. 2024, doi: 10.1109/MRA.2024.3351477.