Guest Editorial
Pushing for Higher Autonomy and Cooperative Behaviors in Maritime Robotics

THIS special issue is the result of a collaborative effort between the IEEE Oceanic Engineering Society, the U.S. Office of Naval Research (ONR), and RoboNation, a nonprofit robotics organization formerly known as AUVSI foundation.

The field of maritime robotics is swiftly moving toward integration of air, surface, and subsurface autonomous systems. For example, where autonomous maritime systems (AMS) are composed of heterogeneous assets, surface vehicles are now often capable of transporting aerial and underwater vehicles, leveraging the benefits of each to increase mission endurance and capabilities.

In seeking to integrate land, sea, and air vehicle systems, it is natural to look toward leveraging advances made separately in each domain. For example, substantial similarities exist between the desired behavioral capabilities of autonomous land vehicles and those of autonomous marine systems. Recent advances in the field of driverless cars may therefore be applicable to autonomous surface vessels, underwater vehicles, and even aerial vehicles.

Multiple cooperative vehicles operating across heterogeneous domains offer many potential capabilities not available with a single vehicle operating in only one domain. These include creation of *ad hoc* wireless networks, supplying additional mobility, range, and duration for the underwater and aerial vehicles, and offering a capability for data reduction and *in situ* data analysis. Cooperative autonomy in a team of vehicles working together in the aerial, underwater, and surface domains has the potential to be a game changer for maritime security, ocean sampling, surveillance, and exploration. In fact, it may be a key to the development of a generation of novel, innovative solutions in these fields. Pushing for Higher Autonomy and Cooperative Behaviors in Maritime Robotics is the theme of this special issue.

So, given the potential, what challenges lie ahead? A longstanding issue in the marine environment is bringing down the cost of the sensor suites needed to make marine robotic platforms effective and useful, allowing multiple vehicles to be economically fielded. For persistent systems, the ability to weather extreme storm events and mitigate biofouling are important issues. Another challenge is to take systems that have been developed to the stage where they work well independently, and integrate them into a cooperative team. Significant progress has been made in this area, but we are still a long way from fully achieving this goal, particularly with respect to forming ad hoc scalable teams. There remain a number of key issues to achieving autonomous vehicle cooperation, including reliable communication links between vehicles in harsh low-bandwidth environments, decentralized/distributed control, sensor integration (both onboard and offboard), network state estimation, energy consumption, and launch and recovery of underwater and aerial systems.

These challenges have inspired a new generation of researchers and spawned innovative ideas in the next crop of leaders in this field. Competitions in Asia, North America, and Europe provide opportunities for up-and-coming engineers of tomorrow to try out their ideas, experience the challenges of teamwork, and develop from practical demonstration and interaction. Coupled with peer-reviewed special issue publications such as this one, these competitions showcase their exciting new ideas.

The international Maritime RobotX Challenge, created by ONR and RoboNation, is one such competition, featuring an in-water challenge held every other year in a variety of real-ocean venues. The RobotX Challenge was created to support the integration of robotics across aerial, surface and subsurface domains by calling for entrants to field systems that work together to solve a given problem.

A new element of RobotX is the RobotX Forum (held in intervening years), an interactive gathering with presentations from academia, senior officials, and industry leaders involved in the development and use of AMS. Starting in 2019, the RobotX Forum will also include a virtual competition in a realistic simulation domain.

The inaugural Maritime RobotX Forum in Sydney, NSW, Australia, held in December 2017, attracted 76 participants and included the following topics:

1) multidomain maritime vehicle cooperation;
2) novel self-localization and mapping (SLAM) approaches in the maritime environment;
3) development and uses of simulation in the maritime environment;
4) understanding vehicle intent;
5) research using the wave-adaptive modular vessel.

The Maritime RobotX Forum included a student poster competition. Out of 26 papers, submitted from 16 universities, ten were selected for presentation. From these, seven were chosen, following rigorous review, for publication in this special

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issue. The papers address a wide cross section of the thematic topics.

The papers you see here are from promising young researchers who are making their mark, many of whom have already contributed to prestigious publications such as the *IEEE International Conference on Robotics and Automation Proceedings*.

The first paper, "Launch and recovery of an autonomous underwater vehicle from a station-keeping unmanned surface vehicle" by Sarda and Dhanak, gives insight into a technology that is in great demand by security forces and scientific research communities. We believe that industry and governments will not be far behind as the need for safe, economic stand-alone systems become more pressing in the public domain. One example is policing expanded economic exclusion zones for coastal countries. Protecting a country's resources has become a vastly greater task as the distance offshore is increased. Enabling technologies described in this paper make it possible to address this problem.

The second paper, "Coastal SLAM with marine radar for USV operation in GPS-restricted situations" by Han *et al.*, addresses a different cooperative need, where precise navigation is required for autonomy in waters where the systems are denied access to satellite navigation and detailed maps. Solving the problem with low-resolution knowledge and clever algorithms to navigate safely in areas with ill-defined coastlines delivers higher autonomy and provides a great contribution to vehicle navigation in uncertain environments.

The third paper, "High-fidelity autonomous surface vehicle simulator for the Maritime RobotX Challenge" by Smith and Dunbabin, presents a simulator that was developed to address gaps in existing robotic marine vehicle simulation software. It interfaces high-fidelity sensor data from a realistic operating environment and includes vehicle motion dynamics, as well as providing a direct interface for hardware-in-the-loop simulation. Key elements required for the simulator to create an effective model of the vehicle included a high-resolution camera, LiDAR, IMU, and GPS sensor simulation, as well as buoyancy and physics simulation for modeling sea state, vehicle motion, and control performance.

The fourth paper, "Toward the generation of mission plans for operation of autonomous marine vehicles in confined areas" by Wheare *et al.*, proposes a planning method for autonomous surface vehicles (ASVs) based on Delaunay-triangulation discretization that accounts for the kinematic constraints of ASVs and offers an interesting path planning solution to navigation in cluttered environments.

The fifth paper, "Obstacle avoidance using multiobjective optimization and a dynamic obstacle manager" by Benjamin *et al.*, describes a set of software modules and algorithms for obstacle avoidance. The approach described in this paper is designed to work in conjunction with any path planning method that generates a viable sequence of waypoints, with obstacle avoidance regarded as a local deviation of the planned path of points.

The sixth paper, "Multimodal sensor fusion for robust obstacle detection and classification in the Maritime RobotX Challenge" by Stanislas and Dunbabin, targets multimodal target detection, localization, and classification in coastal /ocean environments. Several sensor types are considered (radar, LiDAR, camera) and the author's promise that future research will consider stereo cameras, an important sensor for many applications.

The final paper, "Efficient LiDAR-based object segmentation and mapping for maritime environments" by Thompson *et al.* investigates mapping for ASVs. In the maritime environment, maps are sparse and waterborne objects are often floating and not truly stationary as they are in ground terrain. So methods meant to leverage or be efficient in the presence of fine detail, developed for ground terrain, are as yet unproven for ASVs.

In closing, we would like to thank the many reviewers who have given their time and effort and, of course, the authors, without whom none of this would have been possible.

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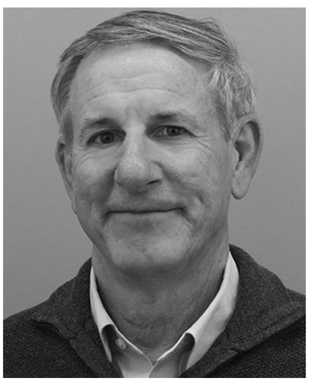

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