Guest Editorial

I. INTRODUCTION

THE marine environment plays a critical role in our ecosystem, economy, and daily lives. Oceans cover 71% of the Earth's surface, and 99% of life on the planet grows in aquatic environments [1]. Over 40% of the world's population lives within 100 km of a coastline [2], and marine ecosystems are estimated to provide more than \$20 trillion of service value annually—nearly two-thirds of all value generated by global ecosystems [3]. Overall, marine systems support a wide range of biodiversity, hold vast natural resources, play critical roles in fundamental environmental cycles, and host a spectrum of human activity from transportation to recreation.

As we increase our reliance on oceans, lakes, estuaries, and waterways for new resources and for expanding our commercial, civil, and scientific activities, we are faced with a need for improved mechatronic systems capable of performing in these environments. Marine mechatronic systems are used for a wide range of applications, such as exploring the extreme depths of our ocean, monitoring our environment, supporting national defence operations, transporting goods, supporting recreational activities, and harvesting resources ranging from food to oil. While doing this, these systems operate in a demanding environment with challenges such as intense hydrostatic pressures, harmful interaction with electronics and materials, powerful hydrodynamic forces, and high attenuation of electromagnetic signals.

This "Focused Section on Marine Mechatronic Systems" of the IEEE/ASME TRANSACTIONS ON MECHATRONICS is dedicated to new advances in the design, control, and implementation of mechatronic devices that are developed to operate in the marine environment. Out of a total of 44 submitted papers, seven have been selected for inclusion in this Focus Section.

II. CURRENT WORK IN MARINE MECHATRONIC SYSTEMS

A strong indicator of innovative work in the area of marine mechatronic systems is provided by the topics of special journal issues in the leading marine technology publications. Over the past three years, such special issues have focused on ocean observing systems, offshore wind power, autonomous vehicles, advanced sonar systems, and bio-inspired designs. Indeed, the range of articles submitted to this Focus Section spanned these same technologies. Here, we review some of the most notable recent work in a few of these areas.

A. Vehicles

Much of the work accomplished in marine environments depends on the use of platforms and vehicles for supporting and placing application-specific payloads. These platforms come in a variety of forms, both manned and unmanned: drifters, profilers, buoys, towfish, tethered underwater robots (ROVs: remotely operated vehicles), autonomous underwater vehicles (AUVs), crawlers, cabled sensor networks, observatories, boats, and submarines.

Robotic vehicles are being used to perform a wide range of applications such as performing visual inspections [4], performing underwater archeology [5], supporting security operations [6], and characterizing the marine environment, particularly in response to disasters such as oil spills [7] and to transient science events such as harmful algae blooms [8]. ROVs have become the robotic workhorse of maritime work, with nearly 1000 work-class vehicles in service [9]. Current trends in ROV development are reviewed in [10] and include initiatives such as improving the use of manipulators [11], [12] and enhancing pilot aids [7]. Recent work on AUVs includes significant innovation in the design and control of gliders, as reviewed in [13], and the development of the Wave Glider [14], a vehicle capable of directly harvesting wave energy for vehicle propulsion. Extensions to more traditional torpedo-style AUVs have focused on making them more fault tolerant [15], enabling automated docking [16], [17], and understanding how to manage the risk involved in deploying these highly complex systems on demanding missions and in extreme environments [18]. Of particular note is the 2010 mission of the Nereus vehicle, a hybrid ROV/AUV, to the Challenger Deep in the Pacific Ocean, which achieved full ocean depth at more than 10 900 m [19].

Reliance on manned submersibles grows with more than 100 submarines in service and with Japan's Shinkai 6500 currently operating with the deepest depth rating of 6500 m [20]. The vaunted Woods Hole Oceanographic Institute's Alvin submarine is being retrofitted to achieve the same depth [21], and U.S. company Hawkes Ocean Technologies is preparing the positively buoyant, winged DeepFlight Challenger for a full-ocean depth mission to the Challenger Deep [22].

B. Sensing Technologies

Sensor technologies are critical both for enabling mission-critical payloads and for managing vehicles and platforms. Cameras, sonar, and light detection and ranging (LIDAR) systems are used to construct images of scenes, each with its own pros and cons with respect to range and resolution given challenges such as the lack of natural lighting, frequency-dependent attenuation, and suspended particulates.

Recent work in this area is summarized in [23]–[25] and includes intriguing advances in stereo imaging, mapping, localization, and three-dimensional scene reconstruction. Researchers are also extending existing sensor processing techniques, such as simultaneous localization and mapping (SLAM) and

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photomosaicing, such that they can be exploited in barren, unstructured environments [26], [27]. For *in situ* characterization, advances in sensing technologies such as laser Raman [28] and "lab-on-a-chip" systems capable of genetic analysis and microbial identification [29], [30] are revolutionizing our ability to rapidly characterize the ocean environment.

C. Control Systems and Automation

Recent work in control systems has ranged from improvements in pilot aids and the motion control of vehicles/platforms to system-level autonomy functions and architectures. With respect to motion control, new work on surface platforms has included advancements in dynamic positioning [31] and improvements in crane operations when handling payloads in harsh offshore environments [32], [33]. Vehicle motion control research has ranged from improving the control of underactuated and towed vehicles [34], [35] to visually servoing ROVs for purposes such as following fish [36], [37].

With respect to navigation, one of the most intriguing advances is the continuing evolution of adaptive sampling techniques. In conventional environmental mapping, a vehicle systematically drives through the region of interest in a "mow-the-lawn" pattern, logging data over time. With adaptive sampling, vehicles change their trajectory based on realtime sensor data with the objective of more efficiently finding and monitoring specific conditions of interest. One such strategy uses realtime data to update ocean models, which in turn are used to aid path planning by forecasting how regions of interest will move over time [38], [39]. Another adaptive strategy uses multiple spatially distributed vehicles to estimate field gradients, thereby providing a navigation reference for moving toward the local minima/maxima within a field, moving along contours of specific concentration levels, and so on [40], [41].

At the system level, impressive work is being performed in the creation, extension, and validation of autonomous control architectures that support varying levels of control abstraction and which are robust to the dynamic marine environment and to modeling uncertainties. Specific autonomy objectives include goal-directed commanding and fault diagnosis, to include the ability to adapt a mission plan in the event of component failures and changing marine conditions [42], [43]. These architectures include frameworks for cooperation and communication among multiple marine vehicles and sensing nodes [44]–[46].

D. Sensor and Vehicle Networks

One of the most exciting developments in the world of marine mechatronics is the rise of networks of sensors and vehicle systems capable of monitoring a wide range of phenomena and performing functions such as detecting tsunami, monitoring the effects of climate change, and tracking targets [47]–[49]. Regional, underwater observatories are being developed around the world, with operational systems that include the North-East Pacific Time-Series Underwater Networked Experiments and Monterey Accelerated Research System observatories [50]. These observatories support nodes that access power and high-speed data connections via cables running from shore, and they are being developed to support wet mating and acoustic communications with locally operating vehicles.

Early work in implementing multivehicle systems includes work with glider networks within the Autonomous Ocean Sampling Network and with the network of Surface Craft for Oceanographic and Undersea Testing (SCOUT) robotic kayaks [51], [52]. The latest work in this area explores techniques to enable long-term environmental monitoring, to protect assets, and to manipulate objects [45], [53], [54].

E. Bio-Inspired Design

The objective of biomimicry is to exploit designs and strategies that have naturally evolved over time given the challenges and constraints of the natural environment. In the marine world, there is enormous diversity in the manner in which organisms are structured, in how they sense their world, in their decision-making approaches, and in their mobility techniques.

These approaches have inspired work in marine vehicle design, actuation, and control. New vehicle designs have been developed with configurations modeled after fish and other sea creatures, such as tuna, tadpoles, and jellyfish [55]–[58]. The spectrum of this work has extended from amphibious configurations [59] to the implementation of several microscale swimming designs [60]–[62]. With respect to vehicle actuation, bio-inspired designs have included the use of fins [63], [64], flapping wings [65], undulating bodies [66], and vortex rings [67]. As for control, biomimetic approaches range from the use of spinal cord-like timing signals to modulate swimming motions [68] to using fish-like schooling behaviors to enable robot-led groups of fish [69].

F. Energy Systems

The use of mechatronic systems to harvest energy from the ocean is an accelerating field. Ocean energy is available from currents, tides, and waves. It is estimated that more than 2 TW of power is readily accessible throughout the world from waves alone [70], although properly assessing the suitability of specific sites for their energy capacity is a challenge [71].

Recent trends in wave and tidal energy systems are reviewed in [72]. In general, wave harvesting strategies include the use of buoys, wave followers, and terminators/overtoppers [73], while tidal energy strategies focus on the use of turbines and tidal damns. Recent work in this area ranges from the development of new energy conversion devices [74]–[76], to sea trials of new systems, to the commencement of services at energy farms [77], [78].

III. HIGHLIGHTS OF THE FOCUSED SECTION

The papers submitted to this "Focused Section on Marine Mechatronic Systems" ranged in topic from sensors to systems and included submissions from authors, laboratories, and organizations from throughout the world. We are pleased to present seven of these papers in this issue; these papers represent a cross section of topics and were judged to be of the highest quality by an outstanding cadre of reviewers. In keeping with the spirit of a mechatronics publication, we specifically note that we have selected papers that include some level of implementation and experimentation.

Our first paper addresses the simply stated yet challenging problem of calibrating sensors. In “Development of an *In Situ* pH Calibrator in Deep Sea Environments,” Tan *et al.* describe their implementation of a novel self-calibrating sensing system that performs calibration functions *in situ* and in high-pressure and high-temperature environments such as those around hydrothermal vents along midocean ridges. The system alternatively measures and logs results for seawater samples and then performs a two-point calibration using a buffer solution stored in the system. While applied to the important task of monitoring pH, this self-calibrating sensing approach is highly applicable for integration with a wide variety of transducers. The paper includes experimental verification data from a demanding field trial among hydrothermal vents at a depth of nearly 800 m.

In “Autonomous Depth Adjustment for Underwater Sensor Networks: Design and Applications,” Detweiler *et al.* present an advanced network of moored vertical profiling sensors. In addition to enabling a robust winch-based actuation system on each sensor node, the nodes are acoustically linked and implement a decentralized control algorithm to produce optimal depth profiles given the phenomena under observation. The positioning algorithm can also be used to optimize acoustic communications among nodes. The paper describes the depth actuation and control system. In addition, the data from experimental trials in river systems are used to verify the capabilities of the system.

Moving from sensors to actuators, Zhou and Low present the design of a robotic manta ray that uses fin-based propulsion in their paper “Design and Locomotion Control of a Biomimetic Underwater Vehicle With Fin Propulsion.” The vehicle maneuvers through the coordinated flapping of each fin. Coordination is achieved by a gait controller that uses a nonlinear oscillator to generate timing signals for the motion and phasing of the wings, similar to the way that biological central pattern generators produce coordinated, rhythmic motions in animals. This paper describes the design of the robot, the design of the swim gait generator and control system, and the use of the gait generator to control flapping, turning, and gliding. Initial pool experiments demonstrate the vehicle’s ability to achieve these basic motions.

In “Modeling, Simulation, and Performance of a Synergistically Propelled Ichthyoid,” Strefling *et al.* describe a second bio-inspired approach to achieving vehicle propulsion. In their design, fluid is pumped through a flexible tail, causing the tail to oscillate. The combined jet action and motion of the fluttering tail produces thrust, which can exceed that of a dimensionally identical rigid tail. Their paper develops two dynamic models for their system, a simplified analytic model as well as a more complex two-dimensional model that is solved numerically. These models are reinforced with experimental pool-test data of a simple prototype operating on the surface.

Moving on to vehicles, Ribas *et al.* present their work with a reconfigurable AUV design in “Girona 500 AUV: From Survey to Intervention.” This paper describes the design and initial testing of the Girona 500 vehicle for applications ranging from traditional AUV-based sampling to autonomous intervention tasks. The vehicle uses multiple, connected, streamlined hulls to balance hydrodynamic performance with hydrostatic stability, supports thruster reconfiguration allowing 3 to 6 degree-of-freedom actuation, and has payload volume to support a range of instruments or even a small manipulator. Initial tests demonstrate the range of capabilities of the vehicle and include controlled pool-based intervention task demonstrations as well as survey tests at sea.

In “Autonomous Underwater Vehicle Operations Beneath Coastal Sea Ice,” Plueddemann *et al.* describe their work in adapting a REMUS AUV for conducting a hydrographic survey under coastal ice. Of particular interest are the challenges and constraints of conducting such work and the resulting development efforts of the authors in meeting these demands, particularly in being able to achieve reliable end-of-survey docking and retrieval of the AUV. Ultimately, an autodocking technique that used both long baseline and ultrashort baseline navigation resulted in a reliable capability to net capture the AUV. This paper describes the AUV adaptations made and presents results from several under-ice deployments, to include a description of the iterations involved in ultimately achieving success.

Finally, Mahacek *et al.* demonstrate a novel multiboat field application in the paper “Dynamic Guarding of Marine Assets Through Cluster Control of Automated Surface Vessel Fleets.” Building upon this research group’s considerable work in the formation control of multirobot systems, this paper describes a control technique that establishes a dynamically created protective wall that shields an asset from an approaching threat. Formal transforms convert a task-level description of the guarding task into spatial formation parameters that are achieved using the cluster space formation control technique. The paper presents experimental verification of the technique and describes how the system can be used to protect ROV dive areas and establish perimeters around mobile sensor platforms.

IV. FUTURE CHALLENGES

Oceans, inland lakes, rivers, and estuaries are critical in supporting human activity and in sustaining a healthy planet. Our reliance on these marine resources will continue to escalate given our expanding demand for food and natural resources, our increasing marine-based transportation and security activities, and our growing interest in exploring and characterizing the underwater environment.

Expanding our marine activities and enabling more sophisticated capabilities will require significant innovation in a range of sensing, control, actuation, and design technologies. It is clear that more capable perception systems and more efficient actuator techniques are demanded. Future control technologies will need to support improved precision and disturbance rejection, provide efficient coordination among networked agents, and enable robust long-term autonomous operations in the face of unanticipated conditions and failed components. Furthermore, our design techniques and tools must evolve in order to support our attempts to synthesize highly capable and cost-effective systems.

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REFERENCES

[1] R. Costanza, “The ecological, economic and social importance of the oceans,” *Ecol. Econ.*, vol. 31, pp. 199–213, 1999.
[2] M. Martinez, A. Intralawan, G. Vazquez, O. Perez-Maqueo, P. Sutton, and R. Landgrave, “The coasts of our world: Ecological, economic and social importance,” *Ecol. Econ.*, vol. 63, pp. 254–272, 2007.
[3] R. Costanza, R d’Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. O’Neill, J. Paruelo, R. Raskin, P. Sutton, and M. van den Belt, “The value of the world’s ecosystem services and natural capital,” *Nature*, vol. 387, pp. 253–260, 1997.
[4] P. Ridao, M. Carreras, D. Ribas, and R. Garcia, “Visual inspection of hydroelectric dams using an autonomous underwater vehicle,” *J. Field Robot.*, vol. 27, no. 6, pp. 759–778, 2010.
[5] B. Bingham, B. Foley, H. Singh, R. Camilli, K. Delaporta, R. Eustice, A. Mallios, D. Mindell, C. Roman, and D. Sakellariou, “Robotic tools for deep water archaeology: Surveying an ancient shipwreck with an autonomous underwater vehicle,” *J. Field Robot.*, vol. 27, no. 6, pp. 702–717, 2010.
[6] T. Pastore and V. Djapic, “Improving autonomy and control of autonomous surface vehicles in port protection and mine countermeasure scenarios,” *J. Field Robot.*, vol. 27, no. 6, pp. 903–914, 2010.
[7] A. Bleicher, “The Gulf spill’s lessons for robotics,” *IEEE Spectrum*, vol. 47, no. 8, pp. 9–11, 2010.
[8] J. Dolan, G. Podnar, S. Stancliff, E. Ratliff, J. Higinbotham, J. Hosler, T. Ames, J. Moisan, T. Moisan, and A. Elfes, “Harmful algal bloom characterization via the telesupervised adaptive ocean sensor fleet,” *Robot. Inst.*, pp. 1–8, 2007.
[9] Remotely Operated Vehicles (ROVs) Market Report To 2015. Infield: The Energy Analysts, London, U.K. (2011). [Online]. Available: http://www.infield.com/brochures/remotely-operated-vehicles-market-report.pdf, accessed on 11/1/11.
[10] S. Cohan, “Trends in ROV development,” *Marine Technol. Soc. J.*, vol. 42, no. 1, pp. 38–43, 2008.
[11] H. Shim, B. Jun, P. Lee, H. Baek, and J. Lee, “Workspace control system of underwater tele-operated manipulators on an ROV,” in *Proc. Eur. Oceans*, Bremen, Germany, 2009, pp. 1036–1047.
[12] J. Han, J. Park, and W. Chung, “Robust coordinated motion control of an underwater vehicle-manipulator system with minimizing restoring moments,” *Ocean Eng.*, vol. 38, no. 10, pp. 1197–1206, 2011.
[13] R. Bachmayer, N. Leonard, J. Graver, E. Fiorelli, P. Bhatta, and D. Paley, “Underwater gliders: Recent developments and future applications,” in *Proc. 4th Int. Symp. Underwater Technol.*, Taipei, Taiwan, 2004, pp. 195–200.
[14] R. Hine, S. Willcox, G. Hine, and T. Richardson, “The wave glider: A wave-powered autonomous marine vehicle,” in *Proc. OCEANS, Biloxi—Marine Technol. Future: Global Local Challenges*, Biloxi, MS, 2009, pp. 1–6.
[15] W. Kirkwood, W. Anderson, and C. Kitts, “Fault tolerant actuation for Dorado Class AUVs,” in *Proc. IEEE Mar. Technol. Conf.*, Barcelona, Spain, 2009, pp. 40–42.
[16] J. Park, B. Jun, P. Lee, and J. Oh, “Experiments on vision guided docking of an autonomous underwater vehicle using one camera,” *Ocean Eng.*, vol. 36, no. 1, pp. 48–61, 2009.
[17] M. Moline and O. Schofield, “Remote real-time video-enabled docking for underwater autonomous platforms,” *J. Atmospher. Ocean. Technol.*, vol. 26, pp. 2665–2672, 2009.
[18] M. Brito, G. Griffiths, and P. Challenor, “Risk analysis for autonomous underwater vehicle operations in extreme environments,” *Risk Anal.*, vol. 30, no. 12, pp. 1771–1788, 2010.
[19] B. Fletcher, A. Bowen, D. Yoerger, and L. Whitcomb, “Journey to the challenger deep: 50 years later with the *Nereus* hybrid remotely operated vehicle,” *Marine Technol. Soc. J.*, vol. 43, no. 5, pp. 65–76, 2009.
[20] W. Kohnen, “2007 MTS overview of manned underwater vehicle activity,” *Marine Technol. Soc. J.*, vol. 42, no. 1, pp. 26–37, 2008.
[21] Alvin: Past, Present, and Future. Woods Hole Oceanographic Institute, Woods Hole, MA. (2010). [Online]. Available: http://www.whoi.edu/fileserver.do?id=70564&pt&=2&p&=19866, accessed on 11/1/11.
[22] DeepFlight Challenger Information Sheet. Hawkes Ocean Technologies, San Francisco, CA. (2011). [Online]. Available: http://deepflight.com/Infosheet1DeepFlIght%20Challenger.pdf, accessed on 11/1/11.
[23] D. Kocak, F. Dalgleish, F. Caimi, and Y. Schechner, “A focus on recent developments and trends in underwater imaging,” *Marine Technol. Soc. J.*, vol. 42, no. 1, pp. 52–67, 2008.
[24] K. Foote, “Underwater acoustic technology: Review of some recent developments,” in *Proc. Oceans*, 2008, pp. 1–6.
[25] P. Jonsson, I. Sillitoe, B. Dushaw, J. Nystuen, and J. Heltne, “Observing using sound and light—A short review of underwater acoustic and video-based methods,” *Ocean Sci. Discuss.*, vol. 6, pp. 819–870, 2009.
[26] S. Barkby, S. Williams, O. Pizarro, and M. Jakuba, “A featureless approach to efficient bathymetric SLAM using distributed particle mapping,” *J. Field Robot.*, vol. 28, no. 1, pp. 19–39, 2011.
[27] H. Singh, C. Roman, O. Pizarro, B. Foley, R. Eustice, and A. Can, “High-resolution optical imaging for deep-water archaeology,” in *Archaeological Oceanography*, R. Ballard, Ed. Princeton, NJ: Princeton Univ. Press, 2008, pp. 30–40.
[28] X. Zhang, P. Walz, W. Kirkwood, K. Hester, W. Ussler, E. Peltzer, and P. Brewer, “Development and deployment of a deep-sea Raman probe for measurement of pore water geochemistry,” *Deep Sea Res. Part I: Oceanograph. Res. Papers*, vol. 57, no. 2, pp. 297–306, 2010.
[29] D. Fries, J. Paul, M. Smith, A. Farmer, E. Casper, and J. Wilson, “The autonomous microbial genosensor, an in situ sensor for marine microbe detection,” *Microsc. Microanal.*, vol. 13, pp. 514–515, 2007.
[30] J. Paul, C. Scholin, G. Van Den Engh, and M. Perry, “In situ instrumentation,” *Oceanography*, vol. 20, no. 2, pp. 70–78, 2007.
[31] A. Sorensen, “A survey of dynamic positioning control systems,” *Annu. Rev. Control*, vol. 35, no. 1, pp. 123–136, 2011.
[32] Q. Ngo and K. Hong, “Sliding-mode antisway control of an offshore container crane,” *IEEE/ASME Trans. Mechatronics*, pp. 1–9, in press. DOI: 10.1109/TMECH.2010.2093907, (Dec. 30, 2010). [Online]. Available: http://ieeexplore.ieee.org

[33] S. Kuchler, T. Mahl, J. Neupert, K. Schneider, and O. Sawodny, "Active control for an offshore crane using prediction of the vessels motion," *IEEE/ASME Trans. Mechatronics*, vol. 16, no. 2, pp. 297–309, Apr. 2011.

[34] K. Do, "Practical control of underactuated ships," *Ocean Eng.*, vol. 37, pp. 1111–1119, 2010.

[35] F. Teixeira, A. Aguiar, and A. Pascoal, "Nonlinear adaptive control of an underwater towed vehicle," *Ocean Eng.*, vol. 37, no. 13, pp. 1193–1220, 2010.

[36] H. Suzuki and M. Minami, "Visual servoing to catch fish using global/local GA search," *IEEE/ASME Trans. Mechatronics*, vol. 10, no. 3, pp. 352–357, Jun. 2005.

[37] J. Rife and S. Rock, "Segmentation methods for visual tracking of deep-ocean jellyfish using a conventional camera," *IEEE J. Ocean. Eng.*, vol. 28, no. 4, pp. 595–608, Oct. 2003.

[38] R. Smith, Y. Chao, P. Li, D. Caron, B. Jones, and G. Sukhatme, "Planning and implementing trajectories for autonomous underwater vehicles to track evolving ocean processes based on predictions from a regional ocean model," *Int. J. Robot. Res.*, vol. 29, no. 12, pp. 1475–1497, 2010.

[39] S. Ramp, R. Davis, N. Leonard, I. Shulman, Y. Chao, A. Robinson, J. Marsden, P. Lermusiaux, D. Fratantoni, J. Paduan, F. Chavez, F. Bahr, S. Liang, W. Leslie, and Z. Li, "Preparing to predict: The second autonomous ocean sampling network (AOSN-II) experiment in the Monterey Bay," *Deep Sea Res. Part II, Top. Stud. Oceanography*, vol. 56, no. 3–5, pp. 68–86, 2009.

[40] N. Leonard, D. Paley, R. Davis, D. Fratantoni, F. Lekien, and F. Zhang, "Coordinated control of an underwater glider fleet in an adaptive ocean sampling field experiment in Monterey Bay," *J. Field Robot.*, vol. 27, no. 6, pp. 718–740, 2010.

[41] P. Mahacek, T. Adamek, V. Howard, K. Rasal, C. Kitts, B. Kirkwood, and G. Wheat, "Cluster space gradient tracking—Control of multi-robot systems," in *Proc. ASME Inf. Storage Process. Syst. Conf.*, Santa Clara, CA, 2011, pp. 1–3.

[42] C. McGann, F. Py, K. Rajan, J. Ryan, H. Thomas, R. Henthorn, and R. McEwen, "Preliminary results for model-based adaptive control of an autonomous underwater vehicle," in *Proc. 11th Int. Symp. Exp. Robot.*, 2009, pp. 395–405.

[43] P. Patron, E. Miguelanez, Y. Petillot, D. Lane, and J. Salvi, "Adaptive mission plan diagnosis and repair for fault recovery in autonomous underwater vehicles," in *Proc. Oceans*, 2008, pp. 1–9.

[44] M. Benjamin, H. Schmidt, P. Newman, and J. Leonard, "Nested autonomy for unmanned marine vehicles with MOOS-IvP," *J. Field Robot.*, vol. 27, no. 6, pp. 834–875, 2010.

[45] L. Elkins, D. Sellers, and W. R. Monach, "The autonomous maritime navigation (AMN) project: Field tests, autonomous and cooperative behaviors, data fusion, sensors, and vehicles," *J. Field Robot.*, vol. 27, no. 6, pp. 790–818, 2010.

[46] T. Schneider and H. Schmidt, "Unified command and control for heterogeneous marine sensing networks," *J. Field Robot.*, vol. 27, no. 6, pp. 876–889, 2010.

[47] G. Baltrami, "Automatic, real-time detection and characterization of tsunamis in deep-sea level measurements," *Ocean Eng.*, vol. 38, no. 14–15, pp. 1677–1685, 2011.

[48] H. Ruhl, M. Andre, L. Beranzoli, M. Cagatay, A. Colaco, M. Cannat, J. Danobeitia, P. Favali, L. Geli, M. Gillooly, J. Greinert, P. Hall, R. Huber, J. Karstensen, R. Lampitt, K. Larkin, V. Lykousis, J. Mienert, J. Miranda, R. Person, I. Priede, I. Puillat, L. Thomsen, and C. Waldmann, "Societal need for improved understanding of climate change, anthropogenic impacts, and geo-hazard warning drive development of ocean observatories in European Seas," *Progr. Oceanography*, vol. 91, no. 1, pp. 1–33, 2011.

[49] K. Baumgartner, S. Ferrari, and A. Rao, "Optimal control of an underwater sensor network for cooperative target tracking," *IEEE J. Ocean. Eng.*, vol. 34, no. 4, pp. 678–697, Oct. 2009.

[50] P. Favali, R. Person, C. Barnes, Y. Kaneda, J. Delaney, and S. Hsu, "Seafloor observatory science," in *Proc. OceanObs'09: Sustained Ocean Observat. Inf. Soc.*, Venice, Italy, 2009, vol. 2, pp. 1–12.

[51] E. Fiorelli, N. Leonard, P. Bhatta, D. Paley, R. Bachmayer, and D. Fratantoni, "Multi-AUV control and adaptive sampling in Monterey Bay," *IEEE J. Ocean. Eng.*, vol. 31, no. 4, pp. 935–948, Oct. 2006.

[52] J. Curcio, J. Leonard, and A. Patrikalakis, "SCOUT—A low cost autonomous surface platform for research in cooperative autonomy," in *Proc. MTS/IEEE OCEANS*, 2005, pp. 725–729.

[53] R. Smith, M. Schwager, S. Smith, B. Jones, D. Rus, and G. Sukhatme, "Persistent ocean monitoring with underwater gliders: Adapting sampling resolution," *J. Field Robot.*, vol. 28, no. 5, pp. 714–741, 2011.

[54] J. Esposito, M. Feemster, and E. Smith, "Cooperative manipulation on the water using a swarm of autonomous tugboats," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2008, pp. 1501–1506.

[55] G. Shuxiang, T. Fukuda, and K. Asaka, "A new type of fish-like underwater microrobot," *IEEE/ASME Trans. Mechatronics*, vol. 8, no. 1, pp. 136–141, Mar. 2003.

[56] D. Barrett, M. Grosenbaugh, and M. Triantafyllou, "The optimal control of a flexible hull robotic undersea vehicle propelled by an oscillating foil," in *Proc. Symp. Auton. Underwater Veh. Technol.*, 1996, pp. 1–9.

[57] B. Kim, D. Kim, J. Jung, and J. Park, "A biomimetic undulatory tadpole robot using ionic polymer–metal composite actuators," *Smart Mater. Struct.*, vol. 14, no. 6, pp. 1579–1586, 2005.

[58] S. Yeom and I. Oh, "A biomimetic jellyfish robot based on ionic polymer metal composite actuators," *Smart Mater. Struct.*, vol. 18, no. 8, pp. 1–10, 2009.

[59] J. Yu, R. Ding, Q. Yang, M. Tan, W. Wang, and J. Zhang, "On a bio-inspired amphibious robot capable of multimodal motion," *IEEE/ASME Trans. Mechatronics*, pp. 1–10, in press. DOI: 10.1109/TMECH2011.2132732, (May 10, 2011). [Online]. Available: http://ieeexplore.ieee.org

[60] K. Abdelnour, A. Stinchcombe, M. Porfiri, J. Zhang, and S. Childress, "Wireless powering of ionic polymer metal composites toward hovering microswimmers," *IEEE/ASME Trans. Mechatronics*, pp. 1–12, in press. DOI: 10.1109/TMECH.2011.2148201, (May 31, 2011) [Online]. Available: http://ieeexplore.ieee.org.

[61] Y. Zhang, M. Cong, D. Guo, and D. Wang, "Design optimization of a bidirectional microswimming robot using giant magnetostrictive thin films," *IEEE/ASME Trans. Mechatronics*, vol. 14, no. 4, pp. 493–503, Aug. 2009.

[62] M. Borgen, G. Washington, and G. Kinzel, "Design and evolution of a piezoelectrically actuated miniature swimming vehicle," *IEEE/ASME Trans. Mechatronics*, vol. 8, no. 1, pp. 66–76, Mar. 2003.

[63] F. Liu, K. Lee, and C. Yang, "Hydrodynamics of an undulating fin for a wave-like locomotion system design," *IEEE/ASME Trans. Mechatronics*, pp. 1–9, in press. (Feb. 28, 2011). DOI: 10.1109/TMECH.2011.2107747.

[64] Z. Chen, S. Shatara, and X. Tan, "Modeling of biomimetic robotic fish propelled by an ionic polymer—Metal composite caudal fin," *IEEE/ASME Trans. Mechatronics*, vol. 15, no. 3, pp. 448–459, Jun. 2010.

[65] P. Bandyopadhyay, H. Leinhos, J. Hrubes, N. Toplosky, and J. Hansen, "Turning of a short-length cable using flapping fin propulsion," *IEEE J. Ocean. Eng.*, vol. 36, no. 4, pp. 571–585, Oct. 2011.

[66] K. Melsaac and J. Ostrowski, "Undulating bodies: A geometric approach to anguilliform locomotion: Modelling of an underwater eel robot," in *Proc. 1999 IEEE Int. Conf. Robot. Autom.*, 1999, vol. 4, pp. 2843–2848.

[67] M. Krieg and K. Mohseni, "Vortex rings: Thrust characterization of a bioinspired vortex ring thruster for locomotion of underwater robots," *IEEE J. Ocean. Eng.*, vol. 33, no. 2, pp. 123–132, Apr. 2008.

[68] K. Seo, S. Chung, and J. Slotine, "CPG-based control of a turtle-like underwater robot," *Auton. Robots*, vol. 28, no. 3, pp. 247–269, 2010.

[69] N. Abaid and M. Porfiri, "Consensus over numerosity-constrained random networks," *IEEE Trans. Automat. Control*, vol. 56, no. 3, pp. 649–654, Mar. 2011.

[70] *Renewable Energy Resources: Opportunities and Constraints 1990–2020*. London, U.K.: World Energy Council, 1993.

[71] A. Izadparast and J. Niedzwecki, "Estimating the potential of ocean wave power resources," *Ocean Eng.,* vol. 38, no. 1, pp. 177–185, 2011.

[72] R. Price, "Trends in emerging tidal and wave energy collection technology," *Marine Technol. Soc. J.,* vol. 43, no. 1, pp. 101–116, 2009.

[73] J. Hayward and P. Osman. (2011). The potential of wave energy. CSIRO. [Online]. Available: http://www.csiro.au/files/files/p10e6.pdf, accessed on 11/3/11.

[74] F. Wu, X. Zhang, P. Ju, and M. Sterling, "Optimal control for AWS-based wave energy conversion system," *IEEE Trans. Power Syst.,* vol. 24, no. 4, pp. 1747–1755, Nov. 2009.

[75] D. Elwood, S. Yim, E. Amon, A. von Jouanne, and T. Brekken, "Experimental force characterization and numerical modeling of a taut-moored dual-body wave energy conversion system," *J. Offshore Mech. Arct. Eng.,* vol. 132, no. 1, pp. 1–6, 2010.

[76] M. Khan, G. Bhuyan, M. Iqbal, and J. Quaicoe, "Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review," *Appl. Energy,* vol. 86, no. 10, pp. 1823–1835, 2009.

[77] C. Douglas, G. Harrison, and J. Chick, "Life cycle assessment of the Seagen marine current turbine," in *Proc. Inst. Mech. Eng., Part M, J. Eng. Maritime Environ.,* vol. 222, no. 1, pp. 1–12, 2008.

[78] A. Sangster, *Energy for a Warming World*. London, U.K.: Springer-Verlag, 2010.

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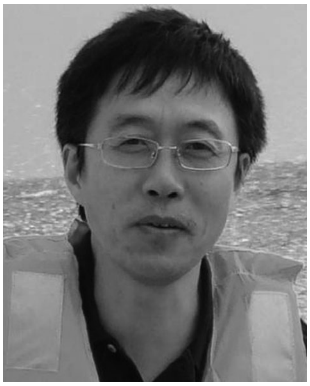

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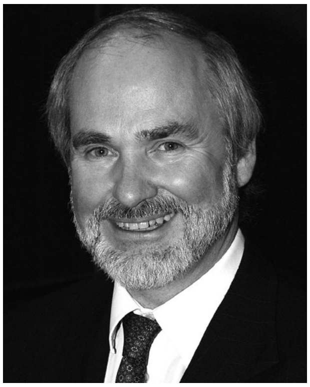

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