Advanced Control in Marine Mechatronic Systems: A Survey

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***Abstract*—This paper surveys the recent advances in marine mechatronic systems from a control perspective. The survey is by no means exhaustive, but introduces some notable results in marine control area. New developments in terms of control system designs for surface vessels, underwater robotic vehicles, profiling floats, underwater gliders, wave energy converters, and offshore wind turbines are briefly reviewed. In addition, a few avenues for future research are identified.**

***Index Terms*—Advanced control, Marine mechatronics, ocean wave energy converter (OWEC), offshore wind turbine, profiling float, surface vessel, underwater glider, underwater robotic vehicle (URV).**

I. INTRODUCTION

THE OCEANS cover two thirds of the Earth and have a crucial impact on our ecosystem. Besides their traditional significance as sources of food, natural resources, and biodiversity, the ecological, economic, and social importance are now better understood. Lakes, rivers, and canals spread all over the land, making the interaction with the marine environment a common daily experience for humans. The increasing reliance on oceans and waterways in a spectrum of human activities such as resource exploitation and transportation have demonstrated the large demand for advanced marine mechatronic systems that facilitate multifarious in-water tasks with improved performance and robustness.

Marine mechatronics are the integration of mechanical, electrical, control, and computer disciplines applied in the marine environment. This demanding environment brings many challenges in design, building, operation, and maintenance of the marine mechatronic system. Harmful consequences of multiple adverse factors, such as hydrostatic pressures, material corrosion, hydrodynamic impact, and attenuation of electromagnetic signals have to be avoided or carefully addressed. Though intractable, these challenges have been promoting the development of marine science and technology toward a promising future.

In this paper, we briefly review the recent advances in marine mechatronics from a control perspective. Surface vessels, underwater robotic vehicles (URVs), profiling floats, underwater gliders, ocean wave energy converters (OWECs), and offshore wind turbines are representative marine mechatronic systems which exemplify the developments of marine transportation, underwater intervention, ocean sampling and monitoring, and offshore energy harvesting technologies. In the following, we attempt to summarize the existing results for these marine mechatronic systems in terms of control system design.

II. CONTROL OF SURFACE VESSELS

Surface vessels are recognized one of the oldest marine mechatronic systems and play a critical role in oversea transportation. Early days, the maneuvering of marine vessels greatly depended on sailers' experience. In 1911, the first autopilot was invented by Elmber Sperry [1], which preluded the extensive control system designs for marine surface vessels.

The dynamic positioning (DP) system is the typical control system for surface vessels and is essential for many marine applications, such as marine oil exploration, pipeline laying and so on; see the survey paper in [2] and references therein. Generally speaking, a DP system refers to the control system of a surface vessel, usually in low-speed, fully-actuated mode, that automatically maintain its position and heading at a fixed point or preset way points along track, by only using its propellers and thrusters. The main challenges for the design of a DP system are as follows.

1) The ship dynamics are nonlinear.
2) The velocities are not available in practice, and only the measurements of positions are available, but subject to noises.
3) The exact system model is unknown and the working condition is generally very harsh, introducing the uncertain external forces from ocean waves, currents, and winds.

To solve the issue of model nonlinearity, the backstepping techniques are widely used in the design of DP systems [3].

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Furthermore, to deal with the second challenge, the Luenberger observer [4], nonlinear observer [5], passivity-based nonlinear observer [3], and Kalman filters [6] are proposed to provide velocity estimates for the control system design.

Recent progresses on DP control are focused more on dealing with the third challenge (i.e., model uncertainties and disturbances) to improve control performance. The hybrid control strategy is one of the most practical choices. Tutturen and Skjetne [7] developed a hybrid control strategy in proportional-integral-derivative (PID)-based controller design of a DP system, and this strategy allows a flexible tuning, leading to improved transient performance. In order to remove the requirement of velocities measurement, Muhammad *et al.* [8] propose an advanced passivity-based control strategy, where the interconnection and damping assignment-passivity-based control methodology is applied for solving the DP problem. To handle disturbance and input delays caused by the command transmission via radio channels, Wang *et al.* [9] develop a robust output "consecutive compensator" for robotic vessels. In addition, the intelligent control strategies also represent an effective way to deal with model uncertainties, nonlinearities and disturbances simultaneously, such as the high-gain observer and radial basis function neural networks-based adaptive DP strategy in [10] and the adaptive fuzzy controller in [11].

It is worth mentioning that the use of tugboats is effective to improve the control performance in the DP, especially for large vessels. An adaptive position control problem is investigated relying on the communication among tugboats in [12], but the location information of the tugboats is not needed. In the same framework, [13] further deals with parameter uncertainties and the work in [14] considers the control saturation. Furthermore, by only using multiple unidirectional tugboats, the work in [15] proposes a robust DP strategy for underactuated vessels. To learn the properties of the model uncertainty, the work in [16] develops an artificial neural network (ANN) based strategy.

Different from DP, the path-following controller is designed such that the vessel, usually in underactuated mode, can automatically converge to and follow a specified path with desired speed profile. Therefore, the first challenge in path-following control is the underactuation of the marine vessel. For most marine vessels, in high-speed applications, such as path-following, the surge, and yaw directions are directly actuated but the sway direction is not, leading to an underactuated system that cannot be stabilized by a pure-static state feedback controller. (Refer to [1] for detailed modeling and nomenclature.) The second challenge faced by the path-following control is model uncertainties and the external disturbances generated by sea waves, currents, and winds.

In general, the tool of backstepping and Lyapunov's direct approach is used to handle the problem caused by underactuated dynamics. The issues on model uncertainties and external disturbances are generally resolved by adaptive control strategy [17], estimation strategy [18] and integral action [19] to compensate for the side-effect of uncertainties and the robust stability of the closed-loop system can be obtained.

For the path-following control problem considering full system model including dynamics and kinematics, three different frameworks have been developed. The first one, e.g., [20], casts the path-following problem as driving the vessels to follow a virtual ship centered at the path and finally moving along the path with desired speed profile. The second one is referred to as the Serret–Frenet frame-based on approach. In this approach, the Serret–Frenet frame is utilized to characterize the yaw angle and cross-track errors, and the yaw moment is used as the control input to make these errors converge to zero. This framework is adopted in [21] for following linear paths and those in [22] and [23] for curve paths. These two frameworks only bring local stability to the path-following controller due to the singularity issues. The third framework, such as in [24], is the global path-following approach that is a combination of the trajectory tracking and path-following, and the path-parameter is utilized as an additional control variable to drive the lateral cross-tracking error to become zero. In this framework, the singularity in the cross-track error dynamics can be avoided by adjusting the lateral path-following error, leading to global results.

To reduce the complexity introduced by vessel dynamics, some researchers study the path-following problem by considering only the kinematic model assuming that the speed of vessel is controlled independently. The ideas are based on the light-of-sight (LOS) guidance law, including proportional LOS and proportional-integral LOS. The LOS guidance law is simple, computationally cheap, and easy to be implemented. The main idea behind the LOS guidance-based path-following approaches is to mimic an experienced sailor. The controller design in [25] utilizes the proportional LOS guidance strategy to follow straight line paths, and in [26], the authors develop a sliding mode controller within the framework of proportional LOS guidance law.

In comparison with the proportional LOS guidance law, the proportional-integral LOS is more effective in terms of handling external disturbances induced by wave, current, and wind. The proportional-integral LOS-based control strategy is introduced in [18] to handle constant ocean current. Recently, in [19], a novel proportional-integral LOS-based path-following system is developed to follow Dubins paths where the sideslip caused by drift forces is fully compensated. A more general framework is proposed in [27], by simultaneously considering kinematics and dynamics for marine vessels, where the simulation and experiment results are reported.

Besides DP and path-following, the trajectory tracking is another practical functionality for surface vessels. In comparison with path-following, apart from steering control laws we now need specific speed laws in the trajectory tracking. Formally, the trajectory tracking problem is defined by controlling a surface vessel to track a spatial and temporal trajectory with strict time requirement. The main challenges identified in trajectory tracking include model uncertainties, unknown disturbances, system constraints, and unmeasurable system states.

In the literature, several approaches can be utilized to design the trajectory tracking system. The most popular approach is based on the backstepping technique. The tracking controller is designed via backstepping procedure and the Lyapunov's direct method [28]. The second widely adopted approach is the sliding model control (SMC), where the sliding surfaces are introduced for characterizing the tracking errors, e.g., [29]. Other approaches mainly include model predictive control (MPC) [30], dynamic surface control (DSC) [31], linear algebra-based approach [32], and intelligent control strategies [33].

In particular, to handle the model uncertainties and external disturbances, Li investigates the trajectory tracking problem of surface vessels with general nonlinear dynamics and model uncertainties in [34], where a modified backstepping procedure is developed. Do studies of trajectory tracking problem for underactuated surface vessels subject to stochastic disturbances in [35], where an adaptive backstepping strategy is adopted to address the effects of disturbances. The effects of wind, ocean current, and wave are modeled by an uniformly distributed stochastic process in [36], and the nonlinear MPC framework is developed to solve the trajectory tracking problem. An observer is designed to provide estimates of the unknown disturbances for the trajectory tracking control system of the vessel in [37].

To address practical constraints, Huang *et al.* [28] study the global trajectory tracking problem of underactuated surface vessels with input saturation, where two separate controllers are designed based on the backstepping strategy. Chwa [31] utilizes the DSC approach to solve the global trajectory tracking problem of underactuated surface vessels with input and velocities constraints. The nonlinear MPC is utilized to solve the same problem for underactuated surface vessels with input constraints in [36]. The fact that the system states cannot be directly measured is another practical issue, requiring the output feedback trajectory tracking strategies. Consolini *et al.* in [38] provide theoretical results on designing output feedback trajectory tracking controller for nonminimum phase underactuated surface vessels. The output tracking problem is solved using complete vessel dynamics including Coriolis and centripetal forces and nonlinear damping in [39], where an observer is designed to offer state estimates. A sampled-data system setup is considered in [40], and both state and output feedback tracking controllers are designed for underactuated surface vessels.

III. CONTROL OF URVS

URVs exemplify the recent advance in underwater mechatronic systems. Submarine science projects such as EMSO [41] have revealed the convenience, efficiency, and safety of the use of URVs. In fields of marine geoscience, offshore industry, and deep-sea archaeology, URVs have been proven effective tools and have been contributing significantly during the past several decades. The integration of robotic manipulators greatly improves the intervention capability in ocean engineering projects, and the widespread use of URVs is becoming an irreversible trend in the future [42]–[44].

The motion control is the key to various URV applications. Similar to surface vessels, the control system designs for DP, path-following, and trajectory tracking are still relevant to URVs. The major difference is probably the availability of the position and external sensor information. For URVs, the global positioning system is unavailable due to the exponential decaying rate of electromagnetic signals in water. Instead, acoustic positioning systems (APSs) are used for practical underwater navigation. The integration of Doppler velocity log and inertial measurement units (IMU) into APS has greatly improved the accuracy and update rate of the measurement. The coming of microelectromechanical IMUs makes the significant drop in both price and size, which stimulates the growth of the URV community. The techniques and challenges in underwater localization are reviewed in [45]. Underwater navigation sensor technology and existing navigation algorithms are summarized in [46]. Nevertheless, from control point of view, the control strategies designed for surface vessels, in principle, work for URVs. However, the motion of URVs is extended from the two-dimensional (2-D) surface workspace to the 3-D underwater workspace. Therefore, besides the horizontal plane, motion in the vertical plane needs to be considered [47]. Likewise, the technical challenges arising in URV motion control mainly come from the following aspects:

1) highly nonlinear and inherently coupled dynamics;
2) parametric uncertainties caused by poor knowledge of the hydrodynamic coefficients;
3) unpredictable external disturbances such as the tether force, end-effector payloads and ocean currents;
4) underactuation of the vehicle.

Various controller designs have been proposed to tackle these challenges [48].

DP functionality traditionally refers to the station-keeping control of marine vehicle with solely thrusters. Recently, the conventional DP functionality has been generalized to a unified system that contains all of the low-speed maneuvering applications of URVs. For feedback control in the DP system, multivariable PID type controllers are universally used due to their easy implementations [2]. The linear-quadratic-regulator (LQR) often combined with Kalman filtering technique represents another effective control method as DP is the low-speed application and a linear approximation of the motion may be sufficient [1]. However, when the transient control performance is pursued, the nonlinearity of the motion has to be considered. The well established nonlinear dynamic model can be arranged in the form of $\dot{x} = f(x) + g(x)u$, so the feedback linearization appears a straightforward way to deal with the nonlinearity by setting $u = -f(x)/g(x) + \bar{u}/g(x)$. However, the feedback linearization-based controllers often require an accurate system model due to its sensitivity to disturbances. To enhance the robustness, the Lyapunov-based beckstepping technique is widely used in DP applications [49]. The Lyapunov-based beckstepping control sometimes suffer from the problem of "explosion of terms," which motivates the designs of dynamic surface controllers [50], [51].

The SMC technique has been successfully applied to URV DP problems in [52]. The charm of SMC owes to its insensitivity to imprecision in URV dynamic models, hence gorgeous for control of marine vehicles whose model inevitably contains parametric uncertainties due to the infinite dimensional fluid dynamics. However, the discontinuity in the control law bring a drawback known as the chattering effect. Therefore, the SMC-based DP controllers have to be enhanced by, for example, an adaptive law [52], [53] or higher order sliding mode [54], to eliminate this side effect. Practical issues, such as input nonlinearities [55], can also be handled.

Adding adaptation mechanism to DP controllers is an effective way to deal with parametric uncertainties. The control performance is improved significantly by involving an adaptive law to the combined PID-SMC controller in [56]. The recently developed L_1 norm minimization technique is integrated into the adaptive control of URVs in [57], which demonstrates an improved robustness and faster adaption convergence. ANNs can be viewed as a special type of adaptive control technique which have been applied to the URVs in [58]. Though effective, one drawback of ANN-based controller may refer to the difficulty in analyzing the closed-loop properties such as stability and robustness. A similar approach based on the reinforcement learning is exploited in [59].

Recent studies on DP system consider more practical issues. The lower-level thruster dynamics is incorporated into the fuzzy SMC-based controller in [60], so that the DP performance can be significantly improved. To handle system constraints in the controller design, the MPC [61], [62] technique is exploited. The constrained DP problem is well studied in a pure theoretical perspective in [63], and the recursive feasibility and asymptotical stability are guaranteed. The combined path planning and DP problem is solved in [64], using a receding horizon optimization method. A fast nonlinear MPC algorithm is developed to improve the computational efficiency in [65]. Fault-tolerant control of URVs is discussed in [66], where the DP system enables the built-in thruster fault tolerance via an optimization setup. An interesting approach is reported in [67], where a robust controller is designed based on a Smith controller and the linear quadratic Gaussian (LQG)/LTR methodology to address the tethered cable induced disturbance in terms of time delays.

A subproblem in DP is the thrust allocation (TA) problem. The DP systems generate the generalized commanded control force and moments, and finding the corresponding thrust force for each thruster that meets the DP commands is called TA. One prominent approach is the 2-norm-based optimization which aims at minimizing the overall control effort. The (weighted) pseudoinverse method [68] is a closed-form solution assuming that the calculated control commands never exceed the thruster limits. Pseudoinverse method is cheap in computation but barely adequate to guarantee the feasibility. More often the TA problem is formulated as a quadratic programming (QP) problem that explicitly takes care of the individual limit on each thruster. To alleviate the burden on the online computation side, a parametric QP solution is proposed in [69]. When the thrusters are rotatable, the allocation problem becomes nonlinear. The direct nonlinear programming solution is discussed in [70]. A piecewise linear approximation is made in [71], extending the results in [69] with the azimuth angle considered as an augmented decision variable. Another effective technique used in TA is the singular value decomposition (SVD). The filtering technique is combined with SVD to perform the optimal allocation in [72]. Other approaches mainly include the 1-norm minimization [73] and infinity-norm minimization [53]. A notable variant is proposed in [74], where a dynamic update law is proposed instead of the static optimization procedure. The asymptotical stability of the update law can be guaranteed providing that an exponentially stable trajectory tracking controller is working. Recent studies on MPC-based URV controller design [75] imply that the TA problem might be simultaneously addressed within the DP control.

Besides DP, the trajectory tracking and path following controller designs for underactuated URVs are of practical interest, especially in the 3-D setup. In context of URV, the underactuation results from the fact that only surge, pitch, yaw, and in a few cases, heave are directly controllable. The trajectory tracking control of underactuated URV is challenging because the vehicle dynamic model cannot be fully feedback linearized and nonholonomic constraints exist in the vehicle motion. (Refer to [76] for these concepts.) Local linearization may be used and followed by the classic linear control techniques, but the drawback is obvious that stability properties can only be ensured in a neighborhood of predefined operating points. For URV tracking control of curves, linear controllers often exhibit unsatisfactory performance because the application of trajectory tracking, by nature, emphasizes the nonlinearity and cross-coupling in motion. Lyapunov-based nonlinear control methods, therefore, become the mainstream in the trajectory tracking controller design. The trajectory tracking problem is well studied for underactuated vehicles in [77]. Based on the direct Lyapunov method, a recursive backstepping procedure is provided with application to underactuated URVs in 3-D workspace. This work has been extended in [78] by adding an adaptive supervisory control to the nonlinear tracking controller to deal with parametric uncertainties. For some practical situations that only position and orientation (but not velocities) are measurable, the observer-controller structure is motivated for solving the trajectory tracking problem. The Luenberger observers together with Lyapunov-based nonlinear tracking controllers are designed in [79]. Experimental results demonstrate quite satisfactory tracking performance. An important alternative is SMC-based URV tracking controller design, e.g., [80]. It has advantages in handling model uncertainty but the chattering phenomenon needs to be carefully avoided.

In many cases, however, we are mainly interested in tracking a specified path, i.e., the spatial requirement and the temporal requirement may be relaxed. Therefore, the path-following problem is much more investigated and used URV application than trajectory tracking. For path-following of underactuated URVs, early results are extended work of those in land robots area. The Serret–Frenet framework developed at the kinematics level is extended to the dynamics level by means of Lyapunov-based backstepping technique, e.g., [81], [82]. However, the target point selected in the Serret–Frenet framework to be the closest point on path relative to the vehicle yields an inherent limitation: there exist singularities for certain initial positions of the vehicle, located exactly at the centers of path curvature. To eliminate the singularities, a different path-following strategy is used in [83], where the target point becomes a virtual moving point, known as path parameter, along the path. The path parameter essentially creates an additional degree of freedom in the controller design which can be utilized to meet the dynamic assignment. (Refer to [84] for detailed concepts.) To further enhance robustness against parametric uncertainties, in [85], an adaption scheme is involved in the Lyapunov-based nonlinear controller design using the same path-following control strategy. The guidance-based path following controller has also been extended to 3-D settings for URV applications. A guidance-based path-following controller is designed for a 5 DOF underwater vehicle addressing the interaction between the LOS guidance and the heading/pitch controller in [86]. In a recent study [87], by means of multiobjective MPC, the prioritization between the geometric assignment and dynamic assignment can be explicitly considered.

There are also some studies devoted to the point stabilization problem of underactuated URVs. However, the nonholonomic constraints prevent the use of smooth feedback control laws to perform the point stabilization [88]. Various discontinuous control are designed for URVs. A hybrid control law with a logic-based switching is proposed in [89] and the global uniform stability is claimed. A notable result is reported in [90], where a nonsmooth coordinate transformation is introduced and followed by the Lyapunov-based backstepping procedure in the transformed coordinate system. An adaptive control law is then provided to make the controller robust against parametric uncertainties. External disturbances are considered in [91], where URV is modeled as a switched seasaw system and a switched controller is designed.

When the URV is equipped with robotic manipulators, the coordination between the vehicle and manipulators will be important. At the early stage, the motions of the vehicle and manipulators were controlled independently. The coordination control hence focused on retaining the set-point of the vehicle while performing the manipulation. Therefore, the influence of manipulation is often considered as external disturbances and compensation schemes are developed complementary to the control law. As proposed in [92], the hydrodynamic interaction force between the vehicle and manipulator is predicted via an accurate model and then fed to the vehicle controller for the improved station-keeping capability. The dynamic coupling effect of the manipulator motion is viewed as disturbances in [93] and an observer is designed to estimate the force-torque information, which is used to compensate the coupling effect. However, in the independent control paradigm, the redundant thruster arrangement of the URV is not fully exploited. Therefore, recent researches incorporate the TA into the motion coordination between the vehicle and manipulators. By means of redundancy resolution, a secondary objective can be achieved without degrading the end-effector's performance. A series of secondary objectives have been defined, among which the most typical include minimal vehicle movement [94], joint limit avoidance [95], manipulability maximization [96], and drag force minimization [97]. Practical issues such as fault-tolerant capability [98] and time-delay compensation [99] are explicitly considered in the most recent results of the coordinated control.

IV. CONTROL OF PROFILING FLOATS AND UNDERWATER GLIDERS

The capability of ocean sampling and monitoring without the need for human presence in the dangerous underwater environments makes AUVs a sustained interest among the worldwide oceanic scientific research community over the past decades [100]. Key for the development of advanced AUVs is an integration of control, communication, and computation technologies, which benefited significantly from the recent sweeping advances in these fields. The technological sophistication, however, usually comes with high economic costs, making AUVs expensive and thus less available to a wide range of ocean-related research. This has been providing impetus for the research and use of a class of small and cheap, though less capable, AUVs, known as profiling floats. A profiling float only has buoyancy control to adjust its vertical position and depends on the ocean currents for lateral motion. Despite underactuation, it can transverse the ocean at different depths for long durations to observe the temperature, salinity, and currents [101], [102]. About 3900 such instruments have been being deployed in global oceans through the internationally collaborative Argo program to collect data for climate and oceanographic research [103].

Depth control of profiling floats, central for their task execution, turns out to be a challenging task—for example, those deployed by the Argo program often exhibit a coarse depth regulation and thus become unsuitable for some marine environments, e.g., shallow coastal waters [104]. This results from 1) the limited precision of depth measurements due to complex marine settings and 2) the lack of effective control mechanisms. There has been ongoing research effort to overcome these disadvantages in the design of new types of profiling floats specifically for observing coastal currents [105]. This is partly due to the progress of sensing technologies, affording better pressure, water density, and salinity sensors for depth determination. Another contributing factor is the improved control. Currently, both model-free and model-based methods find application in this regard. For the former category, the PID control is popular and used in [106]. An approach dependent on trial-and-error, open-loop control is used in [107] for the float in [108]. When a model becomes available to capture the dynamics of the profiling floats, it can be used to achieve better control. A model-based on/off switching controller is designed in [109] and a backstepping controller in [110] for the float in [111].

Underwater gliders are another type of low-cost AUVs that can move forward horizontally while profiling, often considered an extension of the profiling floats [112]. In a torpedo-like shape, a glider does not depend on external active propulsion systems like thrusters or propellers; instead, it propels itself through lower-power buoyancy, movable internal mass, wings, tail, and rudder. By adjusting these propelling units, it can change depth to glide, moving upward or downward in a seesaw pattern at a relatively slow speed. Operating with extreme energy efficiency, the gliders have long-range and long-duration capabilities, some models in use today are able to travel as far as several thousand kilometers, dive to over one kilometer deep, and collect data at spatial resolutions of several meters [113]. Their significant potential for oceanographic research has driven a rapidly growing interest in the research and development effort.

The control system is a glider's performance enabler, expected to achieve accurate navigation and maneuverability with minimum energy consumption. A glider's operation mainly depends on steady motions that include gliding in the seesaw pattern, turning, and gliding in a vertical spiral. The gliding dynamics under the movable internal mass is modeled in [114] using the Newton–Euler formulation. The model identification, however, can be difficult due to the nonlinearities and large number of parameters. Data-driven black-box identification is studied in [115], and parameter-specific identification discussed in [116], where different parameters are determined in turn using either practical knowledge, sensor measurements or least squares. Given a dynamic model, control of buoyancy, pitch (diving angle), and heading angle for steady motions will then be of much interest and importance. One way will be to let the glider follow piecewise linear paths by finding the equilibria of dynamics throughout the gliding [114], [117]. A mix of open- and closed-loop control can be used here. For instance, switching between downward and upward gliding is performed in open loop by changing the buoyancy and moving mass [118]. For the pitch and heading control, the proportional control has become widely deployed in operational gliders [119], but more sophisticated designs, such as PID [120], LQR [121], MPC [122], and integrated switching control and backstepping [123], have also been exploited in the literature. As gliders can have a limited set of sensors and often have no direct location measurements for a long time, effective state estimation is needed for both practical operation and control. In this regard, the extended Kalman filter has been leveraged in [120] and linearized observer design in [118].

Both profiling floats and gliders have only limited control and actuation authority. The underactuation, while posing limitations for control, has stimulated the pursuit of control enhancement leveraging the environmental dynamics. The standpoint is that the effects of ocean currents on profiling floats, if well understood and exploited, will help expand the floats' autonomy. For instance, ocean model-based predictions are utilized to guide the depth control of a profiling float and even enable the horizontal motion control at certain level in [105]. Increased accuracy is brought to glider navigation through the use of predictive ocean models in [124]. Though still under formation, this research line represents an integration of AUV-ocean dynamics and will be in a critical role for the future AUV control.

V. CONTROL OF OWECS

Ocean waves are constantly on the move with tremendous kinetic energy. Harnessing them for electricity generation has long captured the imagination of humans. This dream is being turned into reality by significant headway made in the past decades in the development of various OWECs and the construction of commercial wave farms globally [125]. This trend has been pushed by the mechatronics technology. Today's OWECs can be divided three main categories as follows.

1) Oscillating water columns that use wave-induced inward and outward passage of air in a water column to run a turbine.
2) Oscillating body converters that are buoy-like devices, using the wave motion from all directions (up/down, forward/backward, side to side) to generate electricity.
3) Overtopping converters that use reservoirs to collect and funnel wave water to drive a turbine [126].

One can conduct subdivision of each category based on different criteria, e.g., the ways of converting convert wave energy into pneumatic/mechanical energy (rotation/ translation), power generation (air turbines, hydraulic turbines, hydraulic engines), structures (fixed, floating, submerged), and deployment locations (shoreline, near shore, off shore) [126], [127].

The control system essentially governs the power take-off (PTO) system of an oscillating body converter. To maximize power extraction, PTO control regulates the oscillation of the converter for an optimal interaction between the converter and the incident wave. [128]. Static damp or stiffness was often used in the past for this purpose, yet only useful at a single frequency. Nowadays, the sights are mainly set on active control in two categories: 1) causal control that depends only on wave measurements up to the present, and 2) noncausal control that requires a forecasting of the wave. For the former type, the design thinking of optimal has been well applied, leading to LQG [129], PID-like [130], and bang-bang-type [131] control strategies. It was found in [132] that optimal OWEC control needs information about future wave and thus is noncausal. Fortunately, ocean waves are more predictable and steadier than solar and wind energy. This offers an opportunity to forecast the wave dynamics for the benefits of noncausal control. Different ways have been proposed for wave prediction, e.g., adaptive-filter-based [133], fuzzy-logic-based [134], and Kalman-filter-based [135]. The integration of wave preview data with control design toward better efficiency of converters has been studied for a fuzzy logic controller [136] and constrained optimal control, especially MPC [137]. Besides, the use of controls strategies, including PID and MPC, is studied [138] to balance power output and structural fatigue of wave energy converters for maximum economic value.

Commercialization of wave energy harnessing requires the installation of converter farms. In the past, a large body of work was proposed to characterize and model the dynamic behavior of wave energy converter arrays in specific configurations [139]. Recently, coordination of converters has aroused some interest with its potential benefits for the entire system. Decentralized optimal control provides a significant tool to increase the overall PTO by optimizing the power absorption of individual converters as studied in [140]. However, this area still remains nascent and needs further research and development to push the technology into practice.

VI. CONTROL FOR OFFSHORE FLOATING WIND TURBINES

Wind energy is a primary solution to the global demand for clean and sustainable energy supply for its cost-competitiveness and environmental friendliness, with a rapidly growing penetration now and in the foreseeable future. Control systems are a vital part of wind turbines for their ability to increase the wind turbine efficiency and reduce structural loading, which means practical economic savings and service life extension [141]. Their key application includes blade pitch control that changes the orientation of the blades for optimizing the aerodynamic forces and the wind power capturing, and generator torque control that regulates the rotor speed in order to capture as much power as possible. A variety of methodologies have been put in place thus far [142]–[144]. While the land-based wind energy technology has reached a certain level of maturity, there is a shift of attention to the utilization of offshore winds for their higher speeds and less turbulence [141]. The majority of the offshore wind resources are in waters deeper than 30 m, and a wind turbine installed in these areas needs to be mounted on a floating base for stability. However, the floating platform, e.g., spar buoys, tension leg platforms, and barges, introduces extra degrees of freedom and is exposed to additional motions and uncertainties created by winds and waves. Without effective control, consequences will result including less power production and increased turbine structural load [145]. This makes the development of control systems specifically for floating wind turbines a necessity.

For a floating wind turbine, the blade pitch control has particular importance for stabilizing the platform, capturing power, and reducing fatigue. Because the turbine control is wind-speed-dependent and subjected to significant nonlinearities, a common practice is to design multiple controllers and pick one via gain scheduling in operation [146]. Gain-scheduled PID control for a floating turbine is investigated in [147], which has been often used as a baseline control approach in this area. A synthesis of gain scheduling with the LQR control and the linear parameter-varying model is made in [148] to deal with plant nonlinearity with respect to wind speed. Similar to OWEC control, predictive control [149] taking advantage of future wind information is considered more competent. This thus has led to the application of linear and nonlinear MPC, along with wind preview, to floating turbine control, e.g., [150], [151]. However, wind preview must be obtained prior to the control run. The light detection and ranging (LIDAR), a remote sensing technology, is used to measure the wind speeds in front of the turbine in [151]. The LIDAR data are then fed to the controller in a feedforward manner to improve control. In addition to this, data-driven wind prediction and wind field reconstruction have drawn much interest, with the aid of the Kalman filtering techniques in [152]. Because the running of floating turbines is affected by motion uncertainties and incident wave conditions, the disturbance rejection theory is combined with adaptive control in [153] and the disturbance accommodating control used in [154] to cope with this problem. Another way to handle certainty is through robust control, and a study of robust H_∞ control is presented in [155] for a floating wind turbine.

For floating wind turbines, an emerging research topic is structural control. An actively pursued research subject in the area of civil engineering, structural control aims to mitigate dynamic loading imposed on structures by wind, waves, and earthquakes. Its significance naturally extends to floating wind turbines that often operate in adverse meteorological and oceanographic conditions. In this direction, the status quo mostly concerns passive control, which uses passive systems, e.g., a tuned mass-damper (TMD) system, to take away energy at one of the natural frequencies of the entire system [156]. Active structural control, which includes an actuator to regulate the TMD system, is more complex but more powerful. Recently, H_∞-based control has been applied in this regard, see [157]. A joint floating turbine structure and control design is proposed to optimize the floating platform concurrently with the controller in [158].

VII. CONCLUSION

Historically, the oceans have been an essential part of the humans' life as food sources and transportation routes. The world is looking more to them today to seek solutions to various grand challenges, such as natural resource and energy shortage and climate change. This has stimulated an ongoing effort to develop multifarious mechatronic systems in order to better understand and use the oceans, which have unanimously capitalized on advanced control theory. We have briefly reviewed, in this paper, the recent developments of advanced control system designs for six representative marine mechatronic systems, namely, surface vessels, URVs, profiling floats, underwater gliders, OWECs, and offshore wind turbines.

It is anticipated that the humans' marine activities will expand exponentially in the next decades, and a key enabler of this future will be the mechatronic systems, at the core of which will be high-caliber control. Accordingly, we can envision a growing research and development of advanced control systems specific for marine mechatronics to fulfill this demand. Numerous exciting research challenges will be ahead on the road, of which three primary ones are identified as follows. First, how to achieve precise control of an individual marine vehicle in the presence of severe nonlinearities, underactuation, limited sensing capabilities, and complicated ocean environments? Second, how to coordinate a swarm of marine vehicles, especially the underwater ones, under restricted communication, heterogeneous dynamics, and individual operating constraints? Third, how to enable the execution of advanced control algorithms through the embedded marine mechatronics platforms subjected to computational and communication constraints?

REFERENCES

[1] T. Fossen, *Marine Control Systems: Guidance, Navigation and Control of Ships, Rigs and Underwater Vehicles*. Trondheim, Norway: Marine Cybernetics, 2002.

[2] A. J. Sørensen, "A survey of dynamic positioning control systems," *Annu. Rev. Control*, vol. 35, no. 1, pp. 123–136, 2011.

[3] A. Loria, T. I. Fossen, and E. Panteley, "A separation principle for dynamic positioning of ships: Theoretical and experimental results," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 2, pp. 332–343, Mar. 2000.

[4] A. J. Sørensen, S. I. Sagatun, and T. Fossen, "Design of a dynamic positioning system using model-based control," *Control Eng. Practice*, vol. 4, no. 3, pp. 359–368, 1996.

[5] T. I. Fossen and A. Grovlen, "Nonlinear output feedback control of dynamically positioned ships using vectorial observer backstepping," *IEEE Trans. Control Syst. Technol.*, vol. 6, no. 1, pp. 121–128, Jan. 1998.

[6] T. I. Fossen and T. Perez, "Kalman filtering for positioning and heading control of ships and offshore rigs," *IEEE Control Syst. Mag.*, vol. 29, no. 6, pp. 32–46, Dec. 2009.

[7] S. A. Tutturen and R. Skjetne, "Hybrid control to improve transient response of integral action in dynamic positioning of marine vessels," *IFAC-PapersOnLine*, vol. 48, no. 16, pp. 166–171, 2015.

[8] S. Muhammad and A. Doria-Cerezo, "Passivity-based control applied to the dynamic positioning of ships," *IET Control Theory Appl.*, vol. 6, no. 5, pp. 680–688, 2012.

[9] J. Wang *et al.*, "Output control algorithms of dynamic positioning and disturbance rejection for robotic vessel?" *IFAC-PapersOnLine*, vol. 48, no. 11, pp. 295–300, 2015.

[10] J. Du, X. Hu, H. Liu, and C. L. P. Chen, "Adaptive robust output feedback control for a marine dynamic positioning system based on a high-gain observer," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 26, no. 11, pp. 2775–2786, Nov. 2015.

[11] X. Hu, J. Du, and J. Shi, "Adaptive fuzzy controller design for dynamic positioning system of vessels," *Appl. Ocean Res.*, vol. 53, pp. 46–53, 2015.

[12] D. Braganza, M. Feemster, and D. Dawson, "Positioning of large surface vessels using multiple tugboats," in *Proc. 2007 Amer. Control Conf.*, 2007, pp. 912–917.

[13] V. Bui, H. Kawai, Y. Kim, and K. Lee, "A ship berting system design with four tugboats," *J. Mech. Sci. Technol.*, vol. 25, no. 5, pp. 1257–1264, 2010.

[14] M. G. Feemster and J. M. Esposito, "Comprehensive framework for tracking control and thrust allocation for a highly overactuated autonomous surface vessel," *J. Field Robot.*, vol. 28, no. 1, pp. 80–100, 2011.

[15] B. Bidikli, E. Tatlicioglu, and E. Zergeroglu, "Robust dynamic positioning of surface vessels via multiple unidirectional tugboats," *Ocean Eng.*, vol. 113, pp. 237–245, 2016.

[16] V. Tran and N. Im, "A study on ship automatic berthing with assistance of auxiliary devices," *Int. J. Naval Archit. Ocean Eng.*, vol. 4, no. 3, pp. 199–210, 2014.

[17] K. D. Do, Z.-P. Jiang, and J. Pan, "Robust adaptive path following of underactuated ships," *Automatica*, vol. 40, no. 6, pp. 929–944, 2004.

[18] E. Børhaug, A. Pavlov, and K. Y. Pettersen, "Integral LOS control for path following of underactuated marine surface vessels in the presence of constant ocean currents," in *Proc. 47th IEEE Conf. Dec. Control*, 2008, pp. 4984–4991.

[19] T. I. Fossen, K. Y. Pettersen, and R. Galeazzi, "Line-of-Sight path following for dubins paths with adaptive sideslip compensation of drift forces," *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 2, pp. 820–827, Mar. 2015.

[20] J.-H. Li, P.-M. Lee, B.-H. Jun, and Y.-K. Lim, "Point-to-point navigation of underactuated ships," *Automatica*, vol. 44, no. 12, pp. 3201–3205, 2008.

[21] E. Fredriksen and K. Y. Pettersen, "Global k-exponential way-point maneuvering of ships: Theory and experiments," *Automatica*, vol. 42, no. 4, pp. 677–687, 2006.

[22] Z. Li, J. Sun, and S. Oh, "Design, analysis and experimental validation of a robust nonlinear path following controller for marine surface vessels," *Automatica*, vol. 45, no. 7, pp. 1649–1658, 2009.

[23] K. D. Do and J. Pan, "State- and output-feedback robust path-following controllers for underactuated ships using Serret-Frenet frame," *Ocean Eng.*, vol. 31, no. 5-6, pp. 587–613, 2004.

[24] K. D. Do and J. Pan, "Underactuated ships follow smooth paths with integral actions and without velocity measurements for feedback: theory and experiments," *IEEE Trans. Control Syst. Technol.*, vol. 14, no. 2, pp. 308–322, Mar. 2006.

[25] T. I. Fossen, M. Breivik, and R. Skjetne, "Line-of-sight path following of underactuated marine craft," in *Proc. 6th IFAC Conf. Maneouvring Control Marine Craft*, 2003, pp. 244–249.

[26] A. J. Healey and D. Lienard, "Multivariable sliding mode control for autonomous diving and steering of unmanned underwater vehicles," *IEEE J. Oceanic Eng.*, vol. 18, no. 3, pp. 327–339, Jul. 1993.

[27] W. Caharija *et al.*, "Integral line-of-sight guidance and control of underactuated marine vehicles: Theory, simulations, and experiments," *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 5, pp. 1623–1642, Sep. 2016.

[28] J. Huang, C. Wen, W. Wang, and Y.-D. Song, "Global stable tracking control of underactuated ships with input saturation," *Syst. Control Lett.*, vol. 85, pp. 1–7, 2015.

[29] H. Ashrafiuon, K. R. Muske, L. C. McNinch, and R. A. Soltan, "Sliding-mode tracking control of surface vessels," *IEEE Trans. Ind. Electron.*, vol. 55, no. 11, pp. 4004–4012, Nov. 2008.

[30] B. J. Guerreiro, C. Silvestre, R. Cunha, and A. Pascoal, "Trajectory tracking nonlinear model predictive control for autonomous surface craft," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 6, pp. 2160–2175, Nov. 2014.

[31] D. Chwa, "Global tracking control of underactuated ships with input and velocity constraints using dynamic surface control method," *IEEE Trans. Control Syst. Technol.*, vol. 19, no. 6, pp. 1357–1370, Nov. 2011.

[32] M. E. Serrano, G. J. E. Scaglia, S. A. Godoy, V. Mut, and O. A. Ortiz, "Trajectory tracking of underactuated surface vessels: A linear algebra approach," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 3, pp. 1103–1111, May 2014.

[33] W. Gierusz, N. C. Vinh, and A. Rak, "Maneuvering control and trajectory tracking of very large crude carrier," *Ocean Eng.*, vol. 34, no. 7, pp. 932–945, 2007.

[34] J.-H. Li, "Path tracking of underactuated ships with general form of dynamics," *Int. J. Control*, vol. 89, no. 3, pp. 506–517, 2016.

[35] K. D. Do, "Global robust adaptive path-tracking control of underactuated ships under stochastic disturbances," *Ocean Eng.*, vol. 111, pp. 267 –278, 2016.

[36] C. Liu, H. Zheng, R. R. Negenborn, X. Chu, and L. Wang, "Trajectory tracking control for underactuated surface vessels based on nonlinear model predictive control," in *Proc. 6th Int. Conf. Comput. Logist.*, Delft, The Netherlands, 2015, pp. 166–180.

[37] Y. Yang, J. Du, H. Liu, C. Guo, and A. Abraham, "A trajectory tracking robust controller of surface vessels with disturbance uncertainties," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 4, pp. 1511–1518, Jul. 2014.

[38] L. Consolini and M. Tosques, "A minimum phase output in the exact tracking problem for the nonminimum phase underactuated surface ship," *IEEE Trans. Autom. Control*, vol. 57, no. 12, pp. 3174–3180, Dec. 2012.

[39] M. Wondergem, E. Lefeber, K. Y. Pettersen, and H. Nijmeijer, "Output feedback tracking of ships," *IEEE Trans. Control Syst. Technol.*, vol. 19, no. 2, pp. 442–448, Mar. 2011.

[40] H. Katayama and H. Aoki, "Straight-line trajectory tracking control for sampled-data underactuated ships," *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 4, pp. 1638–1645, Jul. 2014.

[41] D. MihaiToma, A. Manuel-Lazaro, M. Nogueras, and J. DelRio, "Study on heat dissipation and cooling optimization of the junction box of OBSEA seafloor observatory," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 3, pp. 1301–1309, Jun. 2015.

[42] Y. Wang, S. Wang, Q. Wei, M. Tan, and A. J. Y. C. Zhou, "Development of an underwater manipulator and its free-floating autonomous operation," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 2, pp. 815–824, Apr. 2016.

[43] D. Ribas *et al.*, "I-AUV mechatronics integration for the TRIDENT PF7 project," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 5, pp. 2583–2592, Oct. 2015.

[44] J. Gao, A. Proctor, Y. Shi, and C. Bradley, "Hierarchical model predictive image-based visual servoing of underwater vehicles with adaptive neural network dynamic control," *IEEE Trans. Cybern.*, vol. 46, no. 10, pp. 2323–2334, Oct. 2016.

[45] H. Tan, R. Diamant, W. Seah, and M. Waldmeyer, "A survey of techniques and challenges in underwater localization," *Ocean Eng.*, vol. 38, pp. 1663–1676, 2011.

[46] J. Kinsey, R. Eustice, and L. Whitcomb, "A survey of underwater vehicle navigation: Recent advances and new challanges," in *Proc. 7th IFAC Conf. Marine Craft Maneuvering Control*, Lisbon, Portugal, 2006, pp. 1–12.

[47] L. Lapierre, "Robust diving control of an AUV," *Ocean Eng.*, vol. 36, pp. 92–104, 2009.

[48] J. Yuh, "Design and control of autonomous underwater robot: A survey," *Auton. Robots*, vol. 8, pp. 7–24, 2000.

[49] K. Do, Z. Jiang, J. Pan, and H. Nijmeijer, "A global output-feedback controller for stabilization and tracking of underactuated ODIN: A spherical underwater vehicle," *Automatica*, vol. 40, pp. 117–124, 2004.

[50] R. Gomes, J. Sousa, and F. Pereira, "Integrated maneuver and control design for ROV operations," in *Proc. OCEANS*, San Diego, CA, USA, 2003, pp. 703–710.

[51] Z. Peng, D. Wang, and J. Wang, "Cooperative dynamic positioning of multiple marine offshore vessels: A modular design," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 3, pp. 1210–1221, Jun. 2016.

[52] W. Bessa, M. Dutra, and E. Kreuzer, "An adaptive fuzzy sliding mode controller for remotely operated underwater vehicles," *Robot. Auton. Syst.*, vol. 58, pp. 16–26, 2010.

[53] S. Soylu, B. Buckham, and R. Podhorodeski, "A chattering-free sliding-mode controller for underwater vehicles with fault-tolerant infinity-norm thrust allocation," *Ocean Eng.*, vol. 35, no. 16, pp. 1647–1659, 2008.

[54] T. Salgado-Jimenez, J. Spiewak, P. Fraisse, and B. Jouvencel, "A robust control algorithm for AUV: Based on a high order sliding mode," in *Proc. MTS/IEEE Techno-Oceans*, Kobe, Japan, 2004, pp. 276–281.

[55] R. Cui, X. Zhang, and D. Cui, "Adaptive sliding-mode attitude control for autonomous underwater vehicles with input nonlinearities," *Ocean Eng.*, vol. 123, pp. 45–54, 2016.

[56] S. Soylu, A. Proctor, R. Podhorodeski, C. Bradley, and B. Buckham, "Precise trajectory control for an inspection class ROV," *Ocean Eng.*, vol. 111, pp. 508–523, 2015.

[57] D. Maalouf, A. Chemori, and V. Creuze, "L_1 adaptive depth and pitch control of an underwater vehicle with real-time experiments," *Ocean Eng.*, vol. 98, pp. 66–77, 2015.

[58] K. Ishii and T. Ura, "An adaptive neural-net controller system for an underwater vehicle," *Control Eng. Practice*, vol. 8, pp. 177–184, 2000.

[59] M. Carreras, J. Batlle, and P. Ridao, "Hybrid coordination of reinforcement learning-based behaviors for AUV control," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Maui, HI, USA, 2001, pp. 1410–1415.

[60] W. Bessa, M. Dutra, and E. Kreuzer, "Dynamic positioning of underwater robotic vehicles with thruster dynamics compensation," *Int. J. Adv. Robot. Syst.*, vol. 10, pp. 1–8, 2013.

[61] H. Li, W. Yan, and Y. Shi, "Continuous-time model predictive control of under-actuated spacecraft with bounded control torques," *Automatica*, vol. 75, pp. 144–153, 2017.

[62] H. Li, Y. Shi, and W. Yan, "On neighbor information utilization in distributed receding horizon control for consensus-seeking," *IEEE Trans. Cybern.*, vol. 46, no. 9, pp. 2019–2027, Sep. 2016.

[63] H. Li and W. Yan, "Model predictive stabilization of constrained underactuated autonomous underwater vehicles with guaranteed feasibility and stability," *IEEE/ASME Trans. Mechatronics*, 2016, doi:10.1109/TMECH.2016.2587288.

[64] C. Shen, Y. Shi, and B. Buckham, "Integrated path planning and tracking control of an AUV: A unified receding horizon optimization approach," *IEEE/ASME Trans. Mechatronics*, 2016, doi:10.1109/TMECH.2016.2612689.

[65] C. Shen, Y. Shi, and B. Buckham, "Modified C/GMRES algorithm for fast nonlinear model predictive tracking control of AUVs," *IEEE Trans. Control Syst. Technol.*, 2016, doi:10.1109/TCST.2016.2628803.

[66] S. Soylu, B. Buckham, and R. Podhorodeski, "Robust control of underwater vehicles with fault-tolerant infinity-norm thruster force allocation," in *Proc. OCEANS 2007*, Vancouver, BC, Canada, 2007, pp. 1–10.

[67] M. Triantafyllou and M. Grosenbaugh, "Robust control for underwater vehicle systems with time delays," *IEEE J. Oceanic Eng.*, vol. 16, no. 1, pp. 146–151, Jan. 1991.

[68] T. I. Fossen, *Guidance and Control of Ocean Vehicles*. Hoboken, NJ, USA: Wiley, 1994.

[69] T. Johansen, T. Fossen, and P. Tondel, "Efficient optimal constrained control allocation via multi-parametric programming," *AIAA J. Guid., Control Dyn.*, vol. 28, pp. 506–515, 2005.

[70] V. Poonamallee, S. Yurkovich, A. Serrani, D. Doman, and M. Oppenheimer, "A nonlinear programming approach for control allocation," in *Proc. Amer. Control Conf.*, Boston, MA, USA, 2004, pp. 1689–1694.

[71] T. Johansen, T. Fuglseth, P. Tondel, and T. Fossen, "Optimal constrained control allocation in marine surface vessels with rudders," *Control Eng. Practice*, vol. 16, pp. 457–464, 2007.

[72] O. Sordalen, "Optimal thrust allocation for marine vessels," *Control Eng. Practice*, vol. 5, pp. 1223–1231, 1997.

[73] C. S. Chin, M. W. S. Lau, E. Low, and G. G. L. Seet, "Design of thrusters configuration and thrust allocation control for a remotely operated vehicle," in *Proc. IEEE Int. Conf. Robot. Autom. Mechatronics*, Bangkok, Thailand, 2006, pp. 1–6.

[74] T. Johansen, "Optimizing nonlinear control allocation," in *Proc. 43rd IEEE Conf. Desicion Control*, Paradise Island, Bahamas, 2004, pp. 3435–3440.

[75] C. Shen, Y. Shi, and B. Buckham, "Model predictive control for an AUV with dynamic path planning," in *Proc. Joint 34th Chin. Control Conf. 54th Annu. Conf. Soc. Instrum. Control Eng. Jpn.*, Hangzhou, China, 2015, pp. 475–480.

[76] M. Reyhanoglu, A. van der Schaft, N. McClamroch, and I. Kolmanovsky, "Dynamics and control of a class of underactuated mechanical systems," *IEEE Trans. Autom. Control*, vol. 44, no. 9, pp. 1663–1671, Sep. 1999.

[77] A. Aguiar and J. Hespanha, "Position tracking of underactuated vehicles," in *Proc. Amer. Control Conf.*, Danver, CO, USA, 2003, pp. 1988–1993.

[78] A. Aguiar and J. Hespanha, "Trajectory-tracking and path-following of underactuated autonomous vehicles with parametric modeling uncertanty," *IEEE Trans. Autom. Control*, vol. 52, no. 8, pp. 1362–1379, Aug. 2007.

[79] J. Refsnes, A. Sorensen, and K. Pettersen, "Model-based output feedback control of slender-body underactuated AUVs: Theory and experiments," *IEEE Trans. Autom. Control*, vol. 16, no. 5, pp. 930–946, Sep. 2008.

[80] J. Xu, M. Wang, and L. Qiao, "Dynamical sliding mode control for the trajectory tracking of underactuated unmanned underwater vehicles," *Ocean Eng.*, vol. 105, pp. 54–63, 2015.

[81] P. Encarnacao and A. Pascoal, "3d path following for autonomous underwater vehicle," in *Proc. 39th IEEE Conf. Dec. Control*, Sydney, NSW, Australia, 2000, pp. 2977–2982.

[82] K. Do, J. Pan, and Z. Jiang, "Robust and adaptive path following for underactuated autonomous underwater vehicles," *Ocean Eng.*, vol. 31, pp. 1967–1997, 2004.

[83] L. Lapierre and D. Soetanto, "Nonlinear path-following control of an AUV," *Ocean Eng.*, vol. 34, pp. 1734–1744, 2007.

[84] R. Skjetne, "The maneuvering problem," Ph.D. dissertation, Dept. Eng. Cybern., Norwegian Univ. Sci. Technol., Trondheim, Norway, 2005.

[85] L. Lapierre and B. Jouvencel, "Robust nonlinear path-following control of an AUV," *IEEE J. Ocean. Eng.*, vol. 33, no. 2, pp. 89–102, Apr. 2008.

[86] A. Lekkas and T. Fossen, "Line-of-sight guidance for path following of marine vehicles," *Advanced in Marine Robotics*. Saarbrcken, Germany: Lambert Academic Publishing, 2012.

[87] C. Shen, Y. Shi, and B. Buckham, "Path-following control of an AUV using multi-objective model predictive control," in *Proc. Amer. Control Conf.*, Boston, MA, USA, 2016, pp. 4507–4512.

[88] R. Brockett, "Asymptotical stability and feedback stabilization," in *Differential Geometric Control Theory*. Boston, MA, USA: Birkhauser, 1983, pp. 181–191.

[89] A. Aguiar and A. Pascoal, "Global stabilization of an underactuated autonomous underwater vehicle via logic-based switching," in *Proc. 41st IEEE Conf. Dec. Control*, Las Vegas, NV, USA, 2002, pp. 3267–3272.

[90] A. Aguiar and A. Pascoal, "Regulation of a nonholonomic autonomous underwater vehicle with parametric modeling uncertainty using Lyapunov functions," in *Proc. 40st IEEE Conf. Dec. Control*, Orlando, FL, USA, 2001, pp. 4178–4183.

[91] A. Aguiar, J. Hespanha, and A. Pascoal, "Switched seesaw control for the stabilization of underactuated vehicles," *Automatica*, vol. 43, pp. 1997–2008, 2007.

[92] T. McLain, S. Rock, and M. Lee, "Experiments in the coordinated control of an underwater arm/vehicle system," *Auton. Robots*, vol. 3, pp. 213–232, 1996.

[93] J. Ryu, D. Kwon, and P. Lee, "Control of underwater manipulators mounted on an ROV using base force information," in *Proc. IEEE Int. Conf. Robot. Autom.*, Seoul, South Korea, 2001, pp. 3238–3243.

[94] G. Antonelli, *Underwater Robots: Motion and Force Control of Vehicle-Manipulator Systems*. Berlin, Germany: Springer-Verlag, 2013.

[95] N. Sarkar, J. Yuh, and T. Podder, "Adaptive control of underwater vehicle-manipulator systems subject to joint limits," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Kyongju, South Korea, 1999, pp. 142–147.

[96] S. Soylu, B. Buckham, and R. Podhorodeski, "Dexterous task-priority based redundancy resolution for underwater-manipulator systems," *Trans. CSME*, vol. 31, pp. 519–533, 2007.

[97] N. Sarkar and T. Podder, "Coordinated motion planning and control of autonomous underwater vehicle-manipulator systems subject to drag force optimization," *IEEE J. Oceanic Eng.*, vol. 26, no. 2, pp. 228–239, Apr. 2001.

[98] S. Soylu, B. Buckham, and R. Podhorodeski, "Redundancy resolution for underwater mobile manipulators," *Ocean Eng.*, vol. 37, pp. 325–343, 2010.

[99] H. Esfahani, V. Azimirad, and M. Danesh, "A time delay controller included terminal sliding mode and fuzzy gain tuning for underwater vehicle-manipulator systems," *Ocean Eng.*, vol. 107, pp. 97–107, 2015.

[100] R. Cui, Y. Li, and W. Yan, "Mutual information-based multi-AUV path planning for scalar field sampling using multidimensional RRT$*$," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 46, no. 7, pp. 993–1004, Jul. 2016.

[101] H. Fang, R. A. de Callafon, and J. Cortés, "Simultaneous input and state estimation for nonlinear systems with applications to flow field estimation," *Automatica*, vol. 49, no. 9, pp. 2805–2812, 2013.

[102] H. Fang, R. A. de Callafon, and P. J. S. Franks, "Smoothed estimation of unknown inputs and states in dynamic systems with application to oceanic flow field reconstruction," *Int. J. Adaptive Control Signal Process.*, vol. 29, no. 10, pp. 1224–1242, 2015.

[103] S. C. Riser *et al.*, "Fifteen years of ocean observations with the global Argo array," *Nature Climate Change*, vol. 6, no. 2, pp. 145–153, Feb. 2016.

[104] L. Barker, "Closed-loop buoyancy control for a coastal profiling float," 2014 Intern Papers of Monterey Bay Aquarium Research Institute, 2014.

[105] R. N. Smith and V. T. Huynh, "Controlling buoyancy-driven profiling floats for applications in ocean observation," *IEEE J. Ocean. Eng.*, vol. 39, no. 3, pp. 571–586, Jul. 2014.

[106] A. Schwithal and C. Roman, "Development of a new lagrangian float for studying coastal marine ecosystems," in *Proc. OCEANS 2009 - EUROPE*, 2009, pp. 1–6.

[107] E. Aro, M. Vainio, Z. Hu, and A. Halme, "Diving in density: Controlling the depth of a profiling float in coastal waters," in *Proc. 12th IASTED Int. Conf. Control Appl.*, 2010, pp. 1–8.

[108] E. Aro, Z. Hu, M. Vainio, and A. Halme, "Coordinating a group of autonomous robotic floats in shallow seas," *in Distributed Autonomous Robotic Systems*. Berlin, Germany: Springer-Verlag, 2013.

[109] Y. Han, R. A. de Callafon, J. Cortés, and J. Jaffe, "Dynamic modeling and pneumatic switching control of a submersible drogue," in *Proc. 7th Int. Conf. Informat. Control, Autom. Robot.*, 2010, vol. 2, pp. 89–97.

[110] M. Ouimet and J. Cortés, "Robust coordinated rendezvous of depth-actuated drifters in ocean internal waves," *Automatica*, vol. 69, pp. 265–274, 2016.

[111] J. Jaffe and C. Schurgers, "Sensor networks of freely drifting autonomous underwater explorers," in *Proc. 1st ACM Int. Workshop Underwater Netw.*, 2006, pp. 93–96.

[112] R. E. Davis, C. C. Eriksen, and C. P. Jones, "Autonomous buoyancy-driven underwater gliders," in *Technology and Applications of Autonomous Underwater Vehicles*, G. Griffiths, Ed. Boca Raton, FL, USA: CRC Press, 2002, ch. 3, pp. 37–58.

[113] D. L. Rudnick, R. E. Davis, C. C. Eriksen, D. M. Fratantoni, and M. J. Perry, "Underwater gliders for ocean research," *Marine Technol. Soc. J.*, vol. 38, no. 1, pp. 48–59, 2004.

[114] S. Zhang, J. Yu, A. Zhang, and F. Zhang, "Spiraling motion of underwater gliders: Modeling, analysis, and experimental results," *Ocean Eng.*, vol. 60, pp. 1–13, 2013.

[115] N. A. A. Hussain, M. R. Arshad, and R. Mohd-Mokhtar, "Underwater glider modelling and analysis for net buoyancy, depth and pitch angle control," *Ocean Eng.*, vol. 38, no. 16, pp. 1782–1791, 2011.

[116] J. G. Graver, R. Bachmayer, and N. E. Leonard, "Underwater glider model parameter identification," in *Proc. 13th Int. Symp. Unmanned Untethered Submersible Technol.*, 2003, pp. 1–12.

[117] N. Mahmoudian, J. Geisbert, and C. Woolsey, "Dynamics & control of underwater gliders I: Steady motions," Virginia Center for Autonomous Systems, Virginia Polytechnic Institute & State University, Blacksburg, VA, USA, Tech. Rep. VaCAS-2007-01, 2009.

[118] J. G. Graver, "Underwater gliders: Dynamics, control and design," Ph.D. dissertation, Dept. Mech. Aerosp. Eng., Princeton Univ., Princeton, NJ, USA, 2005.

[119] S. A. Jenkins *et al.*, "Underwater glider system study," Scripps Inst. Oceanography, San Diego, CA, USA, Tech. Rep. 53, 2003.

[120] A. Bender, D. M. Steinberg, A. L. Friedman, and S. B. Williams, "Analysis of an autonomous underwater glider," in *Proc. Aust. Conf. Robot. Autom.*, 2008, pp. 1–10.

[121] N. E. Leonard and J. G. Graver, "Model-based feedback control of autonomous underwater gliders," *IEEE J. Ocean. Eng.*, vol. 26, no. 4, pp. 633–645, Oct. 2001.

[122] K. Isa, M. Arshad, and S. Ishak, "A hybrid-driven underwater glider model, hydrodynamics estimation, and an analysis of the motion control," *Ocean Eng.*, vol. 81, pp. 111–129, 2014.

[123] A. Caiti, V. Calabr, S. Geluardi, S. Grammatico, and A. Munaf, "Switching control of an underwater glider with independently controllable wings," in *Proc. 9th IFAC Conf. Manoeuvring Control Marine Craft*, 2012, pp. 194–199.

[124] D. Chang, F. Zhang, and C. R. Edwards, "Real-time guidance of underwater gliders assisted by predictive ocean models," *J. Atmospheric Ocean. Technol.*, vol. 32, no. 3, pp. 562–578, 2015.

[125] J. Khan and G. S. Bhuyan, "Ocean energy: Global technology development status," Powertech Labs IEA-OES, Surrey, BC, Canada, Tech. Rep. IEA-OES Document T0104, 2014.

[126] R. Kempener and F. Neumann, "Wave energy," Int. Renewable Energy Agency, Abu Dhabi, United Arab Emirates, Tech. Rep. IRENA Ocean Energy Technology Brief 4, 2014.

[127] Y. Hong, R. Waters, C. Bostrm, M. Eriksson, J. Engstrm, and M. Leijon, "Review on electrical control strategies for wave energy converting systems," *Renew. Sustain. Energy Rev.*, vol. 31, pp. 329 –342, 2014.

[128] U. Korde, "Efficient primary energy conversion in irregular waves," *Ocean Eng.*, vol. 26, no. 7, pp. 625–651, 1999.

[129] A. M. Kassem, A. H. Besheer, and A. Y. Abdelaziz, "A linear quadratic gaussian approach for power transfer maximization of a point absorber wave energy converter," *Elect. Power Compon. Syst.*, vol. 43, nos. 8–10, pp. 1173–1181, 2015.

[130] F. Fusco and J. V. Ringwood, "Suboptimal causal reactive control of wave energy converters using a second order system model," in *Proc. 21st Int. Offshore Polar Eng. Conf.*, 2011, pp. 687–694.

[131] E. Abraham and E. C. Kerrigan, "Optimal active control and optimization of a wave energy converter," *IEEE Trans. Sustain. Energy*, vol. 4, no. 2, pp. 324–332, Apr. 2013.

[132] A. O. Falcao and P. Justino, "{OWC} wave energy devices with air flow control," *Ocean Eng.*, vol. 26, no. 12, pp. 1275–1295, 1999.

[133] F. Paparella, K. Monk, V. Winands, M. F. P. Lopes, D. Conley, and J. V. Ringwood, "Up-wave and autoregressive methods for short-term wave forecasting for an oscillating water column," *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. 171–178, Jan. 2015.

[134] M. Ozger and Z. Sen, "Prediction of wave parameters by using fuzzy logic approach," *Ocean Eng.*, vol. 34, no. 34, pp. 460–469, 2007.

[135] K. Budal and J. Falnes, "Wave power conversion by point absorbers: A norwegian project," *Int. J. Ambient Energy*, vol. 3, no. 2, pp. 59–67, 1982.

[136] M. P. Schoen, J. Hals, and T. Moan, "Wave prediction and fuzzy logic control of wave energy converters in irregular waves," in *Proc. 16th Mediterranean Conf. Control Autom.*, 2008, pp. 767–772.

[137] P. Kracht, B. Fischer, S. Perez-Becker, and J.-B. Richard, "Wave prediction and its implementation on control systems of wave energy converters," Marine Renewables Infrastructure Network for emerging Energy Technologies, Tech. Rep. MARINET-TA1-Adaptive WEC control, 2013.

[138] F. Ferri, S. Ambuhl, B. Fischer, and J. P. Kofoed, "Balancing power output and structural fatigue of wave energy converters by means of control strategies," *Energies*, vol. 7, pp. 2246–2273, 2014.

[139] M. Folley *et al.*, "A review of numerical modelling of wave energy converter arrays," in *Proc. ASME 31st Int. Conf. Ocean, Offshore Artic Eng.*, 2013, vol. 7, pp. 535–545.

[140] D. Oetinger, M. E. Magaa, and O. Sawodny, "Decentralized model predictive control for wave energy converter arrays," *IEEE Trans. Sustain. Energy*, vol. 5, no. 4, pp. 1099–1107, Oct. 2014.

[141] L. Y. Pao and K. E. Johnson, "Control of wind turbines," *IEEE Control Syst.*, vol. 31, no. 2, pp. 44–62, Apr. 2011.

[142] W. He and S. Ge, "Vibration control of a nonuniform wind turbine tower via disturbance observer," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 237–244, Feb. 2015.

[143] D. Jena and S. Rajendran, "A review of estimation of effective wind speed based control of wind turbines," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 1046–1062, 2015.

[144] Y. Lin, L. Tu, H. Liu, and W. Li, "Hybrid power transmission technology in a wind turbine generation system," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 3, pp. 1218–1225, Jun. 2015.

[145] K. T. Magar, M. Balas, Y. Feng, and S. Frost, "Adaptive pitch control for speed regulation of floating offshore wind turbine: Preliminary study," in *Proc. 51st AIAA Aerosp. Sci. Meeting Including New Horizons Forum Aerosp. Expo.*, 2013, vol. 8, pp. 6766–6775.

[146] F. D. Bianchi, M. de Battista Hernan, and R. J., *Wind Turbine Control Systems Principles, Modelling and Gain Scheduling Design*. New York, NY, USA: Springer, 2007.

[147] J. Jonkman, "Influence of control on the pitch damping of a floating wind turbine," National Renewable Energy Laboratory, Denver, CO, USA, Tech. Rep. NREL/CP-500-42589, 2008.

[148] O. Bagherieh and R. Nagamune, "Gain-scheduling control of a floating offshore wind turbine above rated wind speed," *Control Theory Technol.*, vol. 13, no. 2, pp. 160–172, 2015.

[149] H. Li and Y. Shi, *Robust Receding Horizon Control for Networked and Distributed Nonlinear Systems*, (ser. Studies in Systems, Decision and Control). New York, NY, USA: Springer, 2017, vol. 83.

[150] E. Lindeberg, H. G. Svendsen, and K. Uhlen, "Smooth transition between controllers for floating wind turbines," *Energy Procedia*, vol. 24, pp. 83–98, 2012.

[151] D. Schlipf, P. Grau, S. Raach, R. Duraiski, J. Trierweiler, and P. W. Cheng, "Comparison of linear and nonlinear model predictive control of wind turbines using LIDAR," in *Proc. Amer. Control Conf.*, 2014, pp. 3742–3747.

[152] F. Cassola and M. Burlando, "Wind speed and wind energy forecast through Kalman filtering of numerical weather prediction model output," *Appl. Energy*, vol. 99, pp. 154–166, 2012.

[153] K. S. T. Magar and M. J. Balas, "Adaptive individual blade pitch control for large wind turbines with LiDAR measurement of wind speed," in *Proc. 33rd Wind Energy Symp., AIAA SciTech*, 2015, pp. 1212–1217.

[154] H. Namik and K. Stol, "Performance analysis of individual blade pitch control of offshore wind turbines on two floating platforms," *Mechatronics*, vol. 21, no. 4, pp. 691–703, 2011.

[155] G. Betti, M. Farina, A. Marzorati, R. Scattolini, and G. A. Guagliardi, "Modeling and control of a floating wind turbine with spar buoy platform," in *Proc. IEEE Int. Energy Conf. Exhib.*, 2012, pp. 189–194.

[156] Y. Si, H. R. Karimi, and H. Gao, "Modelling and optimization of a passive structural control design for a spar-type floating wind turbine," *Eng. Struct.*, vol. 69, pp. 168–182, 2014.

[157] X. Li and H. Gao, "Load mitigation for a floating wind turbine via generalized H_∞ structural control," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 332–342, Jan. 2016.

[158] F. Sandner, D. Schlipf, D. Matha, and P. W. Cheng, "Integrated optimization of floating wind turbine systems," in *Proc. ASME 2014 33rd Int. Conf. Ocean, Offshore Arctic Eng.*, 2014, pp. 1–10.

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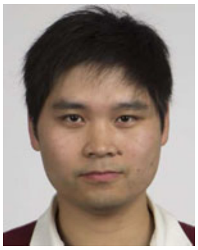

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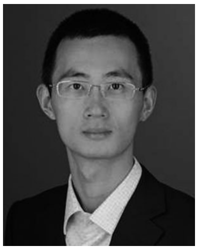

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