Unmanned surface vehicles: An overview of developments and challenges

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4 authors:

Zhixiang Liu
Concordia University Montreal

Youmin Zhang
Concordia University Montreal

Xiang Yu
Concordia University Montreal

Chi Yuan
Concordia University Montreal

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Review

Unmanned surface vehicles: An overview of developments and challenges

Zhixiang Liu, Youmin Zhang*, Xiang Yu, Chi Yuan

Department of Mechanical and Industrial Engineering, Concordia University, Montreal, Quebec H3G 1M8, Canada

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ABSTRACT

With growing worldwide interest in commercial, scientific, and military issues associated with both oceans and shallow waters, there has been a corresponding growth in demand for the development of unmanned surface vehicles (USVs) with advanced guidance, navigation and control (GNC) capabilities. This paper presents a comprehensive literature review of recent progress in USVs development. The paper first provides an overview of both historical and recent USVs development, along with some fundamental definitions. Next, existing USVs GNC approaches are outlined and classified according to various criteria, such as their applications, methodologies, and challenges. Finally, more general challenges and future directions of USVs towards more practical GNC capabilities are highlighted.

1. Introduction

1.1. Background

Roughly two-thirds of the earth is covered by oceans (Yuh, Marani, & Blidberg, 2011), but comparatively not a lot of the area has been thoroughly explored. Climate change, environmental abnormalities, personnel requirements, and national security issues have all led to a strong demand from commercial, scientific, and military communities for the development of innovative unmanned surface vehicles (USVs), also known as autonomous surface vehicles (ASVs) or autonomous surface crafts (ASCs). Despite this, only semi-autonomous USVs have normally been used rather than fully-autonomous USVs, owing to numerous challenges facing by the latter, such as limited autonomy due to the challenges in automated and reliable guidance, navigation and control (GNC) functions for all different operating conditions in face of sophisticated and hazardous environments, and sensor, actuator and communication failures. Further development of fully-autonomous USVs is required in order to minimize both the need for human control and the effects to the effective, safe and reliable USVs operation due to human error (Campbell, Naeem, & Irwin, 2012).

USVs can be defined as unmanned vehicles which perform tasks in a variety of cluttered environments without any human intervention, and essentially exhibit highly nonlinear dynamics (Breivik, 2010). Further development of USVs are expected to produce tremendous benefits, such as lower development and operation costs, improved personnel safety and security, extended operational range (reliability) and precision, greater autonomy, as well as increased flexibility in sophisticated environments, including so-called dirty, dull, harsh, and dangerous missions (Bertram, 2008; Breivik, 2010; Breivik, Hovstein, & Fossen, 2008; Roberts & Sutton, 2006).

With the aid of more effective, compact, commercially available and affordable navigation equipment, including global positioning systems (GPSs) and inertial measurement units (IMUs), as well as more powerful and reliable wireless communication systems (Manley, 2008), greater opportunities have been provided for USVs and their applications than ever before. USVs can be developed for a wide range of potential applications (as listed in Table 1) in a cost-effective way, such as scientific research, environmental missions, ocean resource exploration, military uses, and other applications.

USVs are always in competition with other manned or unmanned systems in terms of some specific applications (Savitz et al., 2013). Table 2 provides a brief comparison of these systems, and following advantages of USVs can be identified: (1) USVs can perform longer and more hazardous missions than manned vehicles; (2) maintenance costs are lower and personnel safety is far greater since no crew is onboard; (3) the low weight and compact dimensions of USVs give them enhanced maneuverability and deployability in shallow waters (riverine and coastal areas) where larger craft cannot operate effectively; (4) USVs also have greater potential payload capacity and are able to perform deeper water

* Corresponding author. Tel.: +1 514 848 2424 x5225.
E-mail addresses: l_zhixia@encs.concordia.ca (Z. Liu), youmin.zhang@concordia.ca, ymzhang@encs.concordia.ca, youminzhang163@163.com (Y. Zhang), xiangyu1110@gmail.com (X. Yu), chi_yua@encs.concordia.ca (C. Yuan).

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Table 1
Potential applications of USVs.

Types	Specific applications
Scientific research	Bathymetric survey (Roberts & Sutton, 2006); ocean biological phenomena, and migration and changes in major ecosystems (Goudey et al., 1998); ocean activities research; multi-vehicle cooperation (cooperative work among aerial, ground, water surface or underwater vehicles) (Majohr & Buch, 2006; Yan, Pang, Sun, & Pang, 2010); as experimental platforms for the purpose of testing hull designs, communication and sensor equipments, propulsion and operating systems, as well as control schemes (Breivik, 2010; Vaneck, Rodriguez-Ortiz, Schmidt, & Manley, 1996)
Environmental missions	Environmental monitoring, samplings, and assessment (Caccia et al., 2005; Naeem et al., 2008; Rasal, 2013; Svec et al., 2014b); disaster (like tsunami, hurricane, eruption of submarine volcano) aided prediction and management, and emergency response (Murphy et al., 2008); pollution measurements and clean-up
Ocean resource exploration	Oil, gas and mine explorations (Pastore & Djapic, 2010; Roberts & Sutton, 2006); offshore platform/pipeline construction and maintenance (Bertram, 2008; Breivik et al., 2008)
Military uses	Port, harbor, and coastal surveillance, reconnaissance and patrolling (Caccia et al., 2007; Kucik, 2004; Pastore & Djapic, 2010; Svec & Gupta, 2012); search and rescue (Murphy et al., 2008; Roberts & Sutton, 2006); anti-terrorism/force protection (Campbell et al., 2012); mine countermeasures (US Navy, 2007); remote weapons platform (Bertram, 2008); target drone boats (Roberts & Sutton, 2006)
Other applications	Transportation (Kiencke et al., 2006); mobile communication relays (Caccia et al., 2008a); refueling platform for USVs, unmanned aerial vehicles (UAVs), unmanned underwater vehicles (UUVs), and other manned vehicles

Table 2
Performance comparison of USVs and other vehicles.

● Clear advantage of USVs ◐ Near parity ○ Clear disadvantage of USVs

Attributes	UUVs	Float Platforms	Satellites	Manned Ships	UAVs	Manned Aircrafts
Endurance	●	○	○	◐	●	●
Payload capacity	●	◐	●	◐	●	◐
Cost	◐	○	●	◐	●	◐
Maneuverability	●	●	●	●	○	●
Deployability	●	●	●	●	○	●
Water depth measurement	○	◐	●	◐	●	◐
Autonomy requirement	◐	●	●	●	◐	●

depth monitoring and sampling compared to other aircraft/UAVs and spacecraft.

1.2. Motivation and major work

The future progress of USVs depends on the development of full-autonomy, enabling USVs to work in any unstructured or unpredictable environment without human supervision. The development of such an autonomy is very challenging, since it in turn demands the development of effective and reliable USV systems, including reliable communication systems, suitable hull design, and powerful GNC strategies. Despite strong demand for comprehensive reviews reporting, organizing and comparing the large diversity of existing USV research, only a few survey papers have been published reviewing selected subsets in a specific area of USV research, such as Campbell et al. (2012) for collision avoidance, Caccia (2006b) for basic research issues, and Bertram (2008), Manley (2008) and Motwani (2012) for USVs prototypes.

Motivated by the scarcity of comprehensive surveys, and the particular needs of this field, this paper is intended to review and highlight the specific requirements of USVs development based on notable research conducted to date, focusing primarily on different GNC techniques, which are necessary and challenging for achieving fully-autonomous USVs in the near future to be practically and reliably used for different applications. This survey can be divided into three sections: (1) an overview of fundamental elements of USV systems, their current development, and their basic research issues; (2) a systematic summary of the key GNC methodologies and techniques of USVs that have so far been explored; and (3) a description of current technical challenges and possible future research directions. Due to space limitation, emphasis has been placed mainly on refereed journal publications. Despite authors' best effort, many conference papers may not be included, we sincerely apologize for any omission.

1.3. Contributions

By offering a comprehensive overview of significant milestones and open problems in the field of USV GNC systems, this work can be employed to the benefit of the USV research community, enabling a reduction in research duplication, better identification of bottlenecks in this field, and a significant increase in the autonomous capabilities of future USVs systems. To the best knowledge of authors, no attempt has so far been made to compile such a comprehensive survey in this area.

1.4. Organization

This paper is organized as follows: Section 2 provides an overview of USVs systems. Section 3, 4 , and 5 conduct comprehensive surveys of guidance, navigation, and control techniques, respectively. Section 6 presents an overview of multi-USV coordination systems. Challenging issues and future directions are introduced in Section 7. Finally, concluding remarks are drawn in Section 8.

2. State-of-the-art USV systems

2.1. R&D progress of USVs

Numerous institutions, universities, businesses and militaries have begun developing USVs for various applications over the past two decades. Recent developments are listed in Table 3, which in spite of our best efforts may not constitute an exhaustive list. Current USVs development remains immature (Roberts & Sutton, 2006). Most existing USVs are confined to experimental platforms, comprised primarily of relatively small-scale USVs with limited autonomy, endurance, payloads, and power outputs (Savitz et al., 2013), as well as still requiring remote operation

Table 3
USV development from 1985 to date.

Country	Year	USV name	Research purpose and major achievements
	1993	ARTEMIS (Vaneck et al., 1996)	1) Systems test; 2) Bathymetry sampling
	1996	ACES (Manley, 1997)	1) Oceanographic data collection
	1998	SCOUT (Goudey et al., 1998)	1) Cooperative control; 2) Testbed
	1990*s*	Roboski (Bremer, Cleophas, Fitski, & Keus, 2007)	1) Surveillance; 2) Target drones
	1990*s*	Owls USVs (Motwani, 2012)	1) Harbor and ship security
	2000	AutoCat (Manley, Marsh, Cornforth, & Wiseman, 2000)	1) Survey of shipwreck
	2001	Spartan Scout (Motwani, 2012)	1) Port surveillance; 2) Force protection
	2003	USSV-HTF (Motwani, 2012)	1) Towing various sensors and effectors
	2005	WASP (Mahacek, 2005)	1) Stability test; 2) Bathymetric mapping
	2005	Seadoo Challenger 2000 (Ebken, Bruch, & Lum, 2005)	1) Collision avoidance; 2) Autonomous recovery
	2005	HUSCy (Curcio et al., 2005)	1) Hydrographic survey
	2008	Wave Glider (Bingham et al., 2012)	1) Data collection
	2008	Nereus (Beck et al., 2009)	1) Stability test; 2) Bathymetric mapping
	2009	SeaWASP (Furfaro, Dusek, & Von Ellenrieder, 2009)	1) Environmental monitoring; 2) Testbed
	2010	Piranha (Yang, Chen, Hsu, Tseng, & Yang, 2011)	1) Reconnaissance
USA	2011	MUSCL (Bertram, 2008)	1) Surveillance and reconnaissance
	1990*s*	MIMIR (Roberts & Sutton, 2006)	1) Shallow water search and survey
	2000*s*	C-series USVs (Anon, 2014a)	1) Assets security; 2) Environmental monitoring; 3) Mining
	2000*s*	FENRIR (Roberts & Sutton, 2006)	1) Relay between UUV and control center
	2000*s*	Sentry (Murray, 2008)	1) Harbor and shore survey and protection
	2003	SWIMS (Roberts & Sutton, 2006)	1) Mine sweeping
	2003	SeaFox (Yakimenko & Kragelund, 2011)	Maritime security operations
	2004	Springer (Naeem et al., 2008)	1) Environment monitoring; 2) Test platform
UK	2008	Blackfish (Sonnenburg, 2012)	1) Harbor protection and patrol
	1983	DOLPHIN (Curcio et al., 2005)	1) Bathymetric mapping
	2000*s*	Barracuda (Bertram, 2008)	1) As sea-surface target system
Canada	2000*s*	Hammerhead (Bertram, 2008)	1) Simulating a multi-vehicle swarm threat
	2004	SESAMO (Caccia et al., 2005)	1) Environmental sampling
	2005	Charlie (Caccia et al., 2007; Caccia, 2006a)	1) Environmental sampling and survey
	2007	ALANIS (Bibuli et al., 2012)	1) Environmental sampling and survey
Italy	2008	U-Ranger (Motwani, 2012)	1) Mine sweeping; 2) Harbor protection
	2000	CARAVELA (Pascoal, Silvestre, & Oliveira, 2006)	1) Oceanographic sampling; 2) Testbed
	2004	DELFIM (Alves et al., 2006) and DELFIMX (Gomes, Silvestre, Pascoal, & Cunha, 2006)	1) Oceanographic sampling; 2) Communication with UUVs
	2006	ROAZ I & II (Martins et al., 2007a)	1) Search and rescue
Portugal	2006	Swordfish (Ferreira et al., 2007)	1) Environmental survey
	2008	Kaasbøll (Breivik et al., 2008)	1) Navigation and control systems test
	2008	Viknes (Breivik, 2010)	1) Multi-purpose system tests
Norway	2000*s*	Mariner (Breivik, 2010)	1) Environmental surveillance and sampling
	2003	Protector (Breivik et al., 2008)	1) Reconnaissance; 2) Counter-mine
	2005	Seastar (Yang et al., 2011)	1) Port, coastal survey; 2) Reconnaissance
	2005	Stingray (Bertram, 2008)	1) Homeland security and coastguard
Israel	2007	Silver Marlin (Bertram, 2008)	1) Surveillance and reconnaissance
Germany	1998	MESSIN (Majohr & Buch, 2006)	1) Water ecological study
	2005	Basil (Bertram, 2008)	1) Offshore pipelines survey
	2005	MiniVAMP (Bertram, 2008)	1) Remote survey of offshore pipelines
France	2007	Inspector (Yang et al., 2011)	1) Surveillance and reconnaissance
Sweden	2002	Piraya (Yang et al., 2011)	1) Cooperative control
Singapore	2010	Venus (Bertram, 2008)	1) Multi-tasks test
	2008	Tianxiang One (Yan et al., 2010)	1) Meteorological survey
China	2010	USV-ZhengHe (Yang et al., 2011)	1) Inshore marine data collection
	2000	Kan-Chan (Desa et al., 2007)	1) Study of global warming
Japan	2004	UMV series (Bertram, 2008)	1) Ocean and atmosphere exploration
India	2006	ROSS (Desa et al., 2007)	1) Oceanographic sampling

(Breivik et al., 2008). USVs remain scarce in commercial markets, and the majority of industrial-level USVs are still used within military and research applications. For an overview of the developed prototype vessels and basic design issues, readers can also refer to the publications by Bertram (2008), Manley (2008) and Motwani (2012).

2.2. Elements of USVs

Depending on practical applications, USVs may come in a variety of appearances and functionalities. However, the following basic elements that must be included in every USV (see also Fig. 1):

1. *Hull and auxiliary structural elements*: Hull variations can be grouped into one of four different types: rigid inflatable hulls (Motwani, 2012), kayaks (single hull) (Curcio, Leonard, & Patrikalakis, 2005), catamarans (twin hulls) (Naeem, Xu, Sutton, & Tiano, 2008), and trimarans (triple hulls) (Peng, Han, & Huang, 2009). These variations in hull design correspond to different USV applications, revealing some basic design issues and trends in USVs development. Rigid inflatable hulls are suitable for military applications primarily because of their greater endurance and payload capacity. Kayak and catamaran designs are popular due to their convenient mounting and loading. Moreover, Kayak USVs are easy to manufacture or modify from manned surface vehicles. Catamaran and trimaran USVs are often preferred due to their greater system stability, decreasing the risk of capsizing in rough water (Campbell et al., 2012), along with providing greater payload capacity and redundancy.
2. *Propulsion and power system (Khare & Singh, 2012)*: Heading and speed control of most existing USVs are provided by rudder and propeller (or water jet) propulsion systems, respectively,

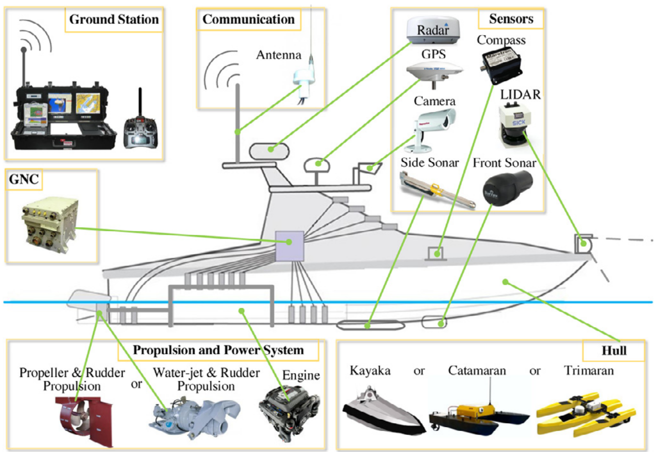

Fig. 1. Fundamental architecture of a typical USV.

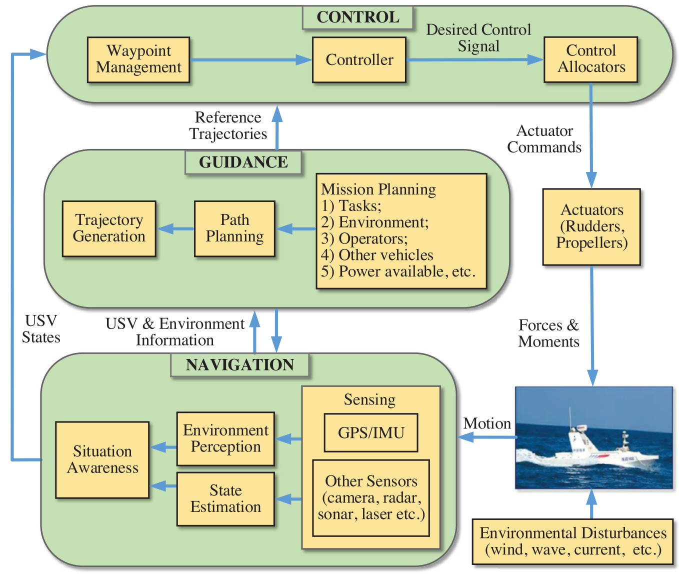

Fig. 2. General structure of USV guidance, navigation, and control systems.

- Guidance system
  - Path planning
    - Global planning
      - Optimization methods
      - Heuristic search algorithms
    - Local planning
      - Line-of-sight methods
      - Potential fields
    - Hybrid planning
  - Path replanning
    - Protocol-free methods
    - Protocol-based methods

Fig. 3. Classification of USV guidance systems with respect to functions and methods.

while others (mainly catamaran USVs) are steered by differential thrust, provided by two independent motors attached to each hull. However, these USVs are typically not equipped with additional side actuators and thus can be considered as under-actuated USVs. In other words, the number of available actuators is less than the USVs' degrees of freedom (DOF) in motion. This represents a significant challenge to safe and precise control in under-actuated USVs. Other fully- and over-actuated USVs are relatively easier to operate than under-actuated USVs, but these come with comparatively higher costs (Breivik, 2010).

3. *GNC systems*: As the most vital component of a USV, GNC modules are generally constituted by onboard computers and software, which together are responsible for managing the entire USV system.
4. *Communication systems*: Communication systems include not only wireless communication with ground control stations and other vehicles to perform cooperative control, but also onboard wired/wireless communication with a variety of sensors, actuators, and other equipment. Reliability of communication systems is therefore of paramount importance.
5. *Data collection equipment*: Together with the above-mentioned components, IMUs and GPS as the basic sensors are typically used in combination with the system to guarantee the USV remains in good operating condition, and to improve its performance. Besides, cameras, radar, sonar, as well as other kinds of sensors are optionally adopted, depending on the specific task at hand, such as monitoring and operating USV under all different conditions (i.e. cabin temperature and humidity, electronic equipment health, fuel consumption, etc.) (Roberts & Sutton, 2006).
6. *Ground station*: Ground station also plays an important role in USV GNC, which can be located in an onshore facility, a mobile vehicle or an offshore ship. In general, missions are assigned to USVs via wireless communication systems. The real-time status of the USV and its onboard equipment are all monitored by the ground station, while for remotely operated USVs, control commands are also sent from ground station.

2.3. Relationships among USV subsystems

As indicated in Fig. 2, the fundamental elements for autonomously operating USVs generally constitute guidance, navigation, and control subsystems (Fossen, 1994; 2002; 2011). These subsystems work in interaction with each other, to the point where imperfections in one subsystem may degrade the performance of the whole system.

1. *Guidance system* is responsible for continuously generating and updating smooth, feasible, and optimal trajectory commands to the control system according to the information provided by the navigation system, assigned missions, vehicle capability, and environmental conditions.
2. *Navigation system* concentrates on identifying the USV's current and future states (such as position, orientation, velocity, and acceleration), and its surrounding environment based on the past and current states of the USV as well as environmental information including the ocean currents and wind speed) obtained from its onboard sensors.
3. *Control system* focuses on determining the proper control forces and moments to be generated in conjunction with instruction provided by the guidance and navigation systems, while at the same time satisfying desired control objectives.

In the following sections, more attention is paid to different GNC methodologies for USVs, presented in the sequence of guidance, navigation, and control.

3. Classification of USV guidance techniques

A feasible guidance system is an essential component for increasing USV autonomy, while more advanced guidance capabilities are required to accomplish tasks under more complicated and strict constraints, including poorly mapped environments and real-time computational requirements (Fossen, 2002; Kendoul, 2012). To provide a basic understanding of current research interests on USV guidance systems, a brief classification is first illustrated in Fig. 3.

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3.1. Path planning

As the fundamental aspect of USV guidance systems, path planning can generally be distinguished between the global and local approaches. From the literature, a broad spectrum of efficient and intelligent path planning techniques for USVs are identified in the following.

3.1.1. Global path planning

1. *Optimization methods*: As an attractive method, advanced optimization method (OM) can directly produce optimal trajectories or paths that might include sophisticated characteristics, such as spatiotemporal-optimal, danger level (collision probability), fuel saving, weather routing, formation control, and scheduled missions.
   Inspired by the behavior of biological systems, evolutionary algorithm (EA) represent a class of artificial intelligence increasingly employed in the design of USV path planners. EA can be characterized into an optimization problem with specified constraints. Genetic algorithm (GA) are to date the most widely adopted method for waypoints generation (Campbell et al., 2012). In Svec and Gupta (2011, 2012), a strongly-typed genetic programming (GP)-based evolutionary approach is developed to enable USVs to protect a target from intruder boats.
   Due to their expensive computational costs, especially when constraints such as obstacles, USV dynamic limits, and mission constraints must be satisfied, optimization methods are limited for real-time implementation.
2. *Heuristic search algorithms*: Application of heuristic approaches in path planning first appeared in the early 2000s. The A^* search algorithm is a widely used grid-based strategy, which can quickly find an optimal path with the least number of nodes. But the drawbacks of large computational memory costs and unwanted sharp turns result in difficulty in its practical application in the cases where quick and real-time control of USVs are necessary.
   In Larson, Bruch, and Ebken (2006), the A^* search algorithm is chosen to find an optimal path within a limited amount of time. Another application is presented in Naus and Waż (2013), where the A^* algorithm is employed to search the shortest and safest trajectory in an electronic navigational chart. A^* and locally bounded optimal planning under uncertainty are combined in Svec, Schwartz, Thakur, and Gupta (2011). In Zhuang, Su, Liao, and Sun (2012), a marine radar image-based local path planning method is developed for USVs. The path is searched by Dijkstra's algorithm which is a special case of the A^* algorithm. To improve performance with respect to paths and computational consumption, a modified version of the A^* algorithm named as direction priority sequential selection (DPSS) is applied in Naeem, Irwin, and Yang (2012a). In Svec, Thakur, Shah, and Gupta (2012), a combination of a model-predictive and an A^* based algorithm is introduced. An A^* based curvature path planning algorithm is proposed in Kim, Park, and Myung (2013), where both the actual turning capability of USVs, and the environmental information, such as the terrain, buoy and fairway, are explicitly considered in the cost map.

3.1.2. Local path planning

1. *Line-of-sight*: A successful guidance technique that is widely employed in missile guidance, line-of-sight (LOS) methods are equally valid for USVs (Annamalai & Motwani, 2013; Breivik et al., 2008; Caccia, Bibuli, Bono, & Bruzzone, 2008a; Caccia et al., 2005; Desa, Maurya, Pereira, Pascoal, & Prabhudesai, 2007; Fredriksen & Pettersen, 2006; Naeem, Sutton, & Xu, 2012b; Peng, Wang, Chen, Hu, & Lan, 2013; Sharma & Sutton, 2013; Tran, Choi, Baek, & Shin, 2014; Xu, Sutton, & Sharma, 2007). There are also modified versions for better real-time implementation such as biased-LOS (Naeem et al., 2012a). Despite these, there are still drawbacks associated with LOS, including: (1) the potential to overshoot, caused by the environmental disturbances compensating action (Campbell et al., 2012), and (2) the connection between the waypoints still being rigid lines, even though paths have been smoothed to some extent.
2. *Potential fields*: As defined in the potential field (PF) approach, the objectives are assigned with attractive fields, while obstacles are distributed with repulsive fields. USVs are thus moving toward the attractive fields and away from the repulsive fields (Khatib, 1986). Although this method is characterized by its effective implementation and low computational consumption in real-time, it is normally only employed for local path planning since it is prone to guide USVs to local minima instead of the objectives (Campbell et al., 2012).
   An interesting implementation of a PF-based USV path planning scheme is introduced in Healey, Horner, Kragelund, Wring, and Monarrez (2007). In Soltan, Ashrafiuon, and Muske (2009), obstacles are approximately enclosed by ellipse fields which are the solutions of a class of ordinary differential equations (ODEs). However, much effort is still required to overcome the local-minima problem by employing depth-first and best-first search techniques, wavefront-based strategies, or harmonic potential functions.

3.1.3. Hybrid path planning

In order to ensure the safe and effective path planning for USV moving among the preliminarily specified or dynamically changing waypoints in the dynamic and hazardous environment, increasing efforts have recently been dedicated to the hybrid path planning strategy that consists of both global and local path planning approaches. In Larson et al. (2006) and Larson, Bruch, Halterman, Rogers, and Webster (2007), a hybrid path planning approach is presented, which is constituted by a two-layered hierarchical architecture combining with both global and local path planning functions. The A^* algorithm is employed to find a feasible solution for the global path planning, while a behavior-based common world model approach is utilized to manage the near-field changes that arise to the previously defined path, so that the USV can keep following the preplanned path. Casalino, Turetta, and Simetti (2009) presents a multi-layered hierarchical architecture, a global path is computed in the first layer based on the Dijkstra algorithm, while the second layer modifies this predefined path in a locally optimal way adopting the A^* method. In Svec et al. (2012), a lattice-based hybrid path planning method is developed with consideration of the USV dynamics.

3.2. Path replanning

As the major role of path replanning, collision avoidance (Yu & Zhang, 2015) is generally overlooked in the basic guidance laws (an obstacle-free path is commonly assumed). Unfortunately, recent statistics show that 60% of casualties at sea are caused by collisions (Naeem et al., 2012a). Obstacles, such as lobster traps, buoys, fishing nets, submerged rocks, other maritime traffic, new constructions, variable water levels, and sea debris, can all potentially contribute to collision risks. Without the ability to avoid collisions, USVs may collide with any objects present along the planned path. In addition, a collision avoidance module can also enhance the autonomy of USVs to avoid approaching objects by conducting autonomous path replanning.

3.2.1. Protocol-free collision avoidance

In Soltan, Ashrafiuon, and Muske (2011), obstacles are assumed to be enclosed by elliptical shapes, and a set of ordinary differential equations are defined for collision avoidance. This technique is validated using multiple dynamical obstacles in simulation, and stationary obstacles in experiments. Xu, Stilwell, and Kurdila (2013) present a path replanning approach based on the level set methods, which is employed to compute the minimum risky path. In Kim, Kim, Shin, Kim, and Myung (2014), an angular rate-constrained *Theta** (*ARC* − *Theta**) is proposed to regenerate paths in real-time with consideration of constraints in both yaw rate and heading angle of USV. An optical-flow based approach is designed to provide local reactive collision avoidance in El-Gaaly et al. (2013). This research employs a monocular camera, overcoming the challenges of water reflections and visual noises in an acceptable range. In Bertaska et al. (2013), a lattice-based path planning method is implemented with a priori knowledge of the USV characteristics.

Most of the existing research focuses only on detecting and avoiding obstacles above the water. Until recently, little attention has been paid to underwater collision avoidance in USVs, despite the significant risk of collision from submerged obstacles, including reefs and shallow banks. Pioneering work on this issue is carried out in Heidarsson and Sukhatme (2011) and Onunka, Bright, and Stopforth (2013), where active acoustic sonar is mounted on their USVs in order to provide information on underwater obstacles. Additionally, a direct method based on inverse dynamics in the virtual domain (IDVD) strategy is reported in Yakimenko and Kragelund (2011) to compute a near-optimal collision-free trajectory.

3.2.2. Protocol-based collision avoidance

56% of collisions at sea are caused by violations of coast guard collision regulations (COLREGs) (Naeem et al., 2012a; Statheros, Howells, & Maier, 2008). In order to suggest possible maneuvers to avoid collisions and increase the autonomy of USVs, COLREGs should be included in USV design, describing most potential collision scenarios, such as overtaking, head-on, and crossing situation (Campbell et al., 2012).

Lee, Kwon, and Joh (2004) devised and demonstrated a modified virtual force field (MVFF) method that satisfies COLREGs guidelines in a USV simulation, which was successful in avoiding both stationary and dynamic obstacles. Such a method may encounter greater difficulty in the case of multiple obstacles. Another study employs a behavior-based control and multi-objective action selection method in a kayak USV under the COLREGs rules (Benjamin & Curcio, 2004). Subsequent work by the authors (Benjamin, Leonard, Curcio, & Newman, 2006) presented the first in-field implementation of COLREGs on two kayak-based SCOUT USVs. In Larson et al. (2007), a near-field reactive control technique is applied in a "SSC San Diego" USV. Although being able to rapidly and effectively avoid most obstacles, the generated trajectory under this method is not optimal. Obeying the COLREGs, a relative coordinate based collision avoidance strategy with integration of an evolutionary path planner is discussed in Zhuang, Su, Liao, and Sun (2011). A successful application of avoiding both static and dynamic obstacles along a non-optimal trajectory is proposed by Naeem et al. (2012a), who adopted a simple manual biasing scheme and a direction priority sequential selection (DPSS) strategy under COLREGs. As an on-line extension of the standard A^* algorithm, a rule-based repairing A^* ($R-RA^*$) algorithm in compliance with COLREGs is introduced in Campbell, Abu-Tair, and Naeem (2013). This approach differs from the offline global path planning methods, being able to update and smooth the local path in real-time, responding to any changes along the predefined trajectory. Recently, a velocity obstacles (VO) method is adopted in Kuwata, Wolf, Zarzhitsky, and Huntsberger (2014), avoiding dynamic and static hazards while conforming to COLREGs constraints.

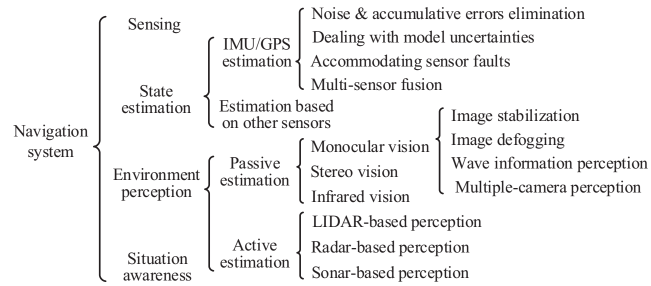

Fig. 4. Classification of USV navigation systems with respect to functions and methods.

More relative research can be referred to Shah et al. (2014) and Svec et al. (2013, 2014a, 2012).

4. Classification of USV navigation techniques

Safe and efficient control of USVs depends heavily on an appropriate navigation system with sensing, state estimation, environment perception, and situation awareness capabilities. This section briefly reviews existing USV navigation techniques (as shown in Fig. 4).

4.1. Sensing technologies

Adequate sensing capabilities are generally required to enhance the performance of USVs. Furthermore, marine environments also impose harsh restrictions on sensory requirements. Heterogeneous sensors are usually employed in order to make the best use of different sensors' characteristics, and achieve superior navigation performance. Table 4 indicates the characteristics of various sensors used in the development of USV navigation systems.

4.2. USV state estimation

In general, only the position and orientation of the USV are provided by onboard sensors. Determination of its velocity and acceleration requires reconstruction based on measured information. Critical to this process is the state estimation technique, which traces the current state of the USV. In terms of currently utilized sensing technologies, state estimation methods can be classified into either conventional GPS-IMU-based approaches or techniques based on other sensors.

4.2.1. State estimation with conventional GPS-IMU

Performance specifications often require that GPS and IMU systems provide high-resolution position, orientation and velocity estimates. Unfortunately, these estimates can be very imprecise in practical applications (Bibuli, Bruzzone, Caccia, & Lapierre, 2009) due to influences from (1) environmental noises; (2) accumulative errors resulting from inherent drift; (3) time-varying model uncertainties; and (4) sensor faults. Additional correction actions are hence required to improve navigation performance.

1. *Noise and accumulative error elimination*: In Lefeber, Pettersen, and Nijmeijer (2003), a nonlinear passive observer (Fossen & Strand, 1999) is employed to estimate the position and velocity of the USV. Based on the Kalman filter, the heading estimate of a Springer USV is provided by a combination of the actual compass measurement and the predicted information of a dynamic compass model (Annamalai & Motwani, 2013). In Bibuli et al. (2009), Caccia et al. (2008a) and Tran et al. (2014), the USV's position and velocity are estimated using an extended Kalman filter (EKF) on the basis of a practical dynamic model

Table 4
Advantages and limitations of various sensors with application to USVs.

Sensors	Advantages	Limitations
Radar	1) Long detecting range; 2) Provides nearly all-weather and broad-area imagery; 3) High depth resolution and accuracy.	1) Skewed data from fast turning maneuvers; 2) Limited small and dynamic targets detection capability; 3) Susceptible to high waves and water reflectivity.
LIDAR	1) Good at near range obstacle detection; 2) High depth resolution and accuracy.	1) There exists sensor noise and calibration errors; 2) Sensitive to environment and USV motion.
Sonar	1) No visual restrictions; 2) High depth resolution and accuracy.	1) Limited detecting range in each scanning; 2) Impressionable to the noise from near-surface.
Visual sensor	1) High lateral and temporal resolution; 2) Simplicity and low weight in practical application.	1) Low depth resolution and accuracy; 2) Challenge to real-time implementation; 3) Susceptible to light and weather condition.
Infrared sensor	1) Applicable for dark condition; 2) Low power consumption.	1) Indoor or evening use only; 2) Impressionable to interference and distance.
IMU	1) Small size, low cost, and power consumption.	1) Sensitive to accumulated error and magnetic environment.
GPS/DGPS	1) Small size, low cost, and power consumption.	1) Susceptible to shelters and magnetic environment.

and both GPS and compass measurements. An adaptive unscented Kalman filter (UKF) is proposed for state estimation without a priori knowledge of noise distribution (Peng et al., 2009). In Vasconcelos, Silvestre, and Oliveira (2011b), a DELFIM catamaran USV is equipped with both GPS and IMU systems. Inertial sensor bias and noise are compensated by using EKF, integrating vector observations, and taking into account the dynamics of the USV. Subsequent research by Vasconcelos, Cardeira, Silvestre, Oliveira, and Batista (2011a) applies a complementary filter to the DELFIM USV that combines the strapdown inertial measurements, vector observations, and GPS aiding to estimate its attitude, while the bias of rate gyro is also compensated.

2. *Dealing with model uncertainties*: In Motwani, Sharma, Sutton, and Culverhouse (2013), a robust USV heading estimation technique named after an interval Kalman filter (IKF) is investigated in an attempt to bound model uncertainties caused by varying environment, payload, and operating conditions. A high-gain observer is employed to estimate immeasurable states in Tee and Ge (2006).
3. *Accommodating sensor faults*: Salt spray and moisture can potentially damage sensors, communication interfaces, and cables. USV navigation is thereby extremely difficult in marine environments, requiring the development of more intelligent techniques. Some studies (Naeem et al., 2012b; Xu et al., 2007) propose and implement a federated Kalman filter (FKF), modified by a fuzzy logic adaptive (FLA) technique, in order to deal with different types of sensor faults that are injected in a Springer USV. Triple redundancy in compasses is used, and global estimates of the real state of the USV are provided by this intelligent multi-sensor data fusion methodology.
4. *Multi-sensor fusion*: In practice, multiple sensors are usually adopted for state estimation in order to offer the control system with sufficient navigation information to effectively perform the desired tasks. But some sensors provide data with low update rates (like GPS) while others provide data at high rates. State estimation methods that fuse these measurements have clear advantages on accurate and reliable navigation information. The existing work in this area includes complementary filter (Vasconcelos et al., 2011a), federated Kalman filter and fuzzy adaptive technique (Xu et al., 2007), and multiple model adaptive estimation (Sutton, Sharma, & Xao, 2011).

4.2.2. State estimation based on other sensors

In addition to conventional state estimation techniques, active ranging sensor (LIDAR, radar and sonar) methods can also be employed for state estimation, especially in cases of a loss or jamming of GPS signals. Additionally, vision-based approaches outperform active navigation in terms of power consumption, size, weight, and cost, and are therefore an excellent option for both navigation and data collection.

4.3. Environment perception

In order to perform missions in real-world environments, USVs are normally required to possess the ability to detect obstacles, recognize and track targets, and map environments, all in real-time. Furthermore, the unique conditions experienced in marine environments, such as environmental disturbances (winds, waves, and currents), sea fog, and water reflection, can also impact the performance of environmental perception. Environment perception approaches for USVs can be generally grouped into two categories according to the characteristics of intended application: (1) passive perception methods, and (2) active perception methods.

4.3.1. Passive perception methods

Passive perception methods adopting visual/infrared sensors are widely employed in environment perception applications.

1. *Monocular vision*:
   (a) *Image stabilization*: To solve the problem of warp and shaking due to USV motion, it is of paramount importance to stabilize the obtained images before subsequent image processing. Gal (2011a) uses a low-cost camera, and applies image stabilization and smoothing techniques to recognize and identify obstacles around the USV.
   (b) *Image defogging*: As a common maritime phenomenon, sea fog can cause serious image degradation. In Ma, Wen, and Liang (2013), the accuracy of obstacle detection and target tracking are significantly improved by developing a visual-based image defogging method. Given that this method is only validated by video, future investigation on real-time implementation and defogging approaches without the obvious sea-sky-line is recommended.
   (c) *Wave information perception*: Liu and Wang (2013) present an interesting application of detecting wave grade using visual-based techniques to provide USVs with environmental information. Based on the Fourier transform theory, this method can effectively determine the wave grade in different light conditions and sea states.
   (d) *Multiple-camera method*: Traditional fixed and moving sensors are concerned only with short timescales. In Subramanian, Gong, Riggins, Stilwell, and Wyatt (2006) and Wolf et al. (2010), a novel 360-degree omni-directional camera head is developed for environment perception, which can identify targets over long timescales. A probability of existence method is invented to cope with the challenge of

reliability of target tracking, in particular when targets leave the camera scope during some timescales.

2. *Stereo vision*: A depth map can be employed to generate an obstacle map of the area in front of a USV, which is appropriate for near-field collision avoidance. In Huntsberger, Aghazarian, Howard, and Trotz (2011), a first fielded stereo vision system “Hammerhead” is tailored for use with a USV to generate both probabilistic hazard maps and targets with estimated speed and heading. However, higher resolution cameras and dedicated hardware are required to increase the range of perception, and stereo vision techniques suffer from precise calibration requirements each time a camera is mounted.
3. *Infrared vision*: Long-wave infrared (IR) cameras are an ideal solution to overcome the impact of various light conditions (such as night and fog) on environment perception, enabling both day and night operation. Unfortunately, research on IR applications on USV environmental perception remains minimal.

4.3.2. Active perception methods

LIDAR, radar, and sonar are the main active sensors to be extensively adopted in environment perception.

1. *LIDAR*: Cluttered and moving platforms challenge real-time target detection and tracking using LIDAR. Solutions for decluttering LIDAR measurement are proposed in Gal and Zeitouni (2013), while a probability hypothesis density (PHD) Bayes filter is also developed to identify and track targets. Further practical implementation for algorithm validation of these methods is still required.
2. *Radar*: Radar is the main option for obstacle detection in the far-field (Larson et al., 2006). In Onunka and Nnadozie (2013), USVs are equipped with obstacle and target tracking filters for detecting obstacles and tracking targets by processing radar images. The results conclude that the narrower variability of radar signals, the wider coverage of detection, and the growth of echo power and frequency are possible by increasing the radar sweep width. A radar-based target detection method is proposed in Ji, Zhuang, and Su (2014), which addresses background noise and variant brightness issues, and allows targets to be successfully extracted in real-time.
3. *Sonar*: To date, sonar remains the most suitable option for collecting data on underwater environments. In Heidarsson and Sukhatme (2011), a forward-facing active acoustic sonar is mounted on a USV for obstacles detection. In Yakimenko and Kragelund (2011), detection and localization of obstacles are provided by a forward looking sonar system deployed on a SeaFox USV. In order to reduce the uncertainties and exceptions adversely affected by the sonar propagation characteristics, a sonar-based obstacle detection method is investigated in Onunka et al. (2013). In Leedekerken, Fallon, and Leonard (2014), sonar images are used for mapping the underwater environment as well.

4.4. Situation awareness

Situation awareness (SA) is essential for designing USVs with higher levels of autonomy. Wolf et al. (2010) is one of the few existing research studies examining SA in USV systems, in which an object-level tracking and change detection (OTCD) method is developed for detecting targets, confirming their location, and recognizing variations in the surrounding environment during patrol missions. An additional problem is that GPS signals may become weak when the USV is in close proximity to bridges, foliage canopies, and other sheltered environments. Simultaneous localization and mapping (SLAM) is deemed as a potentially effective choice for USV navigation in these scenarios. In Leedekerken et al. (2014), a SLAM method for concurrently mapping the marine environment above and below the water is addressed, which attempts to navigate the USV with the degradation of GPS signals in close proximity to bridges or foliage canopies.

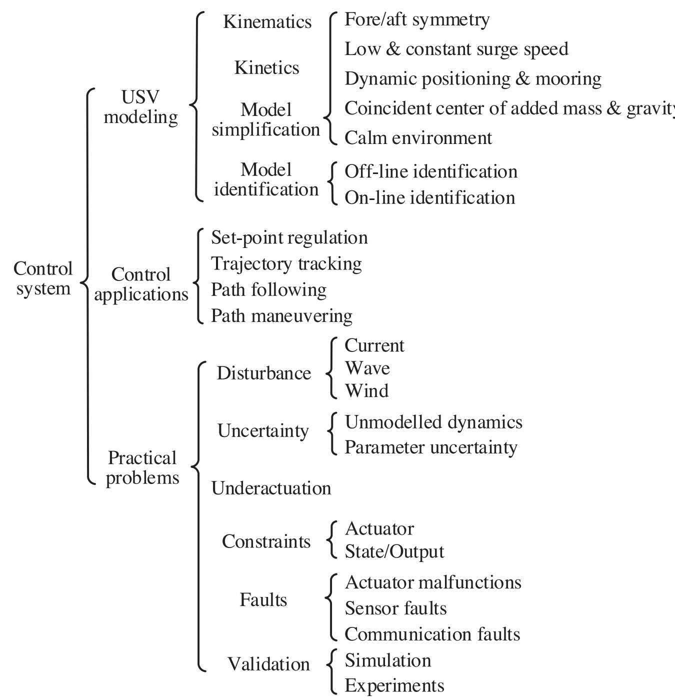

Fig. 5. Classification of USV control systems in terms of problems and functions.

5. Classification of USV control techniques

With the considerable development of advanced control theory, state-of-the-art control techniques are continually being designed to enhance USV performance in the marine research community (Campbell et al., 2012), see Fig. 5 for an overview of the work on USVs control systems.

5.1. USV modeling

The availability of a sufficiently accurate USV model enabling effective control design is imperative for both control methodology design and simulation study purposes. This in turn requires prior investigation of both a precise mathematical USV model and reasonable system parameters. Generally, a standard USV model consists of both kinematics and kinetics.

5.1.1. Kinematics

With respect to USV control, there is no requirement for consideration of either passenger comfort or cargo stability. Its primary purpose is merely to ensure the USV follows the desired path as accurately as possible. Based on this characteristic, the general six-DOF model can be reduced to only consider motion in the surge/forward, sway/lateral, and heading/yaw categories only, while the dynamics associated with the motion in roll, pitch, and heave are generally neglected to maintain model simplicity (Do & Pan, 2009). As shown in Fig. 6, the typical USV kinematic model (Fossen, 2002) in planar motion and without the presence of disturbances can then be expressed as:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu}, \tag{1}$$

where $\boldsymbol{\eta} = [x, y, \psi]^T$ denotes the vector of position and orientation with coordinates in the earth-fixed reference frame, $\boldsymbol{\nu} = [u, v, r]^T$

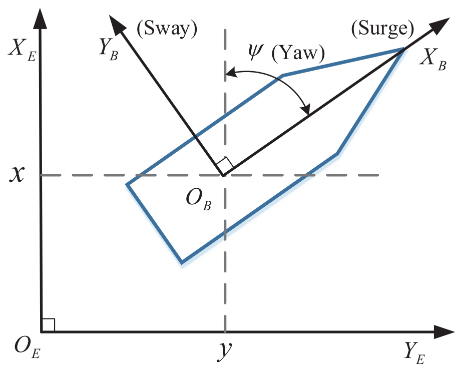

Fig. 6. Schematic diagram of USV planar motion (note: $X_EO_EY_E$ is the earth-fixed reference frame, while $X_BO_BY_B$ denotes the body-fixed reference frame).

denotes the vector of linear and angular velocity with coordinates in the body-fixed reference frame, $\boldsymbol{R}(\psi)=\begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}$ denotes the transformation matrix between the earth-fixed reference frame and body-fixed reference frame. (x, y) and ψ are the position and orientation (yaw/heading angle) of the USV in the earth-fixed reference frame, while u, v, and r represent the velocity of surge, sway, and yaw in the body-fixed reference frame, respectively. Due to the existence of disturbances (winds, waves, and currents) and the rapid turning of the USV with high surge speed, the so-called sideslip phenomenon may also occur (Sonnenburg & Woolsey, 2013). To consider this phenomenon with the resultant velocity $V=\sqrt{u^2+v^2}$, the sideslip angle β, and the course angle χ; $\boldsymbol{R}(\psi)$ and $\boldsymbol{\nu}$ can be written as:

$$\boldsymbol{R}(\psi)=\begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\cos\beta & -\sin\beta & 0\\ \sin\beta & \cos\beta & 0\\ 0 & 0 & 1\end{bmatrix}$$
$$=\begin{bmatrix}\cos\chi & -\sin\chi & 0\\ \sin\chi & \cos\chi & 0\\ 0 & 0 & 1\end{bmatrix} \text{ and } \boldsymbol{\nu}=\begin{bmatrix}V\\ 0\\ r\end{bmatrix}, \tag{2}$$

where $\beta=\arcsin(\frac{v}{V})$, and $\chi=\psi+\beta$.

5.1.2. Kinetics

In addition to kinematic models, USV dynamic models have also been extensively studied. The reason for this is their crucial importance for advanced controller design (Do & Pan, 2009), as well as the fact that kinematic models on their own are not sufficient for USV motion modeling, particularly when USVs exhibit significant side-slip (Gadre, Sonnenburg, Du, Stilwell, & Woolsey, 2012). For a more comprehensive history of USV dynamic model development, readers are encouraged to refer to Do and Pan (2009); Fossen (1994, 2002, 2011).

In order to better facilitate control design, existing research assumes that: (1) USVs are moving in a horizontal plane in the ideal fluid; (2) USV masses are uniformly distributed; (3) the body-fixed coordinate axis coincides with the center of gravity (CG); (4) both the CG and the center of buoyancy (CB) point vertically along the Z-axis; (5) USVs own the port-starboard symmetry; and (6) surge and sway-yaw dynamics are essentially decoupled. Based on these assumptions, the widely used dynamic model can then be obtained (Fossen, 1994):

$$\boldsymbol{M}\dot{\boldsymbol{\nu}}+\boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu}+\boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu}+\boldsymbol{g}(\boldsymbol{\eta})=\boldsymbol{\tau}+\boldsymbol{\tau}_E, \tag{3}$$

where the physical meanings of symbols in (3) are all outlined in Table 5, while the representation of each symbol is introduced as below:

$$\boldsymbol{M}=\boldsymbol{M}_{RB}+\boldsymbol{M}_A=\begin{bmatrix}m_{11} & 0 & 0\\ 0 & m_{22} & m_{23}\\ 0 & m_{32} & m_{33}\end{bmatrix},$$
$$\boldsymbol{M}_{RB}=\begin{bmatrix}m & 0 & 0\\ 0 & m & m\chi_g\\ 0 & m\chi_g & I_z\end{bmatrix},$$
$$\boldsymbol{M}_A=\begin{bmatrix}-X_{\dot{u}} & 0 & 0\\ 0 & -Y_{\dot{v}} & -Y_{\dot{r}}\\ 0 & -N_{\dot{v}} & -N_{\dot{r}}\end{bmatrix},$$
$$\boldsymbol{D}(\boldsymbol{\nu})=\boldsymbol{D}+\boldsymbol{D}_n(\boldsymbol{\nu})=\begin{bmatrix}d_{11}(u) & 0 & 0\\ 0 & d_{22}(v,r) & d_{23}(v,r)\\ 0 & d_{32}(v,r) & d_{33}(v,r)\end{bmatrix},$$
$$\boldsymbol{D}=\begin{bmatrix}-X_u & 0 & 0\\ 0 & -Y_v & -Y_r\\ 0 & -N_v & -N_r\end{bmatrix},$$
$$\boldsymbol{D}_n(\boldsymbol{\nu})=\begin{bmatrix}-X_{u|u|}|u| & 0 & 0\\ 0 & -Y_{v|v|}|v|-Y_{|r|v}|r| & -Y_{|v|r}|v|-Y_{|r|r}|r|\\ 0 & -N_{v|v|}|v|-N_{|r|v}|r| & -N_{|v|r}|v|-N_{|r|r}|r|\end{bmatrix},$$
$$\boldsymbol{C}(\boldsymbol{\nu})=\boldsymbol{C}_{RB}(\boldsymbol{\nu})+\boldsymbol{C}_A(\boldsymbol{\nu})$$

Table 5
Nomenclature of USV parameters.

Symbols	Explanation
$\boldsymbol{M}$	System inertia matrix (including added mass)
$\boldsymbol{M}_{RB}$	Rigid-body system inertia matrix
$\boldsymbol{M}_A$	Added mass (forces and moments induced by the pressure from a forced harmonic motion of the USV body)
$\boldsymbol{C}(\boldsymbol{\nu})$	Coriolis and centripetal matrix (including added mass)
$\boldsymbol{C}_{RB}(\boldsymbol{\nu})$	Rigid-body Coriolis and centripetal matrix
$\boldsymbol{C}_A(\boldsymbol{\nu})$	Hydrodynamic Coriolis and centripetal matrix
$\boldsymbol{D}$	Linear damping matrix
$\boldsymbol{D}(\boldsymbol{\nu})$	Hydrodynamic damping matrix induced by skin friction, potential damping (due to the energy carried away by waves), vortex shedding damping, and wave drift damping
$\boldsymbol{D}_n(\boldsymbol{\nu})$	Nonlinear damping matrix
$\boldsymbol{g}(\boldsymbol{\eta})$	Restoring forces and moments due to gravitation/buoyancy
$\boldsymbol{\tau}$	Control inputs (the forces and moments of propulsion system and control surfaces) acting on USV $\boldsymbol{\tau}=[\boldsymbol{\tau}_u,\boldsymbol{\tau}_v,\boldsymbol{\tau}_r]^T$ is for fully-actuated USV, while $\boldsymbol{\tau}=[\boldsymbol{\tau}_u,0,\boldsymbol{\tau}_r]^T$ is for underactuated USV
$\boldsymbol{\tau}_u$	Control inputs (forces) in surge direction
$\boldsymbol{\tau}_v$	Control inputs (forces) in sway direction
$\boldsymbol{\tau}_r$	Control inputs (moments) in yaw direction
$\boldsymbol{\tau}_E$	Environmental disturbances (winds, waves and currents)
m	Mass of USV
I_z	USV inertia about the Z axis of body-fixed frame
χ_g	USV CG along the X coordinate of body-fixed frame

$$= \begin{bmatrix} 0 & 0 & -m_{22}v - \frac{1}{2}(m_{23}+m_{32})r \\ 0 & 0 & m_{11}u \\ m_{22}v + \frac{1}{2}(m_{23}+m_{32})r & -m_{11}u & 0 \end{bmatrix},$$

$$\boldsymbol{C}_A(\boldsymbol{\nu}) = -\begin{bmatrix} 0 & 0 & -Y_{\dot{v}}v - \frac{1}{2}(Y_{\dot{r}}+N_{\dot{v}})r \\ 0 & 0 & X_{\dot{u}}u \\ Y_{\dot{v}}v + \frac{1}{2}(Y_{\dot{r}}+N_{\dot{v}})r & -X_{\dot{u}}u & 0 \end{bmatrix},$$

$$\boldsymbol{C}_{RB}(\boldsymbol{\nu}) = \begin{bmatrix} 0 & 0 & -m(\chi_g r + v) \\ 0 & 0 & mu \\ m(\chi_g r + v) & -mu & 0 \end{bmatrix},$$

where the parameters are all introduced in Table 5. With regard to other hydrodynamic coefficients (hydrodynamic derivatives), they can be referred to Do and Pan (2009) and Fossen (1994).

5.1.3. Model simplification

Although a more accurate and complete USV model that represents the physics of the real world is normally required, some common model simplifications and reductions are still inevitable in order to facilitate controller design. These phenomena are primarily due to the many practical challenges faced USV development, including hydrodynamic phenomenon (hydrodynamic forces and moments), which are still not fully understood. A unified numerical model for USV control is usually difficult, expensive and time-consuming to establish due to the need for highly specialized equipment and facilities, not to mention the many inherent and external nonlinear influences (Skjetne, Smogeli, & Fossen, 2004a). The following list provides an overview of these model simplifications and reductions:

1. *Fore/aft symmetry*: The off-diagonal entries and couplings in $\boldsymbol{M}$ and $\boldsymbol{D}(\boldsymbol{\nu})$ can thereby be eliminated based on this assumption (Behal, Dawson, Dixon, & Fang, 2002; Do, Jiang, & Pan, 2002a; Dong & Guo, 2005; Jiang, 2002; Lefeber et al., 2003; Ma, 2009; Mazenc, Pettersen, & Nijmeijer, 2002; Pettersen, Mazenc, & Nijmeijer, 2004; Pettersen & Nijmeijer, 2001; Thakur & Gupta, 2011). It follows $\boldsymbol{M} = diag\{m_{11}, m_{22}, m_{33}\}$ and $\boldsymbol{D}(\boldsymbol{\nu}) = diag\{-X_u, -Y_v, -N_r\}$;
2. *Low and constant surge speed*: In some papers (Pettersen & Fossen, 2000; Pettersen et al., 2004), the USV is assumed to be at rest or only moving with low speed. This means that $\boldsymbol{C}(\boldsymbol{\nu})$ is negligible and the off-diagonal terms of $\boldsymbol{M}$ and $\boldsymbol{D}(\boldsymbol{\nu})$ can therefore also be omitted since they are small in comparison with the diagonal terms;
3. *Dynamic positioning and mooring*: With these assumptions, both $\boldsymbol{D}_n(\boldsymbol{\nu})$ and $\boldsymbol{C}(\boldsymbol{\nu})$ can be disregarded (Fossen & Grovlen, 1998; Fossen & Strand, 1999; Robertsson & Johansson, 1998);
4. *The coincident center of added mass and gravity*: In this case, $N_{\dot{v}}$ can be replaced by $Y_{\dot{r}}$, then the added mass $\boldsymbol{M}_A = \boldsymbol{M}_A^T$ and $\boldsymbol{C}_A(\boldsymbol{\nu}) = -\boldsymbol{C}_A^T(\boldsymbol{\nu})$ (Børhaug, Pavlov, Panteley, & Pettersen, 2011; Fredriksen & Pettersen, 2006; Kyrkjebø, Pettersen, Wondergem, & Nijmeijer, 2007; Skjetne, Fossen, & Kokotović, 2005; Skjetne et al., 2004a; Wondergem, Lefeber, Pettersen, & Nijmeijer, 2011);
5. *Calm environments*: Under this assumption, the environmental disturbances $\boldsymbol{\tau}_E$ can be neglected (Behal et al., 2002; Do et al., 2002a; Dong & Guo, 2005; Jiang, 2002; Lefeber et al., 2003; Ma, 2009; Mazenc et al., 2002); In addition, it is possible to assume that the hydrodynamic coefficients are time-invariant, resulting in the parameters in matrices $\boldsymbol{M}$, $\boldsymbol{D}(\boldsymbol{\nu})$, and $\boldsymbol{C}(\boldsymbol{\nu})$ all being constant (Li & Sun, 2012; Skjetne et al., 2005).

5.1.4. Model identification

Model identification plays a key role in obtaining a reasonable USV model. As reported in the literature, USV model identification typically constitutes off-line and on-line identification methods.

1. *Off-line identification*: A USV model is generally calculated and identified off-line based on the data collected from onboard sensors through extensive trial-by-trial experiments. The existing off-line identification methods can be roughly grouped into: (1) frequency domain methods (Selvam, Bhattacharyya, & Haddara, 2005); and (2) time domain methods, including least squares regression (Mišković, Vukić, Bibuli, Bruzzone, & Caccia, 2011; Sonnenburg et al., 2010), onboard sensor-based identification (Caccia, Bruzzone, & Bono, 2008b), continuous time models (Muske, Ashrafiuon, Haas, McCloskey, & Flynn, 2008), hybrid-extended Kalman filtering (Yoon & Rhee, 2003), and artificial neural network (Rajesh & Bhattacharyya, 2008).
2. *On-line identification*: In this research field, black/gray-box identification techniques are widely employed to learn and construct USV dynamics on-line. These methods include recursive neural networks (Sharma & Sutton, 2012), neural network feedback-feedforward compensating methods (Zhang, Jia, & Qi, 2011a), and weighted least square techniques (Annamalai, Sutton, Yang, Culverhouse, & Sharma, 2014b).

5.2. Review of control approaches from control objectives viewpoint

In essence, the development of control strategies is oriented by different control objectives. As briefly summarized in Table 6, these objectives can be generally classified into one of four categories (Bibuli, Caccia, Lapierre, & Bruzzone, 2012; Fossen, 2011; Fredriksen & Pettersen, 2006):

1. *Set-point regulation*: This is the most basic control objective, which converges the position and orientation of the USV with the desired requirements without temporal constraint. However, it is impossible to achieve continuous control actions for underactuated USVs.
2. *Trajectory tracking*: The USV is driven to track a desired temporal reference, while simultaneously obeying predefined spatial constraints. For fully-actuated USVs, this problem is now reasonably understood, though it is still an active research topic for underactuated USVs (which exhibit nonholonomic constraints).
3. *Path following*: The USV is required to follow a scheduled path by independently tracking an expected forward speed profile and steering its orientation. Compared with trajectory tracking, a smoother path and lower probability of actuator saturation can be achieved due to the fact that spatial constraints are given priority over the temporal constraints.
4. *Path maneuvering*: As a subset of path following, path maneuvering (Skjetne, 2005; Skjetne, Fossen, & Kokotović, 2004b) involves two tasks. The first geometric task, enabling the USV to follow a feasible desired path under maneuverability constraints, while the second is dynamic task, requiring the USV to satisfy some additional dynamic behaviors (such as time, speed, and acceleration assignment) along the desired path. In this case, the spatial specification (the first task) is considered to be more important than the temporal constraint (the second task).

5.3. Review of control approaches from a practical perspective

USVs may diverge from the predefined path due not only to poor controller design, but also because of environmental disturbances, uncertainties (unmodeled dynamics and parameters), actuator saturation, strong couplings, underactuation, and system faults (faults of sensors, actuators and communication links). Despite

Table 6
Classification of the research in USV control techniques.

Applications	References
Set-point regulation	Abril, Salom, and Calvo (1997), Annamalai and Motwani (2013), Annamalai et al. (2014a), Beck et al. (2009), Caccia et al. (2005), Desa et al. (2007), Ding et al. (2013), Fredriksen and Pettersen (2006), Hurban (2012), Kim et al. (2012), Li, Lee, Jun, and Lim (2008), Mazenc et al. (2002), Moreira, Fossen, and Guedes Soares (2007), Peng et al. (2009, 2013), Pereira et al. (2008), Pettersen and Fossen (2000), Pettersen et al. (2004), Reyhanoglu (1997), Sharma and Sutton (2013), Tokekar et al. (2010), Tran et al. (2014), Vaneck (1997)
Trajectory tracking	Ashrafiuon et al. (2008), Breivik et al. (2008), Dai et al. (2012), Do et al. (2002a), Do et al. (2002b); 2003), Do (2010), Feemster and Esposito (2011), Gadre et al. (2012), Ghommam, Mnif, Benali, and Derbel (2006), Ghommam et al. (2010), Guerreiro et al. (2013), Jiang (2002), Kyrkjebø et al. (2007), Liu, Zou, and Hou (2014c), McNinch, Ashrafiuon, and Muske (2009), Naeem et al. (2012a), Pan et al. (2013), Pettersen and Nijmeijer (2001), Song (2014), Sonnenburg and Woolsey (2012), Sonnenburg and Woolsey (2013), Tee and Ge (2006), Svec et al. (2014b), Yang et al. (2014), Yu, Zhu, Xia, and Liu (2012), Zhang et al. (2011a)
Path following	Alfaro-Cid, McGookin, Murray-Smith, and Fossen (2005), Annamalai et al. (2014b), Bibuli et al. (2009, 2012), Caccia et al. (2008a), Do and Pan (2006a); 2006b), Elkaim (2006), Li et al. (2009), Li and Sun (2012), Liu, Zou, and Yin (2014b), Naeem et al. (2012b), Oh and Sun (2010), Skjetne et al. (2004a), Wondergem et al. (2011), Yu, Bao, and Nonami (2008)
Path maneuvering	Arrichiello et al. (2006), Fossen (2005), Ma (2009), Skjetne et al. (2005)

Table 7
Classification of challenges in USV control systems.

Exper.	Dist.	Uncer.	Faults	Const.	References
√	√	√	×	√	Annamalai et al. (2014a); 2014b), Do and Pan (2006b), Feemster and Esposito (2011), Li et al. (2009), Tee and Ge (2006)
√	√	√	×	×	Bibuli et al. (2012), Caccia et al. (2008a), Naeem et al. (2012b), Pettersen et al. (2004)
√	√	×	√	×	Naeem et al. (2008)
√	√	×	×	√	Ding et al. (2013), Gadre et al. (2012), Guerreiro et al. (2013), Kyrkjebø et al. (2007), Li and Sun (2012), Sonnenburg and Woolsey (2013), Tokekar et al. (2010)
√	√	×	×	×	Abril et al. (1997), Alfaro-Cid et al. (2005), Annamalai and Motwani (2013), Beck et al. (2009), Bibuli et al. (2009), Do and Pan (2006a), Hurban (2012), Kim et al. (2012), Lefeber et al. (2003), Ma (2009), Naeem et al. (2012a), Pereira et al. (2008), Pettersen and Fossen (2000), Sonnenburg and Woolsey (2012), Vaneck (1997), Wondergem et al. (2011), Yu et al. (2008)
√	×	×	×	√	Skjetne et al. (2005)
√	×	×	×	×	Adamek et al. (2015), Ashrafiuon et al. (2008), Breivik et al. (2008), Caccia et al. (2005), Desa et al. (2007), Elkaim (2006), Moreira et al. (2007), Pettersen and Nijmeijer (2001), Sharma, Naeem, and Sutton (2012), Skjetne et al. (2004a), Song (2014), Tran et al. (2014), Svec et al. (2014b)
×	√	√	×	×	Dai et al. (2012), Li et al. (2008), Liu et al. (2014b), Pan et al. (2013), Peng et al. (2009), Peng et al. (2013b), Zhang et al. (2011a)
×	√	×	×	√	Peng et al. (2013), Sharma and Sutton (2013)
×	√	×	×	×	Do et al. (2002b); 2003), Do (2010), Ghommam et al. (2006), Ghommam et al. (2010), Liu et al. (2014c), Chen and Cheng (2010), Yang et al. (2014)
×	×	√	×	×	Annamalai et al. (2014a)
×	×	×	×	√	McNinch et al. (2009), Oh and Sun (2010), Yu et al. (2012)

Note: (√) considered; (×) not considered; (Exper.) experiment; (Dist.) disturbances; (Uncer.) uncertainties; (Const.) constraints.

this, much of the literature focuses only on USV control without consideration of the above-mentioned factors. Control design for such nonlinear systems remains a challenging issue. For the sake of space, Table 7 briefly identifies current researches that consider the above-mentioned challenges. It is noteworthy that no prior attempt has been made to compile an exhaustive list since large amount of published literature in this direction.

Within the published literature, control design approaches fall into either one of the following methods, or some combination thereof: adaptive control (AC), backstepping control (BC), behavior-based control (BBC), cascaded control theory (CCT), cluster space control (CSC), decentralized synchronization (DS), dynamic surface control (DSC), fuzzy logic control (FLC), feedback linearization (FL), gradient-based adaptive technique (GBAT), gain scheduling (GS), input-output linearization (IOL), moving long base line (MLBL), linear quadratic regulator (LQR), linear quadratic Gaussian (LQG), Lyapunov's direct method (LDM), long base line positioning (LBLP), Lagrangian multiplier method (LMM), linear parameter varying (LPV), local control network (LCN), model reference adaptive control (MRAC), model predictive control (MPC), nonlinear model predictive control (NMPC), neural network (NN), null-space-based behavioral control (NSBBC), proportional integral derivative (PID), robust control (RC), reinforcement learning (RL), synchronization control (SC), sliding mode control (SMC), and vision-based control (VBC). In practical applications, hardly any USV control methods rely on a single control design technique, since a combination of different control approaches and structures is often more appropriate for improving system performance. Although great effort has been dedicated to the development of more advanced control methodologies, PID control still dominates USV control system design. In the following, more advanced control methodologies that are expected to overcome the above-mentioned challenges are discussed in order to provide an overview of the new trends on USVs control.

5.3.1. Control of underactuated USVs

With the exception of the fully-actuated USVs adopted in Feemster and Esposito (2011), Svec, Thakur, Raboin, Shah, and Gupta (2014b), Tee and Ge (2006) and Wondergem et al. (2011), most existing USVs are underactuated due mostly to the higher costs and impracticality of full actuation. In fact, most commonly used USVs are usually configured by mounting either two independent aft thrusters (Ashrafiuon, Muske, McNinch, & Soltan, 2008; Caccia et al., 2008a; Majohr & Buch, 2006; Sharma, Sutton, Motwani, & Annamalai, 2014) or one main aft thruster and one rudder (Breivik et al., 2008; Sonnenburg & Woolsey, 2013). This configuration produces only two distinct inputs (propulsion force and yaw moment), while the USV is moving in an environment with three DOF. As indicated by the Brockett necessary condition (Brockett, 1983), even if an underactuated system is open-loop controllable, it cannot be stabilized by any time-invariant continuous state feedback control methods. Additionally, it is impossible to

Table 8
Classification of USV control methods considering actuator deflection constraint (ADC), actuator deflection rate constraint (ADRC), and yaw rate constraint (YRC).

ADC	ADRC	YRC	Methods	References
√	√	√	MPC	Li and Sun (2012)
√	√	√	NMPC	Guerreiro et al. (2013)
√	√	×	AC	Feemster and Esposito (2011)
√	√	×	BC	Gadre et al. (2012), Tee and Ge (2006)
√	√	×	MPC	Annamalai et al. (2014a); 2014b), Oh and Sun (2010)
√	√	×	NMPC	Sharma and Sutton (2013)
√	×	×	BC	Do and Pan (2006b), Li et al. (2009)
√	×	×	AC	Skjetne et al. (2005)

Note: (√) considered; (×) not considered.

straightforwardly apply the classical control techniques designed for fully- or over-actuated systems on the underactuated ones due to their nonholonomic constraints (Do & Pan, 2009).

5.3.2. USV control under actuator and state constraints

As the bridge between control commands and physical actions in the system, each physical actuator is potentially subject to saturation. Control design without any actuator amplitude and rate constraints may induce significant performance degradation in the control system, wear and tear to the actuators, and even the instability of the closed-loop system when actuators saturate (Do & Pan, 2009). In addition, the abrupt turn of USVs should likewise be avoided in terms of the possibility of undesirable motion, or even capsizing in extremely fast turns.

Most of the existing work (Ding, Wu, & Wang, 2013; Feemster & Esposito, 2011; Gadre et al., 2012; Kyrkjebø et al., 2007; Li, Sun, & Oh, 2009; Sharma & Sutton, 2013; Skjetne et al., 2005; Sonnenburg & Woolsey, 2013; Tee & Ge, 2006) only introduces amplitude/rate limiters in the control system without consideration of the dynamics of the actuators and system states. To overcome these issues, there is a surge of interest (as summarized in Table 8) in integrating the actuator and state saturation effect into control design to increase the practical applicability of USVs (Annamalai & Motwani, 2013; Annamalai, Sutton, Yang, Culverhouse, & Sharma, 2014a; 2014b; Do & Pan, 2006b; Guerreiro, Silvestre, Cunha, & Pascoal, 2013; Peng et al., 2013).

5.3.3. Control of USV in the presence of environmental disturbances

USV control applications are inevitably influenced by environmental disturbances from winds, waves, and currents, while the small-scale USV in particular are more sensitive to environmental disturbances owing to their low inertia and small size. Despite this, most of the existing research imposes disturbances into the USV control system for control robustness assessment with little consideration of disturbance compensating mechanisms (as shown in Table 9). There are two dominant approaches for counteracting environmental disturbances: (1) model-based control techniques, where an adaptive control law is commonly derived to estimate and attenuate disturbances (Dai, Wang, & Luo, 2012; Ding et al., 2013; Do, 2010; Ghommam, Mnif, & Derbel, 2010; Kim, Lee, Yang, & Shell, 2012; Li & Sun, 2012; Peng et al., 2009; Peng et al., 2013; Yang, Du, Liu, Guo, & Abraham, 2014); and (2) approximation-based control methods, where disturbances are usually mitigated by adopting an extra integral action (Caccia et al., 2008a; Do, Jiang, & Pan, 2002b; 2003; Do & Pan, 2006b; Feemster & Esposito, 2011; Gadre et al., 2012; Hurban, 2012; Li et al., 2009; Pan, Lai, Yang, & Wu, 2013; Pereira, Das, & Sukhatme, 2008; Pettersen & Fossen, 2000; Tee & Ge, 2006).

On the one hand, the approximation-based method does not provide any deep insight into USV dynamics with environmental disturbances. Besides this, a steady-state error can also be produced when the desired heading rate is a function of the reference yaw angle, or when the USV moves in a complicated and rough environment (Bibuli et al., 2009). However, this method is capable of guaranteeing the local stability, and a simpler controller suitable for practical implementation can also be obtained. On the other hand, the model-based control approach normally requires a precise system model which is both generally difficult and costly to obtain, and is sensitive to model uncertainties.

5.3.4. Control of USVs under uncertainties

Real world applications of USVs will inevitably encounter a variety of unpredictable and immeasurable conditions, such as sensor uncertainties, unmodeled dynamics, and mass variation (Annamalai et al., 2014b). The presence of such uncertainties can cause high-frequency unmodeled dynamics, which consequently affect the performance of model-based controllers, and can even result in close-loop instability. Despite this, system dynamics and parameters are usually assumed to be explicitly known in controller design since it is usually difficult and costly to obtain accurate system parameters. The limited existing research that considers such uncertainties is briefly outlined in Table 10.

5.3.5. Fault detection, diagnosis, and tolerant control of USVs

Issues of fault detection and diagnosis (FDD), and fault tolerant Control (FTC) in USVs (Zhang & Jiang, 2008) have attracted increasing attention in a wide range of research communities. Conventional feedback control design methodologies for USVs may cause undesirable performance, and even instability in the presence of sensors, actuators, communications or other components malfunctions (Zhang & Jiang, 2008). This is particularly critical for high speed USVs moving in complicated and hazardous waters since a minor failure in a system component or unacceptable delay in reaction may lead to disastrous consequences for the USVs and their surrounding personnel, vehicles and facilities. Thus, there is a strong demand for more advanced USV control systems that possess the ability to simultaneously tolerate potential system faults, and guarantee the reliability and safety of the system with graceful performance degradation.

Such demand has resulted in the preliminary study of FDD in USVs by one group from Plymouth University. Sensor FDD has been investigated by using a modified fuzzy logic adaptive federated Kalman filter (FLA-FKF)-based multi-sensor data fusion (MSDF) (Naeem et al., 2008; Xu, Chudley, & Sutton, 2006; Liu, Motwani, Sharma, Sutton, & Bucknall, 2014a). Interested readers can refer to their website for more information (Anon, 2014b).

5.3.6. Experimental validation of control methods

Experimental validation plays a vital role in bridging the gap between theory and practice. Due to the tremendous challenges associated with practical implementation, including algorithm development, de-bugging, and platform design and maintenance, researchers typically focus on implementing control algorithms in simulation studies rather than in real environments. Even though significant efforts have recently been made (as listed in Table 11),

Table 9
Classification of USV control methods with consideration of environmental disturbances.

Method	References
AC and KF	Peng et al. (2009)
AC and integrator	Feemster and Esposito (2011)
L_1 AC	Hurban (2012)
MRAC	Hurban (2012)
LDM and BC	Do et al. (2002b)
BC	Do, Jiang, and Pan (2003), Gadre et al. (2012), Ghommam et al. (2006, 2010), Kyrkjebø et al. (2007), Li et al. (2008), Sonnenburg and Woolsey (2012); 2013)
BC and integrator	Do and Pan (2006b), Li et al. (2009)
Vectorial BC	Yang et al. (2014)
BC and observer	Do (2010), Tee and Ge (2006)
BC and NN	Peng et al. (2013b)
LQR	Lefeber et al. (2003)
LQG	Annamalai and Motwani (2013)
MPC	Annamalai and Motwani (2013), Annamalai et al. (2014a); 2014b), Li and Sun (2012)
NMPC	Guerreiro et al. (2013), Sharma and Sutton (2013)
PID	Beck et al. (2009), Hurban (2012), Naeem et al. (2012a), Pereira et al. (2008), Wondergem et al. (2011)
PID and RL	Kim et al. (2012)
GS-PI	Caccia et al. (2008a), Bibuli et al. (2009), Bibuli et al. (2012)
H_2/H_∞	Yu et al. (2008)
FLC	Abril et al. (1997), Vaneck (1997)
NN	Dai et al. (2012), Peng et al. (2013), Pan et al. (2013); Zhang et al. (2011a)
FLC and NN	Chen and Cheng (2010)
SMC	Alfaro-Cid et al. (2005), Liu et al. (2014c, 2014b)
SMC and AC	Ding et al. (2013)

Table 10
Classification of USV control methods considering uncertainties

Methodology	References
AC and KF	Peng et al. (2009)
AC and integrator	Feemster and Esposito (2011)
BC	Pettersen et al. (2004)
BC and high-gain observer	Tee and Ge (2006)
BC and integrator	Do and Pan (2006b), Li et al. (2009)
BC and NN	Peng et al. (2013b)
GS-PI	Caccia et al. (2008a), Bibuli et al. (2012)
MPC	Annamalai et al. (2014a), Annamalai et al. (2014b)
Fuzzy LQG	Naeem et al. (2012b)
NN	Dai et al. (2012), Peng et al. (2013), Pan et al. (2013); Peng et al. (2013b), Zhang et al. (2011a)
SMC	Liu et al. (2014b), McNinch et al. (2009), Yu et al. (2012)

Table 11
Classification of USV control methods with experimental validation.

Test sites	Methodology	References
	CCT	Ma (2009)
	FL	Moreira et al. (2007)
	AC	Skjetne et al. (2005, 2004a)
	Fuzzy PID	Tran et al. (2014)
	BC	Kyrkjebø et al. (2007), Li et al. (2009), Pettersen et al. (2004), Tee and Ge (2006)
	LQR	Lefeber et al. (2003)
Indoor	SMC	Alfaro-Cid et al. (2005), Ashrafiuon et al. (2008)
	PID	Beck et al. (2009), Breivik et al. (2008), Caccia et al. (2005), Hurban (2012), Moreira et al. (2007), Naeem et al. (2012a), Pereira et al. (2008), Song (2014), Svec et al. (2014b), Wondergem et al. (2011)
	GS-PI	Caccia et al. (2008a), Bibuli et al. (2009), Bibuli et al. (2012)
	LCN & PID	Sharma et al. (2012)
	PID & RL	Kim et al. (2012)
	L_1 AC	Hurban (2012)
	CSC	Adamek et al. (2015)
	MRAC	Hurban (2012)
	BC	Do and Pan (2006a); 2006b), Gadre et al. (2012), Sonnenburg and Woolsey (2012); 2013)
	LQG	Annamalai and Motwani (2013), Elkaim (2006), Naeem et al. (2008)
	Fuzzy LQG	Naeem et al. (2012b)
	FLC	Abril et al. (1997), Vaneck (1997)
	MPC	Annamalai and Motwani (2013), Annamalai et al. (2014a); 2014b)
	NMPC	Guerreiro et al. (2013)
Outdoor	H_2/H_∞	Yu et al. (2008)
	PD	Desa et al. (2007)
Outdoor and indoor	AC	Feemster and Esposito (2011)

Table 12
Classification of cooperation of USVs and other diverse vehicles.

Types	Objectives	Methodologies	References
		NN	Peng et al. (2011), Peng et al. (2012)
		NN and DSC	Peng et al. (2013)
		SMC	Fahimi (2007b), Schoerling et al. (2010)
		Graph theory	Peng et al. (2013b)
		NSBBC	Arrichiello et al. (2010), Mahacek et al. (2009)
		NMPC	Fahimi (2007a)
		SC	Kyrkjebø et al. (2007)
	Leader–follower formation	Fast marching	Liu and Bucknall (2015)
		PI-GS	Bibuli et al. (2012)
		Graph theory	Almeida et al. (2010); 2012), Ghommam and Mnif (2009)
		NN and DSC	Wang et al. (2013)
		Passivity control	Ihle et al. (2007)
	Cooperative path following	DS	Børhaug et al. (2011)
		Graph theory	Dong (2010)
		CSC	Mahacek et al. (2012)
		BBC	Elkins et al. (2010)
	Cooperative trajectory tracking	LMM	Ihle et al. (2006a); 2006b)
		CSC	Kitts et al. (2011)
		NSBBC	Arrichiello et al. (2006)
		Graph theory	Dong and Farrell (2008)
		GBAT	Adamek et al. (2015)
	Formation keeping	IOL	Fahimi, Rineesh, and Nataraj (2005)
	Target capture & transport	NSBBC	Arrichiello et al. (2012)
USVs	Task allocation and planning	Contract-based control	Raboin et al. (2014)
		BBC	Morgado et al. (2012)
		MLBL	Fallon et al. (2010)
	Cooperative localization	LBLP	Viegas et al. (2014)
USVs and UUVs	Cooperative sensing	BBC	Murphy et al. (2011)
	Cooperative landing	VBC	Pinto et al. (2014)
		Remote control	Murphy et al. (2008)
		VBC	Lindemuth et al. (2011), Pinto et al. (2013)
USVs and UAVs	Target tracking	Potential field	Healey et al. (2007)

more practical control structures and design methods capable of dealing with the above-mentioned challenges, together with more effective application of research to practical uses remain an important topic for future research.

6. Key GNC technologies for multiple USVs and other unmanned vehicles

In order to enhance USV robustness and reliability against system failures, improve mission performance, increase their spatiotemporal capacity, reduce operational costs, and optimize strategies for larger coverage of surveillance, communication, and measurement applications, current research goes well beyond single USV systems. As outlined in Table 12, much of the focus of recent USV research has shifted to cooperative control issues with applications to: (1) cooperation between USVs, including assets protection (Kitts, Mahacek, Adamek, & Mas, 2011; Mahacek, Kitts, & Mas, 2012; Raboin, Švec, Nau, & Gupta, 2014), surveillance and information sharing (Elkins, Sellers, & Monach, 2010), water surface objective capture and transport (Arrichiello, Heidarsson, Chiaverini, & Sukhatme, 2012), bathymetric sensing (Adamek, Kitts, & Mas, 2015), environmental monitoring (Arrichiello et al., 2010), ship replenishment (Kyrkjebø et al., 2007); (2) cooperation with UAVs, including maritime domain awareness (Healey et al., 2007), emergency and disaster response and management (Lindemuth et al., 2011; Murphy et al., 2008), environmental monitoring (Pinto, Santana, & Barata, 2013; Pinto et al., 2014); and (3) cooperation with UUVs, including search and rescue (Murphy et al., 2011), exchanging information with UUVs (Morgado, Batista, Oliveira, & Silvestre, 2012), providing UUVs with localization information (Fallon, Papadopoulos, & Leonard, 2010; Viegas, Batista, Oliveira, & Silvestre, 2014) since GPS signals are not available in underwater environments. In terms of cooperative navigation, Viegas, Batista, Oliveira, Silvestre, and Chen (2015) provides interesting contributions for formations with time-varying topologies recently.

Even though substantial effort has been devoted towards achieving successful cooperation strategies over the past decade, significant theoretical and practical challenges still exist:

1. *Disturbances and uncertainties*: The researches conducted in Arrichiello, Chiaverini, and Fossen (2006); Arrichiello et al. (2012), Børhaug et al. (2011), Ghommam and Mnif (2009), Ihle, Jouffroy, and Fossen (2006a); 2006b), Kitts et al. (2011) and Viegas et al. (2014) have taken the influence of disturbances into account, while Almeida, Silvestre, and Pascoal (2010), Fahimi (2007a, 2007b), Wang, Wang, Peng, and Wang (2013), Peng et al. (2013); Peng, Wang, and Hu (2011); Peng, Wang, and Li (2013b); Peng, Wang, Lan, and Sun (2012) and Schoerling et al. (2010) have considered both disturbances and uncertainties. Further research is possible on USVs cooperation under the influence of time-varying disturbances, as well as both dynamic and parameter uncertainties;
2. *Communication limitations*: Information sharing over a communication network is fundamental for cooperation, particularly for decentralized cooperative control. It also brings about numerous challenges, including limited communication bandwidth, transmission noise, and communication delays, dropouts and failures. Only a few of these issues have been studied in any detail, including communication delays (Dong, 2010; Dong & Farrell, 2008; Ghommam & Mnif, 2009; Ihle et al., 2006a; Izadi, Gordon, & Zhang, 2013) and dropouts (Ihle, Jouffroy, & Fossen, 2006b; Ihle, Arcak, & Fossen, 2007; Raboin et al., 2014);
3. *Collision avoidance*: Enhancing the safety and autonomy of USVs requires consideration of obstacle avoidance functionality. Despite this, existing research has mostly considered the issue of collision avoidance between cooperating vehicles, while other environmental obstacles are commonly ignored. Cooperation

with consideration of both vehicles and environmental obstacles to date can only be found in Arrichiello et al. (2010), Fahimi (2007a), Raboin et al. (2014) and Tam and Bucknall (2013);

4. *Underway replenishment*: USVs underway replenishment operations, which involve a close coordination of several USVs that move in parallel to conduct cargo (such as fuel, munitions, food, and personnel) transfer tasks, can enable the accomplishment of extended term missions and avoid port time (Kyrkjebø, 2007). Much work concerning the control issues of ships underway replenishment are carried out, such as leader-follower coordinated synchronization scheme is designed in Kyrkjebø and Pettersen (2003) and Kyrkjebø et al. (2007), later on, this method is experimentally verified in Wondergem (2004). Unfortunately, the hydrodynamic interaction effects occurring between the cooperation members are not considered in these investigations.
5. *Experimental validation*: Despite the recent activity in this area, most research is still limited to simulation, with only Adamek et al. (2015), Almeida et al. (2010), Arrichiello et al. (2010), Arrichiello et al. (2012), Bibuli et al. (2012), Børhaug et al. (2011), Elkins et al. (2010), Fallon et al. (2010), Healey et al. (2007), Kitts et al. (2011), Kyrkjebø et al. (2007), Mahacek, Mas, Petrovic, Acain, and Kitts (2009), Mahacek et al. (2012), Morgado et al. (2012), Murphy et al. (2008), Pinto et al. (2014), Schoerling et al. (2010) and Tokekar, Bhadauria, Studenski, and Isler (2010) conducting actual field experiments. Field experiments with good performance still deserve further investigation.

7. Challenges and future directions

Although tremendous effort has been dedicated to make USVs more autonomous, there still exist significant challenges in their development. Numerous key technical issues must be solved to bring the autonomy up to the level required for more sophisticated and hazardous applications.

7.1. Autonomous GNC of single USV

7.1.1. Guidance

1. *Path planning*
   (a) *Global path planning*: Most existing global path planning methods are computationally time consuming, such as heuristic search algorithms (Kim et al., 2013; Svec & Gupta, 2011; Zhuang et al., 2012) and optimization methods (Larson et al., 2006; Naus & Waż, 2013). As such, they are usually inappropriate for real-time applications in rapidly changing dynamic environments;
   (b) *Local path planning*: Local path planning approaches, such as potential fields (Healey et al., 2007; Soltan et al., 2009), only guarantee local convergence, which may lead the USV to the trapped situation instead of global convergence;
   (c) *Hybrid path planning*: The combination of global and local path planning approaches offers an effective solution for USVs working in both static and dynamic environments, but little attention to date (Casalino et al., 2009; Larson et al., 2006; Larson et al., 2007; Svec et al., 2012) has been paid to this hybrid path planning method. The fully observable environment is normally assumed in the existing research, partially observable environment and more efficient and reliable searching methods are still demanded. In addition, the system transient performance and stability is also a concern when switching between different path planning strategies;
   (d) *Path planning under practical issues*: Environmental disturbances and uncertainties are inevitable in USV path planning (Svec et al., 2012). It is also dynamically infeasible to follow a path by operating USVs with infinite engine thrust, rudder deflection and rates, and turn rates and accelerations. Too little research (Bibuli et al., 2009; Gal, 2011b) has concerned these issues in their path planning approaches. Furthermore, discontinuous command inputs should be avoided, and actuator saturation induced by dramatic jumps in tracking error should also be prevented, since sufficiently smoothed trajectories can contribute to more gentle acceleration, less redundant operations, and less energy consumption;
   (e) *Sternward/backward motion planning*: It is occasionally necessary for USVs to exhibit sternward/backward motion to enhance their maneuverability, improve environmental adaptability, and avoid environmental hazards (Gadre et al., 2012; Sonnenburg & Woolsey, 2012). Current studies are still limited to low speed USVs.
   Practical applications of hybrid path planning strategies combining global and local methods, along with consideration of other challenging issues such as USV dynamics, uncertainties, environmental disturbances, stationary and dynamical obstacles, computational issues and control objectives (spatiotemporal, energy, weather-optimal, danger level or mission), all deserve further investigation.
2. *Path replanning*: With the further development of USVs, more advanced collision avoidance capabilities are increasingly needed. Unfortunately, only the avoidance of static and semi-dynamic obstacles has been investigated, while the availability of more effective, accurate and reliable methodologies to avoid both static and dynamic obstacles are still of great interest for further investigation.
   (a) *Protocol-free case*: One potentially important area for research is developing the ability to effectively and reliably plan an optimal path in real-time, integrating nautical chart data, USV dynamics, and surrounding stationary and dynamical obstacles (both above- and under-water (Heidarsson & Sukhatme, 2011; Onunka et al., 2013));
   (b) *Protocol-based case*: Because COLREG regulations were originally devised as navigation rules for human operators to steer ships, the incorporation and implementation of this regulation in USV collision avoidance strategy presents a huge challenge (Benjamin et al., 2006; Lee et al., 2004), especially for the identification of lights, flags, and horns. Additionally, COLREGs regulation provides safe operation along with chattering behavior issues due to the uncertainties in situation awareness, which may cause frequent switches in COLREG constraints. Another area of ongoing improvement is the ability to consider both COLREG regulations and nautical chart data in path replanning.

7.1.2. Navigation

Although there have been some applications of current navigation technologies on USVs, long-range and real-time navigation needs further investigation.

1. *Sensing technologies*: Navigation of USVs in unknown, complicated, and cluttered environments normally requires effective sensing technologies and onboard data processing algorithms.
   (a) *Radar*: Radar is currently the main choice for far-field obstacle detection (Ji et al., 2014). Despite this, it may still fail to detect small-size and popup objects at close range. Obstacle detection precision may also be decreased due to cumulative deviation (more serious due to the fast turning behavior of USVs), high waves, and water reflectivity;
   (b) *Sonar*: Sonar is primarily applied for underwater obstacle detection and information perception (Onunka et al., 2013), but the gathered data is easily influenced by noises,

especially at the near-surface. Additionally, automatic sonar image interpretation is also challenging. These issues demand sonar data processing methods that are more robust and intelligent than at present;

(c) *Vision sensors*: Although vision sensors are identified as potential candidates for active sensing methods in USV navigation, current research is limited to the use of visual sensors (Gal, 2011a; Huntsberger et al., 2011). Infrared sensors have not yet been applied in USV navigation. Common maritime phenomena, such as sea fog (blurs images), wave occlusions and continuously changing viewing angle and range (induces images vibration), variation of lighting and weather (disturbs detection laws), and reflections of obstacles and surroundings (causes false identification), may also seriously affect its performance. Further research to increase the reliability and effectiveness of vision sensors is needed;

(d) *Multi-modal sensing*: In order to compensate the weakness of single sensing application, the multi-modal sensing can be a suitable choice to proceed to ensure USVs as safe as possible (Elkins et al., 2010), while the real-time data processing and heterogeneity of the data sources are still challenging.

2. *State estimation*
   (a) *State estimation with conventional GPS-IMU*:
      i. GPS and IMU are widely adopted for USV state estimation (Bibuli et al., 2009; Caccia et al., 2008a; Motwani et al., 2013), while state estimation results are inevitably affected by environmental noises, inherent errors, and the accumulative bias of sensors. An interesting research in terms of the estimation of accelerometer bias has been presented in Batista, Silvestre, and Oliveira (2011). Data fusion of multiple sensors in order to develop more accurate and reliable navigation schemes and obtain the desired information is worthy of further investigation (Sutton et al., 2011; Vasconcelos et al., 2011a; Xu et al., 2007);
      ii. USVs occasionally operate in some special waters (such as under bridges or trees) with non-existent/degraded GPS signal reception, or near targets (metal objects) with strong magnetic signatures which can disturb onboard sensors. In these situations, using only one method is insufficient for localization and attitude measurement. The currently adopted solution is to use active ranging sensors or vision sensors for state estimation (Naeem et al., 2012b; Xu et al., 2007);
      iii. Since each individual sensor may suffer from failure (Zhang & Jiang, 2008), sensor (hardware) and analytical (software) redundancies are generally employed (Sutton et al., 2011). Furthermore, smart sensors with fault diagnosis capabilities can also be a potential solution to sensor failure.
   (b) *State estimation based on other sensors*: Active (LIDAR, radar and sonar) and passive (vision sensors) ranging sensor-based methods can also be adopted in state estimation, in particular for the application of USV navigation with degraded/lost GPS signals. Current research on USV navigation using active and passive ranging sensors remains minimal.
3. *Environment perception*
   (a) *Obstacle recognition*: One of the difficulties facing USV navigation is the recognition of surrounding obstacles without human intervention. Despite this, existing research in this area (Subramanian et al., 2006; Wolf et al., 2010) is still scarce, and the development of methods with higher detection rates are needed in future studies;
   (b) *Varying environment effects*: The most challenging issue for USV real-time vision-based perception is the influence of widely varying environmental conditions (Ma et al., 2013), such as fog, lighting, rain, wave occlusions, sophisticated background, as well as variational view angle and range. In addition, the reflections of obstacles and surrounding environment may show up clearly and incorrectly be classified as obstacles. Thus, subsequent work to increase the reliability of vision-based methods and remove image reflections are highly needed. Infrared and laser illumination are commonly suggested as the solution to these issues in other unmanned navigation fields, but their application in USVs is still minimal. Besides the above-mentioned issues, salt spray, winds, waves, currents, and tides also present significant challenges (image blurring and vibration). Although pioneering research on this has been conducted (Gal, 2011a), further investigation of the above-mentioned challenges are deserved.
4. *Situation awareness*: SA is crucial for enhancing USV navigation performance, but issues related to the SA of USVs (Leedekerken et al., 2014; Wolf et al., 2010) have not yet been extensively introduced, and USV SA performance still depends solely on human operators (the autonomy level is somehow low). Unlike UGV and UUV, USV SLAM has to take into account the information both above and below the waterline. Accurately fusing these two separate regions is challenging due to their different resolutions and levels of accuracy, as well as the tide-caused water-level variation (Murphy et al., 2008).

7.1.3. Control

USV control systems still have significant limitations in their current state of development, and many critical aspects must be clarified to fulfill the increasing demand for greater autonomy.

1. *Modeling of USVs*:
   (a) *Nonlinear modeling*: Most existing control methods usually depend on highly idealized dynamic models, using strict assumptions. There is a great demand for the development of control schemes based on a more general and precise dynamic model to cover a wider range of sea conditions;
      i. Hydrodynamic coefficients are always time-varying, which cannot be accurately estimated in advance, while USVs generally do not have fore/aft symmetry. Because of these practical issues, the coupling interactions of velocity and acceleration in each DOF, Coriolis and Centripetal forces, and nonlinear viscous effects will become increasingly apparent and significant for steering USVs with high surge speeds (Skjetne et al., 2004a). Hence it is more reasonable and practical to consider both $\boldsymbol{C}(\boldsymbol{\nu})$ and the off-diagonal terms in $\boldsymbol{M}$ and $\boldsymbol{D}(\boldsymbol{\nu})$ to enhance controller performance (Børhaug et al., 2011; Do & Pan, 2006a; Pettersen & Nijmeijer, 2001; Wondergem et al., 2011);
      ii. Although taking account of non-diagonal matrix elements is trivial for fully-actuated USVs, it remains challenging for underactuated USVs (Pettersen & Nijmeijer, 2001).
   (b) *High-speed USV control*: Coupling interactions, environmental disturbances, the influence of hydrodynamic damping, and measurement noises can all seriously degrade the performance of USVs in high-speed operational conditions (Pettersen et al., 2004). It is also difficult to conduct linear translations of surge and sway velocities. In contrast to the control design for low-speed USVs (Skjetne et al., 2004a), more complete models and advanced control strategies are needed in high-speed situations;

(c) *Model identification*: In the existing research, USV model is generally identified off-line (Rajesh & Bhattacharyya, 2008; Sonnenburg et al., 2010). Owing to the complexity of this practice and its benefits (Sharma & Sutton, 2012; Zhang et al., 2011a) (improved model accuracy and real-time model learning and updating), on-line identification is a potentially useful topic for further investigation.

2. *Control of USVs*:
   (a) *Control under environmental disturbances and uncertainties*: Due to the presence of uncertainties in model dynamics and parameters, as well as hard-to-predict time-varying environmental disturbances, the expected motion may be unachievable when the USV controller is designed using an ideal model assuming disturbance-free conditions. This adverse effect becomes particularly serious for low inertia and small size USVs operating in a priori unknown and cluttered environments (Thakur, Svec, & Gupta, 2012). Furthermore, the drawbacks of existing methods that reject environmental disturbances include: (1) sensitive reactions to high-frequency noises and disturbances, inducing the increase of wear and tear on actuator systems; (2) constant and slow time-varying disturbance assumptions are usually needed for controller design; and (3) it is still an open issue for an underactuated USV fully compensating disturbances in three DOF (Fredriksen & Pettersen, 2006). Therefore, designing a controller that is capable of rejecting time-varying disturbances without frequent and abrupt action of actuators is still worth further investigation;
   (b) *Control with consideration of state & actuator limits*: The limitations on amplitude and rate of states and actuators all need to be considered in controller design to avoid control performance degradation, and even system instability (Annamalai et al., 2014b; Do & Pan, 2006b). To avoid undesirable motion and excessive tear and wear on actuator systems, actuator actions should not be excessively sensitive to external disturbances, while control signals should also be continuous. It is noteworthy that MPC has recently been adopted for USV control, which can inherently incorporate the limitations of actuators and states into controller design (Li & Sun, 2012; Oh & Sun, 2010);
   (c) *Fault tolerant capability of USV control systems*: As the operational periods and ranges of USVs increase, the demand for more reliable systems also rises. The ability to detect, diagnose and tolerate malfunctions in the mechanical and electrical elements of USV systems, as well as reliably and safely operating USVs under a wide range of environmental conditions is an important area of concern (Elkins et al., 2010). The current solution consists of a combination of redundancy (multiple groups of identical system configuration) of electrical and mechanical components with advanced fault detection, diagnosis and reconfiguration mechanisms (Zhang & Jiang, 2008), though such a strategy also significantly increases the costs of USV development and the complexity of USV control (Manley, 1997). Although consideration has been given to detection and diagnosis of faults in USVs sensors (Naeem et al., 2008; Xu et al., 2006), no effort has been made to apply fault detection and diagnosis techniques, or to develop FTC techniques to deal with failure in USVs actuators and communication systems. The significant development of FDD and FTC in USV control is definitely expected in the near future;
   (d) *Autonomous departure and docking*: In general, USVs are manually controlled until their position and velocity satisfy some specific requirements during their departure and docking. Autonomous, safe and robust self-docking (Breivik & Loberg, 2011) and undocking of USVs (Martins et al., 2007b) would be a tremendous advantage in terms of reducing personnel cost and extending USV working durations. Despite this, a significantly challenging technical issue arises due to the existence of continuous and unpredictable external disturbances (Kim et al., 2012). Research on this issue can only be found in Breivik and Loberg (2011); Dunbabin, Lang, and Wood (2008); Kim et al. (2012). Vision-based docking strategies are one technique that has already been adopted (Dunbabin et al., 2008; Kim et al., 2012);
   (e) *Coupling influences among each motion*: Some motions coupled in reality, including the roll moment generated by disturbances, thrusters and rudders, can affect turning performance. The sway force induced by the deflection of the rudder may further complicate the control design (Fredriksen & Pettersen, 2006; Ma, 2009);
   (f) *Control reallocation* (Johansen & Fossen, 2013; Johansen, Fossen, & Tndel, 2005): For over-actuated USVs (the feasibility of control reallocation depends on over-actuation), optimally distributing control commands to different actuators offers numerous advantages, including reduced energy consumption and enhanced control capabilities. From an energy saving perspective, the active operation of rudders owns more potential advantages especially when USV is moving in the low surge speed maneuvering case (such as station-keeping, docking, and dynamic positioning) because the consumption of fuel and excessive wear and tear on the thrust system (it is much energy- and life- consuming in the case of frequent operation of thrust) could be relatively decreased by maneuvering a rudder servo compared to operating the thrust system (Johansen, 2013; Johansen, Fuglseth, Tndel, & Fossen, 2008; Lindegaard & Fossen, 2003). From the enhanced control capabilities viewpoint, the reconfiguration of control strategies can also significantly improve the system performance in the presence of actuator faults (Casavola & Garone, 2010; Cristofaro & Johansen, 2014) and operating condition variations. These adverse phenomena are mitigated by only reallocating the control signals without reconfiguring the control laws, which is particularly desirable for the model-based control methods. But the computationally fast control reallocation approaches considering time-varying operating conditions are still scarce (Casavola & Garone, 2010);
   (g) *Dynamic positioning (DP)* (Sø rensen, 2011): Due to the depletion of oil and gas resources in shallow waters and their significantly increasing demand from both industrial and civil consumptions in recent years, a growing number of marine surface structures have been dynamically positioned to harsher and more sophisticated environments for offshore exploration and exploitation of hydrocarbons (He, Ge, How, & Choo, 2014). Most of the early DP systems are deployed subjecting to a certain limit of environmental conditions and relatively simple tasks. As the DP technology becomes more mature, research efforts are gradually put into the existing challenges, such as the unpredictable and time-varying environmental disturbances from winds, wave and current (Chen, Ge, How, & Choo, 2013; Du, Yang, Wang, & Guo, 2013), system parametric uncertainties (Chen et al., 2013; Du et al., 2013), varying operational conditions (Nguyen, Sø rensen, & Quek, 2007), as well as sensor and actuator failures. The recent developed hybrid DP strategy (Nguyen et al., 2007) capable of dealing with varying environmental and operational conditions is an effective and promising method, which is worth further investigation. Although the stability of switching between strategies in hybrid DP has also been concerned (Nguyen et al., 2007),

further research on the switching-induced chattering prevention is deserved. Additionally, the safety of DP operations is increasingly demanded. More research efforts are thereby expected to be dedicated into FDD of sensors as well as FDD and FTC of actuators (Fang & Blanke, 2011). For more references and further detailed information on the topic of DP, readers can refer to Fossen (2011) and Sø rensen (2011);

(h) *Active control of offshore steel jacket platform*: Offshore steel jacket platforms, as one type of the marine vehicle platforms, play an increasingly important role in the oil and gas drilling, extraction, transportation, and storage (Terro, Mahmoud, & Abdel-Rohman, 1999). The ocean environment that the platforms located is normally sophisticated and harsh, and where they may be subject to a variety of dynamic forces from winds, wave, current, ice, and even earthquake, as well as suffer from the erosion of sea water and salt atmosphere (Sakthivel, Selvaraj, Mathiyalagan, & Park, 2015). In addition to that, the flexible and complicated structure of the offshore steel jacket platforms tends to cause self-excited hydrodynamic force and nonlinear responses, those issues may result in adverse consequences, such as the large deformations and vibration of platforms, fatigue damage, and risky working conditions. As a result, the safety and durability of the offshore steel jacket platforms have raised great concerns from the marine research community. Extensive efforts have been dedicated to this area, which can also be made use of in other marine vehicles research. The stabilization of the platform subject to wave-induced forces is investigated in Sarrafan, Zareh, Khayyat, and Zabihollah (2012), Zhang, Ma, and Han (2013), Zhang and Tang (2013), Zhang, Han, Zhang, and Yu (2014b) and Nourisola, Ahmadi, and Tavakoli (2015). The research of actuator time-delay has been reported in Zhang, Han, and Han (2011b), Zhang and Tang (2013), Zhang, Hu, and Tang (2012) and Zhang, Huang, and Han (2015). The parameter perturbations of the platform and the external disturbances have been considered in Zhang et al. (2014b, 2013). Moreover, the actuator FTC problem in offshore steel jacket platforms has recently drawn increasing attention. But only partial loss of actuator effectiveness to date is studied in Sakthivel et al. (2015) and Zhang, Feng, and Li (2014a), while other kinds of sensor and actuator failures deserve further investigation.

7.2. Autonomous GNC of USVs and other vehicles

In order to achieve more efficient and effective missions, USVs usually cooperate with not only themselves, but also other similar vehicles, such as UUVs, UAVs, as well as manned air and surface vehicles. GNC aspects, however, can be more sophisticated.

7.2.1. GNC in cooperative systems

1. *Centralized vs. decentralized control*: Compared with centralized control, decentralized control techniques are more flexible, desirable, and generally reduce the structural requirements on communication network topologies (Børhaug et al., 2011). But they are also more challenging due to the communication constraints (noises, delays, dropouts and failures), obstacles, and uncertainties;
2. *Protocol-based cooperative control*: Because USVs are often forced to give way to larger and higher priority ships (such as cargo and passenger ships), multiple USVs in combination with multiple COLREGs rules and real-time computational capabilities is another significant research direction that merits consideration (Murray, 2007; Tam & Bucknall, 2013);
3. *Cooperation with safety requirements*: In order to increase USV autonomy and safety, further development of collision avoidance capabilities, especially those directed towards preventing inter-USVs collisions (Adamek et al., 2015; Mahacek et al., 2012; Viegas et al., 2014), as well as static and dynamic environmental objects is needed (Raboin et al., 2014; Tam & Bucknall, 2013);
4. *Cooperative control with fewer sensors*: Most existing cooperative control methods rely on velocity information by adopting velocity sensors (especially for leader-follower cases). Provided that the desired performance is satisfied, developing a cooperative control technique using only position measurements or estimates of velocity even without velocity sensors (using e.g. accelerometers) would be much preferred in practice, allowing decreases in both equipment cost and network burden (Peng et al., 2013; Xiao, Hu, & Zhang, 2011; Xiao, Hu, Zhang, & Huo, 2014);
5. *USV cooperation under abnormal conditions*: Influences from disturbances (Arrichiello et al., 2012; Viegas et al., 2014), uncertainties (Almeida et al., 2010; Schoerling et al., 2010), and communication limitations (Dong, 2010; Raboin et al., 2014) can all undermine individual USV performance, and ultimately affect USV cooperation. Moreover, it is important to consider the proper cooperative control of USVs even if some USVs experience sensor, actuator or communication failures. Due to the complex nature and underactuation characteristic of most USVs, the implementation of FTC in cooperative control systems of multiple USVs has only just been investigated (Izadi et al., 2013), although many recent developments in UAVs and UGVs have been carried out (Chamseddine, Zhang, & Rabbath, 2012; Sharifi, Zhang, & Aghdam, 2014; Xu, Yang, Jiang, Zhou, & Zhang, 2014);
6. *Underway replenishment*: Ships underway replenishment operations are currently performed manually, demanding the superb seamanship to maintain the expected trajectories that provide joint motion suitable for the replenishment manipulation (Brown & Carlyle, 2008). Although much effort (Kyrkjebø et al., 2007) has been devoted to the investigation of ships underway replenishment, the relative work on USVs is still scarce. Moreover, when the cooperating ships move in close proximity, ships' maneuvering behavior becomes much susceptible to the hydrodynamic interaction effects between them, and which may cause strong and sudden attraction or repulsion effects between them and make it difficult to precisely perform the anticipated operation. This situation can be further developed into disastrous consequences (threatening the personnel safety or even collision) if the environmental loads between the involved ships are significant (Breivik, 2010). But most of the existing research assumes that the underway replenishment operations are conducted in calm water, while the hydrodynamic interaction loads (such as the added mass, damping, and wave diffraction force), waves, and winds for two ships involved in close-proximity maneuvers that are of great concern are normally ignored. Only little existing research (Fu & Haddad, 2003; McTaggart, Cumming, Hsiung, & Li, 2003; Skejic, Breivik, Fossen, & Faltinsen, 2009) takes into account part of these unfavorable effects. The manned/unmanned helicopter, as another promising application of underway replenishment, can also be employed for vertical replenishment of USVs that may be some distance away.

7.2.2. Cooperation of USVs and other unmanned/manned Systems

1. *Cooperation with UUVs*: As GPS cannot be directly used in underwater environments, the navigation of UUVs generally depends solely on onboard sensors which inevitably experience

error accumulation (Fallon et al., 2010). USVs with high maneuverability have been employed to overcome this obstacle, tracking UUVs and providing them with real-time accurate navigation information (Murphy et al., 2011);

2. *Cooperation with UAVs*: To increase their spatiotemporal capacity, USVs can potentially cooperate with UAVs to conduct specific missions, such as acting as landing, launching, refueling, and replenishment platforms for UAVs (Murphy et al., 2008);
3. *Cooperation with other manned vehicles*: To take advantages of each other, USVs and manned vehicles are occasionally required to cooperate to conduct specific missions. But no existing research up to date considers this topic.

8. Conclusions

In the near future, the development of fully autonomous USVs in highly dynamic maritime environments remains an open question, and there are numerous ongoing research works on this topic. This paper has presented a technical review and bibliographical list on historical and contemporary developments in USV GNC systems. The basic definitions of USVs system are given. The adopted methodologies for USV GNC are categorized and outlined. Some challenges and future directions have also been presented to facilitate the research progress of autonomous and practically applicable USVs.

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Zhixiang Liu is currently a Ph.D. candidate in mechanical engineering with the Department of Mechanical and Industrial Engineering at Concordia University, Montreal, QC, Canada. His research interests include guidance, navigation, and control of unmanned vehicles, robotic systems design, as well as fault detection, diagnosis, and tolerant control of safety-critical systems.

Youmin Zhang received the B.S., M.S., and Ph.D. degrees with a specialization in automatic controls from Northwestern Polytechnical University, Xian, China, in 1983, 1986, and 1995, respectively. Dr. Zhang is currently a Professor with the Department of Mechanical and Industrial Engineering and the Concordia Institute of Aerospace Design and Innovation, Faculty of Engineering and Computer Science, Concordia University, Montreal, Quebec, Canada. His current research interests include condition monitoring, health management, fault diagnosis, and fault-tolerant (flight) control systems, cooperative guidance, navigation, and control of unmanned aerial/space/ground/surface vehicles, dynamic systems modeling, estimation, identification, advanced control techniques and advanced signal processing techniques for diagnosis, prognosis, and health management of safety-critical systems, renewable energy systems and smart grids, and manufacturing processes. He has authored four books, over 390 journal and conference papers, and book chapters. Dr. Zhang is a Senior Member of the American Institute of Aeronautics and Astronautics (AIAA) and the Institute of Electrical and Electronics Engineers (IEEE), and a member of the Technical Committee (TC) for several scientific societies, including the International Federation of Automatic Control TC on Fault Detection, Supervision and Safety for Technical Processes, the AIAA Infotech@Aerospace Program Committee on Unmanned Systems, the IEEE Robotics and Automation Society TC on Aerial Robotics and Unmanned Aerial Vehicles, the ASME/IEEE TC on Mechatronics and Embedded Systems and Applications, and the International Conference on Unmanned Aircraft Systems (ICUAS) Association Executive Committee. He has been invited to deliver plenary talks at international conferences/workshops and research seminars worldwide for over 60 times. He is the Editor-in-Chief of the Journal of Instrumentation, Automation and Systems, an Editorial Board Member, and/or Editor-at-Large, Senior or Associate Editor of six other international journals (including three newly launched journals on Unmanned Systems). He has served as the General Chair, the Program Chair, the Program Vice Chair, and IPC Member of many international conferences, including the General Chair of the 10th International Conference on Intelligent Unmanned Systems (ICIUS) in 2014, Montreal, Canada, the Program Chair of the International Conference on Unmanned Aircraft Systems (ICUAS) in 2014, Orlando, FL, USA, and one of General Chairs of the ICUAS in 2015, Denver, CO, USA. Dr. Zhang is currently serving as Co-General Chair for ICIUS 2016, Xian, China, Aug. 23–25, 2016, and Program Chair for ICUAS 2017, Miami, USA, June 13–16, 2017.

Xiang Yu received the B.S., M.S., and Ph.D. degrees from Northwestern Polytechnical University, Xian, PR China, in 2003, 2004, and 2008, respectively. He is currently a research associate at the Department of Mechanical and Industrial Engineering in Concordia University, Montreal, QC, Canada. His expertise includes fault-tolerant control design of safety-critical systems, guidance, navigation, and control of unmanned systems, and networked based control systems.

Chi Yuan is currently a Ph.D. candidate in mechanical engineering with the Department of Mechanical and Industrial Engineering at Concordia University, Montreal, QC, Canada. Her research interests include unmanned systems based forest fire monitoring and detection, image processing, as well as visual navigation in agricultural application.

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