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Review

Unmanned surface vehicles: An overview of developments and challenges

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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

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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