Review on Motion Control of Unmanned Surface Vehicles (USVs)

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Abstract

For the last two decades, numerous governments, companies and organisations across the world are developing full autonomy Unmanned surface vehicles (USVs) for surveillance, intelligence, search and rescue, reconnaissance and strike missions, etc. applications. USVs are playing an increasingly significant role in modern marine operations in shallow waters and in the oceans. The plethora of opportunities and threats that come with modern daily living have created a niche demand for USVs to extend their capabilities to include more complex and optimal mission planning in order to perform missions faster, more autonomously, with a great-deal of flexibility, less reliant on human interactions and effect of human errors. In addition, because of its practical importance and low cost, the vast majority of surface vessels are underactuated vehicles which have only two actuator inputs as well as it operates in uncertain environments, and is exposed to large disturbances from hydrodynamic effects, wave, wind and current, and its high nonlinearity. Safe and precise control of a USV under disturbances and actuator saturation is a significant challenge, especially for the practical application. A motion control system for an underactuated USV needs to be designed appropriately to enable it to cope with these tough and real-life requirements.

This report summarizes a survey of the literature on USVs and different motion control algorithms/strategies mainly applicable to USVs worldwide. Totally, more than 100 references (mostly journals, theses and books) in open literature are compiled to provide an overall picture of historical, current, and future research and development in this area.

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1 Introduction

Following decades of research and development focused on the autonomy of aerial, ground, aerospace and underwater vehicles, a resurging interest in Unmanned Surface Vehicles (USVs) has come [24]. An Unmanned Surface Vehicle (USV) is a kind of autonomous marine vehicles which travels on the complicated surface of water and performs missions without any human intervention, and essentially exhibit highly nonlinear dynamics. It operates in uncertain environments, and is exposed to large disturbances from hydrodynamic effects, wave, wind and current. Thus, the importance of USVs lies in the fact that they are able to carry out tasks in variety of environments without jeopardizing human life [140].

With the latest developments in the fields of artificial intelligence, advanced smart sensors, wireless networks and optimization techniques now present greater opportunities than ever before for USVs and maritime technology on the whole [26]. In the past 15 years, a large number of USVs have been developed for a large set of applications such as: mapping of riverine environments, environmental monitoring and sampling, oil and gas exploration, deep sea pipeline monitoring, mine detection, coastal protection, bathymetric surveys, and support for Autonomous Underwater Vehicle (AUV) operations [83]. However, motion control of underactuated ships in the presence of harsh environmental disturbances and an open navigational space poses far greater challenges [24]. Current research and development efforts aim at improving existing technical challenges to have USVs widely accepted: (1) affordable over-the-horizon (OTH) communications to extend the range that USVs can operate from host ship or base; (2) safe, reliable USV launch and recovery; (3) greater USV autonomy; (4) increased reliability and survivability [130]. To overcome all these ever increasing requirements and challenges, greater USV autonomy together with more advanced motion control system constitute the key enabling technologies for ensuring intelligent, safe, reliable and efficient USV.

Research in this field has recently been conducted more and more in both academia and industry. There have been a few books and review papers on USVs and motion control of USVs published in open literature [2, 12, 24, 27, 34, 52, 81, 106, 108, 121–123, 129, 130, 141]. In addition, there are some papers and books available which deal with general aspects of modelling of USVs [12, 57, 59, 70, 78, 82, 106, 110, 117, 124, 125]. However, most of the former researches and publications are about the motion control of USV without any disturbances from wave, wind and current as well as actuator saturation, obstacle avoidance, fault in sensor, actuator, communication and others. In addition, given the significance of motion control algorithms together with actuator saturation, disturbances, obstacle avoidance, fault in sensor, actuator, communication and others, there are few well-organized, comprehensive survey publication about the state of current research in this new and active area along with opportunities for the future.

This critical literature review reports an updated and more comprehensive review of the literature on different algorithms/strategies for motion control mainly applicable to USVs. The remainder of the report is organized as follows: The development of USVs are briefly reviewed in Section 2. USV is described in Section 3. The existing techniques to motion control system are briefly introduced in Section 4. Available USV models and simulation tools are reviewed in Section 5. The status and development of the research on motion control in USV is presented in Section 6. Finally, Section 7 outlines conclusions of this review and points out some remarks on future directions.

2 Brief Review on the Development of Unmanned Surface Vehicles (USVs)

USVs were in use as early as World War II, where remotely controlled vessels were deployed as gunnery and missile target systems [26]. Canadians developed the COMOX torpedo concept in 1944 as a pre-Normandy invasion USV designed to lay smoke during the invasion as a substitute for aircraft [130]. Navy interests in USVs for reconnaissance and surveillance missions emerged in the late 1990s that leads USVs being finding ever increasing applications in today's world, and are being developed by numerous organizations, universities and companies [2].

Figure 1: Spartan [130], San Diego [62] and Sentry [51] USV.

Figure 2: Protector [104], Silver Marlin [130] and XG-2 [141] USV.

A majority of USVs currently under development are found in the United States and Israel, encompassing mostly naval but also scientific applications. No applications currently seem to exist in the commercial market [67]. Most USVs are just experimental platforms, used to test hull designs, communication and sensor systems, propulsion solutions, as well as control algorithms. Compared to the current UAV market and technology, USV development is still in its infancy [67]. The only industrial-level USVs are currently found within the naval segment, mainly applied

Figure 3: Dolphin (MESSIN) [69], Charlie USV [17] and Springer [82] USV.

Figure 4: Piraya [67], ROAZ [39] and Mariner [67] USV.

for Intelligence, Surveillance, and Reconnaissance (ISR) operations. Most of these vehicles are remotely operated. USVs remain so far limited to small to medium vessels with limited autonomy [26]. The countries that pursue USV development (see also [68,130]) include (Just several pictures of USVs for each country are listed for readers' reference): (1) USA (Spartan, San Diego, Sentry (see Figure 1), Blackfish, Piranha, Freedom Sentinel, Sea Fox, Stingray, Draco, Ribcraft, Roboski, Owl MK II, UHSV, ARTEMIS, ACES, AutoCat, SCOUT). (2) Israeli (Protector, Silver Marlin (see Figure 2)). (3) Canada (Barracuda, Mako, Hammerhead, Dolphin, Seal (see Figure 5)). (4) France (Argonaute, Basil (see Figure 5), Seakeeper). (5) Japan (UMV-H, UMV-O (see Figure 5)). (6) Germany (Measuring Dolphin (see Figure 3), Rescuing Dolphin). (7) Italy (Alanis, Charlie (see Figure 3), SESAMO). (8) Norway (Mariner (see Figure 4), Kaasboll, Viknes). (9) Portugal (Delfim, Caravela, ROAZ (see Figure 4)). (10) Sweden (Piraya (see Figure 4), SAM). (11) United Kingdom (MIMIR EV1, SWIMS, Mimir, SASS, Springer (see Figure 3), FENRIR). (12) China (XG-2 (see Figure 2), Tianxiang One)

3 General Description of an Unmanned Surface Vehicle System

This section is organized to provide readers with a basic understanding of a USV system. For additional reading and background information, the readers are referred to the papers [12,57,59,70,78,82,110,117,125,125] and textbooks by Fossen [124], Roberts and Sutton [106].

When people hear of unmanned vehicles today they mostly think about either Unmanned Aerial Vehicles (UAVs), Unmanned Underwater Vehicles (UUVs) or Unmanned Ground Vehicles (UGVs). Little attention has so far been paid to USVs. In fact, the US Navy did not release its

Figure 5: Seal, UMV-O and Basil USV [130].

first USV Master Plan until 2007 [129], where a USV is defined by (1) Unmanned: Capable of unmanned operation. Can be manned for dual use or test and evaluation. Has varying degrees of autonomy. (2) Surface Vehicle: Displaces water at rest. Operates with near continuous contact with the surface of the water. Interface of the vehicle with the surface is a major design driver.

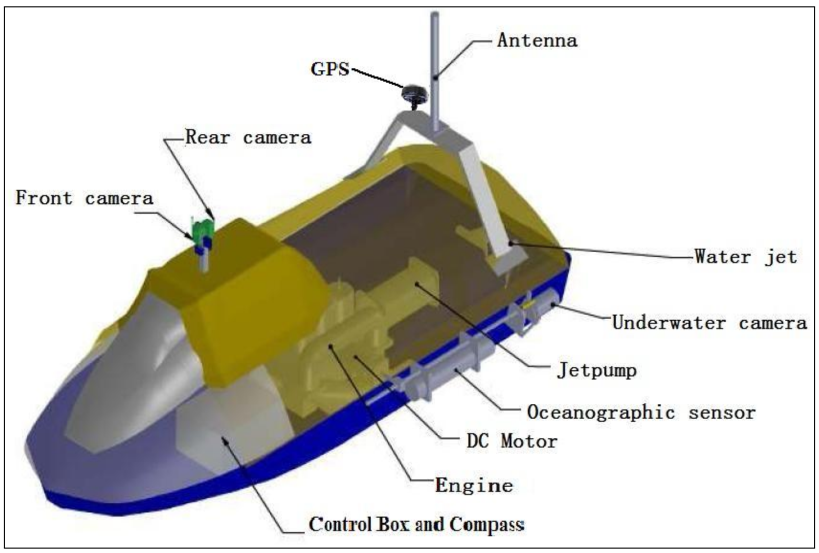

Figure 6: General description of unmanned surface vehicle [85].

A USV consists of several parts (shown in Figure 6): (1) Hull (or multi-hull) and auxiliary structural elements. (2) Engines and associated propulsion subsystems. (3) On-board communications, command and control subsystem which includes onboard processing subsystems for USVs engine management systems, payload sensor systems and navigation, guidance and control (GNC) subsystems [106]. (4) Sensors (Cameras, GPS and sensors to measure speed, heading as well as conditions of the USV in term of engine, water temperatures and fuel consumption of the USV [140]).

4 Overview on Motion Control Systems

The purpose of this section is to give a brief overview of motion control system developed for USVs including basic concepts.

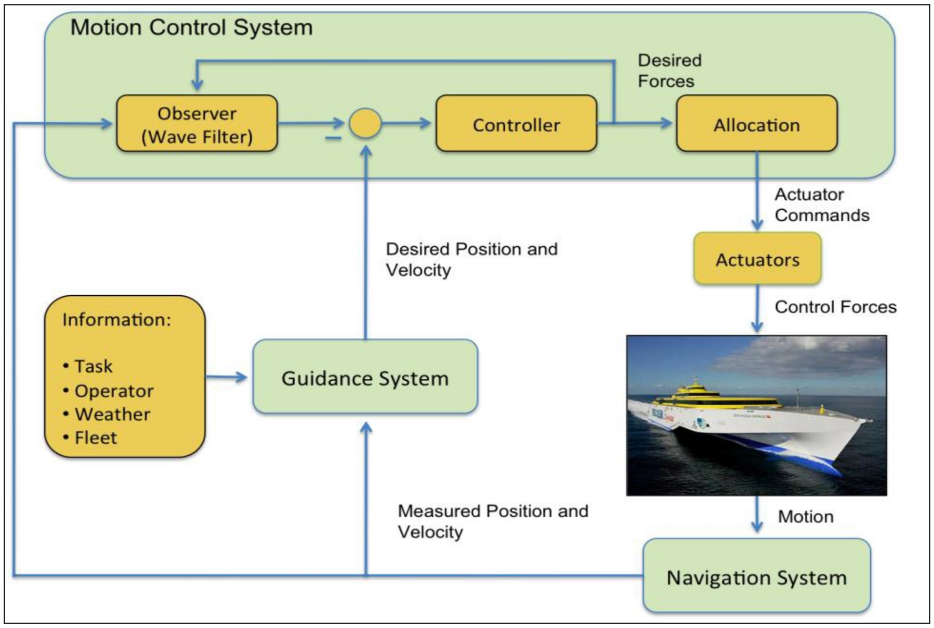

Figure 7: Overview of an unmanned surface vehicle system [124].

USVs research is a comparatively new specialization in the realm of marine robotics [52, 130]. The basic approach for controlling a surface vehicle, and as described by Fossen in Figure 7, using a motion control system which is usually constructed as three independent blocks denoted as the Guidance, Navigation and Control (GNC) systems [45] which are the fundamental blocks that enable vehicles to operate autonomously. These systems interact with each other through data and signal transmission. In [124], Fossen gave a comprehensive definition of guidance, navigation and control respectively:

- **Guidance**: is the action or the system that continuously computes the reference (desired) position, velocity and acceleration of a vessel to be used by the control system. These data are usually provided to the human operator and the navigation system. A survey of different guidance strategies is discussed in detail by Naeem, et al. [81] and Fossen, et al. [20].

- **Navigation**: originally denoted the art of ship driving, including steering and setting the sails. This includes planning and execution of safe, timely, and economical operation of ships, underwater vehicles, aircraft, and spacecraft. Autonomous navigation can be divided into two major areas of research: collision avoidance (CA) and track-keeping (TK) [119].

- **Control**: is the action of determining the necessary control forces and moments to be provided by the vessel in order to satisfy a certain control objective [124], such as tracking of a reference trajectory given by a guidance law with a real-time information on the USV provided by a navigation law.

The vast majority of surface vessels are underactuated vehicles ([97]) which have only two actuators as inputs for actuating the vehicle and is composed of two individual controls, namely surge force and yaw moment, but without sway force control. They are for regulating the position (sway and surge) and orientation (yaw angle) of the USV to track the reference position and orientation generated by a virtual reference ship respectively. Safe and precise control of an underactuated USV is a significant challenge. In the literature [124], underactuated control scenarios of USVs were usually classified into three main categories (point stabilization, trajectory tracking and path following).

5 Unmanned Surface Vehicle Models and Simulation Tools

Control design essentially deals with the dynamics of a physical system. Modelling and simulation of USV is an emerging approach in the field of USV. The use of the same system for simulation reduces the cost of hardware tests and facilitates enormously the portability of the theoretical design to the real world.

5.1 Unmanned Surface Vehicle Models

The objective of determining a model is (1) sufficiently rich to enable effective motion planning and control, (2) sufficiently simple to allow straightforward parameter identification, and (3) sufficiently general to describe a variety of hull forms and actuator configurations [116]. After surveying and considering a set of simple models whose parameters can be quickly and easily identified from standard motion data. Having selected an appropriate model, one may then use it to generate dynamically feasible trajectories for the USV to follow.

There are some existing papers and books available which deal with general aspects of modelling of USVs [12,57,59,70,78,82,106,110,117,124,125]. The mostly referred, most close to the practical situation and widely used model is developed by Fossen in [124].

It is usually sufficient to consider only the 3 horizontal Degrees of Freedom (DOF) when designing control systems for surface vessels since for most of them, the low frequency vertical plane dynamics and the thruster action does not influence each other [4]. The motion of a vessel can be divided into two parts: The *kinematics* treats the geometrical aspects of the motion, while the *dynamics* analyse the forces causing the motion. The availability of mathematical models of marine vessels are essential for both control design and simulation study purposes. A standard 3 DOF dynamic model, representing the horizontal surge, sway, and yaw modes, can be found in [124], and consists of the kinematics

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

and the dynamics

$$\mathbf{M}\dot{\nu} + \mathbf{C}(\nu)\nu + \mathbf{D}(\nu)\nu = \tau + \mathbf{R}(\psi)^T\mathbf{b} \tag{2}$$

where $\eta \triangleq \begin{bmatrix} x & y & \psi \end{bmatrix}^T \in \mathbb{R}^2 \times \mathbb{S}$ represents the earth-fixed pose (i.e., position and heading); $\nu \triangleq \begin{bmatrix} u & v & r \end{bmatrix}^T \in \mathbb{R}^3$ represents the vessel-fixed velocity; $\mathbf{R}(\psi)$ is the transformation matrix; $\mathbf{M}$ is the inertia matrix; $\mathbf{C}(\nu)$ is the centrifugal and Coriolis matrix; while $\mathbf{D}(\nu)$ is the hydrodynamic damping matrix. The system matrices satisfy the properties $\mathbf{M} = \mathbf{M}^T > 0, \mathbf{C} = \mathbf{C}^T$ and MD $>$ 0. The vessel-fixed propulsion forces and moments is represented by τ, while $\mathbf{b}$ represents low-frequency, earth-fixed environmental disturbances. Details concerning this model can also be found in [109, 125].

For the purpose of easier control, the vessel is sometimes modeled as a low-speed surface vessel described by [124] as:

$$\dot{\eta} = R(\psi)v \tag{3}$$

$$M\dot{v} = -Dv + \tau \tag{4}$$

where τ is the vector of control forces in surge and sway and moment in yaw. M and D are the mass and damping matrices respectively.

5.2 Simulation Tools

Closely related to the autonomous systems and their control are the simulation tools. A poor control design could have dramatic consequences to the vehicle itself, the rest of vehicles and even the environment in a real scenario. Thus, these tools are essential to test the correct design and behaviour of the modelling and control algorithms theoretically [15].

Several high-fidelity USV simulation models have been developed by various research group, centre and laboratories around the world. Recently, easy-to-use graphical modelling and simulation tools, like the SIMULINK environment from the MathWorks, have been widely used to develop high-fidelity simulation models as well as control systems with a wide variety of tools for control design. Three validated and verified (V&V) models are developed by the research teams from Norwegian University of Science and Technology (NTNU), the National Distance Education University (UNED) and the University of Maryland Eastern Shore to meet the increasing interest and need for a common research and development platform for USV controls.

- A benchmark which is developed by a research team from NTNU (see [94]), it is possible to run Simulink models in real-time for experiments within the laboratory, without writing a single line of code. The GNC system as well as disturbances of wave, wind and current for the experiments are implemented in the Simulink environment.

- The benchmark is constructed in a modular way by a research group from UNED, the vehicle can be simulated (or tested) with a slight modification of the program. It can run in continuous and discrete simulations and it is constructed over LabView as Hardware-In-The-Loop (HIL) simulation platform [15].

- The simulation for navigation of USVs in MATLAB environment is presented by a research team from University of Maryland Eastern Shore [37]. It is designed with a decentralized control structure for navigation system and does not require much knowledge about the navigation environment, like a global or local map. Effect of uncertainties and errors in locations of the vessel, the obstacles, and the destination can be shown in this environment.

All of the mentioned models contain various motion scenarios and give a possibility to plan different kinds of trajectories, implement various control algorithms and accommodation schemes on a realistic USV model. However, the benchmark developed by NTNU is a higher-fidelity, more realistic and easier to operate USV benchmark. Its model makes the simulation results more applicable to the real situation. It contains disturbances of wave, wind and current which also exploits more realistic scenarios. And many later research work on USV motion control are based on this benchmark model.

6 Motion Control Systems in Unmanned Surface Vehicles

This section addressed the difficulties and current status of the research on the motion control system in underactuated USV. Readers can refer to the review papers of motion control system in USVs [12, 24, 44, 81, 121, 123] for more information.

In case of USVs there is no need to investigate passenger comfort and stability of cargo as it is devoid of passengers and heavy cargo. Hence, it is sufficient to limit the discussion of USV autopilots to heading or yaw and surge control. In addition, only the underactuated vehicles are reviewed, the papers such as [57, 59, 60, 64] with fully actuated surface vessel are not considered. Due to the underactuated nature of the system, only discontinuous or smooth time-varying control of such systems is possible if all three coordinates are to be stabilized. Therefore, the control approaches are divided into discontinuous and smooth time-varying controllers. The smooth time-varying control literature is much richer due to the more practical nature of the controllers in terms of implementation [12]. So only the time-varying control approaches are reviewed in this report.

With the development of intelligent control theory, researchers have made considerable progress in applying intelligent control systems into USVs. Set-point, trajectory tracking, and path following control approaches for autonomous underactuated surface vessels have received increased attention during the last two decades. Most of the research activity in the development of underactuated intelligent control laws for underactuated USV systems has focused on feedback linearisation and backstepping methods. However, other control approaches such as fuzzy logic control, adaptive control, passivity-based, direct Lyapunov, sliding mode control, model predictive control and their combination methods have also been developed [12]. Despite the efforts and enthusiasm of numerous researchers, from all areas of control engineering, to persuade industry to adopt more sophisticated controller designs, PID (proportional-integral-derivative) controllers remain the industry preference and industry standard for automatic control systems [44].

6.1 Motion Control without Disturbances and Actuator Saturation

Referring to the papers presented on the motion control of underactuated USVs, there are a large variety of solutions, as in [123], Sperry and Minorski developed the first steering autopilots using PID (proportional-integral-derivative) controllers for automatic ship steering. In [103], Polkinghorne et al. reported the first commercial fuzzy autopilot for USV which is evaluated for both course-keeping and course-changing. Very recently, Ashrafiuon et al. [13] presented an exponentially stable tracking control law for underactuated surface vessel following any desired trajectory based on the sliding mode control approach. The existing motion control algorithms in Table 1 has been listed roughly to highlight the historical evolution of motion control design techniques.

Table 1: Motion Control Methods for Underactuated Surface Vehicle without Disturbances and Actuator Saturation

Control Approaches	References
PID	[123]
Sliding mode control	[13]
Fuzzy logic control	[103]
Backstepping	[3, 25, 56, 95, 111, 118, 127]
Feedback linearisation	[16, 58, 99]
Lyapunov's direct method	[53]
Feedback control with robust control	[100]

Although each individual control design method has been summarized in Table 1, in practice, a combination of several methods may be more appropriate to achieve the best overall motion control. In this regard, hardly any motion control technique relies on a single control design technique, rather it uses a combination of different control structures and control design algorithms. But seldom of these algorithms used the combination. Moreover, most of the early researches on USVs didn't take the disturbances, environment uncertainties and actuator saturation into consideration. Meanwhile, none of them are applied into practical situation.

6.2 Motion Control with Disturbances, Actuator Saturation or Faults

After reviewing the recent relevant researches, researchers gradually paid more attention and did much significant work in the area of preventing disturbances, actuator saturation and faults around the world. A list of publications in this area is summarized in Table 2.

USV works in a high nonlinear, uncertain and disturbed from hydrodynamic effects, wave, wind and current environment. And stability is one of the primary requirements in any control system. As it can be seen in Table 2, although a large amount of researches have been carried out to prevent disturbances, how to stably control USV in this cruel environment is still a challenge problem.

Table 2: Motion Control Methods for Underactuated Surface Vehicle with Disturbances, Actuator Saturation or Faults

Considered Factors	Control Approaches	References
Disturbances	Backstepping	[31,50,54,55,117]
		[32,49,53]
Disturbances	Robust adaptive control	[31]
Disturbances	Adaptive control	[23]
Disturbances	H_∞ robust control	[126,128]
Disturbances	Backstepping	
	with Lyaounov's direct method	[30,33]
Disturbances	Feedback linearisation	[76]
Disturbances	Linear model predictive control	[65]
Actuator saturation	Linear parameter varying	
	with linear matrix inequality	[46]
Actuator saturation	Robust with sliding mode control	[87]
Actuator saturation	Nonlinear model predictive control	[75]
Actuator saturation	Linear model predictive control	[88]
Actuator saturation	Nonlinear model predictive control	
	with sliding mode control	[74,79,86,105]
Actuator saturation	Sliding mode control	[14,72,112,113]
Disturbances & actuator saturation	Linear model predictive control	[120]
Disturbances & actuator saturation	PI with backstepping	[59]
Disturbances & actuator saturation	Fuzzy logic	
	with linear quadratic gaussian	
	and model predictive control	[85]
Disturbances & actuator saturation	Robust with sliding mode control	[115]
Disturbances & actuator saturation	Model reference adaptive control	[11]
Sensor faults	Fuzzy logic with Kalman Filter	[137]
Sensor faults	Fuzzy logic with	
	Linear quadratic gaussian	
	and model predictive control	[85]
Sensor faults	Fuzzy logic with adaptive control	[120,138,139]
Sensor faults	Linear quadratic gaussian	
	with model predictive control	[84]

In addition, actuator saturation should also be taken into account since every physical actuator is subject to saturation. When the actuator saturates, the performance of the control system designed will seriously deteriorate. Currently, there is a surge of interest in increasing the practical applicability of control theory by incorporating the effect of saturation into the design of a control system [66]. As shown in Table 2, the existing papers referred to this area are rare, further investigation on this topic remains an important issue.

Another approach which worth deeper research and investigation is Model Predictive Control (MPC). After chemical and process industries have successfully used model predictive controllers to improve efficiency of the overall system performance. Recently, some researchers implemented this approach into USVs and achieved good results. As underactuated USVs motion control systems are complex systems and essentially exhibit highly nonlinear dynamics. Applying Nonlinear Model Predictive Control (NMPC) approach will be more practical. Some NMPC approach are presented in [75,86,105] and the combination of nonlinear model predictive controller and sliding mode control is presented in [74, 79].

Although fault detection, diagnosis and tolerant control (refer to [142]) have been used in other kind of unmanned vehicles for many years, applying these in USV control is also a very important and significant application of unmanned systems since many USVs are high speed vehicle and work on busy, complex and danger water. There is always a possibility of having sensor fault, actuator failure and communication interruption which may cause the vehicle out of control. Hence, to realize reliable and robust guidance, navigation and control on USVs, fault detection, diagnosis and tolerant control are the main concerns of USVs as well. This fact motivates the design and development of USVs with remarkable robustness and fault tolerant capabilities.

Existing literature on USV Fault Tolerant Control (FTC) is still scarce. There are few papers [84, 85, 120, 137–139] from Plymouth university involve in this novel area in USV which are about the fault detection and tolerant in navigation. Except for these few papers, the papers refer to fault detection, diagnosis and tolerant control in controlling of USV cannot be found in early, even very recent researches all over the world.

Though the intelligent systems performed well in simulation studies, application in real life systems still produced performance and stability issues which needs further researches.

6.3 Motion Control Applied into Practical Situation

Experimental results are important for understanding of the value and the limitations of the theory of underactuated USVs motion control systems that exists now or will be developed in the future. Even though there has been many theoretical developments in the area of underactuated USVs, there has been relatively few experimental results reported that makes use of the developed theories. The only experimental work in the underactuated surface vessel control area, until the recent 15 years (especially the late 8 years), have been presented which are listed in Table 3. Only [7, 28, 68] used their USV system platforms tested their motion control systems in the real environment with disturbances, but without dangerous obstacles. [1, 13, 29, 41, 42, 60, 64, 73, 97, 98, 101, 110, 136] were just tested in the laboratory. And these experimental work were carried out using small model vessels rather than actual unmanned surface vessel system platforms. All of these experimental work have also been performed in only seven different laboratories (Massachu-setts Institute of Technology, University of Rostock, Norwegian University of Science and Technology, Plymouth University, Villanova University, Shanghai Maritime University and Shanghai University. Companies are not included).

Table 3: Motion Control Methods for Underactuated Surface Vehicle Tested in Real Situation

Experimental Places	Control Approaches	References
Laboratory	Feedback linearisation	[100]
Laboratory	Feedback linearization with integral action	[101, 102]
Laboratory	Feedback linearization with backstepping	[96, 97]
Laboratory	PI with backstepping	[60]
Laboratory	Sliding mode control	[13, 71, 114]
Laboratory	Robust adaptive control	[110]
Laboratory	Time-varying state feedback control	[98]
Laboratory	PID with feedback linearisation	[41]
Laboratory	Backstepping	[22]
Outdoor	PID	[18, 28, 68]
Outdoor	Backstepping with nonlinear robust control	[64]
Outdoor	Robust adaptive control	[29, 30]
Outdoor	H_2 robust control	[70]
Outdoor	Gain-scheduling control	[90]
Outdoor	PID with Kalman Filter	[93]

Based on the difficulties and challenges, safe and precise control of an underactuated USV under disturbances and actuator saturation is still a significant challenge for current research, especially for practical application. Stability analysis and stability robustness for real-time motion control systems in practical environment still need further investigation.

6.4 Collision Avoidance (CA)

Water-based transportation is more complex than land-based transportation and there are various environmental factors and vessel characteristics that should be considered in the control of ships for maneuvers. Convenient navigation systems for ship maneuvering should allow quick avoidance of obstacle to find the shortest distance in the whole seaway is important. Until now industry has not demanded USV development in preference to manned vehicles, primarily due to deficiencies in the decision-making and collision avoidance abilities of an autonomous system [24].

In the last few years, noteworthy reviews [24, 61, 119, 121] have been carried out outlining USV obstacle avoidance methodologies. To limit the human subjective factor, the International Marine Organization (IMO) has defined the international rules for collision avoidance (COLREGs) [119]. It is worth noting that COLREGs have been applied in most reviewed research work.

The work of most researchers in collision avoidance can be grouped into: mathematical models and algorithms, vision-based and intelligent algorithms, and hybrid autonomous navigation systems [119]. Optical camera, infrared camera, sonar and laser range finder are commonly used to detect obstacles in the existed researches. A list of relative publications is summarized in Table 4.

Table 4: Collision Avoidance Methods for Underactuated Surface Vehicle

Collision Avoidance Categories	Control Approaches	References
Mathematical models and algorithms	Measuring algorithms	[113, 119]
Vision-based and intelligent algorithms	Neural networks	[36]
Vision-based and intelligent algorithms	Fuzzy logic control	[63]
Vision-based and intelligent algorithms	Genetic algorithms	[80]
Vision-based and intelligent algorithms	Vision-based algorithms	[35, 132–135]
Vision-based and intelligent algorithms	Sliding mode control	[105]
Hybrid autonomous navigation systems	Fuzzy logic control with H_2 robust control	[61]
Hybrid autonomous navigation systems	Stereo vision algorithms with rule-based approach	[47]
Hybrid autonomous navigation systems	Vision with radar approach	[5]

In severe weather conditions, the ship manoeuvres have to combine safety (avoid capsizing or sinking) and collision avoidance concurrently. In most autonomous navigation algorithms, the sea weather conditions are rarely considered [119]. Furthermore, there are also time-delays and false alarms associated with collision avoidance decisions. Rapid and reliable obstacle detection and avoidance are necessary for the performance in motion control. A shift toward more autonomy will require the introduction of new, advanced motion control concepts, where perhaps the most important contributor is collision avoidance [21].

6.5 Formation and Cooperative Control for Unmanned Surface Vehicles

Formation control technology enables multiple vehicles to collaborate with each other to solve difficult challenges, and such technology plays an increasingly important role for commercial, scientific, and military applications. Specifically, USVs might cooperate with other unmanned vehicles such as UAVs and UUVs to form large communication and surveillance networks that are able to provide unique situational awareness capabilities wherever needed. In this regard, USVs are unique in the sense that they are able to communicate with vehicles both above and below the sea surface simultaneously, capable of acting as relays between underwater vehicles and vehicles operating on land, in the air, or in space [21].

Within recent 5 years, researchers gradually paid attention to formation and cooperative control of underactuated USVs all over the world. But most of the researches [6, 8, 10, 19, 38, 40, 43, 48, 91,92,131] are just tested by simulation with several USVs. Only in [9,107], two USVs are tested in the practical situation. In [107], the formation controllers are designed using the nonlinear robust model-based sliding mode control. In [9], PI controllers are used to control a team of two underactuated USVs in the field performing a joint mission motivated by environmental monitoring. Moreover, just one of the researches referred to cooperative or formation control among USV and an Unmanned Underwater Vehicles (UUV) [89]. And in [77], the first known use of cooperative control between USVs and manned aerial vehicles. More new and practical approaches to deal with such area deserve further investigation.

7 Conclusions and Future Directions

The control of underactuated surface vessels has become an active area of research in recent years not only because it poses many challenging questions in applied nonlinear control theory, but also because of its practical importance and it is costly and not very practical to fully actuate a surface vessel in each DOF in practice. They operate in uncertain environments, are exposed to large disturbances from hydrodynamic effects, wave, wind and current, has more degrees of freedom (outputs) to be controlled than the number of independent actuators (inputs) and with actuator saturation. Many USVs are high speed vehicle and work on busy, complex and danger water. There is always a possibility of having sensor fault, actuator failure and communication interruption which may cause the vehicle out of control. So, efficiency, reliability, and availability of such systems are highly affected by the chosen control strategy, especially for the practical application.

In the case of an underactuated USV faced with strong disturbances from wave, wind or currents, a situation may arise where control authority is drastically reduced. Furthermore, tracking control often leads to jerky motions of the vehicle (in its attempt to meet stringent spatial requirements) and to considerable actuator activity. Typically, smoother convergence to the path is achieved when path following strategies are used instead of trajectory tracking control laws, and the control signals are less likely to be pushed to saturation. So, this method could be chosen as guidance for tracking control and worth further research.

Although much progress has been made in underactuated USV control theories, there remains a need for the evolution of these current approaches to achieve robust, real-time control laws in the presence of actuator saturation, high sea states and external disturbances (like hydrodynamic effects, wave, wind and ocean current) in uncertain and unstructured environments (like obstacles from surface and underwater, other vessels and etc.) which is still a significant challenge for current research. In addition, simulation should be more similar to the real environment since every novel algorithms and methods should be well matured before practical implementation. But none of the former papers and researches considered all of these uncertain parameters and disturbances together. Therefore, it is definitely worth further investigations and researches.

Most of the former researches deal with docking, safety (avoid capsizing or sinking), collision avoidance and tracking control respectively, only few of them combined docking and tracking control together, but no further papers published. Considering these concurrently is a very practical and potential area. A possible way is that set-point control is used for autonomous docking and collision avoidance, path following control is applied in tracking the planned path. Furthermore, vision-based collision avoidance also needs further work since most of the current researches in this area are about vision-based obstacle detection.

While fault detection, diagnosis and tolerant control (refer to [142]) have been used in unmanned aerial vehicle and other unmanned vehicles for many years. But existing literature just mentioned on sensor fault detection and tolerant. Applying these in USV control is very significant since many USVs are high speed vehicle and work on busy, complex and danger water. There always the possibility of having sensor fault, actuator failure and communication interruption which may cause the vehicle out of control.

Even though there has been many theoretical developments in the area of underactuated USV there has been relatively few experimental results reported that makes use of the developed theories. There are comparatively few papers dealing with environmental disturbances or actuator saturation in the real situation respectively. Few of the applications in real life systems produced performance and stability issues. None of this combination are applied in practical situation. Hence, the existed advanced underactuated USV control systems should be well matured before practical implementation. A practical and potential advanced control theory for this area is Nonlinear Model Predictive Control (NMPC) which has been successfully applied in chemical and process industries and just few researchers have paid attention to this theory on underactuated USV within recent 5 years. In addition, most of the limited number of experiments are tested indoor with relatively ideal environment, fewer experiments are conducted outdoor under calm conditions. None of the practical researches deals with the experiments in severe weather conditions. So, more researches can be investigated in this area.

Recently, formation and cooperative control of USVs becomes an active research topic. But most of the researches are just tested by simulation, few of the researches referred to cooperative or formation control among USV and other unmanned vehicles. New and practical approaches to deal with such area deserve further investigation.

References

[1] China's first self-developed unmanned boats can be automatically measured obstacle avoidance. http://www.navaldrones.com/China-USV.html. 2013.

[2] Motwani A. A survey of uninhabited surface vehicles. Technical report, MIDAS Technical Report:MIDAS.SMSE, 2012.TR.001.

[3] Aguiar, A.P., and Hespanha J.P. Position tracking of underactuated vehicles. In *Proceedings of the 2003 American Control Conference, 2003*, volume 3, pages 1988–1993. IEEE, 2003.

[4] Sørensen A.J. Marine cybernetics: Modelling and control, 2nd ed. Marine Technology Centre, Trondheim, Norway, 2002.

[5] Almeida, C., Franco, T., Ferreira, H., Martins, A., Santos, R., Almeida, J.M., Carvalho, J., and Silva E. Radar based collision detection developments on USV ROAZ II. In *Oceans 2009-Europe*, pages 1–6. IEEE, 2009.

[6] Almeida, J., Silvestre, C., and Pascoal A. Cooperative control of multiple surface vessels in the presence of ocean currents and parametric model uncertainty. *International Journal of Robust and Nonlinear Control*, 20(14):1549–1565, 2010.

[7] Alves, J., Oliveira, P., Oliveira, R., Pascoal, A., Rufino, M., Sebastiao, L., and Silvestre C. Vehicle and mission control of the delfim autonomous surface craft. In *14th Mediterranean Conference on Control and Automation, 2006. MED'06*, pages 1–6. IEEE, 2006.

[8] Antonelli, G., Arrichiello, F., and Chiaverini S. The NSB control: A behavior-based approach for multi-robot systems. *Paladyn*, 1(1):48–56, 2010.

[9] Arrichiello, F., Das, J., Heidarsson, H., Pereira, A., Chiaverini, S., and Sukhatme G.S. Multi-robot collaboration with range-limited communication: Experiments with two underactuated ASVs. In *Field and Service Robotics*, pages 443–453. Springer, 2010.

[10] Arrichiello, F., Heidarsson, H., Chiaverini, S., and Sukhatme G.S. Cooperative caging using autonomous aquatic surface vehicles. In *2010 IEEE International Conference on Robotics and Automation (ICRA)*, pages 4763–4769. IEEE, 2010.

[11] Ashrafiuon, H., and Muske K.R. Analytical stability analysis of surface vessel trajectories for a control-oriented model. *Journal of Computational and Nonlinear Dynamics JULY*, 6:031010–1, 2011.

[12] Ashrafiuon, H., Muske, K.R., and McNinch L.C. Review of nonlinear tracking and setpoint control approaches for autonomous underactuated marine vehicles. In *American Control Conference (ACC), 2010*, pages 5203–5211. IEEE, 2010.

[13] Ashrafiuon, H., Muske, K.R., McNinch, L.C., and Soltan R.A. Sliding-mode tracking control of surface vessels. *IEEE Transactions on Industrial Electronics*, 55(11):4004–4012, 2008.

[14] Ashrafiuon, H., and Ren P. Sliding mode tracking control of underactuated surface vessels. In *Proceedings of the ASME IMECE*, pages 5–11. ASME, 2005.

[15] Astorga, A.M., Moreno-Salinas, D., García, D.C., and Almansa J.A. Simulation benchmark for autonomous marine vehicles in labview. In *OCEANS, 2011 IEEE-Spain*, pages 1–6. IEEE, 2011.

[16] Berge, S.P., Ohtsu, K., and Fossen T.I. Nonlinear control of ships minimizing the position tracking errors. *Modeling Identification and Control*, 20:177–187, 1999.

[17] Bibuli, M., Bruzzone, G., Caccia, M., Indiveri, G., and Zizzari A.A. Line following guidance control: Application to the Charlie unmanned surface vehicle. In *IEEE/RSJ International Conference on Intelligent Robots and Systems. IROS 2008.*, pages 3641–3646. IEEE, 2008.

[18] Bibuli, M., Bruzzone, G., Caccia, M., and Lapierre L. Path-following algorithms and experiments for an unmanned surface vehicle. In *Proceedings of IFAC Conference on Control Applications in Marine Systems*, 2007.

[19] Børhaug, E., Pavlov, A., Panteley, E., and Pettersen K.Y. Straight line path following for formations of underactuated marine surface vessels. *IEEE Transactions on Control Systems Technology.*, 19(3):493–506, 2011.

[20] Breivik, M., and Fossen T.I. Guidance laws for planar motion control. In *47th IEEE Conference on Decision and Control, CDC 2008*, pages 570–577. IEEE, 2008.

[21] Breivik, M., and Hovstein V.E. Formation control for unmanned surface vehicles: Theory and practice. In *IFAC World Congress*, 2008.

[22] Bruzzone, G., Caccia, M., Ravera, G., and Bertone A. Standard Linux for embedded real-time robotics and manufacturing control systems. *Robotics and Computer-Integrated Manufacturing*, 25(1):178–190, 2009.

[23] Burger, M., Pavlov, A., Borhaug, E., and Pettersen K.Y. Straight line path following for formations of underactuated surface vessels under influence of constant ocean currents. In *American Control Conference, 2009. ACC'09*, pages 3065–3070. IEEE, 2009.

[24] Campbell, S., Naeem, W., and Irwin G.W. A review on improving the autonomy of unmanned surface vehicles through intelligent collision avoidance manoeuvres. *Annual Reviews in Control*, 2012.

[25] Cao, K.C., and Tian Y.P. A time-varying cascaded design for trajectory tracking control of non-holonomic systems. *International Journal of Control*, 80(3):416–429, 2007.

[26] Corfield, S.J., and Young J.M. Unmanned surface vehicles-game changing technology for naval operations. *IEE Control Engineering Series*, 69:311, 2006.

[27] Draper C.S. Guidance is forever(control, navigation and guidance review, considering application of earth reference coordinates for aircraft, missiles and spacecraft). *Navigation*, 18:26–50, 1971.

[28] Curcio, J., Leonard, J., and Patrikalakis A. Scout-a low cost autonomous surface platform for research in cooperative autonomy. In *Proceedings of MTS/IEEE, OCEANS, 2005*, pages 725–729. IEEE, 2005.

[29] Do, K.D., and Pan J. Global robust adaptive path following of underactuated ships. *Automatica*, 42(10):1713–1722, 2006.

[30] Do, K.D., and Pan J. Robust path-following of underactuated ships: Theory and experiments on a model ship. *Ocean engineering*, 33(10):1354–1372, 2006.

[31] Do, K.D., Jiang, Z.P., and Pan J. Universal controllers for stabilization and tracking of underactuated ships. *Systems & control letters*, 47(4):299–317, 2002.

[32] Do, K.D., Jiang, Z.P., and Pan J. Robust global stabilization of underactuated ships on a linear course: State and output feedback. *International Journal of Control*, 76(1):1–17, 2003.

[33] Do, K.D., Jiang, Z.P., and Pan J. Robust adaptive path following of underactuated ships. *Automatica*, 40(6):929–944, 2004.

[34] Doand, K.D., and Pan J. Control of ships and underwater vehicles: Design for underactuated and nonlinear marine systems. 2009.

[35] Dunbabin, M., Lang, B., and Wood B. Vision-based docking using an autonomous surface vehicle. In *IEEE International Conference on Robotics and Automation, 2008. ICRA 2008*, pages 26–32. IEEE, 2008.

[36] Patterson D.W. Artificial neural networks: Theory and applications. Prentice Hall PTR, 1998.

[37] Eydgahi, A., Falase, S., and Godaliyadda D. A MATLAB-Based simulation for autonomous navigation of unmanned surface vehicles. *Proceedings of The 2006 IJME INTERTECH Conference*, 2006.

[38] Fahimi F. Sliding-mode formation control for underactuated surface vessels. *IEEE Transactions on Robotics*, 23(3):617–622, 2007.

[39] Ferreira, H., Martins, R., Marques, E., Pinto, J., Martins, A., Almeida, J., Sousa, J., and Silva E.P. Swordfish: An autonomous surface vehicle for network centric operations. In *OCEANS 2007-Europe*, pages 1–6. IEEE, 2007.

[40] Fraga, R., and Sheng L. Fuzzy technique tracking control for multiple unmanned ships. *Research Journal of Applied Sciences*, 5, 2013.

[41] Fredriksen, E., and Pettersen K.Y. Global κ-exponential way-point maneuvering of ships: Theory and experiments. *Automatica*, 42(4):677–687, 2006.

[42] Ghaemi, R., Oh, S., and Sun J. Path following of a model ship using model predictive control with experimental verification. In *American Control Conference (ACC), 2010*, pages 5236–5241. IEEE, 2010.

[43] Ghommam, J., and Mnif F. Coordinated path-following control for a group of underactuated surface vessels. *IEEE Transactions on Industrial Electronics*, 56(10):3951–3963, 2009.

[44] Roberts G.N. Trends in marine control systems. *Annual Reviews in Control*, 32(2):263–269, 2008.

[45] Gogarty, B., and Hagger M. Laws of man over vehicles unmanned: The legal response to robotic revolution on sea, land and air. *Journal of Information & Science*, 19:73, 2008.

[46] Gomes, P., Silvestre, C., Pascoal, A., and Cunha R. A path-following controller for the delfimx autonomous surface craft. In *Proc. of 7th IFAC conference on manoeuvring and control of marine craft*, 2006.

[47] Hwang, C.N., Yang, J.M., and Chiang C.Y. The design of fuzzy collision-avoidance expert system implemented by H-autopilot. *Journal of Marine Science and technology*, 9(1):25–37, 2001.

[48] Ihle, I.A.F., Jouffroy, J., and Fossen T.I. Formation control of marine surface craft: A lagrangian approach. *IEEE Journal of Oceanic Engineering*, 31(4):922–934, 2006.

[49] Ihle, I.A.F., Skjetne, R., and Fossen T.I. Output feedback control for maneuvering systems using observer backstepping. In *Proceedings of the 2005 IEEE International Symposium on Intelligent Control, Mediterrean Conference on Control and Automation*, pages 1512–1517. IEEE, 2005.

[50] Indiveri, G., Zizzari, A.A., and Mazzotta V.G. Linear path following guidance control for underactuated ocean vehicles. In *Control Applications in Marine Systems*, volume 7, pages 87–92, 2007.

[51] Murray J. Sentry-an unmanned swimmer intercept system. Technical report, DTIC Document, 2008.

[52] Manley J.E. Unmanned surface vehicles, 15 years of development. In *OCEANS 2008*, pages 1–4. IEEE, 2008.

[53] Jiang and Z.P. Global tracking control of underactuated ships by Lyapunov's direct method. *Automatica*, 38(2):301–309, 2002.

[54] Jiang, Z.P., Lefeber, E., and Nijmeijer H. Saturated stabilization and tracking of a nonholonomic mobile robot. *Systems & Control Letters*, 42(5):327–332, 2001.

[55] JIANGdagger, Z.P., and Nijmeijer H. Tracking control of mobile robots: A case study in backstepping. *Automatica*, 33(7):1393–1399, 1997.

[56] Godhavn J.M. Nonlinear tracking of underactuated surface vessels. In *Proceedings of the 35th IEEE Decision and Control*, volume 1, pages 975–980. IEEE, 1996.

[57] Khaled, N., and Chalhoub N.G. A dynamic model and a robust controller for a fully-actuated marine surface vessel. *Journal of Vibration and Control*, 17(6):801–812, 2011.

[58] Kim, T.H., Basar, T., and Ha I.J. Asymptotic stabilization of an underactuated surface vessel via logic-based control. In *Proceedings of the 2002 American Control Conference*, volume 6, pages 4678–4683. IEEE, 2002.

[59] Krishnamurthy, P., Khorrami, F., and Fujikawa S. A modeling framework for six degree-of-freedom control of unmanned sea surface vehicles. In *44th IEEE Conference on Decision and Control, 2005 European Control Conference, CDC-ECC'05*, pages 2676–2681. IEEE, 2005.

[60] Krishnamurthy, P., Khorrami, F., and Ng T.L. Control design for unmanned sea surface vehicles: Hardware-in-the-loop simulator and experimental results. In *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2007*, pages 3660–3665. IEEE, 2007.

[61] Larson, J., Bruch, M., Halterman, R., Rogers, J., and Webster R. Advances in autonomous obstacle avoidance for unmanned surface vehicles. Technical report, DTIC Document, 2007.

[62] Larson, J., Bruch, M., and Ebken J. Autonomous navigation and obstacle avoidance for unmanned surface vehicles. In *Defense and Security Symposium*, pages 623007–623007. International Society for Optics and Photonics, 2006.

[63] Lee, Y.I., and Kim Y.G. A collision avoidance system for autonomous ship using fuzzy relational products and COLREGs. In *Intelligent Data Engineering and Automated Learning–IDEAL 2004*, pages 247–252. Springer, 2004.

[64] Li, Z., Sun, J., and Oh S. Design, analysis and experimental validation of a robust nonlinear path following controller for marine surface vessels. *Automatica*, 45(7):1649–1658, 2009.

[65] Li, Z., Sun, J., and Oh S. Path following for marine surface vessels with rudder and roll constraints: An MPC approach. In *American Control Conference, 2009. ACC'09*, pages 3611–3616. IEEE, 2009.

[66] Lin, Z.L., et al. Control systems with actuator saturation: Analysis and design. Springer, 2001.

[67] Breivik M. *Topics in guided motion control of marine vehicles.* PhD thesis, Norwegian University of Science and Technology, 2010.

[68] Caccia M. Autonomous surface craft: Prototypes and basic research issues. In *14th Mediterranean Conference on Control and Automation, 2006. MED'06*, pages 1–6. IEEE, 2006.

[69] Majohr, J., Buch, T., and Korte C. Navigation and automatic control of the Measuring Dolphin (MESSIN). *Proceedings of MCMC 2000*, pages 405–410, 2000.

[70] Majohr, J., and Buch T. Modelling, simulation and control of an autonomous surface marine vehicle for surveying applications Measuring Dolphin MESSIN. *IEE Control Engineering Series*, 69:329, 2006.

[71] McNinch, L.C., Ashrafiuon, H., and Muske K.R. Experimental tracking control of an autonomous surface vessel.

[72] McNinch, L.C., Ashrafiuon, H., and Muske K.R. Optimal specification of sliding mode control parameters for unmanned surface vessel systems. In *American Control Conference, 2009. ACC'09*, pages 2350–2355. IEEE, 2009.

[73] McNinch, L.C., Ashrafiuon, H., and Muske K.R. Sliding mode setpoint control of an underactuated surface vessel: Simulation and experiment. In *American Control Conference (ACC), 2010*, pages 5212–5217. IEEE, 2010.

[74] McNinch, L.C., and Ashrafiuon H. Predictive and sliding mode cascade control for unmanned surface vessels. In *American Control Conference (ACC), 2011*, pages 184–189. IEEE, 2011.

[75] McNinch, L.C., Muske, K.R., and Ashrafiuon H. Model-based predictive control of an unmanned surface vessel. In *Proceedings of the 11th IASTED International Conference on Intelligent Systems and Control*, page 385390, 2008.

[76] Moreira, L., Fossen, T.I., and Guedes S.C. Path following control system for a tanker ship model. *Ocean Engineering*, 34(14):2074–2085, 2007.

[77] Murphy, R.R., Steimle, E., Griffin, C., Cullins, C., Hall, M., and Pratt K. Cooperative use of unmanned sea surface and micro aerial vehicles at Hurricane Wilma. *Journal of Field Robotics*, 25(3):164–180, 2008.

[78] Muske, K.R., Ashrafiuon, H., Haas, G., McCloskey, R., and Flynn T. Identification of a control oriented nonlinear dynamic USV model. In *American Control Conference, 2008*, pages 562–567. IEEE, 2008.

[79] Muske, K.R., Ashrafiuon, H., and Nikkhah M. A predictive and sliding mode cascade controller. In *American Control Conference, 2007. ACC'07*, pages 4540–4545. IEEE, 2007.

[80] Naeem, W., and Irwin G.W. Evasive decision making in uninhabited maritime vehicles. In *Proceedings IFAC World Congress, Milan, Italy, August*, pages 12833–12838, 2011.

[81] Naeem, W., Sutton, R., Ahmad, S.M., and Burns R.S. A review of guidance laws applicable to unmanned underwater vehicles. *Journal of Navigation*, 56(1):15–29, 2003.

[82] Naeem, W., Sutton, R., and Chudley J. Modelling and control of an unmanned surface vehicle for environmental monitoring. In *UKACC International Control Conference, August, Glasgow, Scotland* , 2006.

[83] Naeem, W., Sutton, R., and Chudley J. Soft computing design of a linear quadratic gaussian controller for an unmanned surface vehicle. In *14th Mediterranean Conference on Control and Automation, 2006. MED'06.*, pages 1–6. IEEE, 2006.

[84] Naeem, W., Sutton, R., and Xu T. An integrated multi-sensor data fusion algorithm and autopilot implementation in an uninhabited surface craft. *Ocean Engineering*, 39:43–52, 2012.

[85] Naeem, W., Xu, T., Sutton, R., and Tiano A. The design of a navigation, guidance, and control system for an unmanned surface vehicle for environmental monitoring. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 222(2):67–79, 2008.

[86] Nikkhah, M., Ashrafiuon, H., and Muske K.R. Optimal sliding mode control for underactuated systems. In *American Control Conference, 2006*, pages 4688–4693. IEEE, 2006.

[87] Nikkhah, M., and Ashrafiuon H. Robust control of a vessel using camera feedback and extended kalman filter. ASME, 2006.

[88] Oh, S.R., and Sun J. Path following of underactuated marine surface vessels using line-of-sight based model predictive control. *Ocean Engineering*, 37(2):289–295, 2010.

[89] Pascoal, A., Oliveira, P., Silvestre, C., Sebastião, L., Rufino, M., Barroso, V., Gomes, J., Ayela, G., Coince, P., Cardew, M., et al. Robotic ocean vehicles for marine science applications: The European ASIMOV project. In *Oceans 2000 MTS/IEEE Conference and Exhibition*, volume 1, pages 409–415. IEEE, 2000.

[90] Pascoal, A., Silvestre, C., and Oliveira P. Advances in unmanned marine vehicles, chapter vehicle and mission control of single and multiple autonomous marine robots. pages 353–386, 2006.

[91] Peng, Z., Wang, D., and Hu X. Robust adaptive formation control of underactuated autonomous surface vehicles with uncertain dynamics. *IET control theory & applications*, 5(12):1378–1387, 2011.

[92] Peng, Z.H., Wang, D., Chen, Z.Y., Hu, X.J., and Lan W.Y. Adaptive dynamic surface control for formations of autonomous surface vehicles with uncertain dynamics. 2013.

[93] Pereira, A., Das, J., and Sukhatme G.S. An experimental study of station keeping on an underactuated ASV. In *IEEE/RSJ International Conference on Intelligent Robots and Systems, 2008. IROS 2008.*, pages 3164–3171. IEEE, 2008.

[94] Perez, T., Smogeli, O.N., Fossen, T.I., and Sorensen A.J. An overview of the marine systems simulator (MSS): A simulink toolbox for marine control systems. *Modeling, Identification and Control*, 27(4):259–275, 2006.

[95] Pettersen, K.Y., and Nijmeijer H. Tracking control of an underactuated surface vessel. In *Proceedings of the 37th IEEE Conference on Decision and Control, 1998.*, volume 4, pages 4561–4566. IEEE, 1998.

[96] Pettersen, K.Y., and Nijmeijer H. Global practical stabilization and tracking for an underactuated ship-a combined averaging and backstepping approach. *Modeling Identification and Control*, 20(4):189–200, 1999.

[97] Pettersen, K.Y., and Nijmeijer H. Underactuated ship tracking control: Theory and experiments. *International Journal of Control*, 74(14):1435–1446, 2001.

[98] Pettersen, K.Y., Mazenc, F., and Nijmeijer H. Global uniform asymptotic stabilization of an underactuated surface vessel: Experimental results. *IEEE Transactions on Control Systems Technology*, 12(6):891–903, 2004.

[99] Pettersen, K.Y., and Egeland O. Exponential stabilization of an underactuated surface vessel. In *Proceedings of the 35th IEEE Decision and Control*, volume 1, pages 967–972. IEEE, 1996.

[100] Pettersen, K.Y., and Egeland O. Robust control of an underactuated surface vessel with thruster dynamics. In *Proceedings of the 1997 American Control Conference, 1997*, volume 5, pages 3411–3415. IEEE, 1997.

[101] Pettersen, K.Y., and Fossen T.I. Underactuated ship stabilization using integral control: Experimental results with Cybership I. In *Proceedings of the 1998 IFAC Symposium on Nonlinear Control Systems*. Citeseer, 1998.

[102] Pettersen, K.Y., and Fossen T.I. Underactuated dynamic positioning of a ship-experimental results. *IEEE Transactions on Control Systems Technology*, 8(5):856–863, 2000.

[103] Polkinghorne, M.N., Roberts, G.N., Burns, R.S., and Winwood D. The implementation of fixed rulebase fuzzy logic to the control of small surface ships. *Control Engineering Practice*, 3(3):321–328, 1995.

[104] PROTECTOR. Unmanned naval patrol vehicle, December 2010.

[105] Soltan R.A. *Coordinated Tracking Control and Obstacle Avoidance for Underactuated Autonomous Vehicles*. PhD thesis, Villanova University, 2009.

[106] Roberts, G.N., and Sutton R. Advances in unmanned marine vehicles. Institution of Electrical Engineers, 2006.

[107] Schoerling, D., Van, K.C., Fahimi, F., Koch, C.R., Ams, A., and Löber P. Experimental test of a robust formation controller for marine unmanned surface vessels. *Autonomous Robots*, 28(2):213–230, 2010.

[108] Shih, C.H., Huang, P.H., Yamamura, S., and Chen C.Y. Design optimal control of ship maneuver patterns for collision avoidance: A review. *Journal of Marine Science and Technology*, 20:111–121, 2012.

[109] Skjetne, R., Fossen, T.I., and Kokotović P.V. Robust output maneuvering for a class of nonlinear systems. *Automatica*, 40(3):373–383, 2004.

[110] Skjetne, R., Smogeli, Ø.N., and Fossen T.I. A nonlinear ship manoeuvering model: Identification and adaptive control with experiments for a model ship. *Modeling, Identification and Control*, 25(1):3–27, 2004.

[111] Skjetne, R., and Fossen T.I. Nonlinear maneuvering and control of ships. In *MTS/IEEE Conference and Exhibition, OCEANS, 2001*, volume 3, pages 1808–1815. IEEE, 2001.

[112] Soltan, R., Ashrafiuon, H., and Muske K.R. Coordinated trajectory planning and tracking control. In *Proceedings of the 2009 ASME IDETC/CIE Conference*, 2009.

[113] Soltan, R., Ashrafiuon, H., and Muske K.R. Real-time obstacle avoidance for underactuated unmanned surface vessels. In *Proceedings of the 2009 ASME IDETC/CIE Conference*, 2009.

[114] Soltan, R.A., Ashrafiuon, H., and Muske K.R. State-dependent trajectory planning and tracking control of unmanned surface vessels. In *American Control Conference, 2009. ACC'09.*, pages 3597–3602. IEEE, 2009.

[115] Soltan, R.A., Ashrafiuon, H., and Muske K.R. ODE-based obstacle avoidance and trajectory planning for unmanned surface vessels. *Robotica*, 29(5):691–703, 2011.

[116] Sonnenburg, C., Gadre, A., Horner, D., Kragelund, S., Marcus, A., Stilwell, D.J., and Woolsey C.A. Control-oriented planar motion modeling of unmanned surface vehicles. In *OCEANS 2010*, pages 1–10. IEEE, 2010.

[117] Sonnenburg, C.R., and Woolsey C.A. Modeling, identification, and control of an unmanned surface vehicle. *Journal of Field Robotics*, 2013.

[118] Soro, D., and Lozano R. Semi-global practical stabilization of an underactuated surface vessel via nested saturation controller. In *Proceedings of the 2003 American Control Conference, 2003*, volume 3, pages 2006–2011. IEEE, 2003.

[119] Statheros, T., Howells, G., and Maier K.M. Autonomous ship collision avoidance navigation concepts, technologies and techniques. *Journal of Navigation*, 61(1):129, 2008.

[120] Xu T. An intelligent navigation system for an unmanned surface vehicle. 2007.

[121] Tam, C.K., Bucknall, R., and Greig A. Review of collision avoidance and path planning methods for ships in close range encounters. *Journal of Navigation*, 62(3):455, 2009.

[122] Fossen T.I. Guidance and control of ocean vehicles. *New York*, 1994.

[123] Fossen T.I. A survey on nonlinear ship control: From theory to practice. In *Plenary Talk, Proceedings of the 5th IFAC Conference on Manoeuvring and Control of Marine Craft*, 2000.

[124] Fossen T.I. Marine control systems: Guidance, navigation and control of ships, rigs and underwater vehicles. Marine Cybernetics Trondheim, 2002.

[125] Fossen T.I. A nonlinear unified state-space model for ship maneuvering and control in a seaway. *International Journal of Bifurcation and Chaos*, 15(09):2717–2746, 2005.

[126] Toussaint, G.J., Basar, T., and Bullo F. H_∞-optimal tracking control techniques for nonlinear underactuated systems. In *Proceedings of the 39th IEEE Conference on Decision and Control, 2000*, volume 3, pages 2078–2083. IEEE, 2000.

[127] Toussaint, G.J., Basar, T., and Bullo F. Tracking for nonlinear underactuated surface vessels with generalized forces. In *Proceedings of the 2000 IEEE International Conference on Control Applications, 2000*, pages 355–360. IEEE, 2000.

[128] Toussaint, G.J., Basar, T., and Bullo F. Motion planning for nonlinear underactuated vehicles using H_∞ techniques. In *Proceedings of the 2001 American Control Conference, 2001*, volume 5, pages 4097–4102. IEEE, 2001.

[129] Navy US. The navy unmanned surface vehicle (USV) master plan, July 2007.

[130] Bertram V. Unmanned surface vehicles–a survey. *Skibsteknisk Selskab, Copenhagen, Denmark*, 2008.

[131] Dong W. Cooperative control of underactuated surface vessels. *IET Control Theory & Applications*, 4(9):1569–1580, 2010.

[132] Wang, H., Wei, Z., Ow, C.S., Ho, K.T., Feng, B.J., and Huang J.J. Improvement in real-time obstacle detection system for USV. In *2012 12th International Conference on Control Automation Robotics & Vision (ICARCV)*, pages 1317–1322. IEEE, 2012.

[133] Wang, H., Wei, Z., Wang, S.S., Ow, C.S., Ho, K.T., and Feng B.J. A vision-based obstacle detection system for unmanned surface vehicle. In *2011 IEEE Conference on Robotics, Automation and Mechatronics (RAM)*, pages 364–369. IEEE, 2011.

[134] Wang, H., Wei, Z., Wang, S.S., Ow, C.S., Ho, K.T., Feng, B.J., and Zhou L.B. Real-time obstacle detection for unmanned surface vehicle. In *Defense Science Research Conference and Expo (DSR), 2011*, pages 1–4. IEEE, 2011.

[135] Wang, J.H., Huang, P.P., Chen, C.F., Gu, W., and Chu J.X. Stereovision aided navigation of an autonomous surface vehicle. In *2011 3rd International Conference on Advanced Computer Control (ICACC)*, pages 130–133. IEEE, 2011.

[136] Xiong, Y.Z., Zhang, X.J., Feng, H.T., Wang, and J.H. An unmanned surface vehicle for multi-mission applications. *Ship Engineering*, 1:006, 2012.

[137] Xu, T., Chudley, J., and Sutton R. A fault tolerant multi-sensor navigation system for an unmanned surface vehicle. In *Fault Detection, Supervision and Safety of Technical Processes*, volume 6, pages 1503–1508, 2006.

[138] Xu, T., Chudley, J., and Sutton R. A fuzzy logic based multi-sensor navigation system for an unmanned surface vehicle. In *Proceedings of the UKACC International Control Conference, Glasgow, UK*, 2006.

[139] Xu, T., Sutton R., and Sharma S. A multi-sensor data fusion navigation system for an unmanned surface vehicle. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 221(4):167–182, 2007.

[140] Yaakob, O., Mohamed, Z., Hanafiah, M.S., Suprayogi, D.T., Ghani, M.A., Adnan, F.A., Mukti, M.A.A., and Din J. Development of unmanned surface vehicle (USV) for sea patrol and environmental monitoring. In *International Conference on Marine Technology*. Kuala Terengganu, Malaysia, 20-22 October 2012.

[141] Yan, R.J., Pang, S., Sun, H.B., and Pang Y.J. Development and missions of unmanned surface vehicle. *Journal of Marine Science and Application*, 9(4):451–457, 2010.

[142] Zhang, Y.M., and Jiang J. Bibliographical review on reconfigurable fault-tolerant control systems. *Annual Reviews in Control*, 32(2):229–252, 2008.