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Review of Course Keeping Control System for Unmanned Surface Vehicle

M. N. Azzeri[a], F. A. Adnan[b*], M. Z. Md. Zain[a]

[a]*Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*
[b]*Marine Technology Center, Transportation Research Alliance, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia*

*Corresponding author: faizul@utm.my

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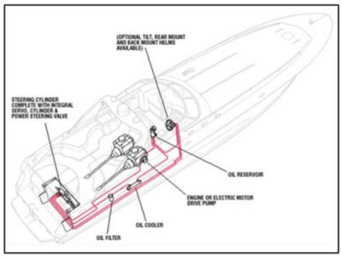
Graphical abstract



Abstract

This paper presents a review of research work done on various aspects of control system approaches of unmanned surface vehicle (USV) in order to improve the course keeping performance. Various methods have been used to produce a course keeping control system for manoeuvring system of USV. However, the review reveals that the adaptive backstepping control system is a powerful tool for the design of controllers for nonlinear systems or transformable to form a tight feedback parameter. It is very suitable for the automated control system of USV in relative motion that involves the disturbances from waves and wind. Fuzzy logic control also had been suggested as an alternative approach for complex systems with uncertain dynamics and those with nonlinearities. This method does not rely on the mathematical models, but the heuristic approach. Further studies may be conducted to combine the control method approach mentioned above to develop a real time system with robust control laws to the motions of a USV in waves, usually at a specific speed, including station keeping or heading in sinusoidal and irregular waves.

Keywords: Unmanned surface vehicle; course keeping; control approach

■1.0 INTRODUCTION

Unmanned surface vehicle (USV) fills an increasingly important knowledge in the marine engineering study for robotic vehicles. Research and development in USV is a specialization in the realm of marine robotics which consists of guidance, navigation, and control as basic approach for controlling surface vehicles [1]. USVs are also called Autonomous Surface Crafts (ASCs) or Autonomous Surface Vehicles (or Vessels) (ASVs) [2-6], is a type of vessel that runs on the surface of water without an operator on the platform and allows new modes of operations [2].

On the design of the USV, there are mostly unique small designs with special purpose craft and not standardized for modularity [6]. This design has limited endurance, payload, and seakeeping ability. In the current design of USV, most small vehicles such as boats have been adapted from ships manned originally designed to accommodate a human occupant [7]. This design provides moderate speed with long endurance and improved capabilities of payload and seakeeping to support special missions.

Thus, USVs can be used for a variety of missions that will be safer and cheaper than human, such as marine environment monitoring, hydrology survey, target object searching, bathymetric mapping, defence, general robotic researches, and scientific studies. [6, 7]. Some of the missions above need advanced control system to manoeuvre the USV. Therefore, this paper is intended to present a literature review of research work done by many researchers concerning various aspects of control system of USV technology in an effort to improve the course keeping performance of its application.

■2.0 HISTORY AND DEVELOPMENT

The history of the development of USVs has actually started since World War II, used for minesweeping purposes and battle damage assessments [6]. It is only during the last decade that they have been considered for more advanced operations. However, it is only in the past few years that USVs have begun to have an impact in many mission areas, including military purposes and science marine research studies.

The USVs available in the market today are mainly used in the military, especially for intelligence, surveillance, and reconnaissance (ISR) [6, 8]. The unmanned surface vehicles developed for military purposes such as the SSC San Diego, based on a sport boat with a jet drive Bombardier SeaDoo Challenger 2000 [9] with robust USV operation in a real world environment, primarily focus on autonomous navigation, obstacle avoidance, and path planning. The Israeli Stingray USV [10] and Protector USV [10] are equipped with electro-optic sensors, radar, Global Positioning System (GPS), inertial navigation system, and a stabilized machine gun. Another military USV, already operated by the British Royal Navy named Shallow Water Influence Minesweeping System (SWIMS) [10] is used to support the Mine

Counter Measures (MCM) operations. SWIMS is basically a boat that can be converted into Boat Combat Support functions that need additional equipment. USV has also been developed under the Officer of Naval Research (ONR) USA named Owl and Spartan Scout. These USVs are primarily used to conduct minefield reconnaissance, swallow water monitoring, maritime interception, and safeguard ports and surrounding areas [11].

For research purpose, USVs have been developed and demonstrated by some academic institutions, companies, and government agencies. Most scientific USVs are just experimental platforms or prototypes and no applications currently exist in the commercial market [8, 12].

The number of USV or ASC prototypes have been developed such as the catamarans Autonomous Coastal Exploration System (ACES) [12] and AutoCat [13] from Massachusetts Institute of Technology (MIT), which are devoted to the collection of hydrographic and bathymetric data. Another prototype of ASC that has been developed by the MIT is Surface Craft for Oceanographic and Undersea Testing (SCOUT), is a single hull for oceanographic and undersea testing that supports multiple ASCs working in cooperative autonomy [14]. The Charlie catamaran, originally designed by CNR-ISSIA, Genova, Italy, is used for the sampling of the sea surface micro layer in the Antarctica [15]. The University of South California has developed an unmanned airboat for surface water biological study [16, 17] and has conducted researches on surface obstacle avoidance using a single beam sonar [18]. A solar-energy-powered ASC designed by the University of Queensland has integrated various sensors to do water researches [19]. The DELFIM, developed by the Institute for Systems and Robotics, Lisboa Portugal, is a surface platform for underwater communication for automatic marine data acquisition, and to serve as an acoustic relay between submerged craft and a support vessel [20]. The ASIMOV ASC [21] project is initiated by the Commission of the European Communities regarding to applications of autonomous surface craft which emphasized ocean observations and data transmission researches. An Italian catamaran USV, developed by CNR-ISSIA, Genoa called SESAMO, has been used in the Antarctica in support of oceanographic researches [22]. A long range of research vessel ASC Caravela, developed by the Instituto Superior Técnico (IST) in Lisbon [6], is used for testing craft in vessel mission control and radar based obstacle avoidance. The University of Plymouth, UK has developed autonomous catamaran Springer for sensing, monitoring, and tracking water pollution [23, 24]. In China, a water-jet propelled USV also has been developed and it looked into the feasibility study on different sailing states of the motion control strategy of the USV [25]. The University Technology of Malaysia also produced a USV based on modified jet-ski hull structure for sea patrol and environmental monitoring [26]. Virginia Tech has developed a Ribcraft boat for riverine USV with robust and accurate abilities for autonomous operation to execute manoeuvres [27].

Another series of USVs have been developed from the companies such as USV-2600, by SeaRobotics, have been used in transportation and bathymetric surveying [28]. The Z-Boat, which is produced by the Ocean Science company, is a small USV platform used for hydrographic surveying [28]. The company of Liquid Robotics produced a small ocean-patrolling USV for ocean observing [28].

3.0 TECHNICAL DEVELOPMENT

The technical development of USVs can be classified into two main categories, which are vehicle control technology, and task oriented design technology [11]. The vehicle control technologies consist of automatic collision avoidance systems, automatic navigation systems, and intelligent control systems. The task oriented is entirely according to the mission requirements to conduct operations under adverse sea conditions and in areas that are unsafe for manned vehicles.

The main thing in the technical development of USV is related to the steering control system. The steering control system is linked to the course keeping control of USV that can be controlled remotely or autonomously. The typical steering control system of the boat using a hydraulic system includes the component of the helm controller, hydraulic motor pump, cylinder actuator, servo motor, rudder, and close loop hydraulic line system, as shown in (Figure 1).

The control of USV is very important and a lot of studies have been conducted lately on course keeping control system to improve system performance and speed of action. Therefore, interest in control system of USV has increased and USV control systems are now an important area of research [29].

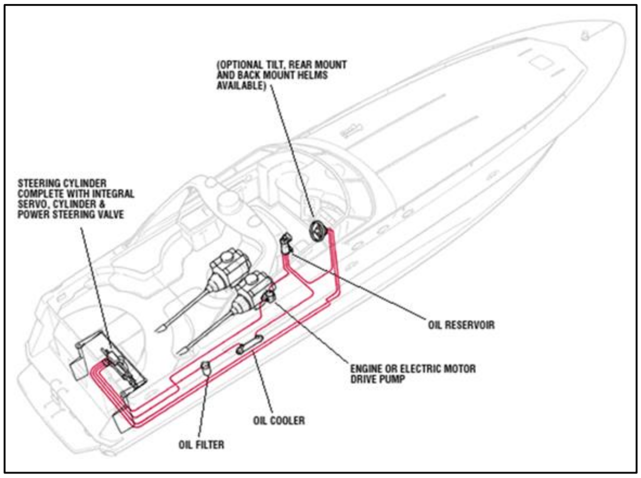


Figure 1 Typical steering control system of boat using hydraulic system [30]

The challenge brought about by the control system configuration of the surface vessel that involves motion on three degrees of freedom that only two actuators are available for controlling these. The propeller thrust is commonly used for controlling the surge speed of the surface vessel. This will require rudder action to control both the sway displacement and the heading angle. The block diagram in (Figure 2) shows the block representations of rudder actuator control from the input surge speed and yaw angle. A reasonable approach to empower the rudder to simultaneously compensate for the sway displacement and heading angle is to couple the ship controller with a guidance system [31-35]. This task is complicated by the ship dynamics, which are highly nonlinear and involve significant modelling imprecision. Therefore, effective surface vessel controllers must be robust for modelling imprecision and capable of adapting to their unpredictable environmental conditions [31, 36-43].

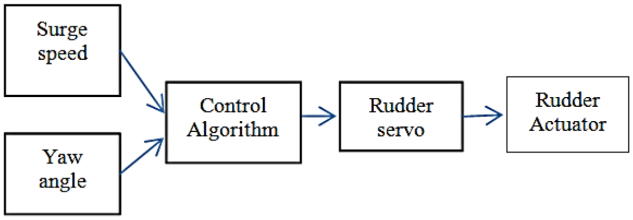


Figure 2 Block representation of rudder actuator control

The dynamic equations of motion for a ship exposed to waves have evolved from two main directions, which is manoeuvring theory, and seakeeping theory. In manoeuvring theory, it is common to assume that the ship is moving at the restricted calm water. Hence, the ship model is derived for a ship moving at positive speed U under the zero-frequency assumption such that added mass and damping can be represented by using hydrodynamic derivatives. Seakeeping analysis is used in operability calculations to obtain operability diagrams according to the adopted criteria. It also refers to the motions of a vessel in waves usually at a specific speed including station keeping and heading in a sinusoidal, irregular or random seaway [44]. Nonlinear control theory has also been extensively used in dynamic equations of motion for a ship exposed to waves of marine vessels [32, 36, 39, 45-49].

■4.0 PRINCIPLES OF COURSE KEEPING CONTROL SYSTEM

Hence, ship manoeuvring is treated as a horizontal plane motion, and only the surge, sway and yaw models are considered. The main aim of the course-keeping control system is to maintain the reference course of the vehicle (= const.) [50, 51]. The course-keeping control system prevails among control systems used in guidance of marine vehicles. The vehicle's course is usually measured by gyrocompass. The block diagram in (Figure 3) shows the course keeping control system for automatic heading. Here, the yaw rate (usually measured by rate gyro) and surge speed are most often used. Surge speed is important because the hydrodynamic parameters of the vehicle depend on it [51]. The system is usually designed in such a way that the ship can move forward with constant speed U, while the sway position is controlled by correction of rudder angle (δ) using steering system [52]. The output from the system will then represent the desired course angle (   ). The necessity of course-keeping control systems has become important because of safety and economic reasons [51].

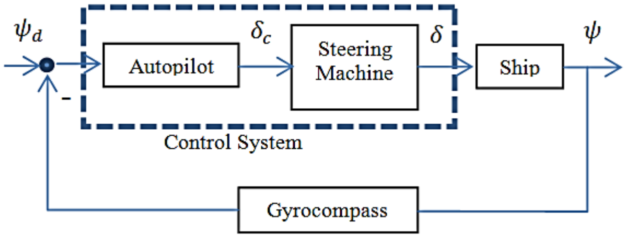


Figure 3 Course keeping control system for automatic heading block diagram

Typically, the most important performance criterion for the course keeping manoeuvre is minimum course deviation with smallest control exerted by the steering machine which controls the rudder angle (δ). However, it is desirable to track the new set course as quickly as possible with minimum overshoot [50].

Automatic system for course-keeping or autopilot is normally based on feedback from a gyrocompass measuring the heading. Heading rate measurements can be obtained from rate sensor, gyro, and numerical differentiation of the heading measurement or a state estimator. This is a common practice in most control laws utilizing proportional, derivative, and integral action [50].

The first autopilots implemented on ships were PID-based autopilots [53]. Later, new types were introduced, including gain scheduling adaptive autopilots, where autopilot parameters change with the speed of the vehicle. The first model reference and self-tuning adaptive autopilots appeared in the mid-1970s and 1980s, respectively [54]. During the 1990s, researches were focused on fuzzy and neuro course-keeping control systems [55].

However, the advanced technique approach using compensators, such as state feedback linearization techniques [32, 46], output feedback controllers, and back-stepping schemes [36, 39, 47, 48] are model based schemes to enhance the robust system to modelling uncertainties. However, PID-type autopilots are still very popular and represent a majority of autopilots in use.

■5.0 COURSE KEEPING CONTROL APPROACHES

Here, various methods have been used to produce a course keeping control system for USV. Thus, this paper discusses the methods of control such as control system design using a variety of methods appropriate to the mission or the use of USV.

Researchers have employed various control approaches to tackle this problem. A sampling of the research was done for different control approaches, as shown in (Figure 4) One of the technologies that have been applied in the various aspects of course keeping control is to compensate for the error in position and reduce it as much as possible. Brief review of the idea to develop a procedure to compensate for the error in position and how they are employed in course keeping control are given below.

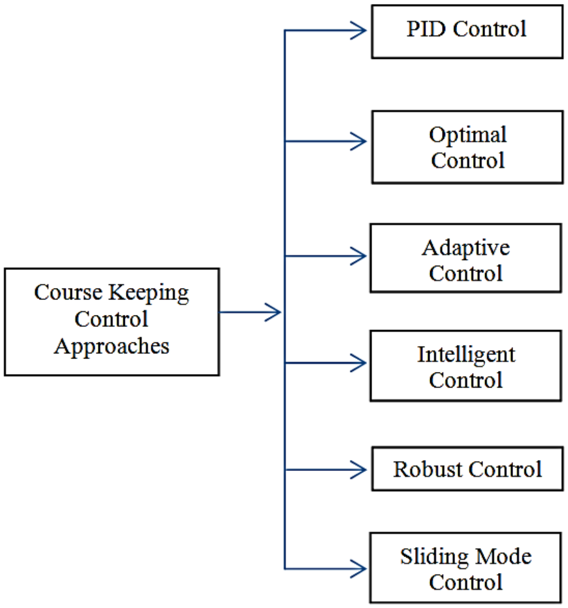


Figure 4 Sampling of course keeping control approaches

5.1 Classical Control Methods Based on PID Control

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism (controller) that is widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs [50]. The first autopilots implemented on ships were PID-based autopilots [53].

Kumar *et al*., [56] reported that a classical PID controller is the most popular controller due to its simplicity of operation and low cost. The classic PID controllers are effective for linear systems, but not suitable for nonlinear and complex systems. As for nonlinear and complex system, fuzzy logic is used to enhance the system due to its ability to translate the control action into the rule base [56].

Caccia *et al*., [10] demonstrated, in particular, experiments of a USV through extension at sea trials carried out with the prototype autonomous catamaran Charlie. The experiments demonstrate the effectiveness both for the precision and power consumption of simple PID guidance with Kalman filter and control laws to perform basic control tasks such as auto-heading, auto-speed, and straight line, following a USV equipped only with GPS and compass.

Curcia *et al*., [14] developed a simple PID guidance implemented on the SCOUT kayak platform. The navigation system was further extended by incorporating the distributed autonomy architecture for sensor adaptive control of USVs in an autonomous oceanographic sampling scenario.

Park *et al*., [57] studied dynamic positioning and a waypoint tracking control experiment to confirm the control performance of designing a PID controller in the sea-trial. The catamaran USV has been developed in carrying out experiments to validate the automatic control performance to keep the USV's position at a fixed point and to track predefined positions. The optimal control performance for the speed and heading control was difficult to obtain using a PID controller, with two fixed thrusters, and is coupled with the dynamics of the surge and yaw motion. In order to solve this problem, the optimal Linear-Quadratic (LQ) controller based on the estimated model was proposed. The simulation results show that the control objective was achieved successfully.

Jutong *et al*., [58] proposed of a Trimaran Unmanned Surface Vehicle (TUSV) control system and a control scheme for such a vehicle. The PID controller was designed to control engine speed, yaw and position. The full system was tested successfully in the manual operation and obtained useful data, which was analysed and used in identifying the TUSV model and design advanced control technologies.

5.2 Optimal Control Methods

Optimal control deals with the problem of finding a control law for a given system, as such that a certain optimality criterion is achieved. An optimal control is a set of differential equations describing the paths of the control variables that minimize the cost function [59]. There are two types of optimal control method that have been used in the USV control system, which are Linear-Quadratic-Gaussian control (LQG), and Model Predictive Control (MPC).

5.2.1 Linear-Quadratic-Gaussian Control (LQG)

Sharma *et al*., [60] reported that in autonomous catamaran Springer control design, an LQG controller was selected which consists of a linear combination of a Linear Quadratic state feedback Regulator (LQR) and a Kalman filter. It concerns uncertain linear systems disturbed by additive white Gaussian noise, having incomplete state information, and undergoing control subject to quadratic costs.

Naeem *et al*., [24] investigated the LQG controller in autonomous catamaran Springer that required a state space model of the system in the form of specified equation. The LQR and Kalman filter were developed independently and then combined to form an LQG controller. In control theory, the LQG control method is one of the most fundamental optimal control problems for linear systems. Athans [61] studied that the LQG controller is also fundamental to the optimal control of perturbed non-linear systems.

5.2.2 Model Predictive Control (MPC)

Siramdasu and Fahimi [62] introduced the MPC, which calculates the future control inputs based on the present state variables by optimizing a cost function. The fact that the cost function incorporates input constraints, as well as state errors, in determining the control inputs were exploited. This method can be applied to all systems with input saturation and suitable for the trajectory tracking guidance system.

Sharma *et al*., [63] used the MPC to generate a prediction of future behaviour of the USV control system. At each time step, past measurements and inputs were used to estimate the current state of the system. An optimization problem was solved to determine an optimal open-loop policy of the present state.

Annamalai *et al*., [64] studied to improve performance of traditional autopilots deterioration due to consistent and persistent changes in the marine environment. One solution to this problem is to apply MPC techniques in the design of an autopilot to USV.

This study also investigated the performance parameters that compared the MPC and LQG in the simulation analysis. The MPC's predictive nature results in the USV had a much smoother trajectory than that was obtained using the traditional LQG optimal control methods. It shows that MPC can cope with fast changing dynamics of the plant and can perform well when integrated with the other subsystem in USV.

5.3 Adaptive Control Methods

Adaptive control is the control method used by a controller which must adapt to a controlled system with parameters which vary or are initially uncertain. Adaptive control is concerned with control law changing themselves as it does not need priori information about the bounds on these uncertain or time-varying parameters [65]. There are two types of optimal control methods that have been used in the USV control system, which are Adaptive Backstepping, and Gain Scheduling.

5.3.1 Adaptive Control Based On Backstepping Control Design

Adaptive backstepping is a tool for the design of controllers for nonlinear systems or transformable to form a tight feedback parameter. Many studies have been conducted to achieve high performance for ship course keeping control system.

Junfang *et al.*, [66] introduced a robust adaptive control algorithm for ship course autopilot with parameter uncertainty and input saturation that applied on USV. The controller was constructed by considering parameter uncertainty and actuator saturation constraints using Lyapunov stability theory and adaptive backstepping technique. Simulation results indicate the effectiveness and the performance of the stability system to the effect of input saturation constraints.

Junsheng and Xianku [67] proposed backstepping adaptive course-keeping controller design for USV autopilot. Therefore, the proposed controller has no need of a priori knowledge about ship's system dynamics. Simulation study verifies the efficiency of the ship course-keeping design and command filter that could bypass the iterative differential manipulations in conventional ship course adaptive backstepping controller.

Liao *et al.*, [68] proposed a method of backstepping adaptive dynamical sliding mode control for the path following control system of the underactuated surface vessel. The system consists of the nonlinear ship response model and the Serret-Frenet error dynamics equations. The control system takes into account of the modelling errors and external disturbances. Using the Lyapunov function, it was proven that the proposed controller could render the path following control system globally asymptotically stable. Simulation results verify that the controller is robust and adaptive to the systemic variations or disturbances.

Fossen *et al.*, [35] studied a three degree of freedom; surge, sway, and yaw, on nonlinear controller for path following of marine craft using only two controls, using the nonlinear control theory. Path following is achieved by a geometric assignment based on a line-of-sight projection algorithm for minimization of the cross-track error in the path. The control laws in surge and yaw are derived using backstepping technique. This results in a dynamic feedback controller where the dynamics of the uncontrolled sway mode enters the yaw control law. A study involving an experiment with a model ship is included to demonstrate the performance of the controller and guidance systems.

Sonnenburg and Woolsey [27] studied the implementation of two trajectory tracking control algorithms which is a cascade of proportional-derivative controllers and a nonlinear controller obtained through backstepping. This study focused on providing riverine USV with the ability to robustly and accurately execute manoeuvres. Experimental results indicate that the backstepping controller is much more effective at tracking trajectories with high variable speed and course angle.

In control theory, backstepping is a technique for designing stabilizing controls for nonlinear dynamical systems [69, 70] using the Lyapunov function method to stabilize the subsystem controllers that progressively stabilize each outer subsystem [71].

5.3.2 Adaptive Control Based on Gain Scheduling

Gain scheduling is a method used to find auxiliary variables that correlate well with the changes in the process dynamics implemented in computer-controlled systems. By changing the parameter variations, which are the functions of auxiliary, variables feedback gains are adjusted [72].

Murali *et al.*, [72] reported that the main problem in designing the gain scheduling controller is to find suitable scheduling variables. This is normally done based on the physics of the system. When scheduling variables have been deformed, the controller parameters are calculated at a number of operating conditions using some suitable design approach. The controller is tuned for each operating condition. The stability and performance of the system are evaluated at different operating conditions.

The experiments of two types of controllers above, Adaptive Backsteepping, and Gain Scheduling, were performed on boat model, conducted by Murali *et al.*, [72]. The effectiveness of the two types of controller is validated for reaching the desired heading angle that satisfies the steering dynamics and the first order of the Nomoto's model. The result indicated that the desired angle reaches faster in case of adaptive controller. The adaptive controller has some notable advantages over the gain scheduling controller.

5.4 Intelligent Control

Intelligent control is a control technique that uses various Artificial Intelligence (AI) computing approaches like genetic algorithms, neural networks, and fuzzy logic [73].

5.4.1 Intelligent Control Basedon Genetic Algorithms

Malecki and Zak [74] introduced the genetic algorithms for designing a fuzzy trajectory control for ships at low speed. For track-keeping precise control, the waypoint line of sight scheme is incorporated and three independent fuzzy controllers are used to generate command signals. In general, the genetic algorithm techniques manipulate sets of individuals by using genetic operators in order to propose better ones. The individuals in a population are represented by chromosomes [75]. An advantage of this control system is its flexibility with regard to the change of dynamic properties of the special ship. From the simulation results presented, the proposed approach provides the autopilot being robust and having good performance both without and in the presence of the sea current disturbances [74].

5.4.2 Intelligent Control Based on Neural Networks

Zhouhua *et al.*, [76] proposed the adaptive dynamic surface control for the formation of autonomous surface vehicles by employing neural network and dynamic surface control technique. The advantages of the proposed formation controller are that: first, the proposed method only uses the measurements of line of sight range and angle by local sensors, no other information about the leader is required for control implementation; second, the developed neural formation controller is able to capture the vehicle dynamics without exact information of coriolis and centripetal force, hydrodynamic damping, and disturbances from the environment. Comparative analysis with a model-based approach is given to demonstrate the effectiveness of the proposed method. Simulation results demonstrate the effectiveness of the formation controller and the learning ability of neural networks.

Furthermore, Peng *et al.*, [77] extended the study from Zhouhua *et al.*, to form a control of autonomous surface vehicles with uncertain leader dynamics and uncertain local dynamics, where backstepping based neural networks control technique is employed to stabilize formations. However, the controller is complicated for the sake of the needs to calculate numerical derivatives of virtual control signals. Hence, there is a need to develop an adaptive formation controller using the neural networks based dynamic approach to derive the relative dynamics between the leader and follower from the kinematics.

5.4.3 Intelligent Control Based on Fuzzy Logic

Fuzzy logic control has been suggested as an alternative approach for complex systems with uncertain dynamics and those with nonlinearities. This method occupies the boundary line between artificial intelligence and control engineering, and it can be considered as an obvious solution which is confirmed by engineering practice [56]. An unconventional control design such as fuzzy control design methods do not rely on the mathematical models [50].

Moreover, Nassim and Nabil [49] introduced a self-tuning fuzzy sliding mode controller for marine surface vessel. It is designed to control the surge speed and the heading angle of an under-actuated marine surface vessel. The actuation signals were restricted to the propeller thrust, and the rudder control torque. The controller was designed based on a reduced order model, which only considers the surge and yaw motions of the vessel. The simulation results illustrate good tracking characteristics of the current guidance and control system in spite of considerable modelling imprecision and environmental disturbances. The results also demonstrate that the proposed guidance scheme enables the marine vessel to converge to its desired trajectory faster.

Junsheng and Xianku [78] proposed ship course-keeping adaptive tracking fuzzy control scheme of the nonlinear system in strict-feedback form. The control objective is to force the ship's course to track the output of the specified reference model. The fuzzy system is employed to approximate the unknown dynamics. The proposed algorithm can guarantee the boundedness of all the signals in the closed-loop system.

5.5 Robust Control

Robust methods aim to achieve robust performance and stability in the presence of small modelling errors. Controllers designed using robust control methods tend to be able to cope with small differences between the true system and the nominal model used for design. The characteristic of the robust system is the norm with the Input constraints, bounded control action, and closed loop system properties [79].

On the other hand, Jerzy [80] introduced the design of robust, nonlinear control system of the ship course angle, in a model following control (MFC) structure based on an input-output linearization. This controller reacts to the difference between the output signal of real ship and its model. The nonlinear plant, linearized by the input-output method, has good properties (short time control, and acceptable control signals). Therefore, the system proposes the use of MFC structure, which is able to compensate for differences of nonlinear characteristics of the process and model and can replace the complex and expensive adaptive control system.

Shr and Jeng [81] investigated the robust nonlinear ship course keeping control under the influence of high wind and large wave disturbances. To design the robust nonlinear ship course keeping controller employs two feedback loops, which are the H approximate input/output linearization in the inner-loop, and μ synthesis in the outer-loop, to address tracking, regulation, and robustness issues. Simulation results indicate that the performance of the proposed robust nonlinear controller design is better than the linear robust controller in handling high wind and large wave disturbances.

5.6 Sliding Mode Control

In control theory, sliding mode control is a nonlinear control method that alters the dynamics of a nonlinear system through the application of a discontinuous control signal that forces the system to slide along a cross-section of the system's normal behaviour. Hence, sliding mode control is a variable structure control method. The multiple control structures are designed so that trajectories always move toward an adjacent region with a different control structure, and so the ultimate trajectory will not exist entirely within one control structure. Instead, it will slide along the boundaries of the control structures [82].

Wei *et al.*, [83] proposed a new nonlinear sliding mode based on formation control scheme for underactuated surface vessels. Since the sway axis is not directly actuated, the vessels were underactuated. The formation model is obtained based on the leader-following approach. The controller was designed using the Lyapunov's direct method and sliding mode control technique. The first-order surface in terms of the surge motion tracking errors and the second-order surface in terms of sway motion tracking errors were introduced. The effectiveness of the designed sliding mode formation controller was validated by numerical simulations.

Ashrafiuon *et al.*, [84] studied a sliding-mode control law on experimentally implemented trajectory tracking of underactuated autonomous surface vessels. The control law is developed by introducing a first-order sliding surface in terms of surge tracking errors and a second-order surface in terms of lateral motion tracking errors. The experimental vessel is a small boat with two propellers in an indoor pool. The control law was developed using a first-order surface in terms of the surge tracking errors, and a second-order surface in terms of the sway tracking errors. The vessel's absolute position and orientation were measured using a camera. The motor input voltages were estimated from the controller propeller forces and transmitted to the motors using wireless transmitters and receivers. Several straight-line and circular experiments were successfully performed.

Piotr [85] investigated a course controlling a USV following three control methods, which are PID, slide, and fuzzy control. PID, slide, and fuzzy controllers were tested for three different changes of course from 0° to 30°, 90° and 180°. Moreover, to counteract sea current, two methods were presented and compared by means of numerical research. The comparison results from the numerical research show that the slide controller achieved more control quality indexes than the others.

5.7 Summary and Future Work

Hence, conclusions can be derived from the list of citations in Table 1 on some of the researches done on course keeping control system for USV. Most of the control approaches were not a real time experimental implementation of nonlinear dynamic algorithms. Therefore, no direct attention has been given on the methods with which parameters of the nonlinear dynamic model can be identified in the control law with uncertain parameters and environmental disturbances.

In addition, the marine operations are characterized by time-varying disturbances and widely changing sea conditions. Thus, the controller design for such nonlinear system is still a challenging problem. Some attempts have been made to solve the problem based on the adaptive control. However, the review also reveals that adaptive backstepping is a powerful tool for the design of controllers for nonlinear systems or transformable to form tight feedback parameters. This type of control method requires much knowledge in mathematical algorithms, involving the Lyapunov function method, and backstepping technique. These methods are suitable for the automated control system of USV in relative motion that involves a disturbance from waves and wind. Fuzzy logic control also has been suggested as an alternative approach for complex systems with uncertain dynamics and those with nonlinearities. The nonlinear and complex system used fuzzy logic to enhance the system due to its ability to translate the control action into the rule base. This type of method does not rely on mathematical models but the heuristic approach.

Therefore, future research should consider the dynamic positioning problem to achieve station keeping mode for a USV to have only two independent control inputs; surge force, and yaw moment. From the previous researches in Table 1, typically, the USV is equipped with two aft thrusters located at a distance from the centre line to give both surge force and yaw moment, but has no side thruster to give sway force control. To control both positions, together with the orientation of three degrees of freedom and having only two independent control inputs available, the system will experience an underactuated control problem. The underactuated USV control problem is inherently nonlinear [86]. Therefore, a nonlinear ship model must be considered. Moreover, the underactuated ship belongs to a class of systems that cannot be asymptotically stabilized by a feedback control law [86]. This implies that the dynamic positioning problem cannot be solved using a linear proportional integral derivative (PID)-controller or any other linear time-invariant feedback control law, and the problem is not solvable using classic nonlinear control theory like feedback linearization [86].

Thus, station keeping is achieved by applying the necessary thrust in opposition to any measured external disturbance. For systems that operate in the ocean, care has to be taken to ensure that the ship is filtered out with high frequency wave disturbances which use the acceleration feedback in dynamic positioning. Such underactuated dynamic positioning describes a feedback control law that keeps a USV in station in an asymptotic manner using accurate visual position feedback.

For control strategies of the USV, one of the ways to stay at the desired location is to arrive at the location in a direction that is parallel to the disturbance and surging forward or reversing. This control strategy needs the USV to align with the direction of current and wave when it is close to the desired target. The designed controller will try to turn back towards the location if it drifts away from the target location. The controller will control the two thrusters with the ability to turn in circles. The movement of the turn-centre is much smaller than the length of the boat, and hence for simplicity, it will assume that it turns about the centre of the desired target.

Table 1 Researches on course keeping control system approaches for USV

No	Control Approches	Researcher	Control Input	Control Algorithms	Platform	Surge Force	Yaw control	Type of Analysis	
								Simulation	Experiment
1	PID Control	Caccia et al. [10]	surge speed and yaw angle	Linear	Catamaran	2 propellers	2 rudders		Y
2		Curcia et al. [14]	surge speed and yaw angle	Linear	Kayak	1 motor thruster	Flexible thruster		Y
3		Park et al. [57]	surge speed and yaw angle	Linear	Catamaran	2 fixed thrusters	-	Y	Y
4		Jutong et al. [58]	surge speed and yaw angle	Nonlinear	Trimaran	1 fixed thruster	1 rudder	Y	-
5	Linear-Quadratic-Gaussian control (LQG)	Sharma et al. [60]	surge speed and yaw angle	Nonlinear	Catamaran	2 fixed thrusters	-	Y	-
6		Naeem et al. [24]	surge speed and yaw angle	Nonlinear	Catamaran	2 fixed thrusters	-	Y	-
7	Model Predictive Control (MPC)	Siramdasu and Fahimi [62]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	-
8		Sharma et al. [63]	surge speed and yaw angle	Nonlinear	Catamaran	2 fixed thrusters	-	Y	-
9		Annamalai et al. [64]	surge speed and yaw angle	Nonlinear	Catamaran	2 fixed thrusters	-	Y	-
10	Adaptive Control Based on Backstepping Control	Junfang et al. [66]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	-
11		Junsheng and Xianku [67]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	-
12		Liao et al. [68]	surge speed and rudder angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	
13		Fossen et al. [35]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	-	Y (model)
14		Sonnenburg and Woolsey [27]	surge speed and yaw angle	Nonlinear	RHIB	1 propeller (OBM)	-	-	Y
15	Adaptive Control Based on Gain scheduling	Murali et al.[72]	surge speed and yaw angle	Linear	Monohull	2 propellers	-	-	Y
16	Intelligent Control Based on Genetic Algorithms	Malecki and Zak [74]	surge speed and yaw angle	Nonlinear	Monohull	3 thrusters	-	Y	-
18		Zhouhua et al. [76]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	-
19		Peng et al. [77]	surge speed and yaw angle						
20	Intelligent Control Based on Fuzzy Logic	Nassim and Nabil [49]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	
21		Junsheng and Xianku [79]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	-
22	Robust Control	Jerzy [80]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	
23		Shr and Jeng [81]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	
24	Sliding Mode Control	Wei et al. [83]	surge speed and yaw angle	Nonlinear	Monohull	1 propeller	1 rudder	Y	-
25		Ashrafiuon et al. [84]	surge speed and yaw angle	Nonlinear	Monohull	2 propeller	-	-	Y
26		Piotr [85]	surge speed and yaw angle	Nonlinear	RHIB	1 propeller	1rudder	Y	-

6.0 CONCLUSION

In this study, the literature related to course keeping control system for USV has been reviewed. Simple classifications of different course keeping control approaches have been defined. The controllers were based on a two dimensional planar model of the system that included surge, sway, and yaw dynamics. The review reveals the significant progress made during the last two decades in the development of USV and the course keeping control system. However, the review also reveals that adaptive backstepping is a powerful tool for the design of controllers for nonlinear systems or transformable to form tight feedback parameters. This method is suitable for the automated control system to USV in relative motion that involves a disturbance from waves and wind. Fuzzy logic control also has been suggested as an alternative approach for complex systems with uncertain dynamics and those with nonlinearities. This type of method does not rely on mathematical models but the heuristic approach.

Furthermore, the review also reveals a weakness in regard to real time experimental implementation of these control approaches for USV. The development of real time control laws that can be implemented to USV with uncertain parameters and environmental disturbances particularly refers to the motions of a vessel in waves usually at a specific speed, including station keeping, heading in a sinusoidal, irregular or random seaway.

Thus, future work should focus on particular problem related to this study. Further studies may be conducted to combine the control method approach to be applied in optimal control theory to find the dynamic positioning problem to achieve station keeping mode. This course keeping control system can play the role as an autopilot controller for the future of USV as a maritime monitoring boat or environmental monitoring boat, and other capabilities, such as disaster monitoring boat that carries out the desired command without any involvement of manpower for control.

References

[1] Furfaro, T. C. 2012. A Modular Guidance, Navigation and Control System for Unmanned Surface Vehicles. Florida Atlantic University, Master Thesis, Florida, USA.

[2] Manley, J. E. 2008. Unmanned Surface Vehicles, 15 Years of Development. In: Proceeding Oceans 2008 MTS/IEEE Quebec Conference and Exhibition, Quebec City, Canada. 1–4.

[3] Caccia, M. 2006. Autonomous Surface Craft: Prototypes and Basic Research Issues. In: Control and Automation, 2006. MED '06. 14th Mediterranean Conference, Ancona. 1–6.

[4] Blank, J., Bishop, B. E. 2008. In-Situ Modeling of a High-Speed Autonomous Surface Vessel. In: System Theory, 2008. 40th Southeastern Symposium System Theory, New Orleans. 347–351.

[5] Higinbotham, J. R., Kitchener, P. G., Moisan, J. R. 2006. Development of a New Long Duration Solar Powered Autonomous Surface Vehicle. In: OCEANS 2006, Boston, USA. 1–6.

[6] Bertram, V. 2008. Unmanned Surface Vehicles–A Survey. In: Skibsteknisk Selskab, Copenhagen, Denmark. 1–14.

[7] Jianhua, W., Wei, G., Jianxin, Z., Jubiao, Z. 2009. An Unmanned Surface Vehicle for Multi-mission Applications. In: Electronic Computer Technology, 2009 International Conference Macau, China. 358–361.

[8] Breivik, M., Hovstein, V. E., Fossen, T. I. 2008. Straight-Line Target Tracking for Unmanned Surface Vehicles. *J. Modeling, Identification and Control*. 29(4): 131–149.

[9] Larson, J., Bruch, M., Ebken, J. 2006. Autonomous Navigation and Obstacle Avoidance for Unmanned Surface Vehicles. In: Proceedings of the SPIE, Unmanned Systems Technology VIII. 6230: 7–22.

[10] Caccia, M., Bibuli, M., Bono, R., Bruzzone, G. 2008. Basic Navigation, Guidance and Control of an Unmanned Surface Vehicle. *J. Autonomous Robots*. 25(4): 349–365.

[11] Yang, W. R., Chen, C. Y., Hsu, C. M., Tseng, C. J., Yang, W. C. 2011. Multifunctional Inshore Survey Platform with Unmanned Surface Vehicles. *International Journal of Automation and Smart Technology*. 1(2): 19–25.

[12] Manley, J. E. 1997. Development of The Autonomous Surface Craft "ACES". In: OCEANS '97. MTS/IEEE Conference Proceedings, Halifax, Canada. 827–832.

[13] Manley, J. E., Marsh, A., Cornforth, W., Wiseman, C. 2000. Evolution of the Autonomous Surface Craft AutoCat. In: OCEANS 2000 MTS/IEEE Conference and Exhibition, Providence, USA. 403–408.

[14] Curcio, J., Leonard, J., Patrikalakis, A. 2005. SCOUT-A Low Cost Autonomous Surface Platform for Research in Cooperative Autonomy. In: OCEANS, 2005. Proceedings of MTS/IEEE. 1: 725–729.

[15] Caccia, M. 2006. Autonomous Surface Craft: Prototypes and Basic Research Issues. In: 14th Mediterranean Conference on Control and Automation, 2006. MED '06, Ancona, Italy. 1–6.

[16] Dhariwal, A., Sukhatme, G. 2007. Experiments in Robotic Boat Localization. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, 2007. IROS 2007. San Diego, USA. 1702–1708.

[17] Bin, Z., Sukhatme, G. 2007. Adaptive Sampling for Estimating a Scalar Field using a Robotic Boat and a Sensor Network. In: IEEE International Conference on Robotics and Automation, 2007 Roma, Italy. 3673–3680.

[18] Heidarsson, H. K., Sukhatme, G. 2011. Obstacle Detection and Avoidance for an Autonomous Surface Vehicle Using a Profiling Sonar. In: Robotics and Automation (ICRA), 2011 IEEE International Conference on, Shanghai, China. 731–736.

[19] Grinham, A., Udy, J., Dunbabin, M. 2009. An Autonomous Surface Vehicle for Water Quality Monitoring. In: Australasian Conference on Robotics and Automation (ACRA), Sydney, Australia. 1–6.

[20] Alves, J., Oliveira, P., Oliveira, R., Pascoal, A., Rufino, M., Sebastiao, L., Silvestre, C. 2006. Vehicle and Mission Control of the DELFIM Autonomous Surface Craft. In: 14th Mediterranean Conference on Control and Automation, 2006. MED '06, Ancona, Italy. 1–6.

[21] Pascoal, A., Oliveira, P., Silvestre, C., Sebastiao, L., Rufino, M., Barroso, V. *et al*. 2000. Robotic Ocean Vehicles for Marine Science Applications: The European ASIMOV Project. In: OCEANS 2000 MTS/IEEE Conference and Exhibition, Providence, USA. 409–415.

[22] Caccia, M., Bono, R., Bruzzone, G., Bruzzone, G., Spirandelli, E., Veruggio, G., Stortini, A. M., Capodaglio, G. 2005. Sampling Sea Surfaces with SESAMO: An Autonomous Craft for The Study of Sea-Air Interactions. *J. Robotics & Automation Magazine, IEEE*. 12(3): 95–105.

[23] Naeem, W., Xu, T., Sutton, R., Chudley, J. 2006. Design of an Unmanned Surface Vehicle for Environmental Monitoring. In: World Maritime Technology Conference, London, United Kingdom, London, U.K. 1–6.

[24] Naeem, W., Xu, T., Sutton, R., Tiano, A. 2008. 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 2008*. 222(2): 67–79.

[25] Gongxing, W., Hanbin, S., Jin, Z., Lei, W. 2009. The Basic Motion Control Strategy for The Water-Jet-Propelled USV. In: International Conference on Mechatronics and Automation, 2009. ICMA 2009, Changchun, China. 611–616.

[26] Yaakob, O., Mohamed, Z., Hanafiah, M., Suprayogi, D., Ghani, M. A., F. A. Adnan, Mukti, M., Din, J.v 2012. Development of Unmanned Surface Vehicle (USV) for Sea Patrol and Environmental Monitoring. In: International Conference on Marine Technology Kuala Terengganu, Malaysia, Kuala Terengganu, Malaysia. 1–6.

[27] Sonnenburg, C. R., Woolsey, C. A. 2013. Modeling, Identification, and Control of an Unmanned Surface Vehicle. *J. Field Robotics*. 30(3): 371–398.

[28] Wang, M. 2012. The Development of and Experiments on an Unmanned Surface Vehicle Platform for Water Sampling and Monitoring. Hong Kong University of Science and Technology, Master Thesis, Hong Kong.

[29] Yulei, L., Lei, W., Jiayuan Z. 2010. Full State-Feedback Stabilization of an Underactuated Unmanned Surface Vehicle. In: Advanced Computer Control (ICACC), 2nd International Conference 2010. 4: 70–74.

[30] Inboard Power Steering. Retrived on Dec 20, 2013 from http://www.seastarsolutions.com/products/hydraulic-new/inboard-power-steering.

[31] Do, K. D., Pan, J., Jiang, Z. P. 2003. Robust Adaptive Control of Underactuated Ships on a Linear Course with Comfort. *J. Ocean Engineering*. 30(17): 2201–2225.

[32] Moreira, L., Fossen, T. I., Guedes Soares, C. 2007. Path Following Control System for a Tanker Ship Model. *J. Ocean Engineering*. 34(14–15): 2074–2085.

[33] Healey, A. J., Marco, D. B. 1992. Slow Speed Flight Control of Autonomous Underwater Vehicles: Experimental Results with The NPS AUV II. In: Proceedings of the 2nd International Offshore and Polar Engineering Conference (ISOPE), San Francisco, California. 523–532.

[34] Zhong-Ping, J., Nijmeijer, H. 1999. A Recursive Technique for Tracking Control of Nonholonomic Systems in Chained Form. *J. Automatic Control, IEEE*. 44(2): 265–279.

[35] Fossen, T. I., Breivik, M., Skjetne, R. 2003. Line-of-Sight Path Following of Underactuated Marine Craft. In: Proceedings of the Sixth IFAC Conference on Maneuvering and Control of Marine Crafts (MCMC'2003), Girona, Spain. 244–249.

[36] Pettersen, K. Y., Nijmeijer, H. 2001. Underactuated Ship Tracking Control: Theory and Experiments. *Int. J. Control*. 74(14): 1435–1446.

[37] Godhavn, J. M., Fossen, T. I. 1998. Nonlinear and Adaptive Backstepping Designs for Tracking Control of Ships. *Int. J. Adapt. Control Signal Process*. 12(Special Issue on Marine Systems): 649–670.

[38] Lauvdal, T., Fossen, T. I. 1998. Rudder Roll Stabilization of Ships Subject to Input Rate Saturations Using a Gain Scheduled Control Law. In: Proceedings of the IFAC Conference on Control Applications in Marine Systems (CAMS'98), Fukuoka, Japan. 27–30.

[39] Fossen, T. I., Strand, J. P. 1999. A Tutorial on Nonlinear Backstepping: Applications to Ship Control. *J. Model, Identification and Control*. 20(2): 83–135.

[40] Çimen, T., Banks, S. P. 2004. Nonlinear Optimal Tracking Control with Application to Super-Tankers for Autopilot Design. *J. Automatica*. 40(11): 1845–1863.

[41] Li, Z., Sun, J., Oh, S. 2009. Design, Analysis and Experimental Validation of a Robust Nonlinear Path Following Controller for Marine Surface Vessels. *J. Automatica*. 45(7): 1649–1658.

[42] Yang, Y., Bo, J. 2004. Robust Adaptive Fuzzy Control (RAFC) for Ship Steering with Uncertain Nonlinear Systems. In: Intelligent Control and Automation, 2004. WCICA 2004. Fifth World Congress on. 3: 2514–2518.

[43] Yang, Y., Zhou, C., Ren, J. 2003. Model Reference Adaptive Robust Fuzzy Control for Ship Steering Autopilot with Uncertain Nonlinear Systems. *Applied Soft Computing*. 3(4): 305–316.

[44] Fossen, T. I. 2005. A Nonlinear Unified State-Space Model for Ship Maneuvering and Control in A Seaway. *J. Bifurcation and Chaos*. 15(9): 2717–2746.

[45] Pivano, L., Johansen, T. A., Smogeli, O. N., Fossen, T. I. 2007. Nonlinear Thrust Controller for Marine Propellers in Four-Quadrant Operations. In: American Control Conference, 2007. ACC '07. 900–905.

[46] Berge, S. P., Ohtsu, K., Fossen, T. I. 1999. Nonlinear Control of Ships Minimizing the Position Tracking Errors. *J. Model Identification and Control*. 20(3): 177–187.

[47] Fossen, T. I., Grovlen, A. 1998. Nonlinear Output Feedback Control of Dynamically Positioned Ships Using Vectorial Observer Backstepping. *J. Control Systems Technology, IEEE*. 6(1): 121–128.

[48] Strand, J. P., Ezal, K., Fossen, T. I. 1998. Nonlinear Control of Ships: A Locally Optimal Design. In: Preprints of The IFAC NOLCOS'98, Enschede, Netherlands. 732–738.

[49] Nassim, K., Nabil, G. C. 2013. A Self-Tuning Guidance and Control System for Marine Surface Vessels. *J. Nonlinear Dynamics*. 73(1–2): 897–906.

[50] Fossen, T. I. 1994. *Guidance and Control of Ocean Vehicles*. John Wiley and Sons, Chichester, England.

[51] Zoran, Vc, Bruno, Bc. 2001. Guidance and Control Systems for Marine Vehicles. in The Ocean Engineering Handbook, F. El-Hawary, Ed. 1st ed. Boca Raton CRC Press. 25–27.

[52] Holzhẗer, T., Schultze, R. 1996. Operating Experience with a High-Precision Track Controller for Commercial Ships. *Control Engineering Practice*. 4(3): 343–350.

[53] Minorsky, N. 1992. Directional Stability of Automatically Steered Bodies. *J. American Society for Naval Engineers*. 34(2): 280–309.

[54] Van Amerongen, J. 1982. Adaptive Steering of Ships-A Model Reference Approach to Improved Maneuvering and Economical Course Keeping, Delft University of Technology, Ph.D. Thesis, Delft, Netherlands.

[55] Hearn, G. E., Zhang, Y., Sen, P. 1997. Alternative Designs of Neural Network Based Autopilots: A Comparative Study. In: Proc. of 4th IFAC Conference on Maneuvering and Control of Marine Craft—MCMC '97, New York, USA.

[56] Kumar, V., Nakra, B.C., Mittal, A. P. 2011. A Review on Classical and Fuzzy PID Controllers. *Int. J. Intelligent Control and Systems*. 16(3): 170–181.

[57] Park, J-H, Shim, H-W, Jun, B-H, Kim, S-M, Lee, P-M, Lim Y-K. 2010. A Model Estimation and Multi-Variable Control of an Unmanned Surface Vehicle with Two Fixed Thrusters. In: OCEANS 2010 IEEE Sydney. 1–5.

[58] Juntong, Q., Yan, P., He, W., Jianda, H. 2007. Design and Implement of a Trimaran Unmanned Surface Vehicle System. In: International Conference on Information Acquisition, 2007. ICIA '07, Seogwipo, South Korea. 361–365.

[59] Donald, E. K. 1998. *Optimal Control Theory: An Introduction*. Prentice-Hall, New Jersey, U.S.A

[60] Sharma, S. K., Naeem, W., Sutton, R. 2012. An Autopilot Based on a Local Control Network Design for an Unmanned Surface Vehicle. *J. Navigation*. 65(2): 281–301.

[61] Athans, M. 1971. The Role and Use of The Stochastic Linear-Quadratic-Gaussian Problem in Control System Design. *J. Automatic Control, IEEE*. 16(6): 529–552.

[62] Siramdasu, Y., Fahimi, F. 2012. Incorporating Input Saturation for Underactuated Surface Vessel Trajectory Tracking Control. In: American Control Conference (ACC), 2012, Montreal, Canada. 6203–6208.

[63] Sharma, S. K., Sutton, R., Motwani, A., Annamalai, A. 2013. Non-Linear Control Algorithms for an Unmanned Surface Vehicle. Proceedings of the Institution of Mechanical Engineers, Part M. *Journal of Engineering for the Maritime Environment 2008*. 227(4): 1–10.

[64] Annamalai, A., Motwani, A., Sutton, R., Yang, C., Sharma, S., Culverhouse, P. 2013. Integrated Navigation and Control System for an Uninhabited Surface Vehicle Based on Interval Kalman Filtering and Model Predictive Control. In: IET Conference on Control and Automation 2013. 1–6.

[65] Astrom, K. J., Wittenmark, B. 1995. *Adaptive Control*. Addison-Wesley, Reading, Massachusetts.

[66] Junfang, L., Tieshan, L., Zhongzhou, F., Renxiang, B., Qiang, L., Jiangqiang, H. 2011. Robust Adaptive Backstepping Design for Course-Keeping Control of Ship with Parameter Uncertainty and Input Saturation. In: International Conference of Soft Computing and Pattern Recognition (SoCPaR), Dalian, China. 63–67.

[67] Junsheng, R., Xianku, Z. 2013. Fuzzy-Approximator-Based Adaptive Controller Design for Ship Course-Keeping Steering in Strict-Feedback Forms. *J. Applied Sciences, Engineering and Technology*. 6(16): 2907–2913.

[68] Liao, Y-l, Wan, L., Zhuang, J-y. 2011. Backstepping Dynamical Sliding Mode Control Method for the Path Following of the Underactuated Surface Vessel. *J. Procedia Engineering*. 15(2011): 256–263.

[69] Kokotovic, P. V. 1992. The Joy of Feedback: Nonlinear and Adaptive. *J. Control Systems, IEEE*. 12(3): 7–17.

[70] Lozano, R., Brogliato, B. 1992. Adaptive Control of Robot Manipulators with Flexible Joints. *J. Automatic Control, IEEE*. 37(2): 174–181.

[71] Khalil, H. K. 2002. *Nonlinear Systems*. 3rd Edition. Prentice Hall, Upper Saddle River, New Jersey

[72] Murali, K., Sundarasiva, R., Ramachandra, R. 2011. Theoretical and Experimental Investigation of Gain Scheduling and Adaptive Autopilots for A Model Boat. *International Journal of Engineering Science and Technology (IJEST)*. 3(2): 902–911.

[73] Spooner, J. T., Maggiore, M., Ordonez, R., Passino, K. M. 2002. *Stable Adaptive Control and Estimation for Nonlinear Systems: Neural and Fuzzy Approximation Techniques*. John Wiley and Sons, New York.

[74] Malecki, J., Zak. B. 2012. Design a Fuzzy Trajectory Control for Ship at Low Speed. In: 12th WSEAS International Conference on Signal Processing, Computational Geometry and Artificial Vision (ISCGAV '12), Istanbul, Turkey. 119–123.

[75] Kacprzyk, J. 1996. *Multistage Fuzzy Control: A Model-Based Approach to Fuzzy Control and Decision Making*. John Wiley and Sons, New York.

[76] Zhouhua, P., Dan, W., Zhiyong, C., Xiaojing, H., Weiyao, L. 2013. Adaptive Dynamic Surface Control for Formations of Autonomous Surface Vehicles With Uncertain Dynamics. *J. Control Systems Technology, IEEE*. 21(2): 513–520.

[77] Peng, Z., Wang, D., Hu, X. 2011. Robust Adaptive Formation Control of Underactuated Autonomous Surface Vehicles with Uncertain Dynamics. *J, Control Theory & Applications, IET*. 5(12): 1378–1387.

[78] Junsheng, R., Xianku, Z. 2013. Ship Course-Keeping Adaptive Fuzzy Controller Design Using Command Filtering with Minimal Parametrization. In: 25th Chinese Control and Decision Conference 2013 (CCDC) Guiyang, China. 243–247.

[79] Mackenroth, U. 2004. *Robust Control Systems: Theory and Case Studies.* Springer-Verlag Berlin Heidelberg, New York, U.S.A

[80] Jerzy, B. 2012. Design of Robust, Nonlinear Control System of the Ship Course Angle, in a Model Following Control (MFC) Structure Based on an Input-Output Linearization. *J. Scientific Maritime University of Szczecin*. 30(102): 25–29.

[81] Shr, S. H., Jeng, Y. J. 2011. Robust Nonlinear Ship Course-Keeping Control Under The Influence of High Wind and Large Wave Disturbances. In: Control Conference (ASCC), 2011 8th Asian. 393–398.

[82] Utkin, V. I. 1993. Sliding Mode Control Design Principles and Applications to Electric Drives. *IEEE Transactions on Industrial Electronics.* 40(1): 23–36.

[83] Wei, M., Chen, G., Yang, L. 2012. Nonlinear Sliding Mode Formation Control for Underactuated Surface Vessels. In: 10th World Congress on Intelligent Control and Automation (WCICA), 2012 Beijing, China. 1655–1660.

[84] Ashrafiuon, H., Muske, K. R., McNinch, L. C., Soltan, R. A. 2008. Sliding-Mode Tracking Control of Surface Vessels. *IEEE Transactions on Industrial Electronics*. 55(11): 4004–4012.

[85] Piotr, S. 2013. Course Control of Unmanned Surface Vehicle. *Solid State Phenomena*. 196(2013): 117–123.

[86] Pettersen, K. Y., Fossen, T. I. 2000. Underactuated Dynamic Positioning of a Ship-Experimental Results. *IEEE Transactions on Control Systems Technology*. 8(5): 856–863.