State of the Art Review on Autonomous Surface Vehicle Maneuvering Assessment

N.I. Jalal, A.F. Ayob, S.A. Rahman and S. Jamaludin

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[1] Universiti Malaysia Tererngganu, Kuala Terengganu, Malaysia
`nurizzatijalal95@gmail.com`

Abstract.
In the preliminary design stage, maneuvering assessment is a prerequisite based on IMO regulations. Traditionally, maneuvering assessment activities are conducted using physical boats and pilots. Such practice is tedious; requires more time to complete, suitable weather conditions, and costly. To overcome such obstacles in conducting maneuvering assessments, it may be hypothesized that simulation methods are more efficient. At present, the autonomous surface vehicle (ASV) is a hot topic within the maritime industry. Therefore, this paper shall review the state-of-the-art applications of ASV for maneuvering assessment. Also, the factors that contributed to the impact of ship maneuverability performance are discussed in this paper. Additionally, the safety aspect is also reviewed concerning COLREGS requirements.

Keywords: Manoeuvring assessment, Autonomous surface vehicle, Ship performance, Ship simulation

1 Introduction

In the preliminary design stage, maneuvering performance assessment (Figure 1) is very important required to avoid poor maneuverability that may result in marine casualties (collision, capsize, and grounding) and pollution **[1]**.In naval architecture, maneuvering assessment is incorporated to evaluate the trade-offs within the design space and may deliver an optimal solution **[2]**. Traditionally, maneuvering assessments are conducted physically using pilots and boats. However, this practice is expensive, time-consuming, and subject to suitable weather conditions. Therefore, simulation methods may be a feasible solution to increase the effectiveness of the assessment. In general, marine casualties were caused by a lack of human skills or certain unwanted behavior on board of a ship. Additionally, some operations such as ship-to-ship transfer may cause accidents, therefore good maneuvering skills between two ship operators are very important **[3]**.

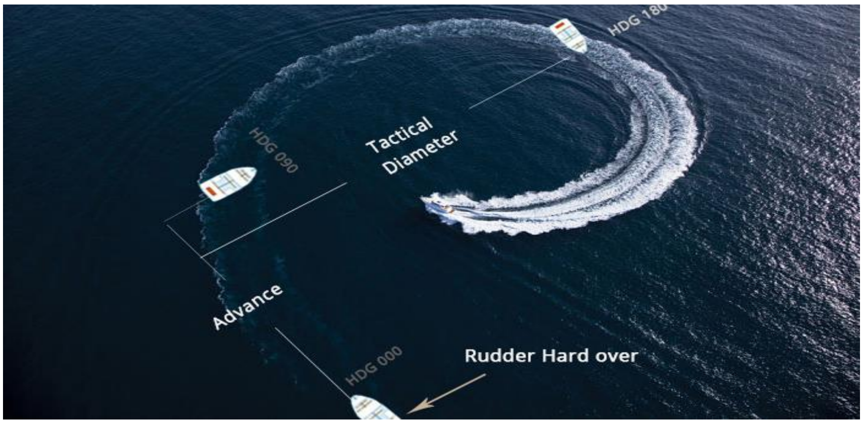

Fig. 1. Typical maneuvering test, depicted is the tactical diameter assessment between two vessels for maneuvering

Ship maneuverability, as highlighted in Vessel Manoeuvrability Guidelines by American Bureau of Shipping, is measured as the ability to balance the act of controlling propulsion and steering. The maneuverability is measured by successful turning ability, course-changing, yaw-checking ability, initial turning ability, and stopping ability [4]. In the measurement of yaw- and course-changing ability, the stability of the ship may be affected by small disturbances and oscillations of rudder or heading. Thus, the course-keeping quality relies on the capability to maintain straight-line stability concerning the rudder angle and yaw rate. Additionally, maneuverability performance is an interplay between hydrodynamic characteristics and other external factors. As a guideline, there are four elements that can be used to predict the maneuvering performance of a ship; maneuvering simulation model, hydrodynamic force characteristics, hydrodynamic force coefficients, and prediction of manoeuvring motion in full-scale [5].

Recently, it can be observed in the literature the increase in the popularity of autonomous marine vehicles. With the implementation of mathematical algorithms and simulation facilities, autonomous capability and control system can be seen as akin to the process of a human brain. Such concepts have become an interest to the marine technologist to study the intelligent aspects of autonomous surface vehicles (ASV) for handling and navigating purposes. Currently, researchers incorporate numerical, computational models and physical experiments to assess the ship's behavior during maneuvering, which also can be achieved via simulation techniques [6]. However, [7] argued via a survey that the available simulators reported in the literature neglected the use of hydro/meteorological data such as current, waves, and water levels.

Heavy traffic in harbors and waterways area are caused mainly due to heavy demand in global ship transportation activity. Therefore, handling and navigating operations are becoming more difficult for a pilot. Hence, the use of autonomous surface vehicles (ASV) may reduce the complexity of operation besides an increase in safety and the reduction of time consumed in waterways. Through the use of artificial intelligence such as artificial neural networks (ANN), ASV can be trained using real data recorded earlier which therefore allows it to operate akin to human capabilities, such as to recognize objects, traffic changes, and identification of environmental situations [8]. As a result, unfavorable incidents in waterways can be prevented.

2 Factors affecting ship maneuvering performance

There are several factors involved in ship maneuvering performance, e.g, internal and external forces. The internal forces can be approximated with sufficient accuracy using ship design method. Meanwhile, external forces such as wind, waves, and currents are uncontrollable forces, which dynamically experienced by the ship operator during the piloting of the ship. The review of literature for both external and internal factors are explained in the following Section 2.1 and Section 2.2.

2.1 External factors that may impact maneuverability performance

To ensure the ship safety and good ship performance, ship designer should ideally possess a broad understanding of the possible impacts. An environment such as wind, waves, and current as well as water depth and confined waterway shall effect ship maneuverability performance [9]. The dynamics of propeller and rudder motion serve as potential factors that may affect ship maneuvering operation in addition to the changes in the velocity of waves and winds [10]. Furthermore, in coastal areas, the reduction of wave velocities compared to the sea state could effect ship maneuverability performance [11]. Additionally, changes in the dynamics of waves depends on the water depth may affect the stability of the rolling motion of a ship [12] . Also, the formation of ice in the sea will influence ship maneuverability performance from the perspective of the attainable speed and cornering performance concerning the ice thickness [13]. In the literature, ship designers may rely on meta-models as a tool to measure the effect of environmental and loading conditions on the ship maneuvering performance [14].

2.2 Internal factors that may impact maneuverability performance

Kinetic and kinematic properties, hull design, and degree-of-freedoms (DOF) are the internal factors that contribute to the performance of the ship's maneuverability. The propulsion power of a ship relies on the efficiency of the rudder control and propeller dynamics. The review of the literature regarding the internal factors are described in *Section 2.2.1* and *Section 2.2.2.*

Kinetic and kinematic properties

In restricted waterways, ship manoeuvering operation consists of a set of complex operations carried out by ship operators. Capsize, grounding, and collision may happen if the pilot fails to perform proper maneuvering of a ship. Also, kinetic and kinematic properties are important contributors when a ship maneuvers in coastal and confined waterways [15]. Thus, the precise ship speed, distances separation from other objects, and channel dimensions are required to be measures intuitively beside other parameters that may impact the change of ship trajectories and yaw angles [16]. Furthermore, the Automatic Identification System (AIS) could be incorporated to assist in measuring the acceleration and deceleration, safe distance, and speed operation [17]. Concerning the ship, zigzag maneuvering assessment is important to indicate the capability of the ship to handle the magnitude of forces and moments with respect to yaw and yaw rate [18].

The ship maneuverability performance can be affected due to the changes of propeller and rudder, the formation of hull forces, and moments [11]. Additionally, stopping maneuvering ability tests is typically conducted via the operation of reversing the propeller and rudder turning which may indicate that the ship is safe and ready for navigation purposes [19]. Moreover, ship maneuvering capabilities can be measured via recording the response of thrust, resistance, steering, and rudder forces [12]. The large power absorption during tight manoeuver also may impact ship maneuverability performance [20]. In improving ship design criteria, unsteady Reynolds-averaged Navier-Stokes (URANS) simulation with simplified propeller theories was incorporated by [21] to correlate between the inflow conditions and propeller loads when the ship manoeuver in straight ahead and steady turning. Additionally, a maneuvering simulation (MANSIM) has been developed by [22] to predict the ship maneuvering capabilities in the preliminary design stage.

Six Degree-of-Freedom (SDOF) Motion

Degree-of-freedom is the ability of a rigid body to move freely in a linear and rotational motion. The linear and rotational movements are according to the axis; translational degrees (heave, sway, surge) and rotational degrees (yaw, roll, pitch) (Figure 2). Hydrodynamically, the work reported by [23] simulates a four-degree-of-freedom movement while maneuver in a turning circle and zigzag movement. To advance such limitation, the work by [24] incorporated ship handling simulators to present a six-degree-of-freedom movement in which validated using the marine automation systems.

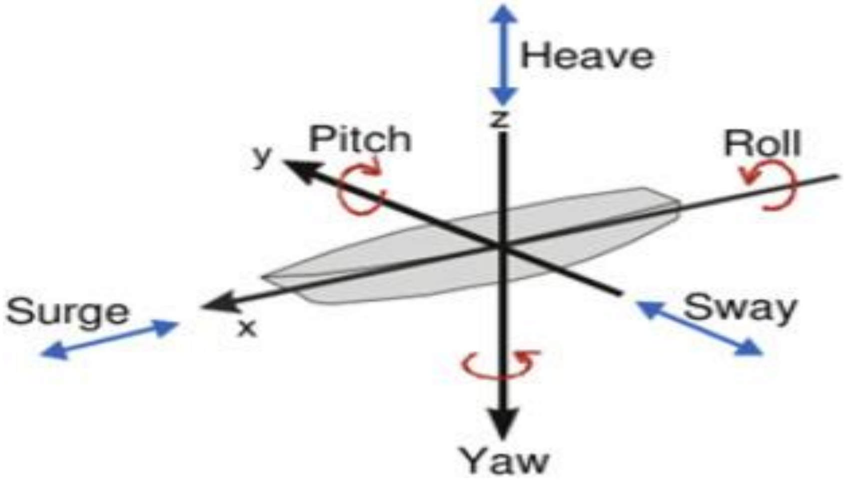

Fig.2. Six-degree-of-freedom motion.

3 Hydrodynamic interactions in maneuvering

Hydrodynamic interactions are a typical contributor in ship navigation incidents such as capsize, grounding, and collision. Additionally, such forces shall influence the ship maneuverability performance [25]. A ship maneuvers in non-calm water (sea states) shall experience high Reynolds numbers which will influence the propeller and rudder performance. Furthermore, the operation of two vessels maneuvering in the curved and restricted waterway is required to ensure their safe speed and an appropriate tactical diameter between two vessels [26]. In view of ship hydrodynamics, [27] has conducted the optimization of hydrodynamic coefficients to operated in confined waterways. Such works are very important to improve ship maneuvering capabilities in confined waterways [15]. In a case of interacting of two ships maneuver in calm water, the hydrodynamic derivatives are used to determine the separation distance between the two maneuvering ships to avoid collision [28], meanwhile, [29] has conducted the work of operation overtaking maneuvers between two moderate-speed vessels with considered hydrodynamic interactions. A narrow channel such as port influence the navigational behaviour that interact with hydrodynamic forces and other forces such as winds, propeller loads and rudder loads [30].

4 Autonomous Surface Vehicles (ASV)

In recent times, harbors and ports have become busier owing to the growing number of transportation vessels and boats. The development of autonomous marine vehicles or autopilot vessels has become a hot topic. Autonomous surface vehicles rely on the integration of mathematical models and physical control to create an automatic system. Typically, autonomous surface vehicles are assisted with measurement and recognization tools, such as; cameras, sensors and radars for safety. Additionally, autonomous surface vehicle operations consist of many maneuvering operations, energy consumption which therefore contributed to environmental impact [31]. In the work of [8], autonomous navigation was demonstrated to solve route-finding and collision avoidance task in congested and restricted areas. In berthing operation, the autonomous tugboat with a slow actuator was used to approach the berthing area [32].

4.1 Artificial Intelligence

As demonstrated by [33], genetic algorithms were developed to integrate Target Path Integration (TPI) to obtain the optimum rudder angle and length of the target trajectory. Ship roll motion during the turning circle and zigzag maneuvering test were conducted using Radial Basis Function Neural Network (RBFNN) with high accuracy [34]. Furthermore, neuro-evolution algorithms were incorporated to ensure safe navigation in restricted waterways as well as improved operation of ships in ports [35]. Reported by [36], artificial neural networks (ANN) were used to determine safe ship trajectories between eight meteorological ships. In the field of deep learning, [37] has demonstrated a framework that applies a visual perception system to recognize objects and route tracking.

In the presence of environmental disturbances, RBFNN control was used to determine the ship's motion, better course-keeping, and trajectory tracking [38]. A catamaran model using Recursive Neural Network (RNN) has demonstrated tactical circles and zigzag maneuvering assessment [39]. In addition, RNN is a network that is more flexible for ship dynamics with good perspectives to solve numerous problems in theory and applications in marine systems [40]. In facilitated the control action and steering of the ship, three algorithms were used to fulfill maneuvering tasks with assistance feedback and feed-forward controllers [41]. A feed-forward neural network was used to control an autonomous underwater vehicle in the work of [42]. Furthermore, [43]demonstrated neuro-autopilot maneuvering to follow parabolic and S-shaped trajectories hence minimize the path deviation.

5 COLREGS – Safety Handling Rules Practises

International Regulations for Preventing Collisions at Sea (COLREGS) provides guidelines for ship operating safely and to avoid accidents at sea. Autonomous surface vehicles are also required to meet this rule before it can be operated. In-line with such requirement, [44]has demonstrated an Ant Colony Algorithm (ACO) and genetic algorithm to perform collision avoidance. [45] proposed a simulation framework to determine a dynamic predictive guidance technique to address collision avoidance. The use of Neuro-evolution of augmenting topologies (NEAT) was demonstrated by [46] for a safe crossing and overtaking of vessels. Furthermore, [47]demonstrated Artificial Potential Field (APF) pseudo-code to analyze COLREGS rules for overtaking, head-on, and crossing assessment. Moreover, [48] reported the use of a decision-making framework to perform safe maneuvering operations which include traffic factors. The issue in maritime collision avoidance is still a major and intractable when ships encounter in the close-quarters situation, thus, a system collision avoidance dynamic support system is essential to eliminate the pilot's negligence in the process of ship maneuver [49].

6 Conclusion

In this paper, the state of the art review on autonomous ship maneuvering has been discussed. In this work, the differences between external and internal factors that impacted maneuvering performance has been explained. To have an accurate prediction, hydrodynamic derivatives are required to estimate the magnitude of forces and moments of rudder and propeller. Maneuvering assessment in the early design stage is very important to assist ship designers to measure the performance and efficiency of a ship which therefore prevents unfavorable incidents such as capsizing, grounding, and collision.

IMO requires certain classes of ships to be assessed in terms of its maneuvering performance. This review has discussed that it may be beneficial for a vessel to be handled by a robotic system compared to a human operator, especially in a complex and dangerous situation. Therefore, with the use of ASV, water transportation will be much safer for both ship operators and their surroundings.

This review has indicated that the interest in ship maneuvering assessment is flourishing, however lacking in terms of the discussion in simulation methods. It will be more beneficial within the ship design discipline to focus on the incorporation of robotics and automation concepts to improve the working condition of ship operators at sea and restricted waters.

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