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SURVEY

Automated Docking for Marine Surface Vessels–A Survey

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ABSTRACT Research on motion control systems for marine surface vessels has generated a vast academic literature and many industrial applications since the early 20th century. The recent focus on autonomous ships has sparked intensive research and innovation activities of dock-to-dock operations, including the final docking phase. Specifically, automated docking involves systems that enable vessels to dock safely, independently, and energy-efficiently at designated locations with a specific heading. Challenges include managing large sideslip angles, static and dynamic obstacles, and navigation in complex port geometries. Despite its complexity, the docking problem has received less attention compared to dynamic positioning or course-keeping systems. This paper therefore provides a thorough overview of the research on automated docking for marine surface vessels, from 1980 to June 2023. The paper introduces the Docking Characteristic Index (DCI) as a metric to identify the scope and approach of systems addressing various docking challenges, not as an evaluation of their overall quality. Using the calculated DCI-Scores, we discuss some of the works in more detail. The survey reveals a rising trend in publications and an increasing emphasis on experimental verification. Despite advancements, current methodologies exhibit trade-offs and limitations, particularly in handling dynamic obstacles, robustness against external forces, and situational awareness. The paper identifies the need for more comprehensive and integrated solutions to these challenges. As the demand for fully autonomous operations grows, the results suggest that future research should focus on developing holistic and robust docking strategies, that are verified experimentally, to achieve safe, efficient, and effective automated docking systems.

INDEX TERMS Autonomous ships, autonomous surface vehicles, berthing, docking, marine robotics, marine surface vessels, motion control, mooring, survey.

I. INTRODUCTION

Autopilots for ships have been extensively researched for many years, beginning with the 1922 article "Directional Stability of Automatically Steered Bodies" by Nicolas Minorsky [1], resulting in a vast existing literature that has tackled the problem utilizing concepts from every branch of control engineering. For example, model, model-free, linear, non-linear, adaptive, optimal, fuzzy, artificial intelligence and stochastic control approaches have been presented in the past, and the relevant research community is currently more active than ever [7], [21], [22], [28], [29], [36], [89], [90]. The increase in activity during the last 5 years can be attributed to the rise of autonomous surface vehicles (ASVs), which does not only reflect the interests of researchers, but also the industry and general public. Indeed, there are many ongoing flagship projects, mainly in Europe and Asia, where the technological challenges of ASVs are tackled in a much more multidisciplinary manner, including situational awareness (SITAW), remote operations centre (ROC), safety and assurance, ship design, and so on.

Naturally, the motion control problem itself is also expanding in scope. Fully autonomous operations will require good performance at the whole spectrum of encountered

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conditions, compared to past automated operations that had a narrower focus. For instance, dynamic positioning (DP) applications are designed considering almost-zero speed, and many path following and trajectory tracking methods often are tested in almost-constant speed scenarios. Future dock-to-dock operations, though, require trajectory planning and tracking approaches that can be implemented during a complete ASV mission, including the repeating cycle of undocking, transit phase, and docking.

Docking has long been an integral aspect of maritime operations, so much so that the terms ''starboard'' and ''port'' owe their origins to this very activity. Historically, ''starboard'' is derived from the placement of the steering oar on the right side of ships. To prevent damage to the steering oar, ships were commonly docked on the left side, giving rise to the term ''port'' [218].

The docking phase is of particular interest due to the challenges it introduces. Docking procedures often start far from the harbor area due to the speed profile that has to be adjusted appropriately, especially for larger vessels, before the vessel enters the harbor. Moreover, the shape and size of the Marine Surface Vessel (MSV) have to be taken into account as accurately as possible, in order to produce safe manoeuvres that will bring the vessel to the desired location, and with the desired orientation, next to the quay. The shape and size consideration will result in largely different approach manoeuvres between a fully actuated and an underactuated vessel. At the same time, an ASV must avoid static and dynamic obstacles during the overall docking phase, and compensate for environmental disturbances at a range of speeds and sideslip angles. The challenges of docking, including dynamical effects, ship factors, and docking operations with tugboats are described in the ship handling guide by C. Rees [170].

A physical demonstration of automated docking is provided in Figure 1, where the autonomous urban passenger ferry milliAmpere2 performs automated docking in Trondheim, Norway. Meanwhile, Figure 2 illustrates the challenges of the docking problem, by using Trondheim Harbor as an example.

For the reasons above, docking is a problem that has attracted the interest of many ocean engineers, especially during the last 4-5 years. The main objective of this paper is to give a thorough overview of the research literature on automated docking for MSVs, starting from the earliest reference the authors were able to find, up to June 2023. The focus of this work is docking in harbor areas, whereas rendezvous and underwater docking are not considered. The investigation revealed over 180 publications since 1980, with the publication rate increasing since 2017. To be able to present the evolution of the docking problem in a more digestible manner, we introduce the novel metric Docking Characteristic Index (DCI). The DCI serves as a measure of the overall performance of an automated docking system. It does not evaluate the quality of the works but rather examines the presence of specific features.

The analysis indicates significant advancements in automated docking strategies over the years. We have seen improvements in handling complex harbor geometries and static obstacles, which has led to the development of more robust real-time systems. There has also been a noticeable increase in the number of physical demonstrations, indicating a shift from theory to practical applications. Furthermore, the survey provides an overview of the most frequently used control strategies in simulated systems compared to those used in physical systems.

FIGURE 1. **The autonomous urban passenger ferry milliAmpere2 performing automated docking in the Canal in Trondheim, Norway on September 22, 2022. Photo: Kai T. Dragland / NTNU.**

In addition, a separate section with an overview of docking systems, or demonstrations, presented by the industry is provided. For those works, there are no specific details available publicly. Finally, we provide a discussion on current challenges regarding docking operations, which new researchers may find useful to tackle. Despite the aforementioned advancements, several challenges remain unresolved: handling dynamic obstacles, enhancing system robustness against multiple, concurrent external forces, and balancing the trade-off between computational efficiency and solving all aspects of the automated docking problem in a safe manner.

In particular, the contributions of this work are:

- A thorough survey on publications related to automated docking in harbors, resulting in a collection of 188 publications spanning from 1980 to June 2023.
- The Docking Characteristic Index (DCI), a novel metric for analyzing and comparing automated docking systems in a condensed manner, and the evolution of docking strategies over time.
- Summaries of 21 publications, selected based on the highest cited article and highest DCI-Score in each epoch.
- An overview of industry contributions to automated docking systems, highlighting their advancements and achievements.

Previously published surveys on automated docking include [139] and [169]. Li et al. [139], with 51 references,

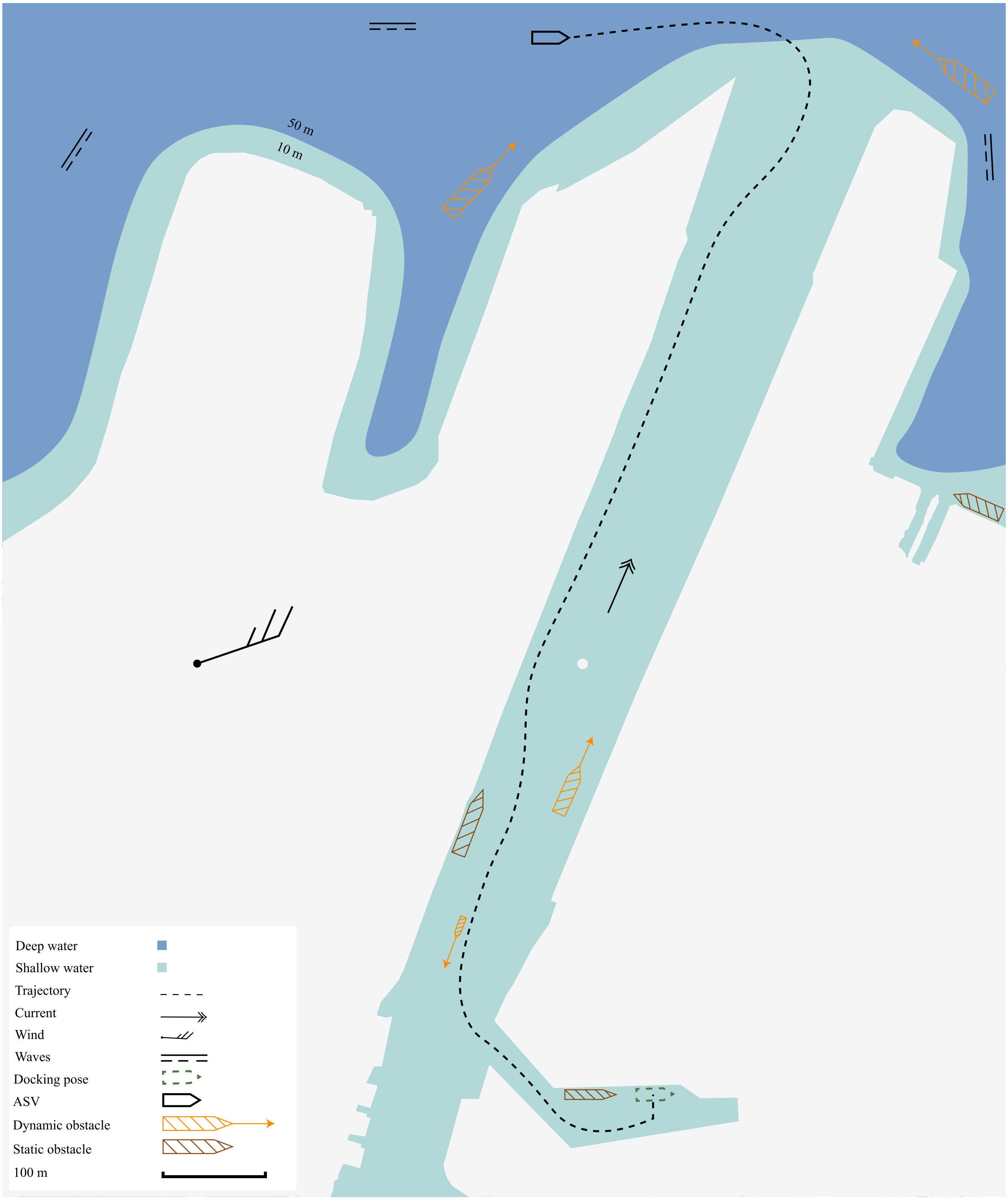


FIGURE 2. An illustration of the challenges related to the docking problem, as seen from an ASV during docking operations in Trondheim Harbor, Norway. The illustration serves as an example of the docking problem in an upstream river. Other harbours might contain some, if not all, of the environmental features depicted here, in varying degrees.

present research on ship-shore information interaction, and lists the control methods for 13 publications from 2005 to 2019. The authors present publications on course control and speed control in their survey. Quaing et al. [169], with 78 references, present industry contributions to automated docking, as well as a broader range of publications, spanning 1986 to 2019. In comparison, the current publication offers more extensive coverage, examining 188 publications specifically dedicated to automated docking methods from 1980 to June 2023. This broader scope provides a comprehensive overview of the advancements in automated docking research over a longer period. Additionally, notable mentions include Choi et al. [208], which reviews autonomous tugboat operations in relation to automated docking, and Yazdani et al. [153], which covers underwater docking guidance systems.

The rest of the paper is structured as follows: Section II points out the key aspects of the docking problem. Section III discusses the methodology which was used to review the exhaustive list of automated docking-related publications. Furthermore, Section IV briefly reviews automated docking solutions by the industry, while Section V lists the control strategies commonly used for automated docking solutions and provides obtained statistics. Section VI presents the publications in chronological epochs, and discusses a selection of articles from each period. Section VII discusses the findings of this paper, and points out future research directions. Finally, the paper is concluded in Section VIII.

II. THE DOCKING PROBLEM

Given the diverse use of the terms automatic, automated, and autonomous docking in the literature, each with varying interpretations, it was decided to adopt a consistent reference to ‘‘automated’’ docking across all systems in this survey. This decision aims to circumvent the ambiguity while acknowledging the complexity of the autonomy concept.

The problem of automated docking for MSVs can be defined as the challenge of designing and implementing systems and technologies that enable MSVs to dock independently and safely at designated locations with a specified final heading, also known as a pose. Situational Awareness (SITAW) is crucial for understanding environmental factors and implications, while Collision Avoidance (COLAV) involves procedures and technologies to prevent physical contact. Given these considerations, the problem encapsulates various sub-problems and challenges, including:

1) **Guidance and control**: Guidance and control involves various aspects of the MSV's motion such as position, heading, and velocity which are regulated by a control method. This is achieved through control allocation, where control signals are assigned to the various actuators of the vessel, enabling it to accurately follow a planned path, or reach a waypoint. During control allocation, the MSV's dynamics should be considered to ensure feasibility and stable maneuvering.
2) **Navigation and SITAW**: Navigation involves safely maneuvering the MSV from one location to another. In the docking problem, the MSV moves from a location in vicinity of the harbor to an assigned docking pose. SITAW is important for ASVs as it provides information about the surrounding environment, enabling an autonomous system to make informed decisions and perform safe and accurate docking.
3) **Path planning and COLAV**: An automated docking system must be capable of planning a safe, time-efficient, and energy-efficient path from the initial position to the docking pose while ensuring COLAV. This includes accounting for static obstacles such as reefs and stationary MSVs, as well as dynamic obstacles including moving MSVs, swimmers, and animals. The complexity of the path planning problem is also influenced by the convexity of the harbor environment. COLAV might also be part of the guidance system, depending on the exact architecture.

Despite the significant strides made in ASV technology, these challenges constitute the primary hurdles to a fully autonomous docking solution. A docking system should not only be effective and reliable but also cost-efficient to facilitate widespread adoption.

III. METHODOLOGY

A. LITERATURE RETRIEVAL METHODOLOGY

The literature search was conducted using four primary academic databases: Google Scholar, Web of Science, and Oria. These databases were selected for their comprehensive coverage of publications relevant to automated docking for MSVs. A search was performed using the following keyword combinations: ‘‘docking,’’ ‘‘berthing,’’ and ‘‘rendezvous,’’ and the search was unrestricted in regard to the To maintain the focus of the survey, articles discussing docking for spacecraft were automatically excluded, while articles on underwater vehicles were manually filtered out.

Each article was manually filtered by examining its abstract to determine its relevance to the study's focus. The initial search and manual filtering yielded 55 candidate articles. Next, the articles were organized as notes in a Canvas document within the Obsidian software for further analysis.

In addition to the initial search, a snowballing technique was employed, where the reference lists of all selected articles were examined to identify additional relevant publications. These newly discovered articles were also recursively checked for further sources. This rigorous methodology culminated in an exhaustive list of 188 relevant scientific publications.

B. DOCKING CHARACTERISTIC INDEX (DCI)

Given the large number of publications (188) considered in this survey, we introduce the Docking Characteristic Index

(DCI) in order to produce a more digestible and intuitive overview of the docking literature. The DCI consists of 12 categories that map features of automated docking systems to numerical values. It offers a quantifiable measure of the overall performance of an automated docking system and allows for a clearer understanding of the evolution and the present state of the field. The numerical values for the features were chosen to reflect their contribution to the implementation of a docking system on a real vessel with automated docking capabilities. The DCI is an indicator of features present in a given work, and should not be considered an evaluation of the quality of the scientific contributions. Furthermore, the index was designed based on the prerequisites of our time. It is important to acknowledge that future researchers, with access to new information and facing different challenges, may modify the index to better reflect the evolving landscape of automated docking systems.

1) SELECTING CATEGORIES AND FEATURES

Before starting the reviewing process, the authors decided on a set, G, of relevant categories corresponding to technical challenges, and a set of features F. The categories are broad, such as *Harbor geometry*, *Environmental forces*, *Instrumentation*, and cover everything of relevance to automated docking systems. The features are specific to each category, which made them noticeable while reading through the publications. Each category $g_k \in G$, with $k \in [1, 12]$, has a corresponding set of features $F_k = [f_{k,1}, f_{k,2}, \ldots]^T \in F$. Each feature, $f_{k,j}$ with $j \in [1, \infty)$, involves different ways of addressing a certain challenge. Table 1 lists all categories and features used in this work.

2) CALCULATING THE DCI

For each category, g_k, representing a technical challenge, the set of features F_k has a corresponding set of points $P_k = [p_{k,1}, p_{k,2}, \ldots]^T$, which were chosen based on the authors' experience regarding the challenges of developing and implementing automated docking solutions, higher points are awarded to those features that are considered more crucial in real-world implementations.

Now let $r_{k,j}(i)$ be 1 if feature $f_{k,j}$ is present in a docking system i, and 0 otherwise. Also, P_k^{MAX} denotes the highest possible score in category g_k. Then we can calculate the score in category g_k for docking system i, as shown in (1).

$$a_k(i) = min(\sum_j r_{k,j}(i)p_{k,j}, P_k^{MAX}) \tag{1}$$

Further, to make the results cleaner and easier to plot, we utilize min-max feature scaling. The lowest possible score is 0 for all categories, while the highest score P_k^{MAX} varies. We denote $a'_k(i)$ as the scaled score of category g_k, and calculate it in (2).

$$a'_k(i) = \frac{a_k(i)}{P_k^{MAX}} \tag{2}$$

Next, the scaled scores, $a'_k(i)$, are elements of the DCI, denoted by the vector $\mathbf{c}(i)$, given in (3).

$$\mathbf{c}(i) \triangleq \begin{bmatrix} a'_1(i) \\ \vdots \\ a'_k(i) \\ \vdots \\ a'_n(i) \end{bmatrix} \tag{3}$$

Figure 6 shows how the DCI is plotted in a Spider chart for a selection of publications from the epoch 1980-1995.

3) THE DCI-SCORE

The DCI-Score denoted $s(i)$, is a useful metric for giving a literature overview in a compressed format. The metric, presented in (4) uses a weight vector $\mathbf{w} = [w_1, \ldots, w_k, \ldots, w_n]$ with $w_k \in [0, 1]$. The vector can be used to weight the categories in relation to each other. In this work, all elements are defined with values of 1.

$$s(i) \triangleq \mathbf{w}^T \mathbf{c}(i) \tag{4}$$

4) CLASSIFICATION

For each publication, $i \in [1, 188]$, all categories were assigned features from F when they were present. The data was gathered in a spreadsheet, and analyzed with a Python script.

5) SELECTED CATEGORIES

A short explanation is given per category in this subchapter. See Table 1 for the complete correspondence of categories, features and their respective points.

Verification is crucial in understanding how the docking solution was evaluated and how the researchers obtained the results presented. Results from simulations can provide clues about the system's performance. Physical full-scale trials, however, require a larger overhead of prerequisite work (one, for instance, cannot just assume ground-truth SITAW information being available to the control system), hence leading to results that better reflect reality.

Harbor geometry is necessary to determine if the proposed solution is limited to simplistic convex harbors or if it can handle more complex and realistic harbor configurations. Such factors can significantly alter the computational demands of a docking solution.

Obstacles can either be static or dynamic, but must be separated from the land geometry.

Environmental forces are crucial to include, as their stochastic nature will significantly affect the control system performance.

Vessel geometry is important information when planning safe and accurate trajectories in potentially complex and non-convex harbor environments.

Self-governance is necessary to ascertain if the solution relies solely on automated control or if it still requires human intervention, such as the captain's input or tugboat guidance.

TABLE 1. Categories and features with assigned points. The maximum score for each category is given, while the lowest score is 0 for all categories. In this work, all categories are assigned a weight of 1.0.

Category (g_k)	w_k	Features ($f_{k,j}$)	Points ($p_{k,j}$)							Max Score (P_k^{MAX})
Verification	**1.0**	Simulated	1p	Small-scale test	4p	Full-scale test	10p			10p
Harbor geometry	**1.0**	Convex	3p	Nonconvex	10p					10p
Obstacles	**1.0**	Static obstacles	3p	Dynamic obstacles	7p					10p
Environmental forces	**1.0**	Wind Dynamic draft	1p 1p	Current	1p	Waves	1p	Water depth	1p	4p
Vessel geometry	**1.0**	Pointmass	1p	Vertices	5p	Accurate vertices	10p			10p
Self-governance	**1.0**	Pilots required	0p	Tugboats required	4p	No help	10			10p
Adaptability	**1.0**	Pre-made environment	0p	Somewhat adaptable	5p	Fully adaptable	10p			10p
Instrumentation	**1.0**	IMU LiDAR Optical reflection	1p 1p 1p	GNSS Anemometer Transponder	1p 1p 1p	Gyro Camera Hyperspectral	1p 1p 1p	Acoustic Radar IR	1p 1p 1p	5p
Estimation	**1.0**	Position EKF Water depth	1p 1p 1p	Velocity Waves Obstacles	1p 1p 1p	Heading Wind	1p 1p	KF Current	1p 1p	8p
Actuation	**1.0**	Fully actuated	1p	Under actuated	2p					3p
Multi-step control	**1.0**	Planning	1p	Tracking	1p	Obstacle avoidance	1p	Collision avoidance	1p	4p
Vessel size	**1.0**	Small	1p	Medium	2p	Large	3p	General	4p	4p

Adaptability is needed to check if the algorithm is designed only for known locations or if it can be easily adapted for docking in unknown harbors, indicating its flexibility and versatility.

Instrumentation is important in assessing the sophistication of the solution. The lack of instruments may indicate that the implementation is limited to simulations only. A few instruments may provide some information, but unforeseen events may remain unobserved due to the limited instrumentation.

Estimation is essential in real applications, as measurements are inherently prone to noise. Through sensor fusion, the noise can be modeled and its effects reduced, given readings from multiple sensors. Further, in the event of a sensor failure, estimating the state using multiple sensors ensures redundancy.

Actuation is used for separating underactuated MSVs from fully actuated MSVs. Underactuated vessels have fewer control inputs than the number of degrees of freedom in their motion. Typically, they are fitted with a single propeller and rudder. Fully actuated vessels have the same number of control inputs as degrees of freedom, allowing for a more direct and precise control over the vessel's motion in all directions. Actuators such as azimuth thrusters and tunnel thrusters are commonly employed by these vessels.

Multi-step control provides insights into how the problem is solved. Path planning involves finding a route in the harbor environment. Trajectory tracking is the process of following a trajectory based on the planned path. Obstacle avoidance is crucial for avoiding static obstacles not given by a map, while COLAV is needed to avoid colliding with dynamic obstacles.

Vessel size indicates the range of vessels for which the system is designed to work. A system that accommodates various vessel sizes is considered challenging to create, but has great utility due to the many areas of use. A vessel is considered small if it is shorter than $30m$, medium if it is longer than $30m$, and large if it is longer than $100m$.

In summary, the design and verification of an automated docking control system require consideration of various factors such as harbor geometry, obstacles, environmental forces, vessel geometry, self-governance, adaptability, instrumentation, estimation, actuation, multi-step control, and vessel size. By taking these factors into account, researchers can ensure the system's reliability and robustness, leading to the development of more effective automated docking control systems.

IV. ADVANCEMENTS FROM THE INDUSTRY AND FUTURE CHALLENGES

A. INDUSTRY CONTRIBUTIONS

The automated docking landscape has witnessed significant industry contributions, with a large number of patents covering the topic, but assessing these systems remains challenging due to the lack of publicly available information. While providing an exhaustive list of all the patents is not covered by the scope of this work, some notable mentions include [40], [104], [122], [135], [137], [144], [162]. Dutch firm Roboat has released research on small ASV docking in urban canals [121], [167]. Yanmar of Japan is developing automated docking systems for leisure crafts [132]. Volvo Penta launched an automated docking solution in 2018 [111], while Kongsberg Maritime demonstrated automated docking on a car ferry in 2020 [138], and completed a live trial of automated shipping technology in Belgia's inland waterways in 2023 [213]. In 2019 Wärtsilä performed automated docking tests on a car ferry [131]. Both Volvo Penta and Wärtsilä provide assisted docking systems [173], [225]. Raymarine also offers docking-assisted systems [128]. Lastly, Cavotech offers automated mooring through their MoorMaster system [206].

B. FUTURE CHALLENGES

Despite demonstrations of automated docking solutions, no company offers fully autonomous docking products for ships without fixed routes. Risk estimation and safe operation assurance are complex tasks, and regulatory bodies impose stringent safety requirements. This may incentivize companies to focus more on docking assist technologies instead, for the time being. Representatives from Kongsberg Maritime made the authors aware of certain relevant technical hurdles, including automated docking for large under-actuated vessels, low-speed maneuvering stability in external forces, obstacle avoidance, and COLAV in harbor areas. These topics are briefly discussed as future research directions in Section VII as well.

V. PLANNING AND CONTROL METHODOLOGIES

In order to develop safe and reliable automated docking systems, it is crucial to address the challenges posed by the 12 identified categories presented in Section III-B5. We consider automated docking as a marine motion control problem and, as such, we will provide a comprehensive overview of the control methodologies and planning strategies employed, along with relevant statistics.

A total of 30 distinct control approaches have been implemented, which we have categorized into 5 broader groups. Figure 3a illustrates the evolution of these 5 groups over time, spanning from 1980 to June 2023. The line in the graph represents the number of physical implementations per year. Figure 3b shows the annual percentage distribution of control strategies in purely simulated solutions, while Figure 3c depicts the percentage-wise distribution of control strategies used in self-governing systems that also demonstrated physical capabilities.

Among the publications, 115 evaluated their systems strictly in simulations, while 49 papers conducted physical tests with self-governing automated docking systems. The remaining publications either lacked simulated and physical verification or developed docking-assist systems for the ship crew.

A. CONTROL METHODOLOGIES

This section outlines the relevant control methodologies used by the surveyed papers. For implementation details, the reader is referred to one of the cited publications under each methodology.

1) TRADITIONAL CONTROL TECHNIQUES

a: PID (PROPORTIONAL INTEGRAL DERIVATIVE CONTROL)

A control method that adjusts the control signal based on the error between the desired and actual states. It uses proportional, integral, and derivative terms to improve tracking performance. A common use of PID control is the Dynamic Positioning (DP) system, where a vessel can maintain its position and heading accurately without the use of anchors or manual control. DP systems consume significant power and are only applicable on fully actuated vessels. PID control was used in 62 publications [2], [8], [9], [11], [25], [26], [37], [41], [45], [47], [48], [52], [53], [55], [56], [61], [62], [67], [69], [73], [74], [75], [77], [80], [81], [85], [86], [87], [92], [93], [94], [96], [97], [99], [100], [101], [110], [116], [117], [118], [126], [130], [134], [142], [143], [149], [151], [155], [161], [163], [166], [156], [180], [186], [190], [192], [193], [204], [205], [221], [224], [227].

b: CPID (CASCADE PID)

A control strategy that utilizes multiple PID controllers in a cascaded structure. It allows for more complex control scenarios by controlling both the setpoint and the process variable of an inner loop and an outer loop. CPID control was used in [112].

c: FEEDBACK LINEARIZATION

A control technique that transforms a nonlinear system into an equivalent linear system through suitable feedback. It can simplify control design and achieve desired performance in systems with nonlinear dynamics, however issues might arise in systems with uncertainties. Feedback linearization was used in [174].

d: BS (BACKSTEPPING CONTROLLER)

A control method commonly used for systems with strict stability and performance requirements. It designs a series of feedback controllers to stabilize the system while achieving desired tracking performance. BS was used by [136] and [212].

e: ADAPTIVE CONTROL

A control approach that adjusts control parameters online to accommodate uncertain or time-varying system dynamics. It aims to adapt the control strategy to changing operating conditions and improve system performance. Adaptive control was used by 7 publications [58], [63], [70], [83], [175], [177], [185].

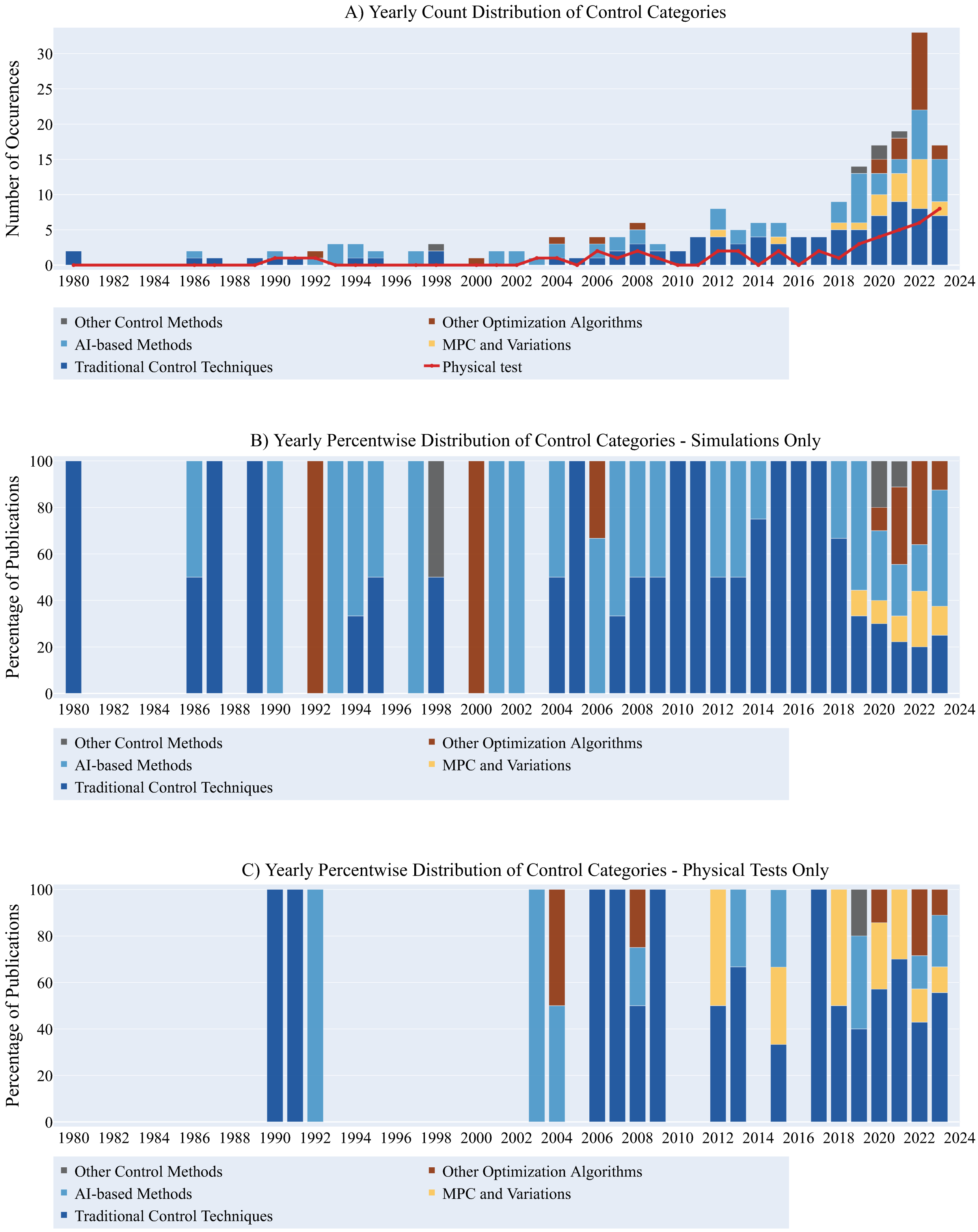


FIGURE 3. Control strategies. 'Physical test' encompass both small-scale and full-scale verifications. A) Number of control strategies per year plotted with the number of physical verifications per year. B) The percentwise distribution of control strategies each year, for purely simulated docking systems. C) The percentwise distribution of control strategies each year, for docking systems with physical tests.

f: LQR (LINEAR QUADRATIC REGULATOR)

LQR is an optimal control technique that aims to minimize a quadratic cost function while considering linear system dynamics. It uses state feedback and optimal control theory to compute control inputs that stabilize the system and optimize performance. LQR is widely used for control problems with linear dynamics. LQR was used in 7 publications [2], [4], [17], [19], [84], [91], [106].

g: BANG-BANG CONTROL

Also known as On/Off control, it is a simple control strategy where the control signal switches between two discrete levels based on a threshold. It is commonly used for binary control actions. Bang-bang control was used by [3].

h: NPID (NONLINEAR PID)

An extension of the traditional PID controller that considers nonlinear dynamics. It can provide improved performance in systems with nonlinearities. NPID control was used by [54], [174], and [194].

i: SMC (SLIDING MODE CONTROL)

A robust control technique that forces the system trajectory to converge to a predefined sliding surface. It is effective in handling uncertainties and disturbances. SMC was used in 6 publications [46], [64], [65], [113], [151], [228].

j: NPDFLAT (FLATNESS BASED FEEDFORWARD WITH PID-CONTROL)

NPDFLAT combines the benefits of both PID control and flatness-based feedforward control to achieve enhanced trajectory tracking performance. By utilizing the system's flatness property, it generates pre-calculated feedforward control signals that anticipate the desired trajectory, while the PID controller provides feedback control to minimize tracking errors. NPDFLAT was used in [174].

2) MODEL PREDICTIVE CONTROL (MPC) AND VARIATIONS

a: MPC (MODEL PREDICTIVE CONTROL)

MPC is a control strategy that utilizes a dynamic model of the system to predict future behavior and optimize control actions over a finite time horizon. It provides a systematic framework for handling constraints and optimizing performance, making it widely used in various applications. MPC was used by [112], [187], and [201].

b: NMPC (NONLINEAR MPC)

NMPC extends the MPC approach to nonlinear systems, allowing for more accurate modeling and control of complex dynamics. It addresses the challenges posed by nonlinearity through advanced techniques such as nonlinear model formulation and optimization algorithms, enabling effective control of nonlinear systems. NMPC was used in 14 publications [71], [88], [120], [134], [140], [142], [155], [156], [166], [183], [184], [192], [193], [212].

c: ILMPC (ITERATIVE LEARNING MPC)

ILMPC combines the principles of model predictive control with iterative learning techniques. It enables the controller to continuously improve its performance by iteratively updating the control strategy based on observed system behavior. This adaptive approach enhances control accuracy and robustness, making it effective in systems with time-varying dynamics or uncertainties. ILMPC was used in [203]

d: RL-MPC (REINFORCEMENT LEARNING)

RL-MPC integrates reinforcement learning algorithms into the model predictive control framework. By learning optimal control policies directly from data and system feedback, the method adapts and optimizes control strategies based on observed performance, offering adaptive and data-driven control approaches. They are particularly effective in systems with complex dynamics or when explicit models are challenging to obtain. RL-MPC was used in [157].

e: ETAHMPC (EVENT-TRIGGERED ADAPTIVE HORIZON MPC)

ETAHMPC is a control strategy specifically devised for ASVs. Incorporating event-triggering and an adaptive horizon, ETAHMPC responds dynamically to changes in the system state, which allows it to adapt the control effort in a more efficient way and balance performance and computational demands. It was used in [230].

3) AI-BASED METHODS

a: ANN (ARTIFICIAL NEURAL NETWORK)

ANNs are computational models inspired by the structure and functioning of the human brain. They consist of interconnected nodes, or neurons, organized in layers, and can learn complex patterns and relationships from data. ANN-based control methods leverage the powerful learning and approximation capabilities of neural networks to model system dynamics, estimate optimal control policies, or approximate control functions. ANN's are often divided into supervised and unsupervised learning. We de not make that division here. The earliest uses of ANNs were so-called shallow networks, consisting of only one hidden layer, while modern methods use deeper networks with vastly more parameters, at the expense of requiring huge computational resources to train. ANNs were used in 52 of the publications [10], [14], [15], [17], [18], [20], [23], [24], [31], [32], [33], [34], [35], [37], [38], [43], [44], [50], [49], [51], [53], [67], [72], [73], [74], [75], [80], [81], [85], [86], [103], [108], [115], [123], [127], [129], [145], [148], [150], [171], [172], [200], [176], [182], [183], [185], [199], [202], [215], [226], [211], [216].

A problematic feature of ANNs is their black-box nature, making it difficult to understand the decision-making process. However, there are some attempts to use methods from explainable AI (XAI) to make sense of the decisions made by ANNs employed for the docking problem [159], [160], [164], [209].

b: GA (GENETIC ALGORITHM)

GA is an evolutionary optimization technique that mimics the process of natural selection and evolution. It employs genetic operators such as mutation, crossover, and selection to explore and exploit the search space. GA is well-suited for control problems with a large solution space and non-differentiable objectives. GA was used in [107] and [211].

c: NOS (NEURODYNAMIC OPTIMIZATION SOLVER)

NOS is a control strategy that uses the principles of neural networks and gradient-based optimization. It leverages the computational efficiency and adaptability of neural networks to solve complex, nonlinear optimization problems in real-time, making it suitable for systems with high-dimensional and dynamic environments. NOS was used in [219].

d: FUZZY CONTROL

Fuzzy control is a rule-based control approach that uses linguistic variables and fuzzy logic to handle complex and uncertain systems. It employs a set of rules based on expert knowledge to map inputs and outputs, allowing for adaptive and flexible control in situations where precise mathematical models are difficult to obtain. Fuzzy control was used in 7 publications [3], [13], [16], [56], [118], [124], [125].

4) OTHER OPTIMIZATION ALGORITHMS

a: CMA-ES (COVARIANCE MATRIX ADAPTION EVOLUTION STRATEGY)

CMA-ES is an evolutionary algorithm that utilizes an adaptation mechanism to optimize control policies. It employs a population-based approach inspired by natural evolution to search for optimal solutions. By iteratively adjusting the covariance matrix of the population, CMA-ES adapts and explores the search space effectively. CMA-ES was used in 8 publications [141], [165], [176], [190], [191], [195], [197], [215].

b: SQP (SEQUENTIAL QUADRATIC PROGRAMMING)

SQP is an optimization algorithm that solves NonLinear Programming problems (NLPs) iteratively. It leverages quadratic programming techniques to approximate the original optimization problem and iteratively updates the solution until convergence. SQP is commonly used in control applications that involve complex nonlinear dynamics and constraints. SQP was used in 4 publications [154], [188], [189], [195].

c: INTERIOR POINT METHODS

Interior point methods are optimization algorithms used to solve NLPs. They work by iteratively moving towards the optimal solution by exploring the interior of the feasible region, rather than approaching it from the boundaries. These methods employ a barrier function that penalizes violations of constraints, allowing the algorithm to efficiently handle both equality and inequality constraints while maintaining good convergence properties. Interior point methods were used in [143], [178], [179].

d: AMBS-P (ADAPTIVE-MUTATION BEETLE SWARM PREDICTION)

AMBS-P is an optimization algorithm inspired by the foraging behavior of beetles. It utilizes adaptive mutation operators and a swarm intelligence approach to search for optimal control policies. By iteratively adjusting mutation rates AMBS-P aims to find efficient solutions to complex control problems. AMBS-P was used in [201].

e: ACO (ANT COLONY OPTIMIZATION)

ACO is a nature-inspired optimization algorithm that draws inspiration from the foraging behavior of ants. It employs a population of artificial ants that iteratively construct solutions by depositing pheromone trails on the edges of a graph. The pheromone trails influence the ant's decisions on path selection, allowing the algorithm to explore and exploit the problem space effectively. ACO is used in [231].

f: SCGR (SEQUENTIAL CONJUGATE GRADIENT-RESTORATION)

SCGR is an optimization algorithm that combines conjugate gradient descent and restoration techniques to solve constrained optimization problems. It offers efficient solutions for control problems with nonlinear dynamics and constraints by iteratively updating the control inputs based on gradient information. SCGR was used in 5 publications [12], [30], [38], [44], [53].

g: EDWA (EXTENDED DYNAMIC WINDOW APPROACH)

EDWA is an optimization-based method used for path planning and obstacle avoidance. It considers dynamic constraints and environmental factors to generate feasible and collision-free paths. EDWA offers a flexible and adaptive approach to path planning in dynamic environments. EDWA was used in [161].

5) OTHER CONTROL METHODS

These methods are not readily categorized under the previous categories and are subsequently placed here.

a: FRS AND BRS (FORWARDS/BACKWARDS REACHABILITY SET)

FRS and BRS are control methods that analyze system dynamics and constraints to determine the set of states that can be reached by a system or the set of initial states from which a desired target state can be reached, respectively. By utilizing mathematical models and simulations, FRS and BRS provide valuable insights into system behavior and enable the design of control strategies that ensure the system operates within desired boundaries. These methods play a crucial role in understanding system reachability and guiding

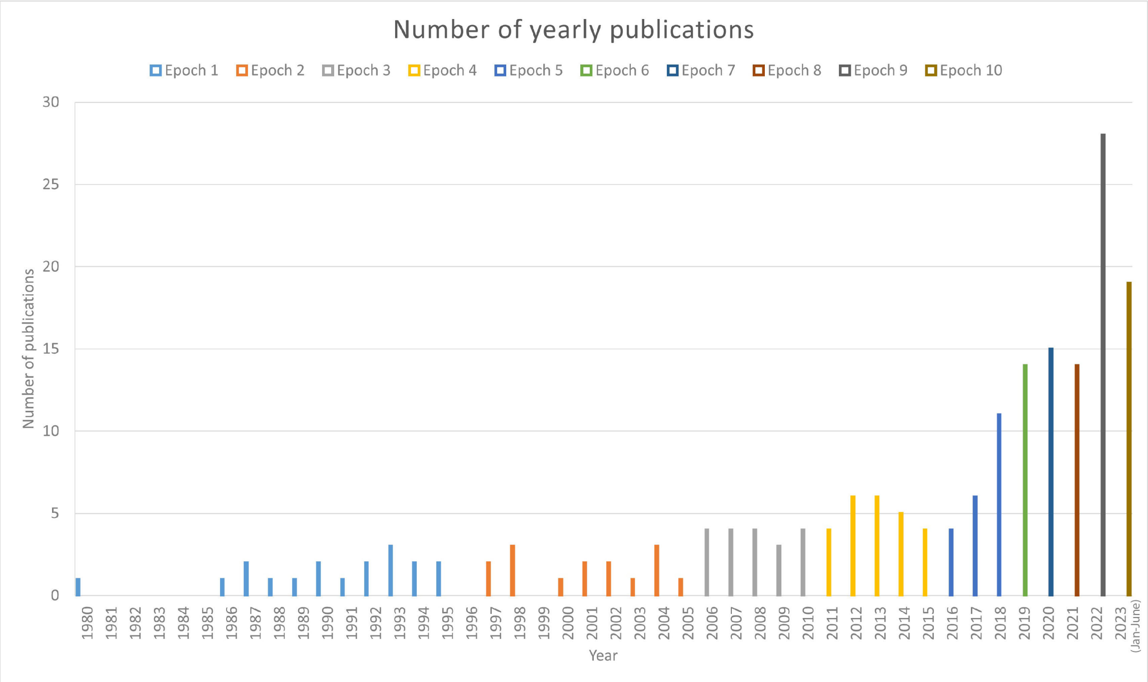


FIGURE 4. Number of yearly publications related to automated docking for MSVs from 1980 - June 2023, separated into 10 epochs.

the development of effective control approaches. FRS and BRS were both used in [146].

b: ADRC (ACTIVE DISTURBANCE REJECTION CONTROL)

ADRC is a control technique that aims to compensate for external disturbances and uncertainties in the system by actively estimating and rejecting them in real-time. It utilizes mathematical models, state estimators, and feedback control to achieve robust and accurate control performance in the presence of disturbances. ADRC was used in [126].

c: MAS (MULTI-AGENT SYSTEM)

MAS is a control approach that involves the coordination and cooperation of multiple autonomous agents to achieve a common goal. Each agent has its own decision-making capability and interacts with other agents to exchange information and collectively accomplish complex tasks. MAS is particularly useful in scenarios where decentralized control and distributed intelligence are required. MAS was used in [27] and [158].

B. PATH PLANNING AND GUIDANCE

This section outlines the relevant path and trajectory planning methodologies used by the surveyed papers. For implementation details, the reader is referred to one of the cited publications under each methodology.

1) GEOMETRIC AND GRAPH-BASED METHODS

a: STATE-LATTICE

State-lattice is a method that discretizes the state space into a lattice structure, allowing for efficient path planning by selecting feasible paths from the lattice points. State lattice control was used in [133].

b: BÉZIER CURVE

Bézier curve is a geometric method used for path representation. They provide a smooth and flexible way to define paths using control points and interpolation. Bézier curves were used in 4 publications [19], [149], [189], [230].

c: DUBINS CURVE

Dubins Curve is a path planning algorithm that calculates the shortest path for a vehicle constrained to move forward and turn with a maximum curvature. This strategy is especially suitable for underactuated systems, such as cars or MSVs, that cannot move sideways, ensuring an efficient and smooth trajectory that respects the vehicles' motion constraints. Dubins curve was used in [204].

d: A (A STAR)*

A* algorithm is a popular graph-based method used for pathfinding. It combines a heuristic search approach with a graph representation of the environment to find optimal paths between nodes. A* was used in 5 publications [110], [143], [192], [193], [230].

e: VD (VORONOI DIAGRAM)

VD is a geometric method that partitions the space into regions based on proximity to points of interest. They are often used in path planning to determine the closest point or region to a given location and are capable of providing obstacle-avoiding paths. VD was used in [196].

FIGURE 5. DCI-Scores A) Yearly mean DCI-Scores for all docking systems, purely simulated systems, and systems with physical verifications. B) Yearly mean, minimum, and maximum DCI-Scores for purely docking systems verified in simulations only. C) Yearly mean, minimum, and maximum DCI-Scores for self-governing docking systems with physical tests.

f: DT (DELAUNAY TRIANGULATION)

DT is a geometric method, similar to VD, that creates a triangulated network based on a set of points. It is useful for path planning and obstacle avoidance, as it provides an efficient way to define connectivity between points in the environment. DT was used in [192] and [193].

2) GUIDANCE LAWS

Guidance laws are responsible for generating reference trajectories to correct any divergence from the desired path. These laws provide high-level instructions to the system. The guidance law defines the desired behavior and objective, such as following a specific route or reaching designated waypoints. It sets the overall guidance strategy for the system, while the implementation of control actions is handled by a separate control algorithm.

a: LOS (LINE OF SIGHT)

A guidance method commonly used in mobile robotics for path, or waypoint, following. It involves calculating the angle between the current position and a desired target point to determine the control action. LOS guidance was used in 8 publications [45], [54], [69], [87], [118], [126], [186], [219].

b: CB (CONSTANT BEARING)

A guidance strategy used in autonomous navigation to maintain a constant bearing angle towards a target point. It allows the vehicle to track a desired direction relative to the target. CB guidance was used in [61] and [62].

c: PP (PURE PURSUIT)

PP involves calculating a steering angle based on the position of a target point on the desired path and the current position of the vehicle. By continuously updating the target point and adjusting the steering angle accordingly, the vehicle can smoothly follow the desired path. It was used in [221].

VI. CHRONOLOGICAL REVIEW

Whereas Figure 3a displays the number of control methods used each year, which can be larger than the number of publications, Figure 4 shows how the number of publications within automated docking for MSVs has increased over the years. Compared to other motion control scenarios, such as dynamic positioning or path following, automated docking was less researched up until 2017 when the number of yearly publications started to grow more than usual.

The International Regulations for Preventing Collisions at Sea, or COLREGS, is a comprehensive set of guidelines instituted to ensure safety in marine navigation [66]. Essentially functioning as the traffic laws of the sea, COLREGS provides protocols for determining right-of-way, utilizing lights and signals, and conducting appropriate actions to avoid collisions. In the literature on automated docking, COLREGS is briefly discussed by 9 publications from 2018 and onward [110], [148], [151], [154], [155], [156], [166], [212], [229]. Other articles mention COLREGS in future work or reference the implementation of COLREGS in other marine motion control works.

Figure 5 illustrates the annual mean, maximum, and minimum DCI-Scores for the studies examined in this work. Figure 5a compares the mean DCI-Scores of all contributions to those of automated docking systems verified both in simulations and physical sea trials. Physical verifications encompass both small-scale and full-scale tests. Figure 5b exclusively presents the annual DCI-Scores for systems tested in simulations, while Figure 5c focuses on physically verified automated docking systems, excluding purely assistive ones.

A. STRUCTURE

The chronological review is divided into sections containing roughly 15-25 papers each. These sections, from now on called epochs, are structured as follows: Firstly, publications are organized into groups based on their affiliated countries, and presented with metadata on citations and number of publications. Another table lays out the highest cited and highest DCI-Scoring articles from that period. The publication with the highest number of citations, at the time of writing, and the publication with the highest DCI score are selected and presented.

B. EPOCH 1: 1980-1995

Between 1980 and 1995, 18 research articles on automated docking for MSVs were published [2], [3], [4], [5], [6], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20]. Table 2 presents a breakdown of the number of publications per country and their accumulated citations for this period. Notably, researchers from Japan contributed to approximately 72% of the publications and garnered about 83% of the total citations this epoch.

TABLE 2. Geographical distribution over the publications from 1980-1995.

Country	Number of publications	Cumulative citations
Japan	13	342
France	2	63
United Kingdom	1	5
South Korea	1	2
Norway	1	0

TABLE 3. Citations and DCI-Score from selected publications and the mean from 1980-1995.

	Author	Publication	Citations	DCI-Score
Mean	-	[2]–[6], [8]–[20]	22.88	3.859
Top cited	Yamato et al.	[10]	**87**	2.327
Top 1 DCI	Djouani et al.	[17]	15	**5.167**
Top 2 DCI	Ohtsu et al.	[11]	18	4.933
Top 3 DCI	Hasegawa et al.	[18]	42	4.750

Table 3 shows that the most-cited publication of this period was Yamato et al. [10], accumulating 87 citations. The paper that achieved the highest DCI-Score was Djouani et al. [17] with a score of 5.167. The average DCI-Score during this period was found to be 3.859. Based on these results, we will further discuss [10] and [17]. Considering its status as the first paper on automated docking, [2] will also be discussed in

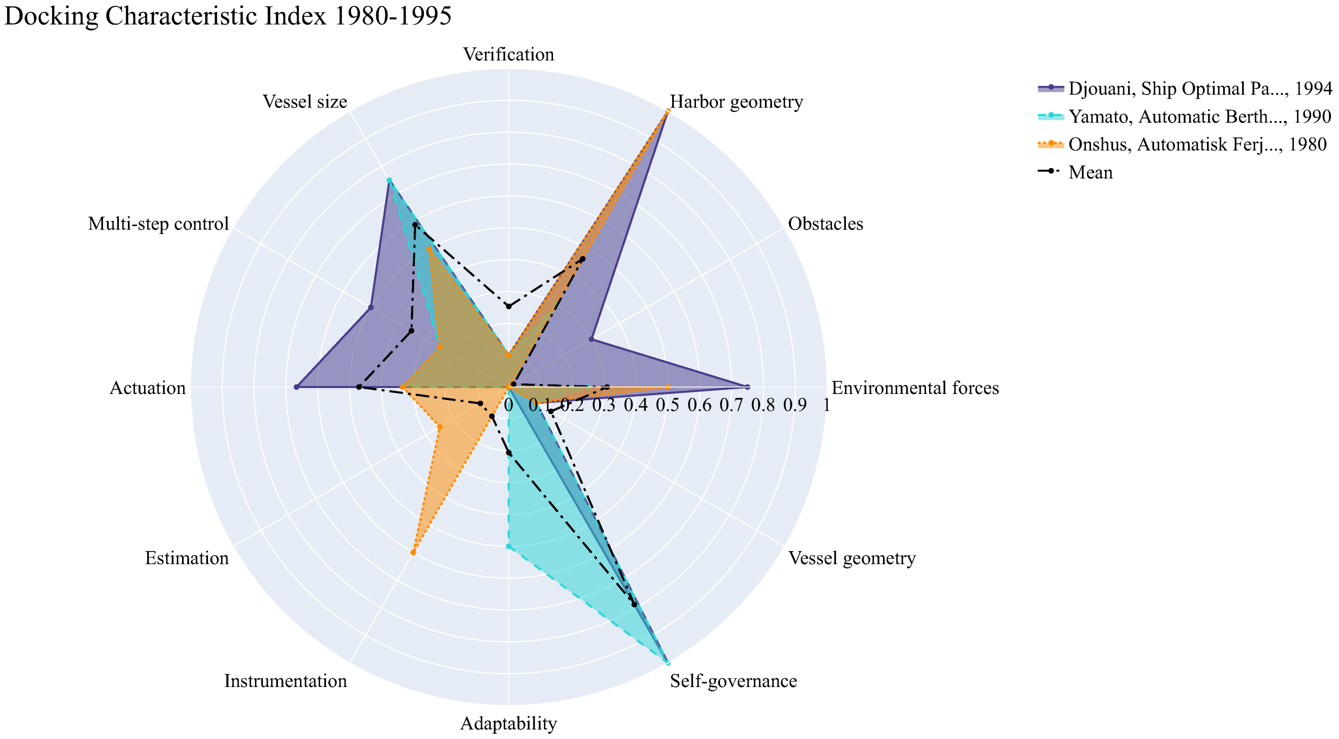


FIGURE 6. DCI for automated docking publications from 1980-1995. The top DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue. Further, the 1980 publication by Onshus [2] is dark orange.

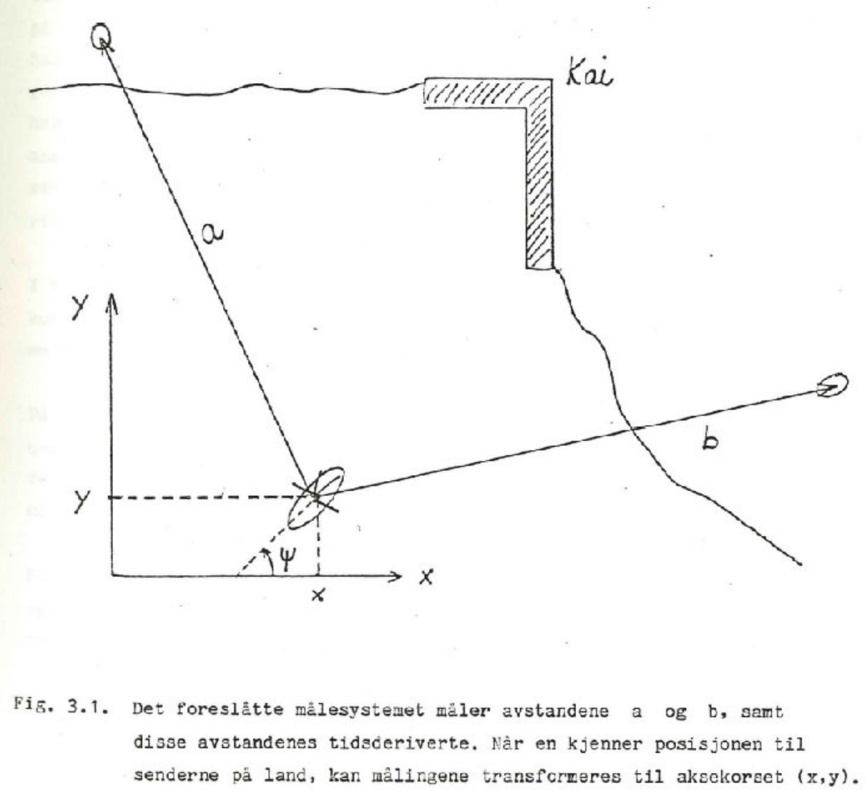


Fig. 3.1. Det foreslåtte målesystemet måler avstandene a og b, samt disse avstandenes tidsderiverte. Når en kjenner posisjonen til senderne på land, kan målingene transformeres til aksekorset (x,y).

FIGURE 7. Facsimile from *Automatisk Ferjemanøvrering* [2]. “Kai” is Norwegian for quay.

this section. The DCI of the selected articles and the period's mean are visualized in Figure 6. It proved difficult to obtain a copy of [5], and a number of publications had to be translated into English.

1) AUTOMATISK FERJEMANØVRERING [2]

Automatisk Ferjemanøvrering (English: Automatic Ferry Manoeuvring.), by Tor E. Onshus, is the earliest source the authors managed to find and is therefore summarized here. The research was done on behalf of *Vegkontoret i Trøndelag* by *SINTEF* with the goal of automating the docking procedure for ferries in fjords. The report was labeled as confidential and could therefore not spark other research endeavors. The next automated docking paper was written six years later by an unrelated research group from Japan. The report was discovered due to the fact that *SINTEF* is an organization with close ties to the authors' affiliated department. Tor E. Onshus and Otto Skovholt, the employee from *Vegkontoret i Trøndelag* who ordered the report, were interviewed for this survey. According to Mr. Skovholt, he ordered the report after the official opening of the Flakk-Rørvik ferry line, on the 14th of June 1979. Prior to King Olav V of Norway cutting the ribbon, the ferry had apparently crashed into the quay during docking with "splinters flying everywhere". Mr. Skovholt described the situation as "awkward", as damages were inflicted on both the ship and the dock. Interestingly, the drama was not reported by the local newspapers at the time, who instead chose to publish headlines such as "Day of jubilation", and "Fosen united into one kingdom by Olav". The accident motivated research into safer and more reliable docking systems using, by the standards at the time, highly advanced computer systems.

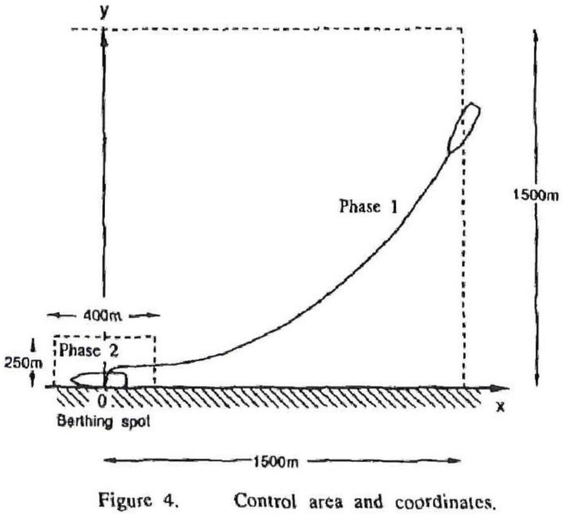


Figure 4. Control area and coordinates.

FIGURE 8. **Facsimile from *Automatic Berthing by the Neural Controller* [10].**

The report aimed to develop automated docking systems to enhance safety and reliability compared to manual control of actuators. To achieve this, the proposed solution introduces a joystick maneuvering scheme with computerized control allocation, eliminating the need for manual control of each actuator. Moreover, the report proposes an automated docking solution by memorizing human maneuvers. Figure 6 depicts how it scores on the DCI compared to a selection of other articles from the epoch.

The proposed automated docking system involves the following steps: Firstly, during the docking process, the computer records the final maneuvers performed by the pilot in a given harbor and creates a trajectory. Then, during the next docking process, an LQR controller generates a smooth trajectory connecting the current position of the ship to the stored docking trajectory. A surge-sway-yaw model is used to create a 7th-degree polynomial as a trajectory reference. The interpolated trajectory serves as a feedforward signal, which is used together with state feedback to control the system. The feedback signal is obtained by filtering measurements through an Extended Kalman Filter (EKF).

To measure the x and y positions, an optical sensor and a reflector located on land are used. The heading is measured with a gyroscope, while wind and velocity are also measured. Moreover, a vertical reference is used to correct any errors in the other measuring instruments caused by roll- and pitch angles. Although the report lacks any real sea trials, the detailed description of the full-scale implementation provides valuable insights into how the proposed automated docking system could have been implemented.

A facsimile from this report is given in Figure 7.

2) AUTOMATIC BERTHING BY THE NEURAL CONTROLLER [10]

The publication by Yamato et al. received the highest number of citations in Epoch 1, for that reason, its summary is presented in this section.

This research explores the innovative use of a three-layered neural network to address the automated docking problem. The controller employs the error backpropagation algorithm for weight and threshold determination and utilizes separate neural networks for operation in near and far fields, each fine-tuned to the precision required in its specific domain.

The control system architecture utilizes two neural networks for navigation in near and far fields, based on the precision required in each area. These networks are trained using pre-obtained docking data from several trajectories within a convex harbor area. Despite its primitive nature and only representing basic docking patterns, it highlights the untapped potential of ANNs in this field.

The performance of this controller is evaluated through simulations conducted on a computer. Despite the presence of constant wind disturbance, the controller is able to navigate the simulated harbor, identical to the training environment, effectively. However, the authors acknowledge that the effect of winds and currents is not fully incorporated into the current iteration of the controller.

The research concludes by affirming the potential of the three-layered neural controller in automated docking but also underlines the need for further development and refinement. It recognizes that while the controller provides appropriate control for automated docking under the given conditions, its extrapolation capabilities are limited and largely unreliable. The authors recommend future research to continue exploring both mathematical investigations and application development to enhance the ANN controller's design and efficacy.

A facsimile from this publication is given in Figure 8.

3) SHIP OPTIMAL PATH PLANNING AND ARTIFICIAL NEURAL NETS FOR BERTHING [17]

The publication by Djouani et al. received the highest DCI-Score of Epoch 1, for that reason, its summary is presented in this section.

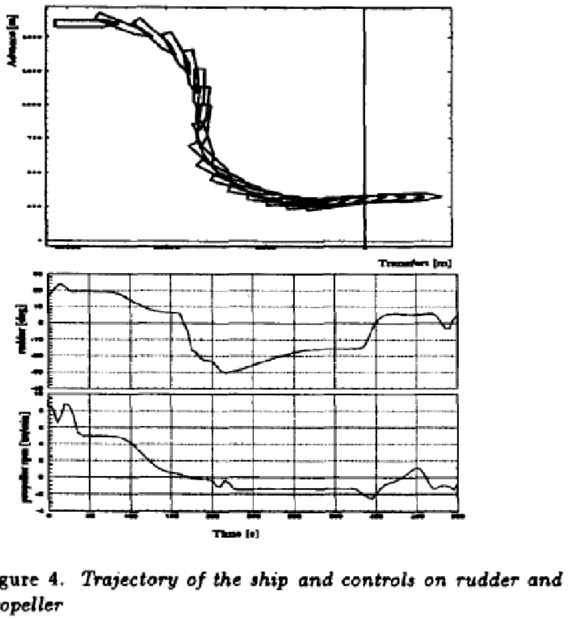


Figure 4. Trajectory of the ship and controls on rudder and propeller

FIGURE 9. Facsimile from ***Ship Optimal Path Planning and Artificial Neural Nets for Berthing*** **[17].**

The study details a two-stage control system that incorporates a non-linear mathematical model for optimal path planning and tracking, considering vessel dynamics, non-linearities, and constraints. An ANN, trained via the Ship Optimal Path Planning (SOPP) algorithm, is proposed for automated docking, offering a strategy that can adapt to any initial state. A dedicated SOPP system enables offline path planning and obstacle avoidance, with potential applications in analyzing ship maneuverability and design.

The study focuses on a system for optimal path planning that takes into account non-linearities, system dynamics, and constraints on states and control. This process is built on the foundation of a non-linear mathematical model designed with a modular approach. This model serves both in the off-line path planning phase and the on-line path tracking phase. It also has potential utility in marine simulators as a decisional system to evaluate the feasibility of maneuvers considering perturbations and collision avoidance possibilities.

The article discusses the use of an ANN that maps an optimal control strategy for automated docking. The training data is generated using the SOPP algorithm, which provides a data base for training the ANN using the back-propagation algorithm. During the test phase, the controller is implemented within a feedback loop on the vessel model, which inputs the current state and delivers a control strategy for ship docking from any initial state.

A SOPP system is built for offline path planning with obstacle avoidance, and this system can also be employed for analyzing the maneuverability of specific vessel architectures. A key point is that an ANN controller is used for ship docking, with ongoing research concerned with the validation of the controller and its interpolation and extrapolation capabilities. The authors foresee their research contributing to enhanced marine safety and ship design.

A facsimile from this publication is given in Figure 9.

C. EPOCH 2: 1996-2005

During the 1996-2005 period, 15 research papers were published [23], [24], [25], [26], [27], [30], [31], [32], [33], [34], [35], [37], [38], [39], [41]. The authors of these papers were affiliated with institutions in Japan, South Korea, the United Kingdom, and Norway, as detailed in Table 4. As with the previous period, Japan made the most significant contribution, accounting for approximately 73% of the total publications and receiving around 62% of the total citations. South Korea contributed 2 papers, while both the United Kingdom and Norway produced 1 paper each.

TABLE 4. **Geographical distribution of the publications from 1996-2005.**

Country	Number of publications	Cumulative citations
Japan	11	131
South Korea	2	6
United Kingdom	1	73
Norway	1	1

TABLE 5. **Citations and DCI-Score from selected publications and the mean from 1996-2005.**

	Author	Publication	Citations	DCI-Score
Mean	-	[23]–[27], [30]–[35], [37]–[39], [41]	14.71	3.606
Top cited	Zhang et al.	[24]	**73**	**4.417**
Top 1 DCI	Zhang et al.	[24]	**73**	**4.417**
Top 2 DCI	Im et al.	[34]	30	4.292
Top 3 DCI	Im et al.	[33]	19	4.292

The paper from the United Kingdom by Zhang et al. [24] gained particular attention, becoming the most cited paper of this period with 73 citations, as shown in Table 5. The paper also received the highest DCI-Score at 4.417, marking a decrease of 0.750 from the top score of Epoch 1 [17]. Thus we shall look into the publication with the second highest DCI-Score, by Im et al. [34], which achieved a score of 4.292.

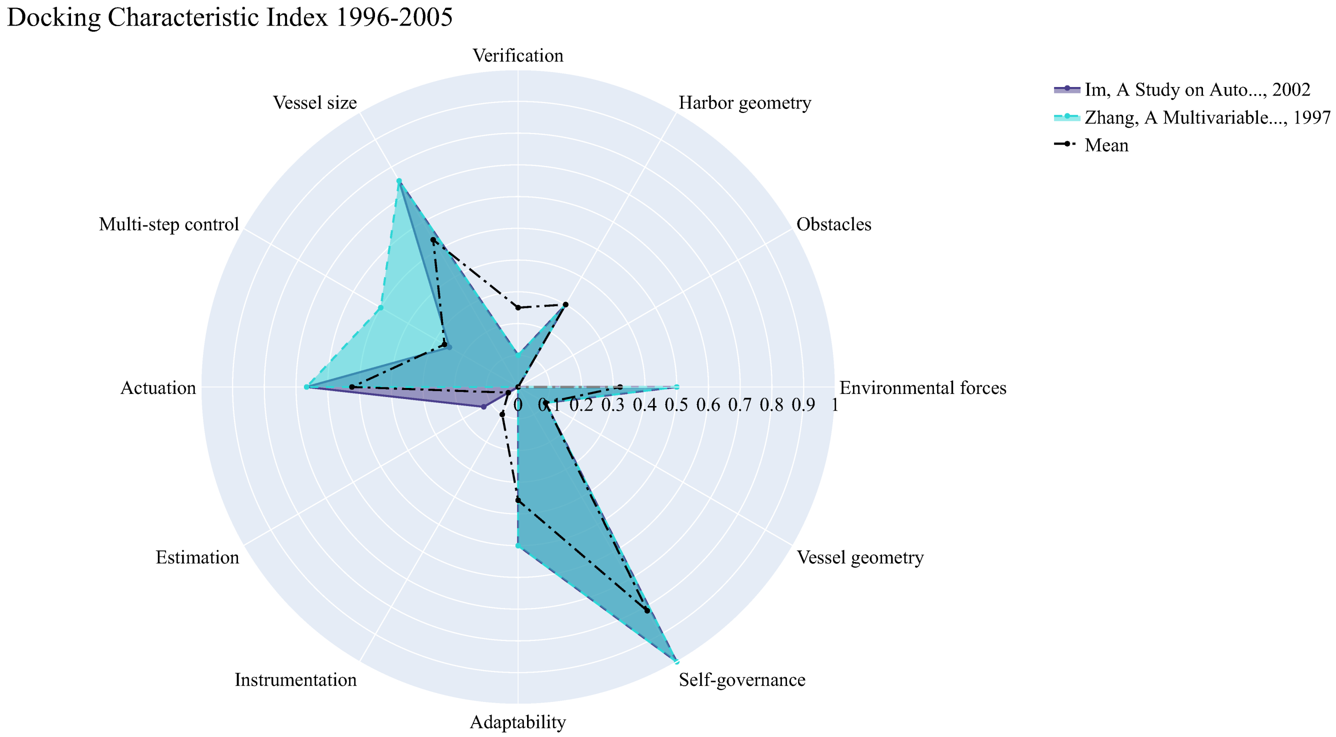


FIGURE 10. DCI for automated docking publications from 1996-2005. The second highest DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.

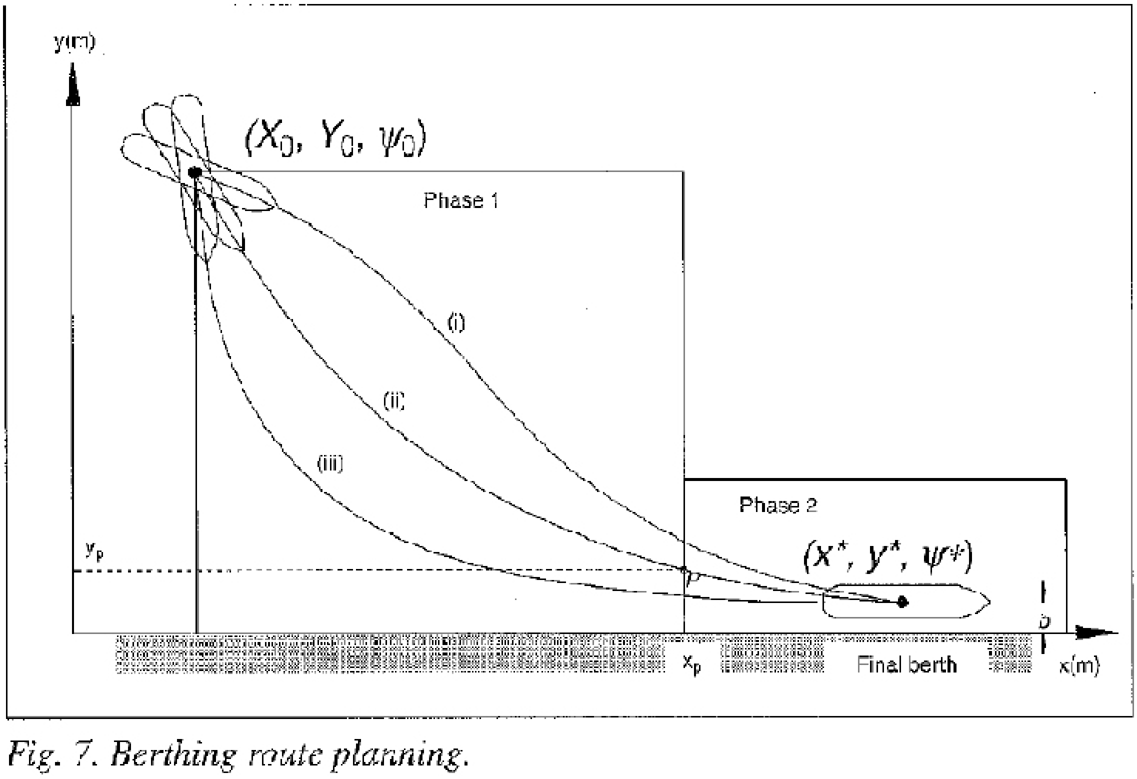


Fig. 7. Berthing route planning.

FIGURE 11. Facsimile from *A Multivariable Neural Controller for Automatic Ship Berthing* [24].

The average DCI-Score for the 1996-2005 epoch was 3.606, representing a decrease of 0.253 from Epoch 1. The DCI of the most-cited paper (also the highest DCI-Score), the paper with the second highest DCI-Score, and the average DCI for this period are graphically presented in Figure 10.

It was challenging to obtain a copy of [39], and as a result, this paper was unfortunately excluded from the review process. A substantial amount of the publications also had to be translated into English.

1) A MULTIVARIABLE NEURAL CONTROLLER FOR AUTOMATIC SHIP BERTHING [24]

The publication by Zhang et al. received the highest number of citations in Epoch 2, for that reason, its summary is presented in this section.

The article proposes an ANN-based control system for automated docking, which is independent of the vessel model. The proposed control system updates its parameters online, eliminating the need for off-line training.

The authors note that the major obstacle to analytical control techniques is the cost of system development and validation. Further, the mathematical models are prone to inaccuracies, and the computations might be too slow for real-time applications. The ANN consists of one input layer, a hidden layer, and an output layer. Noise is added to the input, and the outputted desired rudder angle and propeller speed are appended a transfer lag.

The transfer lag is added to the actuators to simulate the physical constraints of moving the propellers and rudder, increasing the realism of the method. In addition, wind forces and different levels of water depths are considered.

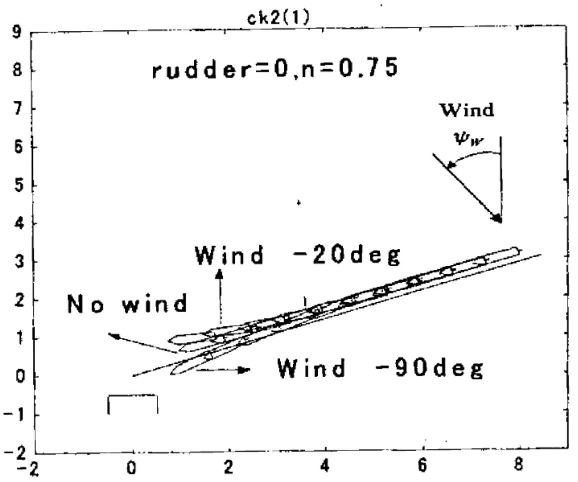


FIGURE 12. **Facsimile from *A Study on Automatic Ship Berthing Using Parallel Neural Controller (2nd Report)* [34].**

The study illustrates that an ANN controller can successfully address docking problems without requiring precise mathematical models of vessel dynamics, adapting to non-linear and time-varying characteristics, and handling new scenarios. The proposed approach allows for a variety of path planning methods depending on vessel type, environmental conditions, and facilities. Future research aims to validate the controller's applicability under varying conditions, culminating in full-scale sea trials, with the overarching objective of enhancing marine safety through the provision of reliable advisory tools for the ship crew.

A facsimile from this publication is given in Figure 11.

2) A STUDY ON AUTOMATIC SHIP BERTHING USING PARALLEL NEURAL CONTROLLER (2ND REPORT) [34]

The publication by Im et al. received the second highest DCI-Score of Epoch 2, for that reason, its summary is presented in this section.

The research paper discusses the use of ANN in automated docking. It explores a motion identification method that estimates the impact of environmental disturbances during docking. If any discrepancies are found between the motion identification and the actual state variables, it is assumed that the ship's movement is influenced by these disturbances. The research proposes two rule-based algorithms that use this difference to mitigate the effects of disturbances, enhancing the performance of automated docking.

The study utilized a tanker of 260,000 tons, with its dynamics and particulars outlined in prior reports. The research introduces a neural controller, where the outputs are rudder angle and engine revolution. Teaching data for motion identification was obtained through simulations when the disturbance was zero. The research employs six patterns of automated docking simulations, trained using a Neural Network Toolbox from MATLAB.

The paper uses the variation of ship's lateral speed and angular velocity to estimate the effect of disturbances and subsequently, to take appropriate actions. By estimating how much a ship will deviate at the docking point, the vessel can anticipate the effect of disturbances and take necessary corrective measures. If the ship's angular velocity is found to increase due to disturbances, the study suggests modifying the rudder angle to decrease this velocity, using a diagram of the ship's turning characteristics as a guide.

The research concludes that the ANN method is effective in estimating the impact of environmental disturbances on automated docking, based on results obtained from numerical simulations. The proposed control algorithms using identification of lateral speed and angular velocity were found to be successful in managing lateral disturbances and changes in the vessel's angular velocity due to disturbances. The findings suggest that such methodologies can significantly improve the performance of automated docking systems, thus presenting a promising direction for further research and practical applications.

A facsimile from this publication is given in Figure 12.

D. EPOCH 3: 2006-2010

During the 2006-2010 period, 19 research articles on automated docking were published [42], [43], [44], [45], [46], [47], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58],

TABLE 6. Geographical distribution of the publications from 2006-2010.

Country	Number of publications	Cumulative citations
South Korea	9	126
Australia	2	64
Japan	2	18
Vietnam	1	27
Taiwan	1	16
China	1	13
Poland	1	11
Portugal	1	3
Norway	1	2

TABLE 7. Citations and DCI-Score from selected publications and the mean from 2006-2010.

	Author	Publication	Citations	DCI-Score
Mean	-	[42]–[47], [49]–[61]	14.7	3.464
Top cited	Lee et al.	[56]	**68**	3.667
Top 1 DCI	Bu et al.	[46]	13	**4.417**
Top 2 DCI	Nguyen et al.	[43]	2	4.417
Top 3 DCI	Sutulo et al.	[57]	3	4.358

[59], [60], [61]. The authors of these articles were associated with institutions based in South Korea, Australia, Japan, Vietnam, Taiwan, China, Poland, Portugal, and Norway. A detailed breakdown by country can be found in Table 6. South Korean researchers made a significant contribution, authoring 9 publications, which accounted for 45% of the total for this period, and receiving approximately 35% of the total citations.

The paper with the most citations came from South Korea and was written by Lee et al. [56], with a total of 68 citations, as indicated in Table 7. The paper with the highest DCI-Score, by Bu et al. [46], achieved a score of 4.417, which is identical to the highest score of Epoch 2 [24]. The mean DCI-Score for this period was 3.464, marking a slight decrease of 0.142. A graphical representation of the DCI for the most-cited paper, the paper with the highest DCI-Score, and the average DCI for the 2006-2010 period can be found in Figure 13.

1) ALGORITHMS TO CONTROL THE MOVING SHIP DURING HARBOUR ENTRY [56]

The publication by Lee et al. received the highest number of citations in Epoch 3, for that reason, its summary is presented in this section.

The study investigates the implementation of automation in MSVs to tackle the shortage of skilled manpower in the marine sector. Focusing on the crucial phase of a vessel's entry into a harbor basin, the study looks at PID control and fuzzy logic control for heading regulation and path keeping.

The paper proposes the use of a conventional PID control algorithm to balance the forces and moments acting on a vessel due to hydrodynamic flow as it enters a harbor. The study conducts simulations using a Mariner class vessel's known hydrodynamic derivatives, considering both deep water and shallow water scenarios. It suggests that the design of the control system should be adaptable, with the ability to adjust the PID parameters depending on sea state and extra loads.

To validate the proposed control methodologies, the researchers perform numerical simulations considering different scenarios and vessel speeds. They examine the vessel's trajectory, rudder angle, and acceleration under both PID and fuzzy logic control systems. Initial conditions like heading and positional offset from the desired path are taken into account, and the hydrodynamic coefficients are modified according to the water depth.

The research concludes that both PID and fuzzy logic control can effectively regulate a vessel's heading and maintain its path during harbor entry. It notes that PID control appears to be the more successful methodology when the constants are appropriately chosen, but emphasizes that fuzzy logic control can also be improved with more membership functions. The findings from the simulations and the versatility of the code developed present potential for further exploration of motion control, including the possibility of combining PID and fuzzy logic algorithms for a new approach to motion control.

A facsimile from this publication is given in Figure 14.

2) NONLINEAR SLIDING MODE BERTHING CONTROL OF UNDERACTUATED SURFACE SHIPS [46]

The publication by Bu et al. received the highest DCI-Score of Epoch 3, for that reason, its summary is presented in this section.

The research paper introduces an output feedback strategy for docking control of underactuated surface vessels, taking into account limitations on actuators, systemic uncertainties, and drift caused by environmental factors such as wind and current. Using an iterative nonlinear sliding mode control (INSMC) method, the issues of trajectory planning and tracking are circumvented. The decentralized sliding mode approach is designed on phase planes in the augmented states space. An incremental feedback control law based on the INSMC is used to stabilize the ship's motion without the need for estimation of uncertainties and disturbances.

The method incorporates an approach to the ship's control problem, where the states and control inputs are ensured to remain within their limits. The controller determines input control quantities of engine revolution rate and rudder angle, guiding the ship to follow a planned trajectory during docking.

To demonstrate the practicality of the proposed algorithm, simulations were conducted using a full nonlinear dynamic model of an underactuated MSV. The simulations covered various scenarios, including environmental disturbances and wind disturbances, showcasing the algorithm's efficiency even in complex situations.

Conclusively, the proposed control scheme effectively plans and tracks docking control for underactuated MSVs. Using the INSMC method, the trajectory planning is decoupled while handling uncertain dynamics and environmental disturbances. Though the initial results are promising, the

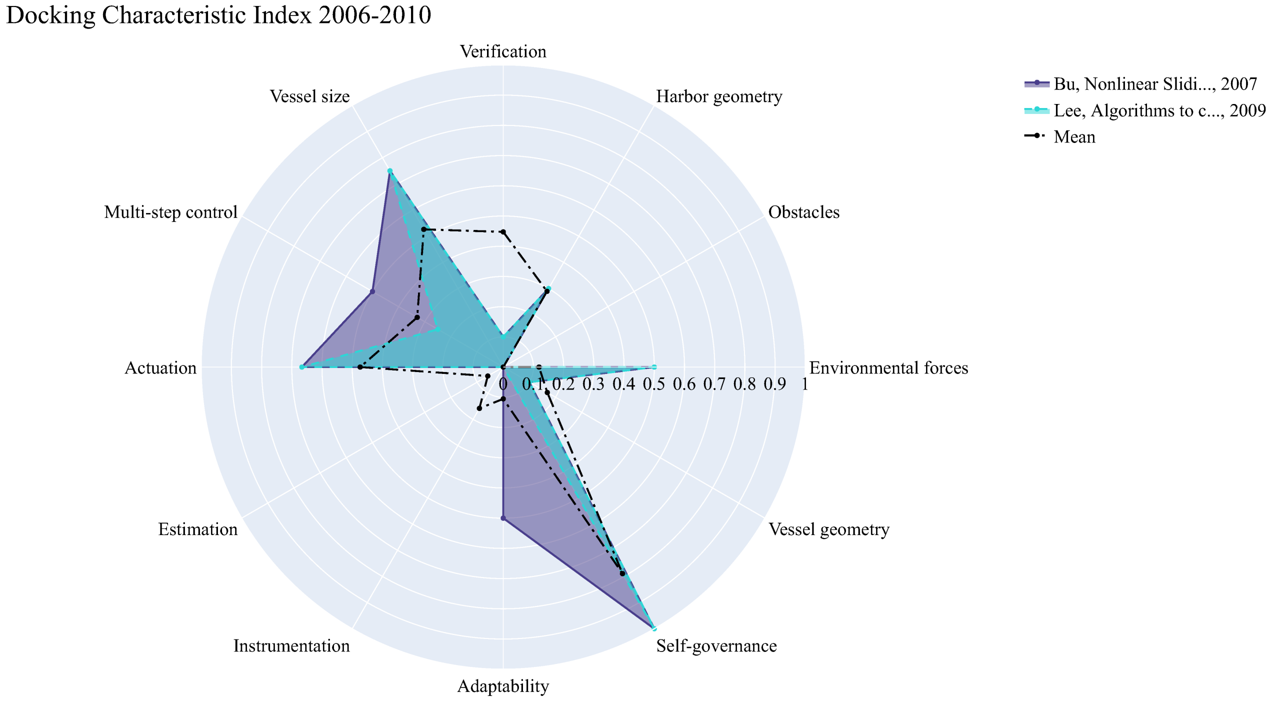


FIGURE 13. **DCI for automated docking publications from 2006-2010. The top DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.**

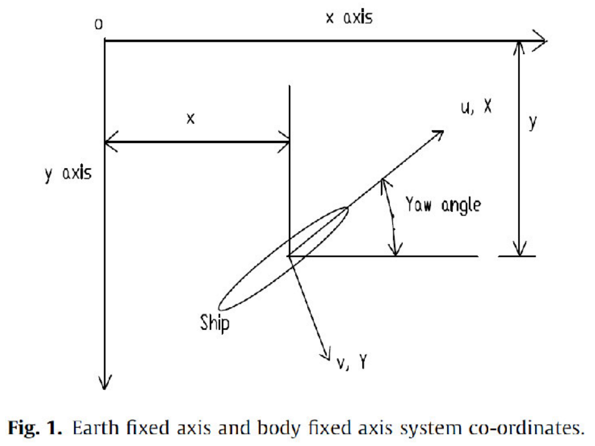


Fig. 1. Earth fixed axis and body fixed axis system co-ordinates.

FIGURE 14. **Facsimile from *Autonomous Surface Vehicle Docking Maneuvre with Visual Information* [56].**

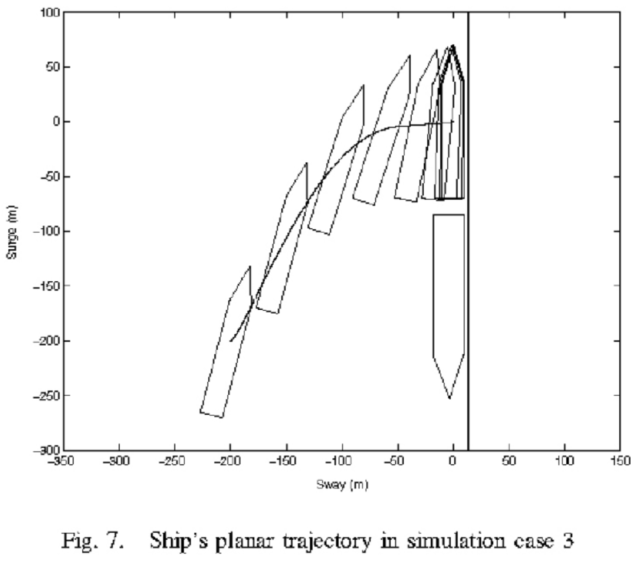


Fig. 7. Ship's planar trajectory in simulation case 3

FIGURE 15. **Facsimile from *Nonlinear sliding mode berthing control of underactuated surface ships* [46].**

study suggests further work on a global and optimal, automatic path-planning method.

A facsimile from this publication is given in Figure 15.

E. EPOCH 4: 2011-2015

A total of 25 research papers were published in the period between 2011 and 2015 [62], [63], [64], [65], [67], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [82], [83], [80], [81], [84], [85], [86], [87], [88]. These papers originated from a variety of countries, including Japan, South Korea, Vietnam, Norway, USA, China, Portugal, and Taiwan. Detailed country-wise distribution of these publications is provided in Table 8. A significant portion, 44%, of these papers, were authored in Japan, which also received approximately 47% of the total citations.

The paper that garnered the most citations during this period was from Japan, by Ahmed et al. [74], and was cited

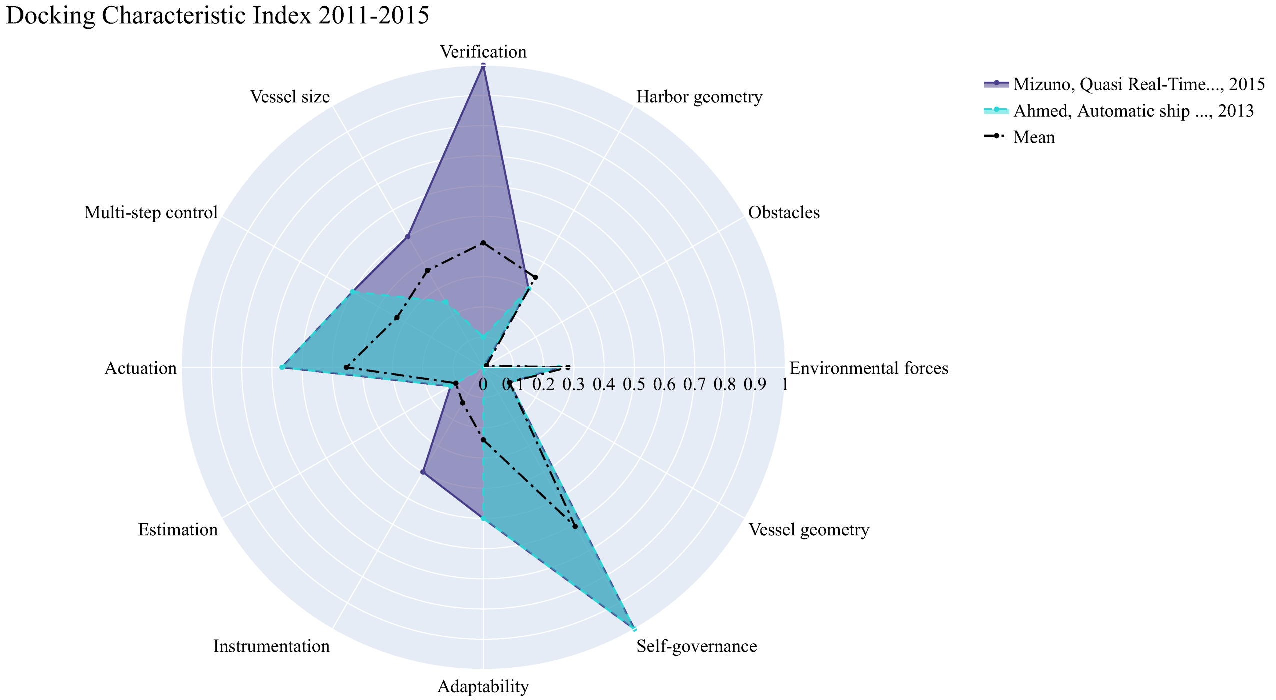


FIGURE 16. DCI for automated docking publications from 2011-2015. The top DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.

TABLE 8. Geographical distribution of the publications from 2011-2015.

Country	Number of publications	Cumulative citations
Japan	11	277
South Korea	8	179
Vietnam	1	57
Norway	1	33
USA	1	17
China	1	9
Portugal	1	7
Taiwan	1	7

TABLE 9. Citations and DCI-Score from selected publications and the mean from 2011-2015.

	Author	Publication	Citations	DCI-Score
Mean	-	[62]–[65], [67], [69]–[88]	23.4	3.390
Top cited	Ahmed et al.	[74]	**84**	3.792
Top 1 DCI	Mizuno et al.	[88]	39	**5.342**
Top 2 DCI	Ahmed et al.	[75]	29	5.092
Top 3 DCI	Ahmed et al.	[85]	7	4.692

84 times as shown in Table 9. The paper with the highest DCI-Score was written by Mizuno et al. [88], scoring 5.342, marking an increase of 0.925 from the highest score in Epoch 3 [46]. The mean DCI-Score for the 2011-2015 period was 3.390, which represents a slight decrease of 0.074 from the previous period. The DCI of the most-cited paper, the highest DCI-Score, and the average for the 2011-2015 period are all graphically represented in Figure 16.

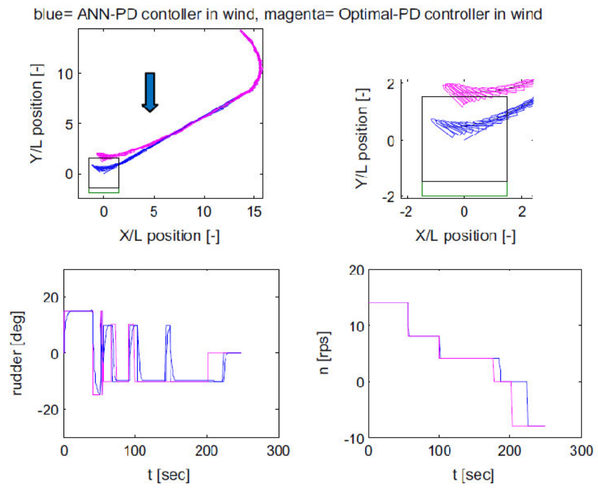


FIGURE 17. Facsimile from *Automatic ship berthing using artificial neural network trained by consistent teaching data using non-linear programming method* [74].

1) AUTOMATIC SHIP BERTHING USING ARTIFICIAL NEURAL NETWORK TRAINED BY CONSISTENT TEACHING DATA USING NON-LINEAR PROGRAMMING METHOD [74]

The publication by Ahmed et al. received the highest number of citations in Epoch 4, for that reason, its summary is presented in this section.

This research introduces an automated docking system that uses ANNs trained with consistent teaching data. The teaching data is enhanced with the virtual window concept and an NLP method for optimal steering. A dual feed-forward neural network approach is used for both rudder angle and propeller revolution output, and verified without wind conditions. Additional ANNs were trained considering wind gust disturbances.

The maneuvering plan for safe docking is divided into course changes, step deceleration, and stopping. Using the NLP method, the authors create virtual windows for course changes, ensuring optimal time maneuvers and a smooth transition to the docking point. Two separate feed-forward multilayered ANN controllers were tested to determine the best-suited structure for teaching data for rudder angle and propeller revolution output. A Proportional-Derivative (PD) controller is utilized for handling low-speed disturbances when the ship's maneuverability decreases due to wind gusts.

The ANN controllers are evaluated and verified using teaching data in different wind conditions. Wind disturbances are recreated with gusts of different velocities and directions. Due to the high noise in low-speed vessel motion, a PD controller is introduced to prevent deviation from the course line. The ANN-PD controller is verified with automated docking simulations under various initial conditions and wind disturbances.

In conclusion, the research demonstrates that an ANN trained with consistent teaching data effectively automates the docking process, even in the presence of gust wind disturbances. The use of NLP methods and the concept of virtual windows in the creation of teaching data led to improved docking maneuvers. The separate feed-forward ANN for rudder and propeller revolution output proved effective under no wind and gust wind conditions. The ANN-PD controller was robust even under different initial conditions and wind disturbances, validating the potential for automated docking systems in real-world applications.

A facsimile from this publication is given in Figure 17.

2) QUASI REAL-TIME OPTIMAL CONTROL SCHEME FOR AUTOMATIC BERTHING [88]

The publication by Mizuno et al. received the highest DCI-Score of Epoch 4, for that reason, its summary is presented in this section.

This paper introduces a quasi real-time method for automated docking using a multiple shooting algorithm for trajectory planning and NMPC for trajectory tracking. This solution overcomes conventional computational time challenges, rapidly generating an optimal trajectory while compensating for tracking errors and disturbances. The system's effectiveness is demonstrated in both computer simulations and real sea trials.

According to the authors, compared to SCGR multiple shooting is less accurate but yields a sufficient solution within minutes, which is deemed an acceptable amount of time for a real-time method. The proposed solution uses an optimal control scheme for quasi-real-time control. A sufficiently accurate solution to the minimum time maneuvering problem, given initial and final docking poses is generated. However, only the input at t_0 is used for real-time control.

The system was evaluated first in a simulation with wind disturbance, and then experimentally on the ship Shioji Maru. The ship is successfully controlled to a final pose with positional errors of $0.5m$ in the x-axis, $5.0m$ in the y-axis, and $-15.10°$ in the heading. A GNSS receiver and a gyroscope are used to obtain estimates of the ship's states.

This paper introduces a novel, quasi real-time optimal control scheme for automated docking, and is one of the first works to use optimal control in a full-scale experimental setup. The system demonstrates effective trajectory tracking performance by generating approximate solutions in a short computing time. Verification through actual sea trials further underscores the effectiveness and potential applicability of the proposed scheme in real-world settings.

A facsimile from this publication is given in Figure 18.

TABLE 10. Geographical distribution of the publications from 2016-2018.

Country	Number of publications	Cumulative citations
South Korea	8	163
Norway	3	12
China	2	47
Japan	2	7
Vietnam	1	32
Netherlands	1	20
Slovenia	1	14
Russia	1	9
Turkey	1	4
Portugal	1	3

TABLE 11. Citations and DCI-Score from selected publications and the mean from 2016-2018.

	Author	Publication	Citations	DCI-Score
Mean	-	[91]–[103], [105]–[110], [112], [113]	15.6	3.704
Top cited	Im et al.	[103]	**66**	4.617
Top 1 DCI	Lee et al.	[96]	11	**6.008**
Top 2 DCI	Park et al.	[97]	40	5.783
Top 3 DCI	Skjåstad et al.	[110]	0	5.458

F. EPOCH 5: 2016-2018

During the 2016-2018 period, 21 articles were produced [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [103], [105], [106], [107], [108], [110], [112], [102], [109], [113]. The publications came from a wide range of nations, including South Korea, Norway, China, Japan, Vietnam, The Netherlands, Slovenia, Russia, Turkey, and Portugal. Refer to Table 10 for distribution by country. South Korean authors were the greatest contributors, with 38% of the publications and 52% of the total citations.

According to Table 11, the article with the highest citation count in this epoch was written by Im et al. [103], originating from South Korea, with 66 citations. Lee et al. [96] was the article with the highest DCI-Score, attaining a score of 6.008. This score represents an increase of 0.666 from Epoch

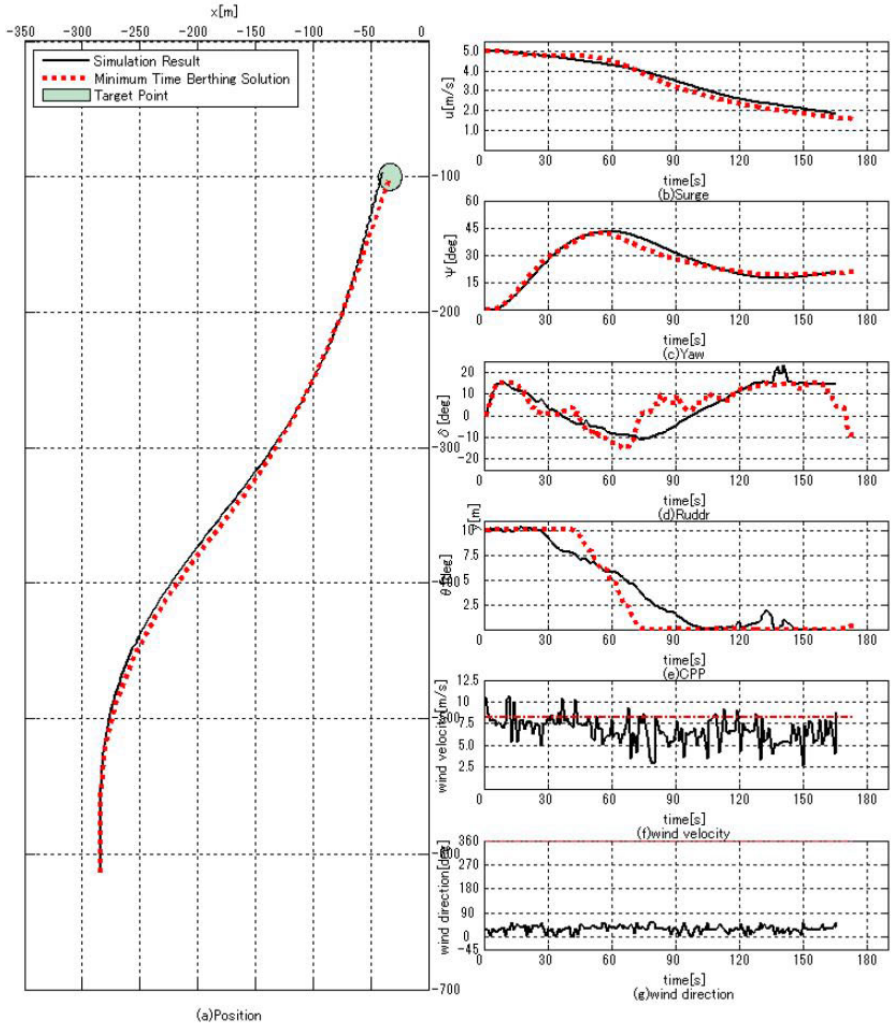


FIGURE 18. **Facsimile from *Quasi Real-Time Optimal Control Scheme for Automatic Berthing* [88].**

4's high score [88]. The mean DCI-Score for this epoch was 3.704, a slight decline of 0.088 from the average score of Epoch 4. The DCI of the most cited paper, the highest DCI-Score, and the epoch's mean are depicted in Figure 19. It proved difficult to obtain a copy of [109], subsequently, it was left out of the DCI.

1) ARTIFICIAL NEURAL NETWORK CONTROLLER FOR AUTOMATIC SHIP BERTHING USING HEAD-UP COORDINATE SYSTEM [103]

The publication by Im et al. received the highest number of citations in Epoch 5, for that reason, its summary is presented in this section.

This research presents a new ANN controller for automated docking. Unlike previous ANN controllers, this model, using a head-up coordinate system, eliminates the need for retraining at each new port, improving efficiency. This model's effectiveness was confirmed through numerical simulations.

The researchers designed a shallow ANN controller for automated docking using a head-up coordinate system, considering the relative bearing and distance from the ship to the berth. A data converter was then employed to transition ship states from the North-up coordinate system into the head-up system for input into the controller. The imaginary line concept was employed to minimize collision risks with the berth during training data generation.

Numerical simulations were conducted in two distinct ports to evaluate this ANN controller. The first was the original port where training data was gathered, and the second had different geometrical coordinates. The results showed successful docking in both ports, even in instances where initial conditions deviated from the original training data.

The introduced ANN controller allows for accurate and adaptable automated docking across a range of ports without the need for retraining. The system is designed to control the vessel from one direction of approach and necessitates a relative bearing within 180 degrees.

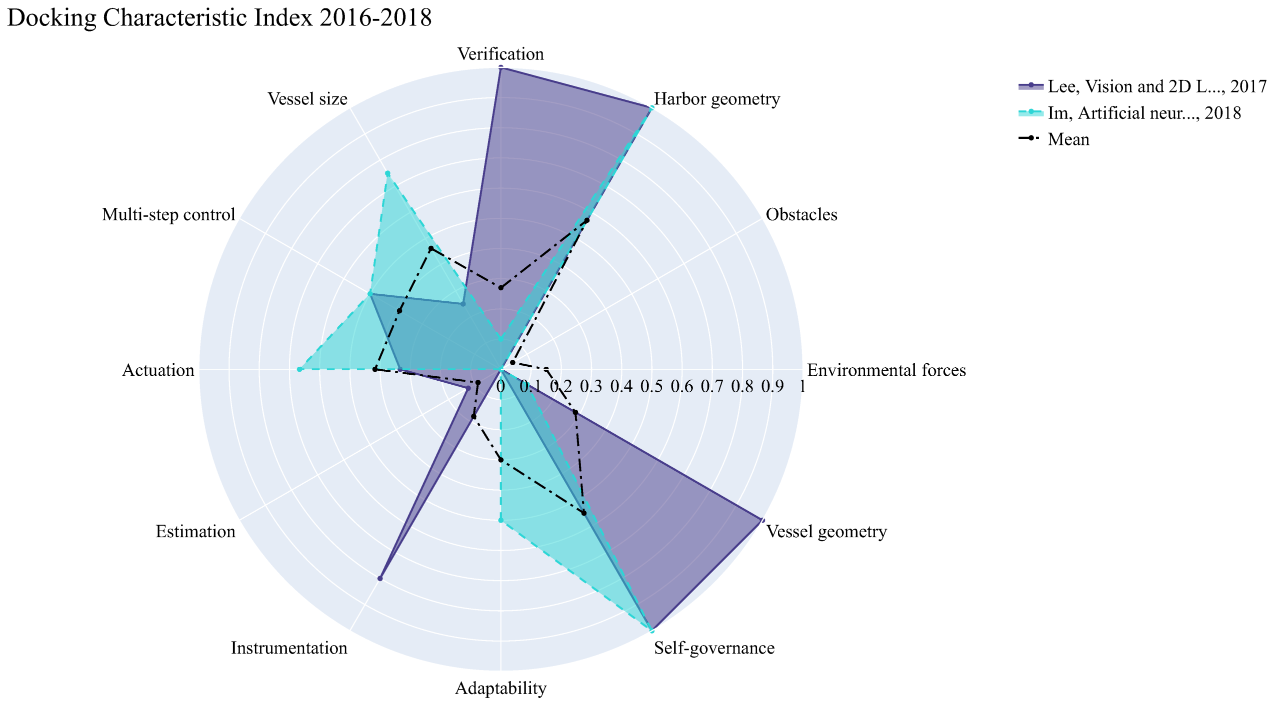


FIGURE 19. DCI for automated docking publications from 2016-2018. The top DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.

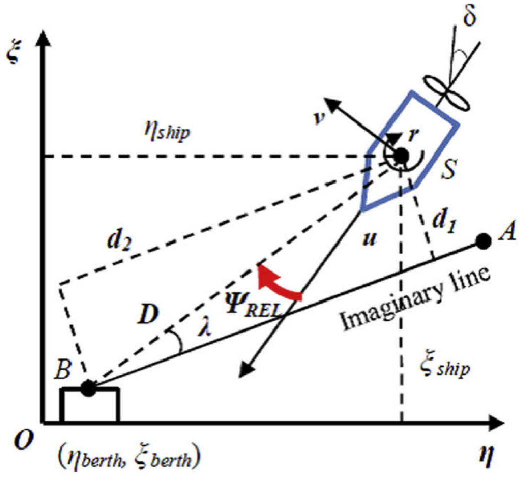


Fig. 3. The parameters in the North-up system and Head-up system.

FIGURE 20. Facsimile from ***Artificial neural network controller for automatic ship berthing using head-up coordinate system*** [103].

A facsimile from this publication is given in Figure 20.

2) VISION AND 2D LIDAR BASED AUTONOMOUS SURFACE VEHICLE DOCKING FOR IDENTIFY SYMBOLS AND DOCK TASK IN 2016 MARITIME ROBOTX CHALLENGE [96]

The publication by Lee et al. received the highest DCI-Score of Epoch 5, for that reason, its summary is presented in this section.

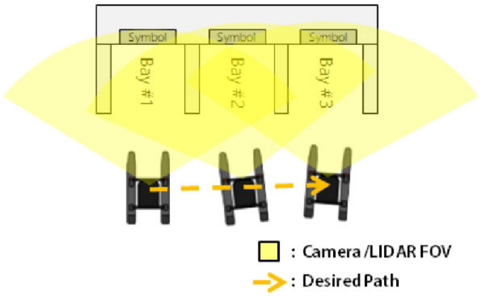


Fig. 6. The ASV moves from one bay to another bay with its heading fixed.

FIGURE 21. Facsimile from ***Vision and 2D LiDAR based autonomous surface vehicle docking for identify symbols and dock task in 2016 Maritime RobotX Challenge*** [96].

The research paper presents an approach for automated docking, incorporating vision and 2D LiDAR technology as part of the 2016 Maritime RobotX Challenge. This involved the automatic location of docking bays using LiDAR, symbol identification through template matching, and Euclidean distance measurement in HSV color space. To minimize collision risks, lateral position alignment was performed before docking.

The docking operation follows a state machine algorithm. The ASV first estimates the positions of the docking bays using LiDAR data, then moves closer to facilitate symbol identification. When sufficiently close, image processing begins with color thresholding and down-sampling using LiDAR-camera calibration data. Before the ASV proceeds to the bay, lateral position alignment, based on the

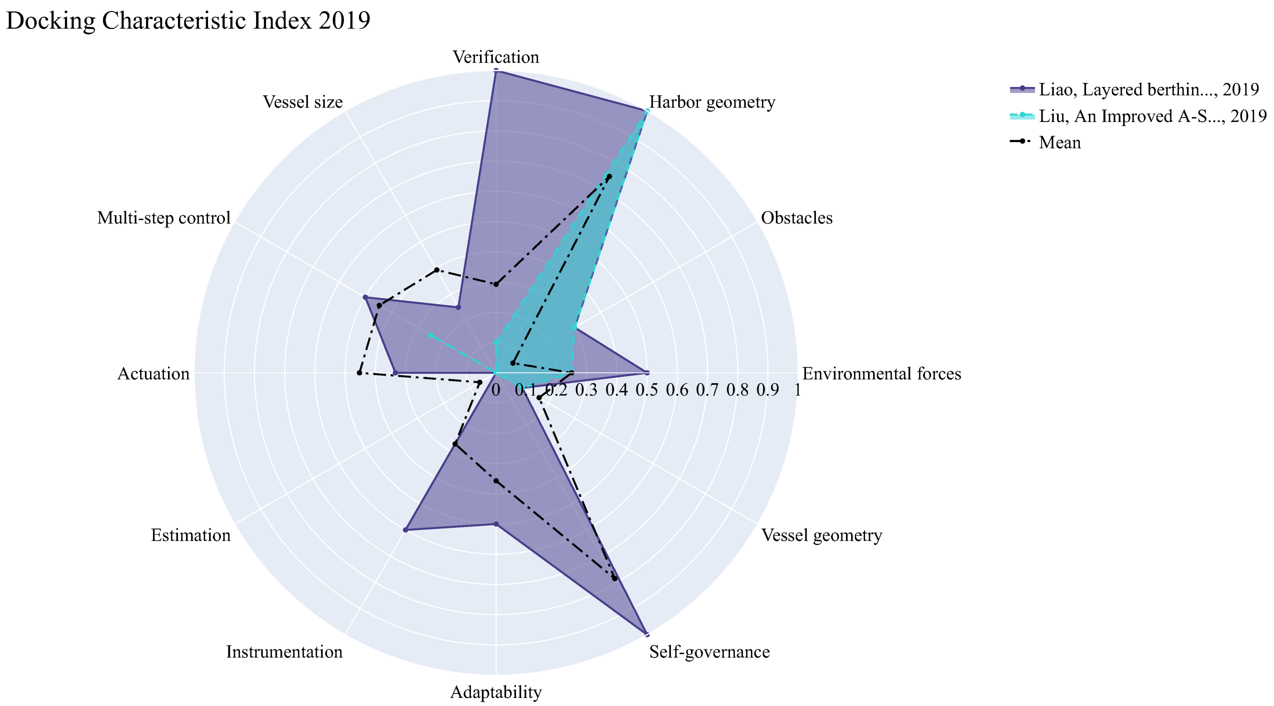


FIGURE 22. DCI for automated docking publications from 2019. The top DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.

TABLE 12. Geographical distribution of the publications from 2019.

Country	Number of publications	Cumulative citations
China	5	203
Norway	3	35
Portugal	2	21
Vietnam	2	20
Japan	1	11
South Korea	1	16

TABLE 13. Citations and DCI-Score from selected publications and the mean from 2019.

	Author	Publication	Citations	DCI-Score
Mean	-	[114]–[120], [123]–[127], [129], [130]	21.9	4.290
Top cited	Liu et al.	[119]	**88**	2.000
Top 1 DCI	Liao et al.	[118]	33	**6.083**
Top 2 DCI	Leite	[117]	2	5.083
Top 3 DCI	Mizuno et al.	[117]	11	4.883

Lidar scanning data, reduces docking failure risk. Next, the ASV sequentially enters the bays using predefined locations, adjusting its position and heading to reduce collision risks. Although not explicitly mentioned, a PID controller is assumed for low-level control based on the standard practice in similar systems.

The ASV was equipped with a computer system, communication module, sensor module, propulsion system, LED indicator, and an emergency switch. The sensor module comprised navigational sensors and a perception system with a 2D LiDAR and two monocular cameras. The propulsion system included four thrusters, two main, and two side thrusters. Full-scale experiments were conducted at Jangseong-lake and Han-river, South Korea, for all procedures except lateral position alignment. The ASV performed the docking task autonomously, mapping the docking bays, detecting symbols, and identifying symbols with high accuracy.

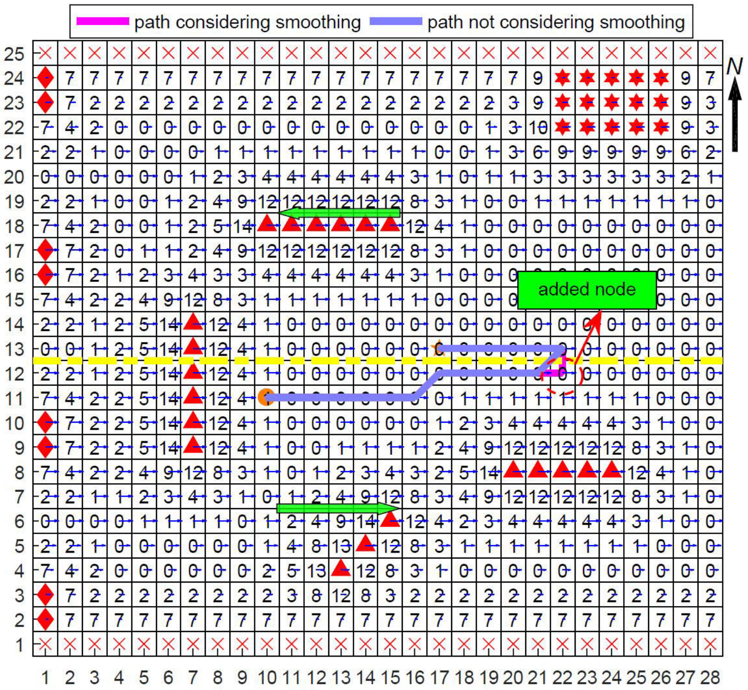
The system leveraged vision and Lidar sensors for perception and symbol identification. The validation of the developed algorithm was done through full-scale physical experiments. Although the solution demonstrates a remarkable application of integrated measurements from multiple sensors in tackling the docking problem for a small ASV within a nonconvex harbor environment, it does rely on installed targets.

A facsimile from this publication is given in Figure 21.

G. EPOCH 6: 2019

The year 2019 saw the publication of 14 articles related to the topic [115], [116], [120], [125], [114], [117], [118], [119], [123], [127], [129], [130], [124], [126]. The authors were associated with institutions in China, Norway, Portugal, Vietnam, Japan, and South Korea. Country-specific distribution can be found in Table 12. Of note, Chinese researchers authored approximately 36% of the articles and received around 66% of the total citations this year.

As highlighted in Table 13, the most-cited article of this period was written by Liu et al. [119], which amassed 88 citations. Liao et al. [118] authored the article with the highest DCI-Score, scoring 6.083. This represents a marginal



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
25	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕
24	◆	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	9	✱	✱	✱	✱	✱	9	7
23	◆	7	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	9	✱	✱	✱	✱	✱	9	3
22	7	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	10	✱	✱	✱	✱	✱	9	3
21	2	2	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	3	6	9	9	9	9	9	6	2
20	0	0	0	0	0	0	1	2	3	4	4	4	4	4	4	3	1	0	1	1	3	3	3	3	3	3	2	1
19	2	2	1	0	0	1	2	4	9	12	12	12	12	12	12	8	3	1	0	0	1	1	1	1	1	1	1	0
18	7	4	2	0	0	1	2	5	14	▲	▲	▲	▲	▲	▲	12	4	1	0	0	0	0	0	0	0	0	0	0
17	◆	7	2	0	1	1	2	4	9	12	12	12	12	12	12	8	3	1	0	0	0	0	0	0	0	0	0	0
16	◆	7	2	1	2	3	4	3	3	4	4	4	4	4	4	3	1	0	0	0						0	0	0
15	7	4	2	2	4	9	12	8	3	1	1	1	1	1	1	1	0	0	0	0						0	0	0
14	2	2	1	2	5	14	▲	12	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	1	2	5	14	▲	12	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	2	2	1	2	5	14	▲	12	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	7	4	2	2	5	14	▲	12	4	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0
10	◆	7	2	2	5	14	▲	12	4	1	0	0	0	0	0	0	1	2	3	4	4	4	4	4	3	1	0	0
9	◆	7	2	2	5	14	▲	12	4	1	0	0	1	1	1	1	2	4	9	12	12	12	12	12	8	3	1	0
8	7	4	2	2	4	9	12	8	3	1	0	1	2	3	4	3	2	5	14	▲	▲	▲	▲	▲	12	4	1	0
7	2	2	1	1	2	3	4	3	1	0	1	2	4	9	12	8	3	4	9	12	12	12	12	12	8	3	1	0
6	0	0	0	0	1	1	1	1	0	1	2	4	9	14	▲	12	4	2	3	4	4	4	4	4	3	1	0	0
5	2	2	1	0	0	0	0	0	0	1	4	8	13	▲	12	8	3	1	1	1	1	1	1	1	1	0	0	0
4	7	4	2	0	0	0	0	0	0	2	5	13	▲	12	8	3	1	0	0	0	0	0	0	0	0	0	0	0
3	◆	7	2	2	2	2	2	2	2	2	3	8	12	8	3	2	2	2	2	2	2	2	2	2	2	2	2	2
2	◆	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
1	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕	✕

Figure 10. Combined path generated by an improved A-Star algorithm considering or not considering smoothing (The definition of the graphic symbols in this figure is the same as the definition in Figure 7).

FIGURE 23. Facsimile from ***An Improved A-Star Algorithm Considering Water Current, Traffic Separation and Berthing for Vessel Path Planning*** [119].

increase of 0.075 from Epoch 5's high score [96]. The mean DCI-Score for 2019 rose by 0.586 to 4.290. Figure 22 graphically presents the DCI of the most cited paper, the highest DCI-Score, and the mean for this epoch.

1) AN IMPROVED A-STAR ALGORITHM CONSIDERING WATER CURRENT, TRAFFIC SEPARATION AND BERTHING FOR VESSEL PATH PLANNING [119]

The publication by Liu et al. received the highest number of citations in Epoch 6, for that reason, its summary is presented in this section.

This paper proposes an improvement to the A-Star (A*) algorithm for path planning. The traditional A-Star algorithm generates an optimal path by minimizing path cost. However, it falls short when considering multiple variables crucial for a vessel, including path length, obstacle collision risk, traffic separation rules, maneuverability restrictions, and water current. The research addresses these drawbacks by incorporating various risk models into the algorithm and validates its proposed method through simulation and real scenarios.

The research introduces a modified A-Star algorithm that prioritizes both path length and safety by considering obstacle avoidance, traffic separation, maneuverability restriction, and the impact of water currents. It categorizes obstacles into five types, each with different navigational risks, and factors these into the path-planning process. The paper also considers the need for vessels to adhere to traffic separation rules to mitigate collision risks and improve operational efficiency. Additionally, it provides insights into docking modeling and turning radius restriction.

The proposed algorithm was evaluated through four simulation case studies, examining normal path planning, path planning for docking, and combined path planning. The simulations demonstrated the algorithm's ability to generate safer paths for vessels, even under the influence of water currents and docking constraints.

The improved A-Star algorithm proves effective in achieving a balance between path length and navigation safety, successfully accommodating various risk models into vessel path planning. Simulations proved that the algorithm works in complex, but discreet, harbor environments. While the study provides a promising strategy for minimizing collision risks and improving operational efficiency, it acknowledges potential areas for future research. These include considering factors such as wind and water depth, which also significantly influence ship navigation safety and energy consumption. However, the paper does not account for whether the proposed paths are feasible considering the ship's dynamics, limitations to actuators, or the geometrical constraints of the ship. Further, the discreet map might not provide the needed accuracy for more confined waters.

A facsimile from this publication is given in Figure 23.

2) LAYERED BERTHING METHOD AND EXPERIMENT OF UNMANNED SURFACE VEHICLE BASED ON MULTIPLE CONSTRAINTS ANALYSIS [118]

The publication by Liao et al. received the highest DCI-Score of Epoch 6, for that reason, its summary is presented in this section.

This paper presents a novel approach to automated docking of unmanned MSVs, employing a two-phased strategy: the remote phase and the terminal phase. It proposes an improved artificial potential field method for trajectory planning, taking into account static obstacles, docking pose constraints, and the MSV's dynamics. To solve control issues associated with weak maneuverability, large disturbances, and constrained water area, it further suggests an adaptive fuzzy PID control method. The method is validated through docking simulations and a field experiment with the Dolphin-I small ASV.

During the remote phase, the method effectively devises a trajectory between the initial position of the MSV and the transitional position of the desired berth. Two significant issues encountered with the traditional artificial potential field method are addressed: local minima and bending angle. These issues are resolved using an obstacle compensation method that considers MSV's movement constraint and the distance between the obstacle and target. The terminal phase employs an enhanced artificial potential field method, combining virtual obstacles and targets to plan the trajectory in the wharf area close to the berth, adhering to the constraints of the MSV and quay. To optimize the system's control, a real-time adjusted PID parameter through fuzzy inference is utilized, applying different fuzzy rules for each phase of docking.

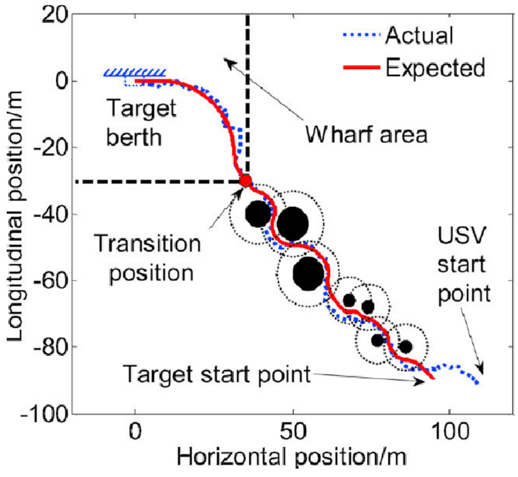


Fig. 31. Berthing track of USV with the proposed APF.

FIGURE 24. Facsimile from *Layered berthing method and experiment of unmanned surface vehicle based on multiple constraints analysis* [118].

The feasibility of the proposed method was verified using the Dolphin-I small ASV in a real-world experiment in the Songhua River, Harbin. The MSV was equipped with various sensors, including a weather station for GNSS position, speed, magnetic yaw, yaw rate, wind speed/direction, temperature, humidity, and atmospheric pressure. A depth sounder for water depth, inertial navigation, and a current and voltage sensor for the propeller, control system, and battery status. The MSV also had a radio communication module for real-time data transmission and communication with the shore terminal.

The paper successfully devises a novel automated docking methodology for small MSVs, presenting obstacle avoidance and virtual target point guidance methods for efficient trajectory planning. The proposed adaptive fuzzy PID control outperformed traditional PID methods in simulation tests, offering better tracking capabilities. The field experiment demonstrated that the improved artificial potential field method proposed is highly effective and feasible. The authors discuss future improvements with the aim to consider dynamic obstacles during docking and conducting experiments in high-disturbance sea conditions.

A facsimile from this publication is given in Figure 24.

H. EPOCH 7: 2020

In the year 2020, a total of 15 papers focusing on automated docking were published, as seen in [133], [134], [140], [142], [146], [147], [149], [150], [151], [136], [141], [143], [145], [148], and [152]. These publications were authored by researchers from a variety of countries, including Norway, Japan, China, Sweden, Slovenia, Vietnam, and South Korea. A breakdown of contributions by country is provided in Table 14. Norwegian researchers authored the largest amount of publications this epoch, with approximately 53% of the total, accounting for about 25% of total citations. Meanwhile, the 2 Japanese publications accounted for approximately 37% of total citations.

As indicated in Table 15, the paper with the most citations in this period was written by Maki et al. [141], gathering 59 citations. Martinsen et al. [142] achieved the highest DCI-Score of the epoch, scoring 6.208. An increase of 0.125 from the top score from Epoch 6 [118]. The mean DCI-Score for this period was 4.527, an increase of 0.237 from Epoch 6. The DCI of the most cited paper, the highest DCI-Score, and the mean for this epoch are visually illustrated in Figure 25.

1) APPLICATION OF OPTIMAL CONTROL THEORY BASED ON THE EVOLUTION STRATEGY (CMA-ES) TO AUTOMATIC BERTHING [141]

The publication by Maki et al. received the highest number of citations in Epoch 7, for that reason, its summary is presented in this section.

This research tackles the complexity of automated docking using optimal control theory based on CMA-ES, a state-of-the-art evolutionary computation approach. The authors modeled the automated docking control problem as a minimum-time problem, addressing the nonlinearity of the low-speed maneuvering model and the risk of collision with the berth.

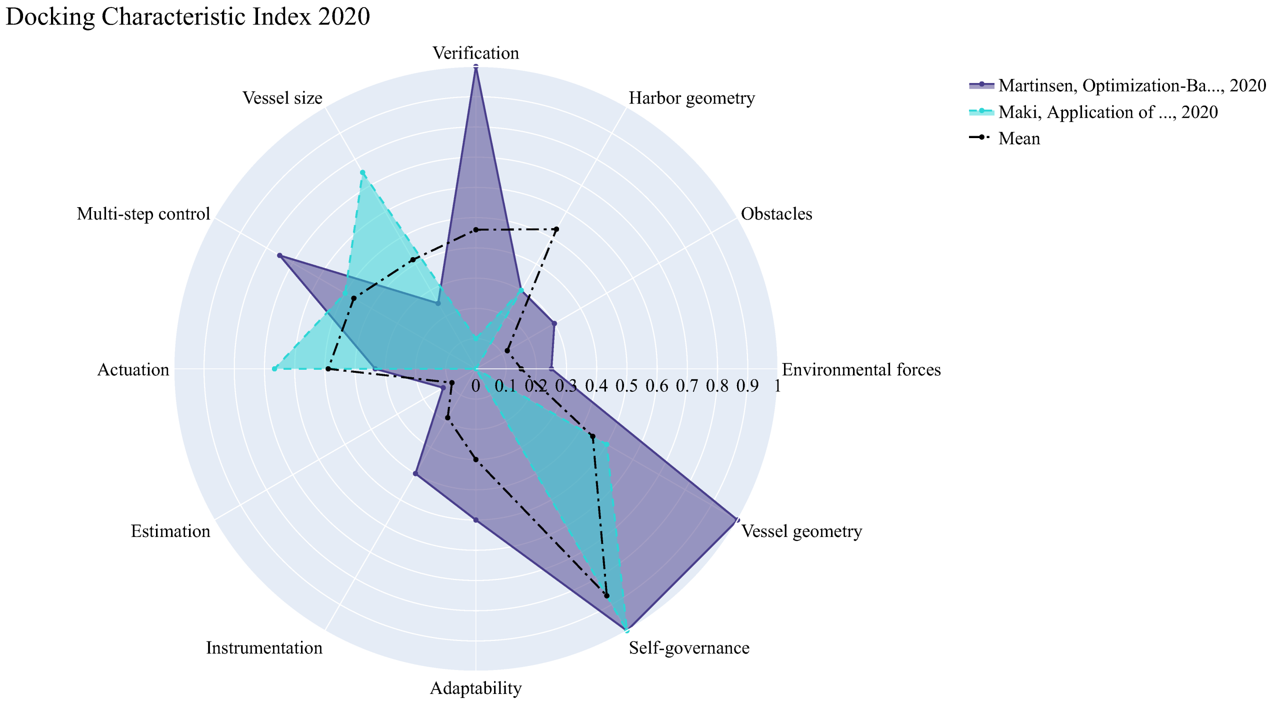


FIGURE 25. DCI for automated docking publications from 2020. The top DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.

Though the calculation method is offline, it lays a robust foundation for future online control improvements.

TABLE 14. Geographical distribution of the publications from 2020.

Country	Number of publications	Cumulative citations
Norway	8	55
Japan	2	83
China	1	33
Sweden	1	22
Slovenia	1	17
Vietnam	1	9
South Korea	1	5

TABLE 15. Citations and DCI-Score from selected publications and the mean from 2020.

	Author	Publication	Citations	DCI-Score
Mean	-	[133], [134], [136], [140]–[143], [145]–[152]	14.9	4.527
Top cited	Maki et al.	[141]	**59**	3.817
Top 1 DCI	Martinsen et al.	[142]	26	**6.208**
Top 2 DCI	Bitar et al.	[134]	18	5.758
Top 3 DCI	Torvund et al.	[151]	2	5.442

The research utilizes CMA-ES to solve the optimal docking problem. The numerical method employed incorporates the control inputs of a main thruster and a rudder. Using the evolutionary computation of CMA-ES, the problem was solved without the need for a high-quality, feasible initial control input. CMA-ES employs multivariate normal distribution for stochastically generating new search points and updating distribution parameters, resulting in promising candidate solutions. The two-point boundary problem, where initial and final states are fixed, was modeled as a minimum-time problem, with additional constraints considered in an extended objective function to avoid collision with the berth.

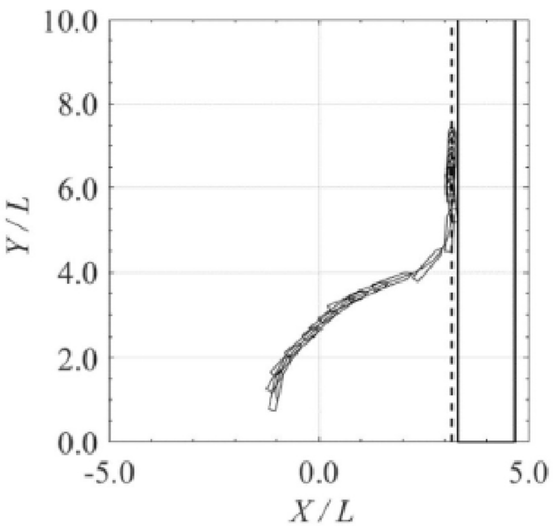


FIGURE 26. Facsimile from *Application of optimal control theory based on the evolution strategy (CMA-ES) to automatic berthing* [141].

A geometric scale model of the supertanker MV Esso Osaka was used for the simulations, complete with propeller forces and rudder forces estimated based on both forward and backward propeller rotations and ship moving speeds. The performance of the system was evaluated with the ship's behavior during a stopping maneuver in simulations. As the calculation method is offline, computation time is not a primary concern and the results can be applied as an initial guess for online calculation methods.

The study employs CMA-ES to address the intricate automated docking problem, achieving satisfactory results without necessitating a good initial guess. The current focus of the research is limited to vessels possessing only a rudder and propeller. However, the authors indicate future work could expand the scope to vessels fitted with advanced features such as bow/stern thrusters and high-performance rudder systems. The authors claim to be working on transitioning the offline findings into online control methodologies and integrating practical constraints on the frequency of propeller switches and rudder speed.

A facsimile from this publication is given in Figure 26.

2) OPTIMIZATION-BASED AUTOMATIC DOCKING AND BERTHING USING EXTEROCEPTIVE SENSORS: THEORY AND EXPERIMENTS [142]

The publication by Martinsen et al. received the highest DCI-Score of Epoch 7, for that reason, its summary is presented in this section.

The paper introduces an optimization-based method for performing docking with MSVs. It formulates the objective as a nonlinear optimal control problem, aiming to plan collision-free trajectories. Key contributions include incorporating harbor map data and exteroceptive sensor readings, such as LIDAR and ultrasonic distance sensors, for dealing with map inaccuracies and unmapped objects. The method also generates a safe operating region in real-time for trajectory planning and employs a trajectory-tracking dynamic positioning controller for tracking the planned path. The method was successfully tested on a small MSV in Trondheim, Norway, demonstrating efficient docking in the presence of static obstacles.

Building on existing methodologies, this work introduces a dynamic map generation approach for identifying safe operating regions in real-time. The study further enhances exteroceptive sensor data integration to offset map inaccuracies and unmapped objects. By leveraging onboard sensors and map data, the approach facilitates real-time planning of secure, feasible trajectories, marking a substantial progression in the field. The docking problem is addressed by formulating an Optimal Control Problem (OCP) considering both vessel dynamics and harbor layout. An NMPC generates the optimal trajectory, consisting of position, heading, and thrust control signals, while a lower-level DP controller performs trajectory tracking, counteracting modeling errors and external forces with feedback signals.

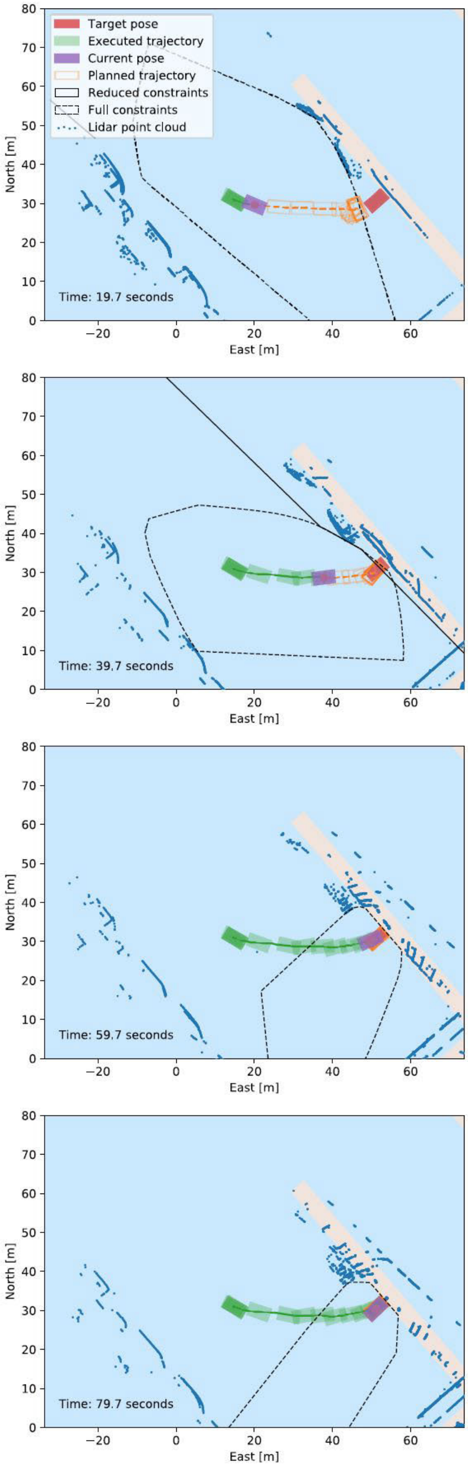


FIGURE 13. Visualisation of the docking motion during the experiments on September 11th 2020 (E2).

FIGURE 27. Facsimile from *Optimization-Based Automatic Docking and Berthing Using Exteroceptive Sensors: Theory and Experiments* [142].

The spatial constraints, derived from map and sensor data, provide a convex inner approximation of the surrounding obstacles. This is done by combining map-based spatial constraints with LIDAR point cloud data and short-range ultrasonic distance measurements, ensuring improved accuracy of spatial constraints. The proposed algorithm was implemented on the experimental autonomous ferry, milliAmpere, and validated in confined waters in Trondheim, Norway.

The proposed technique effectively plans and executes docking maneuvers in confined harbors. The full-scale physical experiments on the milliAmpere ferry validate this method, confirming its capability to plan and implement safe, collision-free docking maneuvers. Future work aims to incorporate additional sensors, enhance sensor data reliability, and devise control and planning strategies for fully autonomous operations, including transportation phases.

A facsimile from this publication is given in Figure 27.

TABLE 16. Geographical distribution of the publications from 2021.

Country	Number of publications	Cumulative citations
Norway	5	49
China	3	33
Japan	2	11
Netherlands	1	17
Portugal	1	15
Germany	1	7
South Korea	1	2

TABLE 17. Citations and DCI-Score from selected publications and the mean from 2021.

	Author	Publication	Citations	DCI-Score
Mean	-	[154]–[158], [161], [163], [165], [166], [168], [171], [172], [174], [175]	9.6	4.700
Top cited	Skulstad et al.	[171]	**27**	3.908
Top 1 DCI	Martinsen	[166]	1	**6.208**
Top 2 DCI	Bitar	[155]	0	**6.208**
Top 3 DCI	Xiong et al.	[175]	12	5.817

I. EPOCH 8: 2021

In 2021, there were 14 scholarly articles on automated docking published by researchers from Norway, China, Japan, The Netherlands, Portugal, Germany, and South Korea [154], [155], [156], [157], [158], [161], [163], [165], [166], [168], [171], [172], [174], [175]. The country-wise distribution of these articles is presented in Table 16. Researchers from Norway were the largest contributors, accounting for about 36% of the articles and receiving approximately 37% of all citations.

Table 17 shows that the article by Skulstad et al. [171] received the highest number of citations for the period, 27. Furthermore, the two publications with the highest DCI-Scores were the Ph.D. theses of Martinsen [166] and Bitar [155] respectively. Interestingly, both Martinsen's and Bitar's Ph.D. theses have the same DCI-Score as Epoch 7's top-scoring publication [142]. This is due to the fact that they both include the article [142] in their theses. To avoid redundancy, we will instead review the publication from Xiong et al. [175], which has a DCI-Score of 5.817, slightly lower than the highest score by 0.391. The mean DCI-Score for the epoch was 4.700, representing an increase of 0.227 compared to the average in Epoch 7. Figure 28 provides a graphical depiction of the DCI of the most cited paper, the work from Xiong et al. [175], and the mean DCI-Score of this epoch.

1) A HYBRID APPROACH TO MOTION PREDICTION FOR SHIP DOCKING - INTEGRATION OF A NEURAL NETWORK MODEL INTO THE SHIP DYNAMIC MODEL [171]

The publication by Skulstad et al. received the highest number of citations in Epoch 8, for that reason, its summary is presented in this section.

This paper proposes an onboard support tool for ship docking operations, offering position predictions by integrating a supervised Machine Learning (ML) model with a ship dynamic model. This hybrid model reduces the black-box nature often found in purely data-driven predictors, while enhancing prediction accuracy. A 30-second ahead prediction during docking operations was examined using historical data from the research vessel Gunnerus. Results indicate the ML model integration significantly improves the prediction accuracy.

The paper focuses on developing an onboard tool to support manual docking operations, facilitating appropriate and timely actuator adjustments. The proposed hybrid model offers future motion predictions, utilizing data from Gunnerus to train the data-driven ML component. The model forecasts the ship's position for the next 30 seconds, thereby assisting the operator in making informed navigation decisions. The process integrates the ship dynamic model, offering an understanding of the ship's likely movement, and an ML model to compensate for unmodeled behavior or inaccuracies.

The hybrid model was validated using data from Gunnerus, a coastal ship owned by the Norwegian University of Science and Technology (NTNU). Historical data from the period between August 2016 and June 2017, acquired via an onboard data acquisition system, was used for model training and testing. The method isolated successful docking instances, creating a matrix of measurements for each operation. The data was processed to generalize the position coordinates across docking locations. After running the vessel model predictor, an error signal was generated to create training targets for the long short-term memory networks. The hybrid model's performance was compared to that of the vessel model, indicating the former's superior accuracy.

The proposed hybrid model effectively combines a ship dynamic model with a data-driven predictor, utilizing the methodology of the long short-term memory neural network. This fusion has heightened the average accuracy throughout the prediction interval. The average distance error in position predictions was reduced from 8.9m, as per the vessel model, to 4.7m with the hybrid model. The authors have indicated that future research will investigate the potential

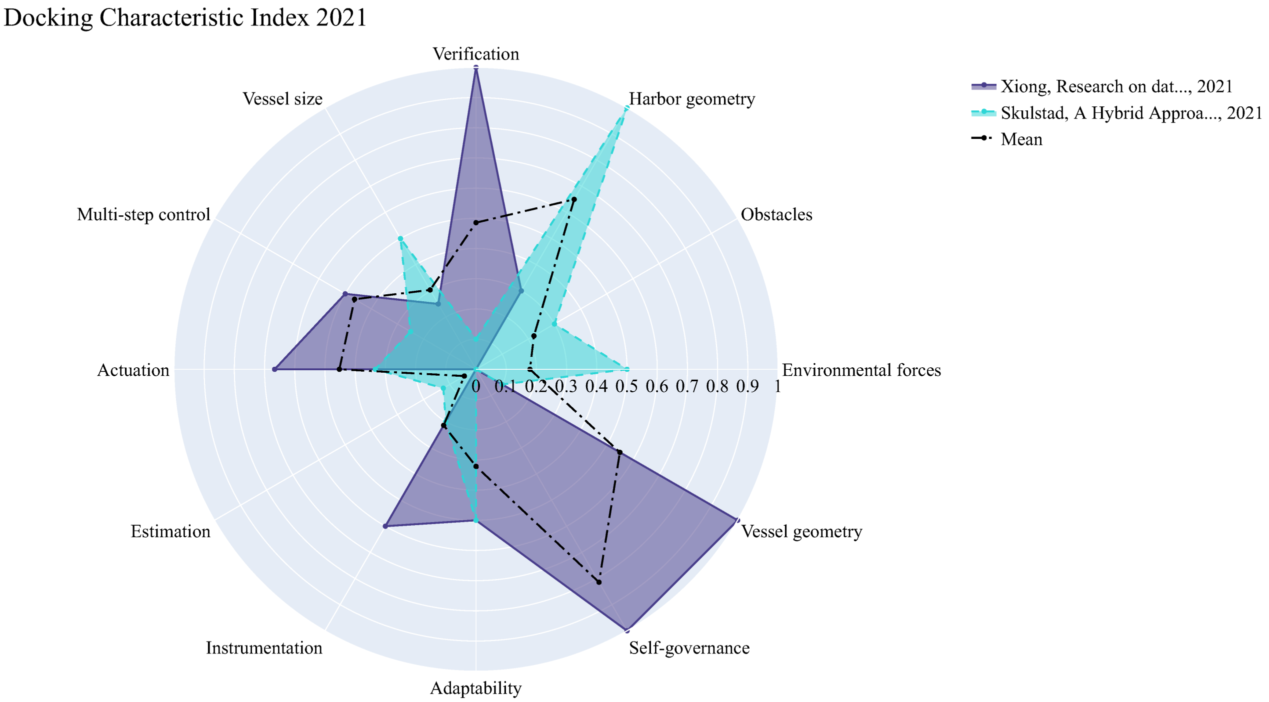


FIGURE 28. DCI for automated docking publications from 2021. The third highest DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.

of employing hybrid position predictions for an automatic motion controller, thereby enhancing the efficiency and precision of automated docking operations. The addition of wind predictions is also slated for future consideration.

A facsimile from this publication is given in Figure 29.

2) RESEARCH ON DATA DRIVEN ADAPTIVE BERTHING METHOD AND TECHNOLOGY [175]

The publication by Xiong et al. received the 3rd highest DCI-Score of Epoch 8, and to avoid restating previous works its summary was decided to be presented in this section instead of [166] or [155].

The paper presents an approach for automated docking of MSVs, utilizing real-time dynamic data collection and direct motion control. It proposes a microwave radar array setup on an MSV for detecting the relative position, attitude of the vessel, and distance from the berth shoreline. The method is composed of upper-level scheduling and lower-level control.

The research method utilizes a real-time data collection hardware architecture and a model-free, data-driven adaptive control approach for direct motion control. The system leverages a vessel-based microwave radar array to detect the relative position, attitude, and distance of the MSV from the berth shoreline. Two controllers are designed as part of this system: the ship course controller and the ship speed controller. The control process is divided into two layers: an upper layer docking scheduling algorithm and a lower layer that performs the actual motion control. The upper scheduling algorithm calculates the MSV's target heading angle and target speed based on the MSV's current position, heading, and speed information.

A critical element of the study is the design and implementation of the hardware architecture. This process encompasses finalizing the hardware design of the experimental ASV, setting up the experimental platform of the automated docking system, and devising appropriate experiments to affirm the system's functionality, stability, and reliability. A key feature of this design is the inclusion of a microwave radar array. Each radar is strategically placed at the vertices of the vessel, which is simplified to a hexagonal shape for the experiment. This setup equips the system with the ability to detect potential shoreline collisions ahead of time, enhancing the safety of the docking process.

In conclusion, the research presents an automated docking algorithm, leveraging real-time data and adaptive control. It achieves automated docking for an MSV by combining microwave radar array and GPS data, and utilizing model-free adaptive control for course and speed management. The algorithm is verified through real experiments using a small-scale ASV.

A facsimile from this publication is given in Figure 30.

J. EPOCH 9: 2022

In 2022, 28 scholarly papers on automated docking were published by authors from Norway, Japan, China, Germany, South Korea, USA, Sweden, and The Netherlands [176], [177], [178], [179], [180], [181], [182], [183], [184], [185], [186], [187], [188], [189], [190], [191], [192], [193], [194],

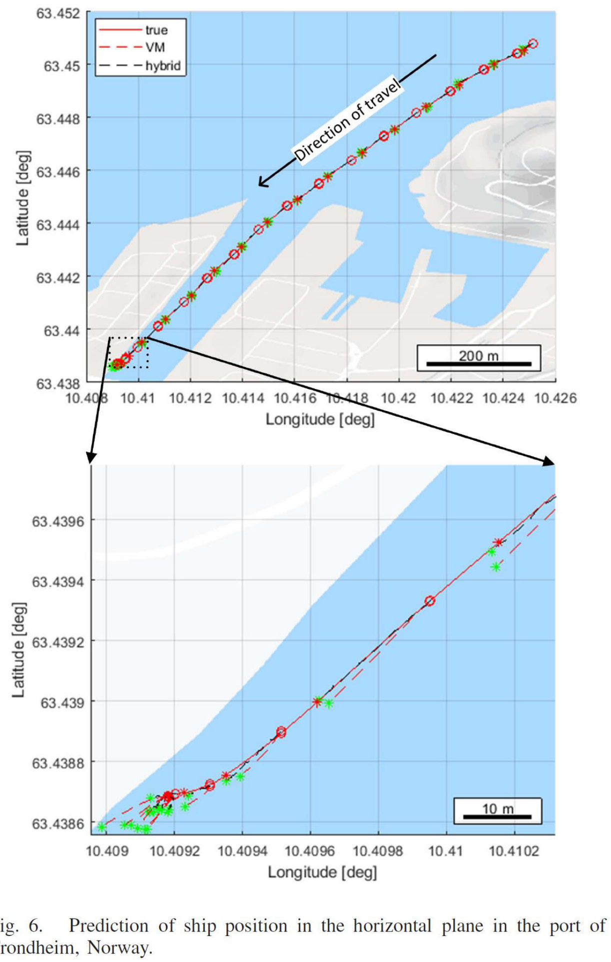


Fig. 6. Prediction of ship position in the horizontal plane in the port of Trondheim, Norway.

FIGURE 29. **Facsimile from *A Hybrid Approach to Motion Prediction for Ship Docking - Integration of a Neural Network Model Into the Ship Dynamic Model* [171].**

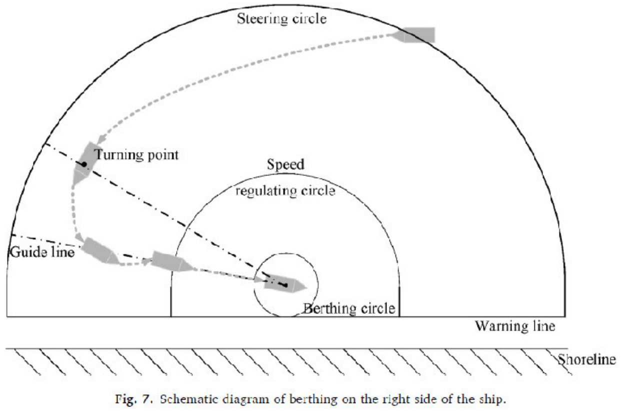


Fig. 7. Schematic diagram of berthing on the right side of the ship.

FIGURE 30. **Facsimile from *Research on data driven adaptive berthing method and technology* [175].**

TABLE 18. **Geographical distribution of the publications from 2022.**

Country	Number of publications	Cumulative citations
Norway	8	27
Japan	6	42
China	5	22
Germany	5	6
South Korea	2	2
USA	1	3
Sweden	1	1
Netherlands	1	0

TABLE 19. **Citations and DCI-Score from selected publications and the mean from 2022.**

	Author	Publication	Citations	DCI-Score
Mean	-	[176]–[203]	2.8	4.093
Top cited	Miyauchi et al.	[191]	**17**	5.558
Top 1 DCI	Kockum et al.	[187]	1	**5.767**
Top 2 DCI	Miyauchi et al.	[191]	**17**	5.558
Top 3 DCI	Miyauchi et al.	[190]	11	5.292

[195], [196], [197], [198], [199], [200], [201], [202], [203]. Table 18 describes the distribution by country. Norwegian researchers were the leading contributors, accounting for around 28% of the articles and earning about 26% of all citations.

Table 19 shows that the publication by Miyauchi et al. [191] received the most citations, 17, and also ranks among the top three in terms of the DCI-Score. The article with the highest DCI-Score was written by Kockum et al. [187], registering a DCI-Score of 5.767, which is a drop of 0.441 from the top scores of epochs 7 and 8. The mean DCI-Score also decreased during 2022, falling by 0.607 to 4.093, possibly due to the broad range of publications produced this year. Figure 31 visually presents the DCI of the most cited paper, the highest DCI-Score, and the mean DCI-Score for this epoch.

1) OPTIMIZATION ON PLANNING OF TRAJECTORY AND CONTROL OF AUTONOMOUS BERTHING AND UNBERTHING FOR THE REALISTIC PORT GEOMETRY [191]

The publication by Miyauchi et al. received the highest number of citations in Epoch 9, for that reason, its summary is presented in this section.

This study introduces an optimized trajectory planning approach for automated docking and undocking of MSVs, accounting for real-world port conditions such as spatial constraints and wind disturbances. The authors propose a collision avoidance algorithm with the port geometry based on the ship domain, which varies in size with the ship's speed. The method accommodates spatial constraints in the optimization process and considers the impact of wind disturbances, ensuring feasible trajectory planning within the actuators' capacity limits. Furthermore, the methodology's applicability extends to both docking and undocking. This study shows the proposed approach's effectiveness in optimizing both control

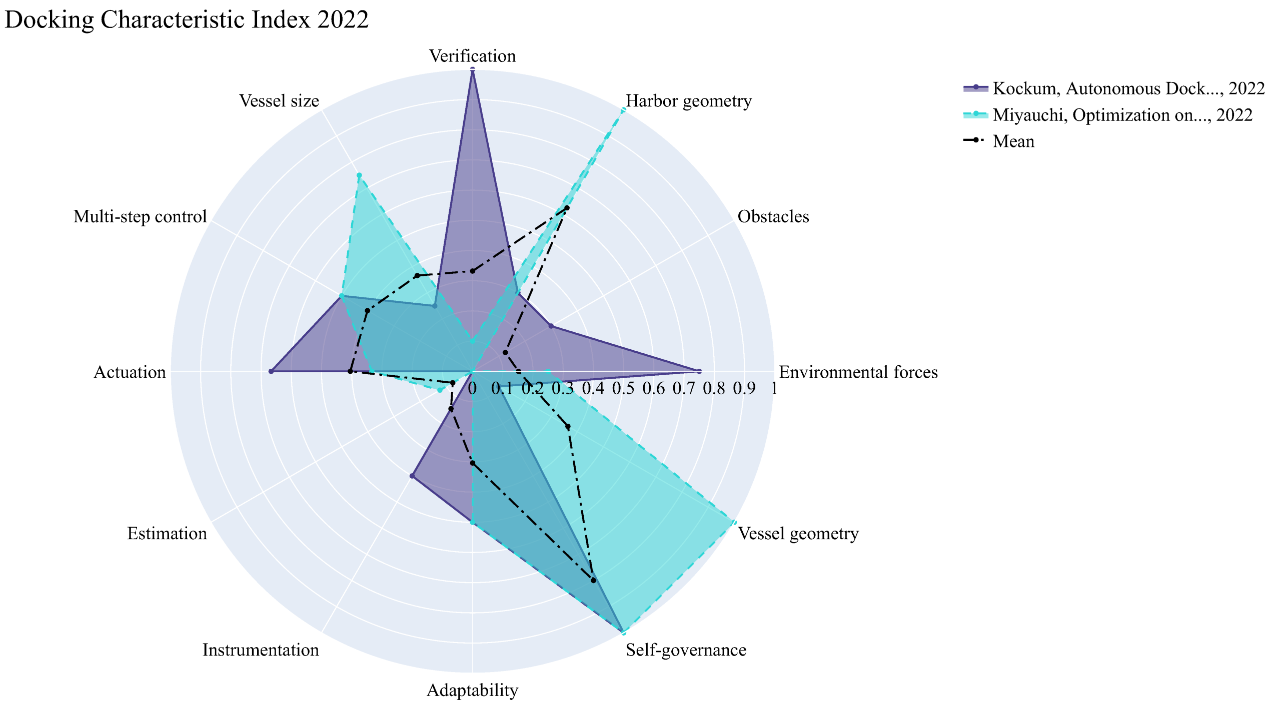


FIGURE 31. **DCI for automated docking publications from 2022. The top DCI-scoring article is dark slate blue, while the highest cited article is turquoise blue.**

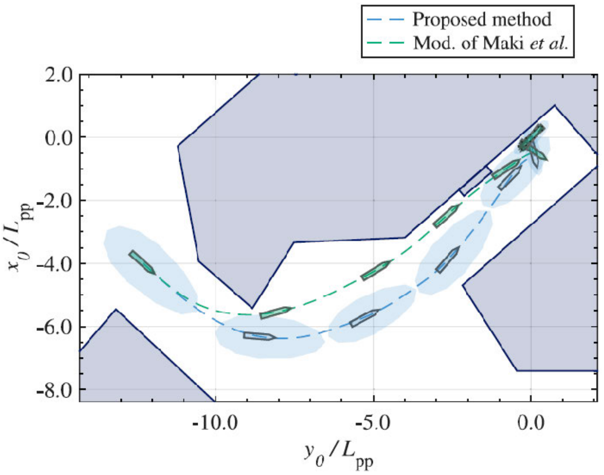


FIGURE 32. **Facsimile from *Optimization on planning of trajectory and control of autonomous berthing and unberthing for the realistic port geometry* [191].**

input and trajectory, while successfully avoiding collisions in two distinct ports.

The authors use the CMA-ES method for trajectory optimization, extending previous research by addressing its limitations like lack of consideration for multiple or arbitrarily shaped berths, safety distance to obstacles, and external disturbances. The proposed collision avoidance algorithm searches for trajectories that maintain an appropriate distance from obstacles. The approach effectively handles complex spatial constraints and wind disturbance, making it suitable for both generating reference trajectories for automated docking and evaluating the ship design's docking capability.

The proposed method is tested on two different ports, Nanko and Ariake, demonstrating its effectiveness in multiple scenarios. The approach's ability to generate collision-free, optimal trajectories, and control inputs while accounting for real port geometry and wind disturbance was confirmed. The optimization, while time-consuming due to its iterative nature, proved suitable for use as a reference in trajectory tracking, and as an evaluation tool to estimate actuator capacity limits under various wind conditions. However, the authors also note the method's current limitations in handling dynamic obstacles and unsteady wind disturbances.

The authors propose a methodology for optimizing trajectory planning in docking and undocking operations, taking into account real port constraints and wind disturbances. Their collision avoidance algorithm ensures sufficient distance from obstacles. This approach has been tested in simulations using real-world port conditions, successfully yielding optimized, collision-free trajectories mindful of spatial constraints and the impact of wind force on the actuators' limits. Despite the long computation time inherent in iterative optimization, this method demonstrates a potential for real-world applications. However, areas identified for future work include improvements in dealing with dynamic obstacles, managing wind fluctuations, and addressing multi-objective optimization problems.

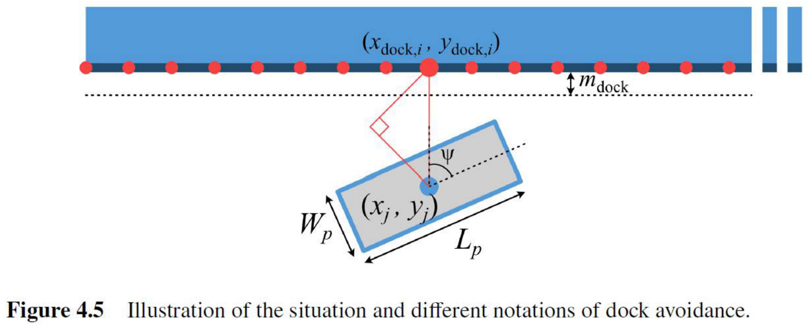


Figure 4.5 Illustration of the situation and different notations of dock avoidance.

FIGURE 33. Facsimile from ***Autonomous Docking of an Unmanned Surface Vehicle using Model Predictive Control*** **[187].**

A facsimile from this publication is given in Figure 32.

2) AUTONOMOUS DOCKING OF AN UNMANNED SURFACE VEHICLE USING MODEL PREDICTIVE CONTROL [187]

The publication by Kockum et al. received the highest DCI-Score of Epoch 9, for that reason, its summary is presented in this section.

This study focuses on the unique challenges of automated docking for MSVs, particularly Saab Kockums' Piraya, an ASV. The main objective was to design and implement an autopilot algorithm using MPC that could manage external disturbances and obstacle avoidance. Several software approaches for optimally reaching the desired position were explored within an MPC framework. The developed controllers were successfully tested through simulations, a small-scale model car, and actual trials on the Piraya vessel.

The core element of the study is the design and implementation of an MPC for automated docking of the MSV. Three navigational approaches each apply different pathfinding strategies: a straight-line path to a single target, a multipoint path via waypoints, and a repeatable path following a previously logged trajectory. Additionally, an obstacle avoidance system was developed, which is adaptable to all three strategies and takes into account static known obstacles, like rocks or docks.

The MPC algorithm was tested through simulations, a small-scale model car with Ilon wheels, and finally, in real-life trials with the Piraya vessel. The experiment included trials to reach a target point, navigate through a set of waypoints, and approach the docking pose. The implementation was evaluated based on computation time, accuracy of position and heading, and adaptability to varying conditions.

The research concluded that the developed MPC can successfully enable an MSV to dock automatically at low speeds with high precision. The three main approaches to reach the docking pose proved effective and adaptable to different situations and environmental conditions. However, some limitations were identified, including an extended computation time in some cases, and discrepancies between simulated and real vessel behavior. Future enhancements could include more autonomous features, such as automatic waypoint generation and obstacle detection, improved optimization for faster computation, and the possibility of using negative throttle for more precise positioning.

A facsimile from this publication is given in Figure 33.

TABLE 20. Geographical distribution of the publications from 2023.

Country	Number of publications	Cumulative citations
China	8	0
Japan	5	0
Norway	3	0
France	1	0
Croatia	1	0
Malaysia	1	0

TABLE 21. Citations and DCI-Score from selected publications and the mean from 2023.

	Author	Publication	Citations	DCI-Score
Mean	-	[204], [205], [207], [210]–[212], [214]–[217], [219]–[221], [224], [226]–[228], [230], [231]	0	4.341
Top 1 DCI	Sawada et al.	[221]	0	**6.042**
Top 2 DCI	Peng et al.	[219]	0	5.433
Top 3 DCI	Volden al.	[224]	0	5.417

K. EPOCH 10: 2023

In the period January to June of 2023, 19 papers on automated docking were published by authors across China, Japan, Norway, France, Croatia, and Malaysia [204], [205], [207], [210], [211], [212], [214], [215], [216], [217], [219], [220], [221], [224], [226], [227], [228], [230], [231]. The country-wise distribution is provided in Table 20. Chinese researchers published approximately 42% of these articles. As per Google Scholar, none of these papers had received citations by June 2023.

Table 21 indicates that the paper by Sawada et al. [221] had the highest DCI-Score in 2023, recording 6.042, an increase of 0.275 from Epoch 9's top score [187]. The mean DCI-Score also rose in 2023, up by 0.248 to 4.341. The DCI of the two highest-scoring publications [219], [221] and the average DCI-Score for Epoch 10 are depicted in

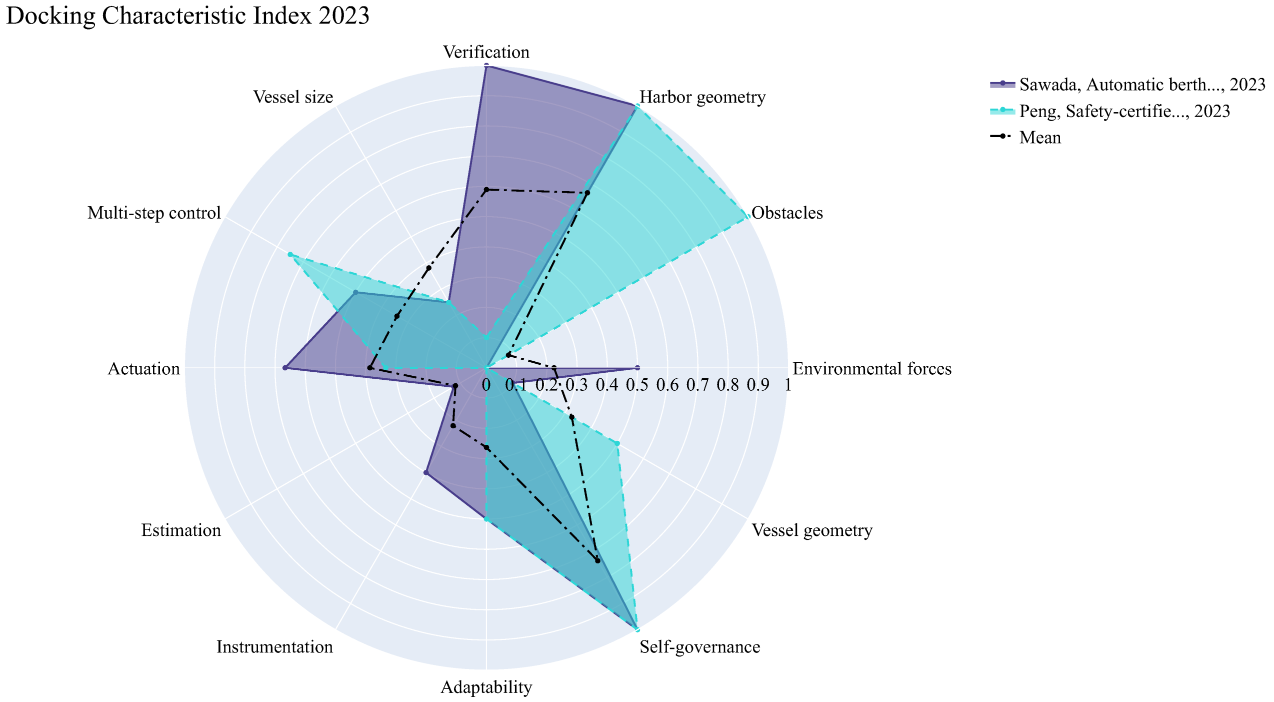


FIGURE 34. DCI for automated docking publications from 2023. The top DCI-scoring article is dark slate blue, while the second highest DCI-scoring article is turquoise blue.

Figure 34. As no articles have yet to receive any citations, the two highest DCI-rated publications are described in further detail here.

1) AUTOMATIC BERTHING CONTROL UNDER WIND DISTURBANCES AND ITS IMPLEMENTATION IN AN EMBEDDED SYSTEM [221]

The publication by Sawada et al. received the highest DCI-Score of Epoch 10, for that reason, its summary is presented in this section.

The article proposes a practical algorithm for automated docking in the presence of wind disturbances. The work is based on previous research conducted in [149]. The algorithm utilizes a 2-DOF controller with feed-forward control to enhance path following and introduces a runway in path planning to reduce path deviation. The effectiveness of the proposed method is validated through numerical simulations and shipboard tests using an experimental ship. The algorithm is implemented in a Programmable Logic Controller (PLC), which demonstrates improved control stability and speed compared to a laptop-based system.

A new path following control algorithm, FeedForward Pure Pursuit and Autopilot (FFPPA), is proposed. The path planning algorithm generates paths by using Bézier curves and incorporates a runway section from the initial position to address the issue of early-stage path deviation during docking maneuvers. The proposed algorithm is based on previous research but introduces feedforward to improve control accuracy and stability.

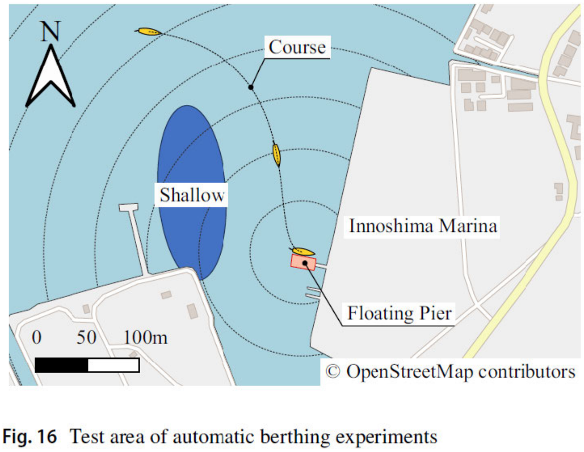


Fig. 16 Test area of automatic berthing experiments

FIGURE 35. Facsimile from ***Automatic berthing control under wind disturbances and its implementation in an embedded system*** **[221].**

Numerical simulations are conducted to assess the algorithm's performance under different wind conditions. Real-world experiments are performed using an experimental ship, Shinpo, equipped with an onboard control system and PLC implementation. The experimental results showcase the method's ability to reduce path deviation and achieve successful automated docking even in challenging wind disturbance scenarios.

The authors identify further improvements, including the design of minimum-risk maneuver capabilities, and the

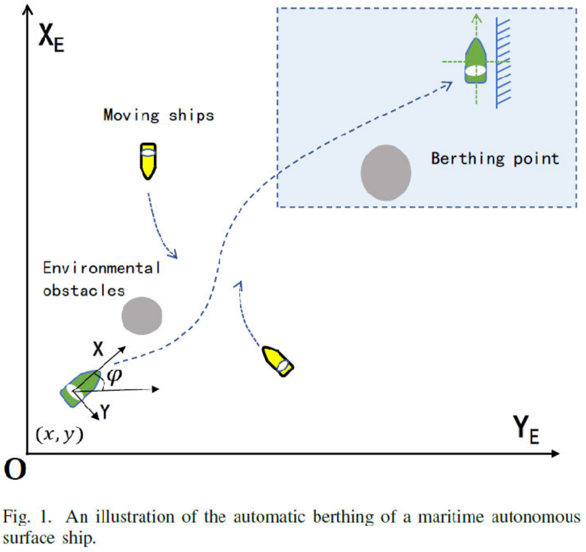


Fig. 1. An illustration of the automatic berthing of a maritime autonomous surface ship.

FIGURE 36. **Facsimile from *Safety-certified Constrained Control of Maritime Autonomous Surface Ships for Automatic Berthing* [219].**

implementation of safety measures for ASV operations. Future work will focus on refining the system, addressing environmental factors beyond wind disturbances, and ensuring safe operation through comprehensive risk assessment and sensor integration.

A facsimile from this publication is given in Figure 35.

2) SAFETY-CERTIFIED CONSTRAINED CONTROL OF MARITIME AUTONOMOUS SURFACE SHIPS FOR AUTOMATIC BERTHING [219]

The publication by Peng et al. received the second highest DCI-Score of Epoch 10, for that reason, its summary is presented in this section.

This paper presents a safety-critical control method for automated docking in constrained water regions. The proposed method addresses velocity constraints, input constraints, collision-avoidance constraints, and ocean disturbances. It incorporates a LOS guidance scheme for position-heading stabilization and an anti-disturbance kinetic control law based on an extended state observer. The method generates safe guidance signals that satisfy all constraints. Simulation results demonstrate the efficacy of the proposed control law in achieving automated docking while ensuring safety and robustness against physical and environmental constraints.

The proposed control method optimizes guidance signals subject to velocity constraints, input constraints, collision-avoidance constraints, and shoreline constraints. Unlike learning-based methods, the proposed approach does not require extensive training and claims a drastically better computational efficiency compared to model predictive control schemes by implementing a NOS control strategy. The control signals are directly optimized within safety constraints, ensuring safety in the control loop.

Simulation results substantiate the efficacy of the proposed safety-critical constrained anti-disturbance control method. The simulations consider a large marine vessel and assess its performance under different initial positions and ocean disturbances. Successful docking is achieved in the presence of disturbances while maintaining safe distances from obstacles and shorelines. Position and heading tracking errors converge to small values, and the control signals remain within constraints. The extended state observer accurately estimates ocean disturbances and models nonlinearities. Control forces and yaw moments are within bounds, and minimal collision avoidance distances are ensured.

By incorporating velocity constraints, input constraints, collision-avoidance constraints, and shoreline constraints, the proposed method ensures safety and stability while optimizing docking performance. The authors state that further enhancements can include extending the method to underactuated vessels and employing machine learning techniques to tune the control parameters. In-field experiments with real marine vessels would provide valuable validation and contribute to the practical implementation of the proposed automated docking control law.

A facsimile from this publication is given in Figure 36.

VII. DISCUSSION

The very first noticeable trend is the almost exponential growth in publications on automated docking systems since 2017, as seen in Figure 4. Figure 3a exhibits an upward trend in the number of physical verifications, starting in 2018. Interestingly, 2018 is also the year when COLREGS in relation to docking started to appear in the literature. Further, the democratization of technology can be attributed to the large growth of publications, and the increased number of physical trials in recent years. Other contributing factors can be a growing interest in willingness to fund research into autonomous vessels due to the shortage of experienced mariners. In Norway, an estimated 50% of mariners are over the age of 60 [222].

Inspecting Figure 3b and 3c reveals the prevalent use of traditional control methods in both simulations and physical tests. During the 1990s and early 2000s, AI-based control strategies were predominantly used in simulations. The physical trials of these AI-based control methods consisted of fuzzy control in 1992 [13], ANN in a small-scale test in 2003 [35], and a combination of ANN and SCGR in a full-scale test in 2004 [38]. Of note, traditional control methods, such as PID in combination with a guidance law, are commonly employed for trajectory tracking or waypoint following, while more sophisticated methods are used for path and trajectory planning, giving rise to a large number of traditional control methods employed both in simulations and physical trials. Recent publications continue this trend, with optimization schemes or MPC for trajectory planning, and geometric or graph-based methods commonly used for path planning. AI-based methods are also employed in physical applications but are more dominantly used in simulations.

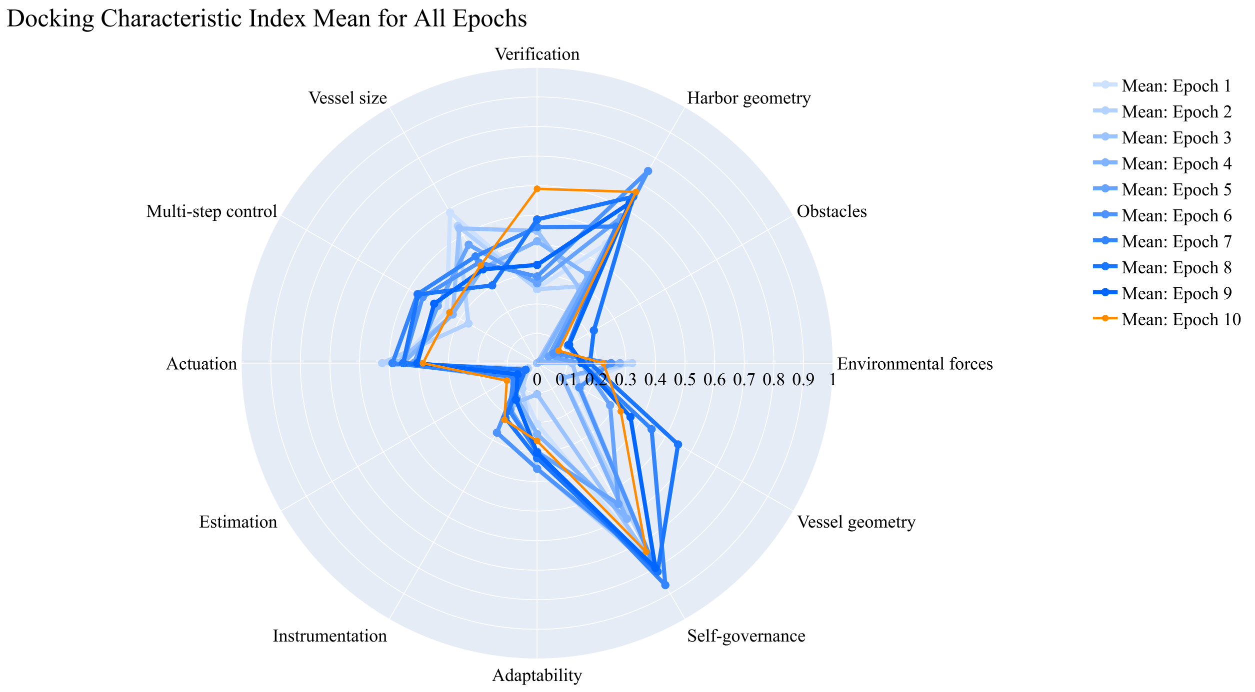


FIGURE 37. **The DCI mean for epochs 1 - 9 in shades of blue. The mean of Epoch 10 is in orange.**

Figure 5 reveals that both the yearly DCI-Scores have increased throughout this study, although characterized by noisy fluctuations up until around 2018. Publications with physical verifications show a pronounced upward trend until 2019, after which the maximum scores level out around a DCI-Score of 6. Publications that are innovating in one aspect of the automated docking problem often simplify the other challenges, resulting in lower DCI-Scores. Meanwhile, the top-scoring publications tend to integrate the advancements from more specialized scientific works. Solving the complexity of the docking problem is necessary for autonomous operations, but it requires improvements in all categories outlined in Section III. Notably, control strategies capable of handling dynamic constraints, robustness towards environmental forces, as well as situational awareness require more work.

The DCI figures from Section VI show trade-offs made in verification, harbor geometry, obstacles, environmental forces, vessel geometry, self-governance, and adaptability, to name the most influenceable. The accuracy of the harbor environment should be seen in relation to adaptability and self-governance, as some systems perform well as docking-assisting tools in complex, but pre-determined harbors. Handling all aspects can increase computational costs, affecting real-time performance. However, these challenges need real-time solutions for safe, reliable automated docking. As an example, Martinsen et al. [142] proposed a docking scheme that dynamically generates convex sets to represent safe waters. The article's DCI is given in Figure 25. This system considers precise vessel geometry when creating safe docking paths and compensates for wind, but has not been tested in complex harbor environments or against various environmental forces. Despite its significant contribution, it faces the same trade-offs seen in all publications surveyed in this work.

A. FUTURE RESEARCH DIRECTIONS

The scientific community has demonstrated automated docking in complex harbor areas, with some offering solutions for dynamic obstacles [172], [188], [203], [219], but still, neither of them can point to any actual sea trials. Furthermore, as we can see in Figure 37, the robustness to various environmental forces acting simultaneously on the vessel is largely untested in the docking problem. Most research approximates the vessel's geometry using simplified shapes to ensure a safe distance to the shore and obstacles. Precise geometry is vital for docking, especially during physical mooring. Publications using optimization or MPC-based control strategies yield the highest level of accuracy for vessel geometries but are prone to large computational costs, reducing their real-time applications. Still, the democratization of technology [68], and the increasing availability of powerful computers are mitigating the problem of large computational times. Truly autonomous surface vessels will need to be able to dock at any port, to ensure safety and flexibility. Most ports are not equipped with detectable QR codes, lasers, or other automated docking-assisting infrastructure. Thus, the literature could benefit from more research into adaptability. Further, Figure 37 reveals a lack of research in regard to instrumentation and estimation, which are necessary for SITAW.

Another issue that is barely covered by the literature is the aspect of cyber security in ASVs during docking [223], [229], which is important to ensure safe operations under threats from foreign governments and private individuals with malicious intentions.

In summary, future research endeavors related to automated docking for MSVs should adopt a multi-disciplinary approach, addressing not just control strategies but also practical, real-world implementations. Specifically, the research field could benefit from the community giving more attention to the points outlined here:

- The scarcity of sea trials indicates an urgent need for empirical validations, specifically to test the robustness of docking systems against environmental forces, primarily wind, waves, and currents.
- More studies are necessary to address the cybersecurity vulnerabilities in ASVs during docking, especially as it pertains to maintaining the operational integrity of ASVs under adversarial conditions.
- As computational power continues to increase, researchers should investigate using more computationally intensive but accurate modeling techniques in real-time docking applications.
- More adaptable docking solutions for a wider range of harbor areas.
- The integration of SITAW systems is essential for real-time environmental sensing and obstacle detection.

This focused approach has the potential to uncover new challenges specific to the docking problem, thus contributing to the ongoing efforts to achieve fully autonomous docking capabilities.

VIII. CONCLUSION

This comprehensive survey of automated docking literature has revealed an increasing interest in automated docking systems, demonstrated by the large growth in publications since 2017. As ASVs rise in popularity and technical feasibility, the complexity of the tasks they are expected to perform, including automated docking operations, becomes progressively more demanding.

The introduction of the Docking Characteristic Index (DCI) offers a quantifiable measure of the overall performance of an automated docking system and has allowed for a clearer understanding of the evolution and the present state of the field. It highlights that the docking problem is being tackled with ever-increasing sophistication, though with notable trade-offs and limitations in the current methodologies.

This paper has identified that there is an increasing emphasis on conducting physical verifications to better understand the real-world complexities involved in automated docking systems. The survey also signals the need for more comprehensive solutions, which address dynamic constraints, robustness against external forces, and situational awareness, among other aspects.

In light of the findings of this survey, future research should aim for integrated solutions to these problems. As the demand for fully autonomous operations continues to grow, the call for more holistic, robust, and adaptive docking strategies will similarly rise. This, combined with comprehensive physical verifications, will ultimately result in safe, reliable, and highly functional automated docking systems for marine surface vessels.

In conclusion, the increasing trend in automated docking research holds great promise for the future. The continuous refinement and integration of control strategies, coupled with advancements in computing power and increasingly accessible sensor technology, will pave the way toward highly efficient and safe ASVs. However, as this survey indicates, achieving this goal requires further advancements and focused research efforts in several aspects of the application.

IX. ACKNOWLEDGMENT

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