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Review

A Review of Autonomous Tugboat Operations for Efficient and Safe Ship Berthing

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Abstract: Autonomous ship technology, which includes real-time monitoring, satellite communication, and automatic navigation, is rapidly advancing. Despite significant research on single unmanned ships, there is a lack of studies on complex tasks, such as ship berthing using a swarm of autonomous tugboats. This review article provides an overview of various projects related to autonomous tugboats for ship berthing and discusses the research trends in the required technologies, including recognition, decision making, modeling, and control. We identify the areas that have been underexplored in existing studies and suggest future research directions to advance the field. Overall, this review contributes to a better understanding of the challenges and opportunities for the development of autonomous tugboats for ship berthing.

Keywords: autonomous tugboats; ship berthing; swarm control; unmanned ship; automatic navigation

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1. Introduction

As advancements in technologies such as real-time monitoring, satellite communication, and automatic navigation continue, the automation of ship operations is becoming increasingly prevalent worldwide. Numerous countries are investing in research and development to advance the field of autonomous navigation technology [1]. Despite this progress, there is a lack of complex research and development in the area of berthing multiple unmanned ships, which presents a range of challenges including collisions with port facilities and other ships, grounding by reefs, and the unpredictable effect of sudden environmental disturbance. Additionally, larger merchant ships lack controllability in low-speed berthing situations, making berthing more difficult [2]. Ship berthing is a complex task that involves various challenges, such as changes in dynamic characteristics when entering narrow canals or busy ports. Due to the actuator's characteristics, large merchant ships often lack the required controllability to move holonomically in tight spaces. As a result, tugboats are frequently employed to control the position of these vessels, as well as oil platforms and barges. Tugboats have the advantage of being able to push and pull large vessels easily on the water. They can maneuver effectively in tight spaces, making them an invaluable asset for berthing operations [3]. According to a recent study, the tugboat market has surged due to several factors, such as increasing maritime trade and fleet size, port construction, and expansion, and is expected to grow at a CAGR of 14.28% from 2022 to 2027. Furthermore, the market size is expected to reach USD 2,720,779 million [4]. The use of tugboats for ship berthing has become standard practice.

However, the current method of berthing using a tugboat requires a pilot who boards the ship and instructs the course and speed of the vessel in consideration of weather, tide, and reefs, thereby controlling the tugboat. This manual control of tugboats incurs high human cost and time. Additionally, communication problems between tugboats must be addressed during berthing, which requires skilled technology. However, with autonomous vessel technology, operating costs and human error are reduced, and communication with other vessels can be facilitated using various wireless technologies such as satellites, mobile networks, and dedicated narrowband systems. This can compensate for economic, safety, and communication issues [5–7]. In addition, unlike existing ships, autonomous tugboats can increase efficiency by minimizing power and increasing maneuverability by applying improved thrust allocation algorithms, such as the RPI (redistributed pseudoinverse) algorithm [2]. Therefore, there is a need for an automated system for ship berthing that can reduce human involvement and improve efficiency, while addressing the challenges of communication and control during berthing [3].

The need for autonomous tugboat technology in ship berthing is becoming increasingly important due to various challenges involved in the process. To enable this technology, several capabilities, such as cognitive technology to recognize and integrate the surrounding situation, task allocation within the group, maintenance of formation, decision-making technology to plan routes, modeling technology to consider multibody dynamics of the mother-ship, and precise control technology for a group of tugboats for berthing, are essential. Incorporating these technologies in autonomous tugboats will reduce human costs and time, as well as improve safety, efficiency, and accuracy in ship berthing.

This paper presents an examination of the research trends in recognition, judgment, modeling, and control technologies for ship berthing using autonomous tugboats from the early 2000s to recent years. Section 2 of this paper provides a brief overview of the technology trends and previous studies on the development of unmanned/autonomous towing technology. Section 3 discusses the need for recognition, judgment, modeling, and control technologies, and provides detailed information on each of these technologies. Finally, Section 4 outlines the current limitations of autonomous towing technology, presents the conclusions drawn from this study, suggests future directions for development, and proposes research areas that require further investigation.

2. Current Developments of Unmanned/Autonomous Towing Technology

Currently, there are numerous ongoing projects in different countries aimed at achieving autonomous ship berthing using tugboats. These projects are exploring various operational scenarios, taking into account the technology involved in the recognition, judgment, modeling, and control of the autonomous tugboats. Additionally, research efforts are focused on developing specific element technologies that will enable safe and efficient ship berthing, even with the absence of a human operator on the tugboat. As such, the field of autonomous ship berthing is rapidly evolving, and it is expected that the continued progress in the development of these technologies will have significant implications for the maritime industry in the coming years.

Projects Related to Autonomous Towing

Figure 1 illustrates the global efforts being made to automate the process of ship berthing using autonomous/remote tugboats. Many countries have presented concept point models of autonomous tugboats and have achieved complete remote control and smart tugboats. The automation of tugboats can be categorized into several levels based on their degree of autonomy. These levels provide a standardized framework for the development and assessment of autonomous tugboats. The first level involves automated process and decision-making support, the second and third levels allow for remote control with or without a crew member on board, and the fourth level represents fully autonomous tugboats capable of making decisions and taking actions on their own. Currently, various countries are conducting research and development projects aimed at achieving different levels of automation in the field of tugboat operations [8].

Figure 1. Ship berthing process using Intellitug developed by Wartsila [9].

In November 2017, Maersk Line, a Danish shipping company, collaborated with Rolls-Royce to achieve a significant milestone in the maritime industry. The world's first remote tugboat, named "Svitzer Hermod", was remotely operated in Copenhagen Harbor. During the navigation test, the vessel was remotely controlled by the Remote Operation Center (ROC) located at the pier. The ship successfully proceeded along the pier, anchored at the target point, and rotated 360 degrees before safely returning to the pier and docking, as shown in Figure 2. The remote control system was made possible by the Dynamic Positioning System (DPS), which is the core of the system, and the ROC, as depicted in Figures 2 and 3. It is worth noting that while the operation was successful, due to the presence of the crew on board, it was not a completely unmanned operation [10].

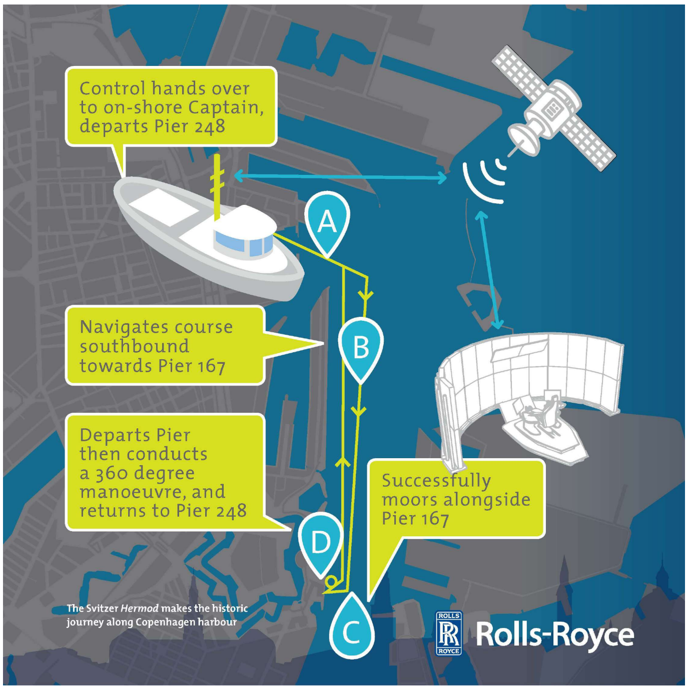

Figure 2. Description of pilot test scenario of the tugboat "Svitzer Hermod" [11].

Figure 3. Tugboat "Svitzer Hermod" (left) and Remote Operation Center (ROC) (right) used in the project [11].

Maersk Line and its subsidiary Svitzer, in collaboration with Kongsberg and the American Bureau of Shipping (ABS), have jointly developed the RECOTUG, which is the world's first fully remotely operated tugboat. This breakthrough has led to a significant increase in research in this area [12]. By remotely controlling the tugboat, it is possible to significantly reduce the risks to human life associated with towing operations, as well as to increase the efficiency and reliability of tugboat services. The ABB/KEPPEL project provides another example of a successful remotely piloted project. Singapore-based Keppel O&M (Keppel Offshore & Marine) and ABB(Asea Brown Boveri) collaborated to remotely control a tugboat for the first time in South Asia using a joystick, which was carried out in Singapore. The ABB Ability™ Marine Pilot Vision digital solution, shown in Figure 4, was used to provide sensor fusion in an onboard system that increased digital situational awareness. Additionally, the ABB Ability™ Marine Pilot Control system, shown in Figure 5, was used to achieve remote control by executing intelligent start-up and control commands. Since more than 130,000 vessels pass through the Port of Singapore annually, it is one of the most complex autonomous port operating environments globally. As a result, this test is a significant step towards demonstrating the safety and efficiency of using digital solutions that are already available for ships' towing operations [13].

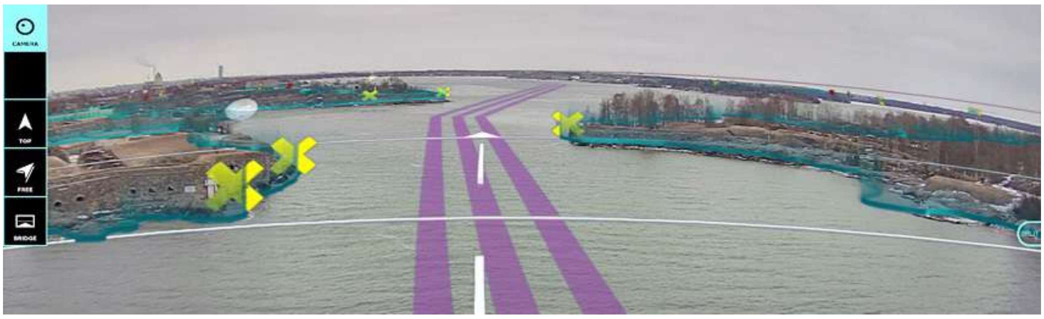

Figure 4. ABB Ability™ Marine Pilot Vision Digital Solutions [14].

Figure 5. ABB Ability™ Marine Pilot Control system [15].

In 2015, Robert Allan of the United States presented a conceptual model of an autonomous tugboat that involves the installation of a towline between the mothership and the tugboat, as shown in Figure 6 [16]. Subsequently, there has been an ongoing effort to develop the world's first remotely controlled unmanned commercial tugboat that can operate over a wide range in collaboration with the Abu Dhabi Port Authority (ADP) of the United Arab Emirates (UAE) [17]. The development of such an autonomous tugboat is expected to provide significant benefits, such as improved safety, efficiency, and cost-effectiveness of towing operations in the region.

Figure 6. Autonomous tugboat designed by Robert Allan [16].

Finally, the IntelliTug project is a large-scale collaboration between PSA(Port of Singapore Authority) Marine, Wartsila, Lloyd's Register, and TCOMS (Technology Center for Offshore and Marine Singapore) aimed at developing an autonomous navigation system for tugboats. The project uses PSA Polaris, a tugboat equipped with a range of sensors including short-range, high-resolution radar and a dynamic positioning (DP) system, as shown in Figure 7. The combination of these sensors enables the construction of a smart navigation system that can determine the optimal route for the tugboat and avoid various obstacles, including moving ships [9]. This enables the possibility of constructing an optimal route while avoiding various obstacles, including those presented by moving ships. In addition, the Virtual Anchoring function demonstrated in Figure 8 is an innovative feature that aims to enable the autonomous performance of daily tasks by the smart tugboat. This technology has the potential to relieve the captain from the burden of executing manual standby maneuvers, thereby allowing them and the crew to concentrate on other critical tasks. The use of such intelligent systems can greatly enhance operational efficiency and safety while reducing workload and crew fatigue [9].

Figure 7. Sensor suite of IntelliTug project [9].

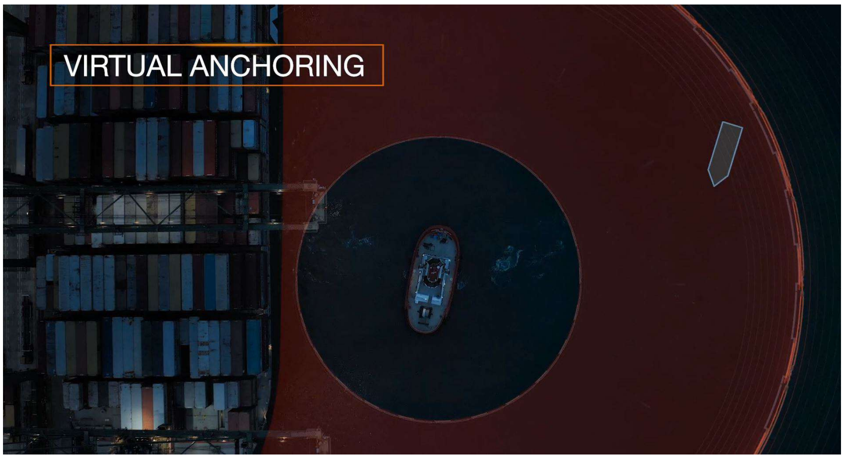

Figure 8. Virtual Anchoring function of IntelliTug project [9].

Table 1 displays a comparison of the advanced tugboat projects mentioned above. Typically, these projects focus on the development of remote control and smart tugboats, with a target automation level of around 2 to 3. To date, there have been no projects that have attempted to berth using fully autonomous or remotely controlled tugboats. Achieving the fully autonomous tugboat stage requires the development of technologies that can handle complex situations, such as allocation of the control forces and compensation for environmental disturbance and interaction effects among tugboats [8]. Furthermore, it is essential to develop technologies that can operate and control a group of tugboats, so-called swarm control.

Table 1. Autonomous/Remote Tugboat Technology Development Project.

Reference	Project	Content	Participating Company	Autonomous Level
[10]	Svitzer Hermod (2017)	The world's first successful remote operation of the tugboat "Svitzer Hermod" at Copenhagen Port	Maersk Line, Rolls Royce	Level 2
[12]	RECOTUG (2021)	[10] Announced the joint development of RECOTUG, a tugboat developed from the project and capable of fully remote control.	Maersk Line, Svitzer, Kongsberg, ABS: American Bureau of Shipping	Aim for Level 3
[13]	ABB/KEPPEL (2021)	First successful remote control of a tugboat in South Asia at the port of Singapore	Keppel Marine, ABB	Level 2
[9]	InteliTug (2019)	Trials are underway at the Port of Singapore, aiming to realize smart tugs autonomously performing a variety of routine tasks.	PSA Marine, Wartsila, Lloyd's Register, TCOMS (Technology Center for Offshore & Marine Singapore)	

Table 1. *Cont.*

Reference	Project	Content	Participating Company	Autonomous Level
[16]	Robert Allan (2015)	Presenting a conceptual model of an autonomous tugboat considering the towline between the mothership and the tugboat	Robert Allan	
[17]	Robert Allan/ADP (2020)	Aiming to develop the world's first remotely operated unmanned commercial tugboat capable of operating in a wide range	Robert Allan, Abu Dhabi Port Authority (ADP)	Aim for Level 3

3. Previous Research

In recent years, there has been a growing interest in the development of autonomous tugboats owing to their potential benefits in terms of cost-effectiveness and safety. To gain a comprehensive understanding of the progress and trends in this field, we present Table 2, which offers an overview of related work conducted from the early 2000s to recent times. The survey table categorizes the related works based on their distinct characteristics, such as perception, decision-making, modeling, and control techniques. Such classification enables researchers to gain a better understanding of the various approaches and methods utilized in the development of autonomous tugboats, thus identifying gaps and opportunities for future research and development in this promising field.

Perception:

- P1—Localization technology;
- P2 —Sensor fusion technology.

Decision Making:

- D1—Path Planning:
  - A. Path planning in the open sea;
  - B. Path planning in a port environment;
  - C. Reactive path planning.
- D2—Determining the swarm formation;
- D3—Algorithm for task allocation.

Control:

- C1—Adaptive control;
- C2—Robust control;
- C3—Reinforcement-learning-based control;
- C4—Tracking control.

Modeling:

- M1—Modeling of tugboat as a thruster;
- M2—Modeling considering environmental disturbance;
- M3—Modeling considering multibody dynamics;
- M4—Hybrid system modeling;
- M5—Modeling using simplified dynamic equations.

Infrastructure and Operation:

- I1—Tugboat planning;
- I2—Allocation problem:

  - A. Berth Allocation Problem (BAP);
  - B. Quay Crane Assignment Problem (QCAP).
- I3—Mooring System;
- I4—Energy efficiency and eco-friendliness.

Table 2. Overview of research work related to autonomous tugboat technology.

Reference	Perception	Decision Making	Control	Modeling	Infrastructure and Operation
[18]	-	D1A	C2,C4	M1	-
[19]	-	D1A	C1,C4	M1	-
[20]	-	D1A	C4	M1	-
[21]	-	D1A	C1,C4	M1	-
[22]	-	-	C4	M1	-
[23]	-	D1A	C1,C4	M1	-
[2]	-	D1A	C1,C4	M1	-
[24]	-	D1A	C2,C4	M1,M2	-
[25]	-	D1A	C2,C4	M1,M2	-
[26]	-	-	C3	M1	-
[3]	-	D1A	C2,C4	M1,M2	-
[27]	-	D1A	C1,C4	M3	-
[28]	-	D1A	C4	M3,M5	-
[29]	-	D1B	C3	M2,M4	-
[30]	-	-	-	M2,M3	-
[31]	-	D3	-	-	-
[32]	-	D2	-	-	-
[33]	-	D1B	-	-	-
[34]	-	D1C	-	-	-
[35]	-	D1B	-	-	-
[36]	P1	-	-	-	-
[37]	P1	-	-	-	-
[38]	P1	-	-	-	-
[39]	P1	-	-	-	-
[40]	P1	-	-	-	-
[41]	P1	-	-	-	-
[42]	P2	-	-	-	-
[43]	P2	-	-	-	-
[44]	-	-	-	-	I1
[45]	-	-	-	-	I1
[46]	-	-	-	-	I2A
[47]	-	-	-	-	I2A, I2B
[48]	-	-	-	-	I3
[49]	-	-	-	-	I4

Figure 9 shows the timeline of notable studies, and Table 3 contains brief descriptions of these studies. In an early study in the early 2000s, tugboats were modeled as azimuth propellers installed in motherships, and it was assumed that the tugboats only exerted pushing forces [18]. Following this work, adaptive control techniques were applied in subsequent studies [19,21,23] to compensate for uncertainty in the contact point between the tugboat and the vessel, as well as the hydrodynamic parameter values. Bui [2] minimized the power consumption of the tugboat and improved controllability by utilizing the redistributed pseudoinverse (RPI) algorithm to determine the thrust and direction of each tugboat. In a later study [24], the sliding mode control technique, a robust control approach, was applied to environments with disturbances, such as wind, current, and waves. It is important to note that the studies discussed in this paragraph modeled the tugboats as thrusters. Therefore, it cannot be considered swarm control. Moreover, these studies did not consider the towing operation of tugboats using towlines.

Table 3. Representative research for ship berthing using autonomous tugboats.

Reference	Main Features
[18]	A tugboat is assumed (modeled) as a single thruster (2006)
[19]	Adaptive control techniques to compensate for the fluidity of hydrodynamic coefficients and unknown contact points (2007)
[2]	Uses RPI (redistributed pseudoinverse) algorithm, an improved thrust allocation algorithm for improved controllability (2011)
[24]	Modeling considering environmental disturbances such as wind, tide, and waves applying the SMC (Sliding Model Control) technique, one of the robust control techniques that is resistant to environmental disturbances such as wind, tide, and waves (2011)
[27]	Modeling considering the dynamics of the tug line leader-following control that follows the route by considering the tug line between the tug and the ship to be towed (2019)
[28]	Modeling considering multibody dynamics considering ships, tugboats, and environmental disturbances using simplified dynamic equations (2020)
[29]	A hybrid system modeling technique that considers ships and tugboats, and the continuous movement of tugboats is applied. Application of control method using PPO (Proximal Policy Optimization) algorithm, which is a reinforcement learning algorithm considering the actual port environment (including obstacles), simulated using PYGAME (2021)

In the work by Quan [27], the vessel to be towed was modeled as a system with three active rudders, and tugboats were independently modeled. The modeling process considered both the dynamics of the towline and the ship characteristics, such as the length of the towline and relative position of the tugboat. In this work, the leader-following control technique was applied to control the mothership. In the work by Choi [28], the contact between the ship and each tugboat was considered as a point contact, and the speed constraint at the contact point was modeled. This work is notable because, for the first time, it considered the towing problem as a multibody dynamics problem that took into account several components, such as the ship, tugboat, towline, and environmental disturbances individually. A tracking control method was applied, which could manipulate the mothership to follow a straight path while maintaining the desired heading angle using tugboats. Lastly, Hong [29] (2021) applied a hybrid system modeling technique in their study that considered ships, tugboats, and the continuous movement of the tugboats. Control was achieved using the PPO (Proximal Policy Optimization) algorithm, which is a reinforcement learning algorithm suitable for continuous action spaces. After applying the technique, it was tested in the Pygame simulation environment to confirm its usefulness.

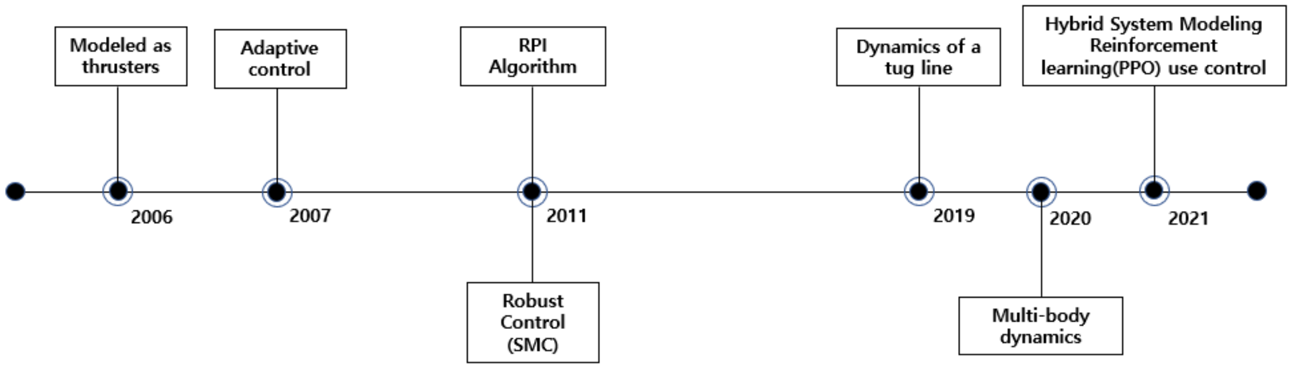

Figure 9. Timeline of notable research on ship berthing with autonomous tugboats.

From the studies that applied control techniques from the early 2000s to recent years, where studies considered actual operation methods and applied control methods using artificial intelligence technology, the technology for autonomous berthing of ships using tugboats has significantly developed. Adaptive control techniques were introduced to compensate for uncertainties, while robust control techniques were considered to deal with environmental disturbances. However, most papers related to ship berthing using tugboats focused on modeling and control methods that assumed fully autonomous tugboats without addressing perception technology through sensors, such as cameras, AIS (Automatic Identification System), and radar, as well as optimal route creation, task allocation algorithms, and decision-making technology to maintain formation within the swarm. Therefore, to analyze previous research on the perception and decision-making aspects, we also searched for research work on single tugboats, USVs (Unmanned Surface Vehicle), or other robotics fields that could be applied to the ship berthing domain.

The perception problem can be divided into two categories: one dealing with localization that estimates accurate vehicle position and attitude, and the other dealing with the problem of situational awareness of the surrounding environment using sensor fusion technology that can integrate information with the remaining sensor information even if one sensor fails or a shadow zone occurs. In [36], an algorithm for determining the exact position through the convergence of relative and absolute position information in a sensor network was presented, while in [37], a complex navigation system for an autonomous vehicle was designed to obtain accurate location information. For the maritime domain, several works have been introduced to address the perception problem. In ship berthing, safe berthing is possible only when the distance between the quay wall and the ship is accurately estimated. In [38], the distance between the quay wall and the ship is estimated using the homodyne phase system, which is composed of an antenna, a reader, and transponders. Several works estimate the distance between the quay wall and the ship using vision sensors. In [39,40], the ship's motion state is estimated in real time by using the SLAM algorithm using 3D LiDAR and monocular camera, respectively, when the ship is berthing. In the work by [41], a vision-based monitoring system for berthing, called AVMS, is proposed. In the works by [42,43], a sensor fusion technique using vision sensors and other perception sensors is proposed to enhance the situational awareness performance in the marine environment.

The decision-making problem can be divided into three categories: task assignment, formation maintenance, and path planning for the towing operation. While there have been no works specifically addressing the task assignment problem in tugboat operations, the Hungarian algorithm [31] has been widely used to assign tasks to a number of unmanned ships and robots. Additionally, to move a swarm of motherships and tugboats to the port for berthing, a certain formation must be maintained to avoid collisions within the swarm, as well as optimize path planning for avoiding obstacles. Tan [32] used the FMS (Fast Marching Squares) method to control the formation of a number of autonomous swarm boats without any collisions. In the context of autonomous ship berthing using tugboats, the problem is often treated as a tracking and controlling problem for the desired trajectory in simulation environments, such as MATLAB or Pygame. Miyauchi [35] considered the berthing path planning problem in a complex port environment, while Cui [34] addressed the route planning problem after reactive collision avoidance in the presence of sudden obstacles or disturbances. Finally, Cox [33] solved the path planning problem for a swarm of tugboats, as opposed to the studies of Cui and Miyauchi, which focused on a single ship.

4. Autonomous Tugboat Element Technologies

To achieve autonomous berthing using tugboats, a range of technologies are required, including perception technology to allow each tugboat to recognize and understand its surrounding situation, allocation of various tasks within a group, maintenance of formation, decision-making technology for path planning, modeling technology considering multibody dynamics such as motherships and tugboats, and precise control technology for tugboat groups during berthing. This chapter reviews the development trends thus far and the necessity of each technology by dividing it into recognition, perception, decision-making, modeling, and control technologies for berthing ships using autonomous tugboats.

4.1. Perception Technology

When berthing a large ship using multiple tugboats, visibility and communication restrictions may occur. For example, when a tugboat is close to a large vessel, it may obstruct the crew's view, and if the position of the tugboat is in a blind spot due to a shadow zone created by the large vessel, it may be difficult to see potential hazards or obstacles. Additionally, factors such as background noise and equipment failure can limit communication, making it difficult to convey important information such as speed or direction changes. These visibility and communication challenges highlight the need for autonomous tugboats equipped with cognitive technologies. First, it is possible to obtain accurate location information between a pier, a ship, and each tugboat due to sensor information such as a camera, LiDAR, and radar, as well as the development of complex navigation technology. In addition, as sensor fusion technology and artificial intelligence technology develop, even if one of the sensors fails or a shadow area occurs, accurate information can be recognized by integrating and converging the information with the remaining sensor information. In [36], an algorithm was proposed that combines GPS information and measured distance information between nodes to determine relative position. Similarly, ref. [37] used INS (Inertial Navigation System), GPS (Global Positioning System), and NHC (Nonholonomic Constraint) to obtain accurate location information. While these studies were not specifically designed for the maritime domain, their approach can be applied to the berthing environment to identify accurate position through relative and absolute position information by designing a complex navigation system. In [38], the distance between the ship and the pier was accurately calculated using a measured phase difference of a low-frequency signal and the predefined distance between the reader and transponder of each antenna. In [39], when the ship docked, the motion state of the ship itself was estimated based on 3D LiDAR, and then the ship's speed and attitude were estimated. In addition, the GPS coordinates of the port shoreline were converted into the ship reference coordinate system to calculate the distance between the ship and the target berth, the transversal velocity, the longitudinal velocity and yaw rate, and [40]; to solve the problem of real-time pose estimation when berthing the ship, the motion process of the ship was monitored in real time according to the SLAM (Simulation Localization and Mapping) of a monocular camera. Both of these studies propose a recognition method based on a feature extraction and matching algorithm based on the SLAM algorithm.

In addition, in terms of perception technology, research using AI technology has been actively conducted recently. When AI technology is applied, it can have advantages in terms of cost and performance compared with existing sensors, and it has the advantage of further enhancing situational awareness in terms of sensor fusion. The information below introduces perception technologies applied with artificial intelligence in studies within the last three years. Ref. [41] proposed a new artificial intelligence vision-based monitoring system for berthing ships (AVMS), as shown in Figure 10. Accurately estimating the relative distance between the wharf wall and the ship is necessary to anchor a ship, but the widely used berthing assistance system (BAS) is expensive and has limitations depending on the size of the ship. An AVMS sensor module is composed of a low-cost camera, DGPS (Differential Global Positioning System) receiver, and inertial measurement unit (IMU), and its performance was compared with the existing BAS. AVMS showed strong performance in poor weather conditions compared with the existing laser distance sensor-based BAS, and it can be applied directly in the actual port by providing real-time image information of ships approaching the quay wall.

The environmental perception sensors installed on a single unmanned tugboat have varying performance and can create shaded areas depending on the environment during the mission. If a sensor fails within the swarm of tugboats, it can cause disruptions in mission execution in both berthing and towing modes. Therefore, it is crucial to have situation awareness technology based on the integration and fusion of perception sensors such as cameras, LiDAR, and radar sensors. Using the sensor fusion technique, if one sensor fails, the information from the other sensors can be integrated and fused to accurately perceive the environment, ensuring no disruption in mission execution during approach or navigation. Ref. [42] reviewed the state of the art of sensor fusion technology, regulations, and performance indices related to autonomous vessels and translated them into operational requirements. After that, a sensor fusion technology was suggested by adopting artificial intelligence technology.

In [43], a new concept called ISAS (Intelligent Situational Awareness System) was introduced to detect maritime objects by fusing information from multiple sensors and tracking object motion. A deep learning algorithm was utilized to detect objects, while PDA ((Probabilistic data association) and JPDA (Joint Probabilistic Data Association) were used to associate data in the tracking process. The ISAS environmental awareness sensor is composed of a camera, LiDAR, and radar. In order to improve situational awareness, the Mask R-CNN (Region-based Convolutional Neural Network) algorithm, an instance segmentation method, was applied to detect overlapping objects on the sea when using camera-based objects. Moreover, a lightweight module-based image noise reduction model was designed and trained using radar images captured in the ocean environment to eliminate noise during radar-based object detection. Figure 11 illustrates the noise reduction outcome for the radar image. The study conducted sensor fusion of camera and radar data.

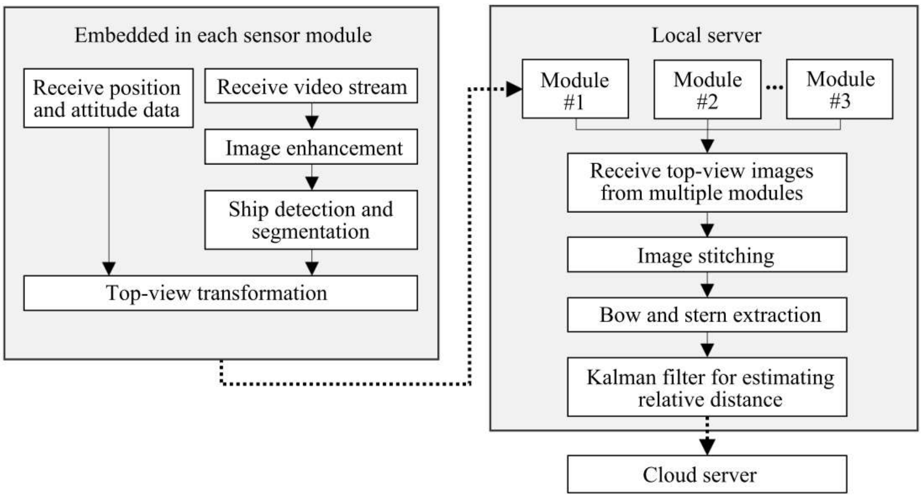

Figure 10. Overview of the system design of the AVMS proposed by Kim et al. [41].

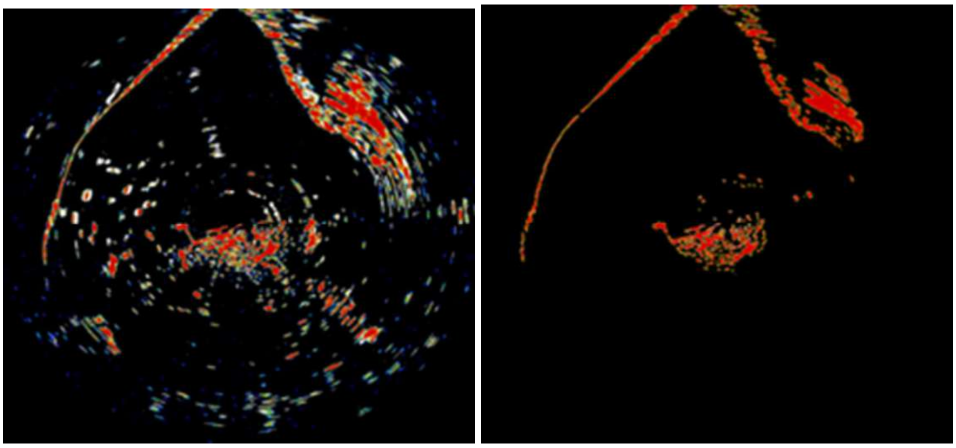

Figure 11. Noise reduction results for radar image proposed by Choi et al. [43]: left: before reduction, right: after reduction.

4.2. Decision-Making Technology

Each tugboat performs an individual mission, and when it arrives near a port, it requires a mission planning process, such as adjusting the thrust of each tugboat and selecting a formation suitable for the condition of the mothership berthing process. For example, if the mothership needs to change its heading angle or speed, a series of mission tasks must be properly planned. For instance, some of the tugboats need to adjust the heading angle direction of the mothership, and the other tugboats should generate longitudinal force by applying thrust to the vessel. Therefore, there is a need for a technology capable of automatically allocating these tasks to each tugboat when operating a swarm of fully autonomous tugboats. Task assignment is made in consideration of the characteristics of the platform itself, and reassignment is made according to environmental conditions and mission status. Currently, the Hungarian algorithm [31] is widely used for allocating tasks to multiple unmanned ships. Its computational complexity is large, and the amount of computation increases when the size of the swarm increases. Therefore, developing an algorithm that can efficiently calculate and cope with uncertainty is necessary. In addition, tugboats and motherships must form a swarm to create an optimal route avoiding static and dynamic obstacles, and there must be no collisions within the swarm. In [32], a fast marching technique was proposed for swarm navigation of multiple unmanned surface vehicles, as shown in Figure 12, and a simulation study was performed in which swarm USVs navigated to and from the swarm to the target point without any collision. In this study, a grid map was created based on the surrounding environment of clustered ships for the fast marching (FM) technique. The potential values of the grid map were defined using information such as the speed and attitude of each ship. When obstacle information for the clustered ships was identified, collision avoidance was performed by generating an avoidance route through the FM technique and cruising [32]. In this study, an arbitrary path was followed using six USVs, but this technology can be applied to a scenario where a group of unmanned survey vessels and motherships move toward the port in towing mode.

Lastly, in studies related to ship berthing using autonomous tugboat swarms, control problems have been addressed by controlling the swarm of tugboats to follow the desired (reference) trajectory of the mothership. However, in complex and difficult berthing scenarios, path planning problems must be addressed, taking into account the spatial constraints of the swarm with respect to the shape of port. The A star search algorithm, which is a commonly applied method, is an optimal path generation algorithm that uses a road map called a "visibility graph" to create an optimal path even in a complex environment. When applied to a swarm of tugboats, it finds the optimal route, but the route is not smooth, causing sudden movements of the tugboats, which can make them difficult to control [33]. Figure 13 illustrates the concept of the visibility graph. In research [33], the autonomous swarm control of unmanned ships was verified through the development and study of path planning algorithms. The A star search algorithm was adjusted for unmanned ships, and an algorithm was developed to explore the path of unmanned ships using information about their dimensions, position, and direction. In addition, the shortest path of all points was calculated offline, improving the speed of the A star search algorithm by 12.3 times. In this study, the path planning system was verified using the Robot Operating System framework.

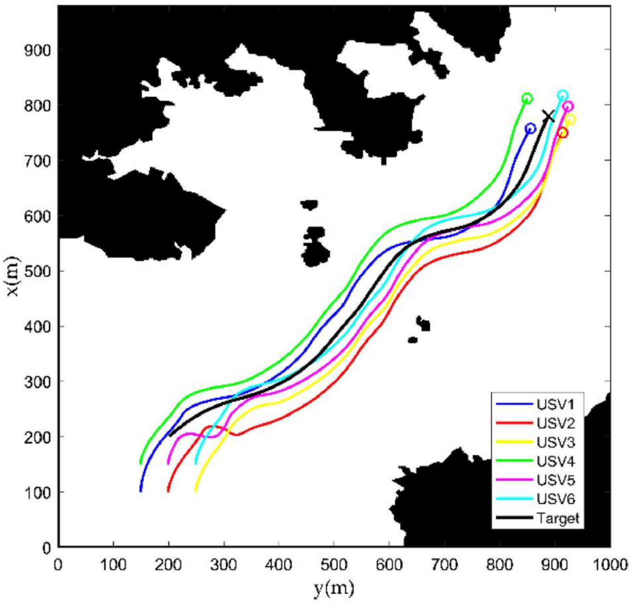

Figure 12. Trajectories of USV swarm control conducted by Tan et al. [32].

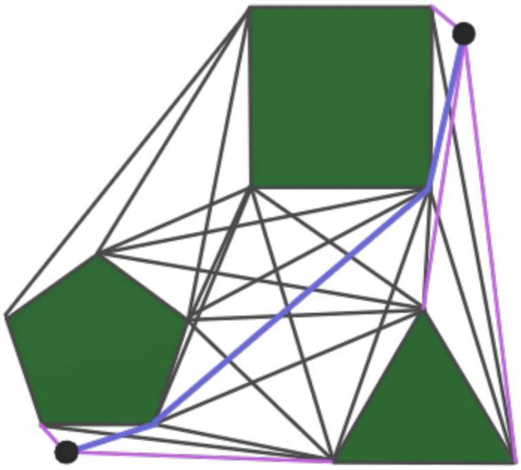

Figure 13. Overview of the concept of visibility graph in path planning problem [33].

In [34], a reactive path planning approach called Dubins APF (Dubins Artificial Potential Field) was proposed to solve the problem of autonomous robot path planning in environments with obstacles. This method adds the use of Dubins curves to the reactive path planning method of the existing APF (Artificial Potential Field) method to plan feasible paths and calculate obstacle avoidance potential. Initially, a path is generated and followed, and if an obstacle is detected, the obstacle avoidance potential field is recalculated, and the path is regenerated along the optimized path. Although this study proposed a path planning method for a single robot rather than a swarm, it is an algorithm that can be applied to future ship berthing research, considering the complex environment of multiple ships, reefs, and sudden obstacles near the port.

In the work by [35], a path planning problem that considers obstacles in two actual harbor environments is presented (as in Figure 14), in contrast to previous studies that performed path following control of the mothership according to the planned path after setting the departure and destination points. To optimize path planning in actual ports, obstacles such as berths, breakwaters, and buoys are represented as polygonal obstacles, and a collision avoidance algorithm is applied based on the ship domain that changes depending on the ship's speed to maintain a sufficient distance from the obstacles. At the same time, an optimization method for path planning, including the effect of wind disturbance and waypoints, is presented. The paper dealt with the optimization problem of path planning that takes into account the complex actual harbor environment of obstacles, external disturbances, and other factors in the berthing situation of a single ship. In addition, if the technique of tracking and controlling the path of the mothership using several tugboats is applied, the path planning optimization problem of the mothership cluster can be solved.

Figure 14. Simulation environment of path planning in the work by [35]. Polygons with white lines represent the obstacles in harbor environment.

4.3. Modeling Technology

Modeling technology is a fundamental aspect that plays a crucial role in the successful operation of autonomous tugboats, as control technology is directly applied based on the modeling form. Tugboats and motherships are treated as a single swarm, and their multibody dynamics must be modeled by breaking down the hull, joints, forces, and contact elements. To achieve an accurate modeling of the multibody dynamics, factors such as the tension of the towline, tugboat specifications such as length and weight, thrust capacity, and the frictional force between the tugboat and the mothership during ship berthing must be taken into account. This comprehensive modeling of the tugboat swarm dynamics enables a better understanding and control of the system during operation.

For autonomous tugboats, high maneuverability and agile maneuvering are crucial; thus, they are commonly equipped with azimuth-type propellers. To investigate their maneuverability and stopping performance, previous studies such as [50,51] have developed models for ships equipped with azimuth propellers.

In the early stage, in studies such as [18–22], each tugboat was modeled as a three-degree-of-freedom azimuth propeller to simulate a fully autonomous tugboat (Figure 15). In Figure 15, f_i is the unidirectional control force of the tugboat, (x_i, y_i) is the position at the contact point, α_i is the clockwise X-axis direction of the tugboat based on the body-fixed coordinate, and θ represents a clockwise X-axis angle based on the body-fixed coordinate system. It is assumed that the tugboats is strategically placed close enough. In other words, the tugboats was modeled as thrusters attached to the mothership. Consequently, the geometric configuration matrix for the thrust allocation of the tugboat is continuously calculated. Subsequently, modeling techniques that incorporate environmental disturbances were developed [24], which differed from previous studies.

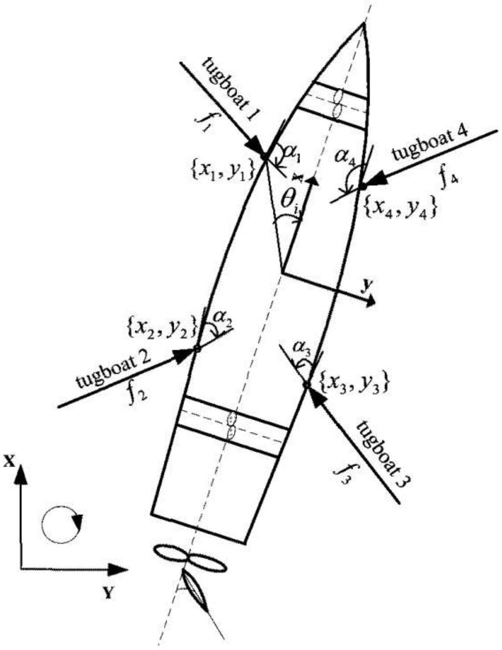

Figure 15. Schematic description of the system composed of tugboats and mothership proposed by Bae [22]. The tugboats were modeled as thrusters.

In the study by [24], the effect of environmental disturbance is decomposed into low-frequency drift motion and wave motion components. The wave frequency component, which describes the vibrational motion of the ship, can be ignored, and the low-frequency components, such as slow wind, tidal current, and waves, are grouped together to form a model of environmental disturbance. To compensate the effect of disturbances, Sliding Mode Control (SMC) was applied, which is a robust control technique commonly used in the presence of uncertainty or disturbance. However, the studies mentioned only modeled tugboats as thruster and assumed that they operated as a single system, which differs from the actual operation of pushing and pulling the mothership.

In 2019, there was a study [27] which controlled a ship using a towline between the tugboat and the ship being towed, as shown in Figure 16. When the tugboat tows the ship using a towline, the system is affected by environmental disturbances such as waves and currents. To address this, the system was controlled using three active directional fins attached to the hull and the towline. In Figure 16, (x_0, y_0) and (x, y) represent the connecting point at the towing point and the center of the towed vessel, respectively. ψ and ψ_T are towed vessels, respectively, the heading angle and towed vessel relative heading angle about the rope, representing the center line. Additionally, γ indicates the relative angle made by the target position and the control position, and σ (=1, 2, 3) indicates the rotation angle of each rudder. Finally, $l_r, l_T, l_b, l_s, l_{ss}$ mean the length shown in the figure.

Although this study did not use a cluster of multiple tugboats to perform berthing operations, it is significant in that it is the first study to model ship characteristics, the dynamics of the towline, and the dynamics of the tugboat and the ship being towed while considering the towline.

Choi [28] proposed a work in 2020 which uses a simplified dynamic equation to model the system, assuming point contact between the ship and each tugboat, with independent variables expressing the speed constraints at the contact point. This was the first time that multibody dynamics, involving the dynamics of both a ship and a tugboat, were considered. The cooperative operation and control of multiple tugboats were demonstrated by modeling the mothership and several tugboats as one system and controlling independent variables using a simplified dynamic equation, excluding the contact force term. In 2021, Hong proposed a hybrid system concept, as shown in Figure 17, where continuous and noncontinuous dynamic models interacted in a combination of a discrete-time dynamic model that considered the position movement of the tugboat and a continuous-time dynamic model that represented the tugboat control. In Figure 17, the mode of the tugboat is switched by the value of q, and q_1 and q_2 mean the towing mode and the berthing mode, respectively. When the mode is switched, the position of the tugboat is changed, and the control input τ is set to 0 during the changing time T. Moreover, $x(t)$ and $u(t)$ mean state variable and control input variable, respectively. In addition, the modeling of environmental disturbances in the paper was dominated by the influence of wind near the port. A control technique using the PPO (Proximal Policy Optimization), a reinforcement learning-based algorithm, was applied.

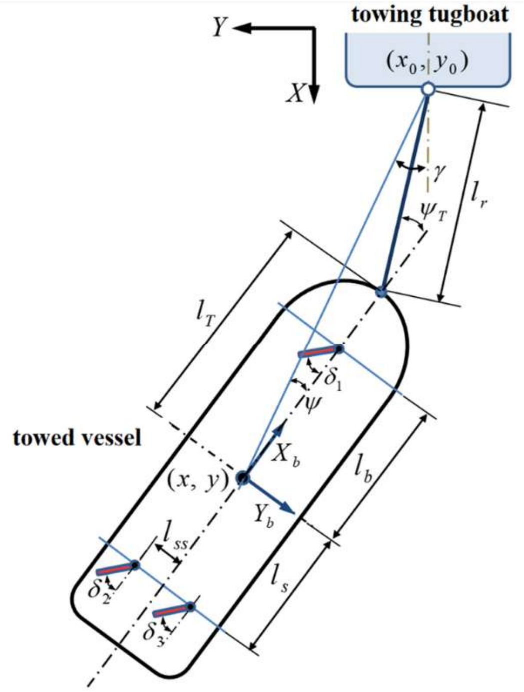

Figure 16. Schematic description of the system proposed by Quan [27]. Towline and tugboats are modeled as multibody dynamics.

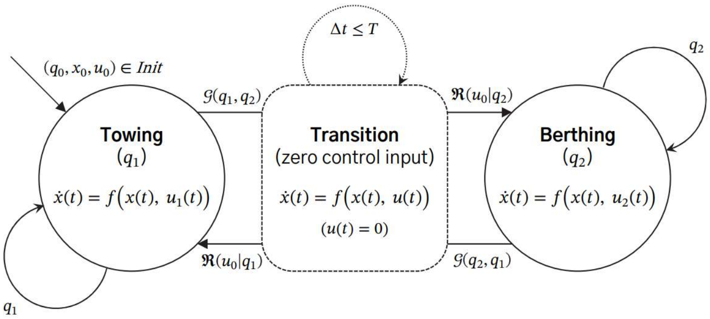

Figure 17. Tugboat transition hybrid system proposed by Hong and Kim [29].

Sano [30] conducted a study focusing on the mathematical modeling of tugboat dynamics. The research aimed to develop mathematical models to describe the cooperative maneuvers between a mothership and a tug during pushing and pulling operations. The equations of motion for the mothership and the tug were categorized into three scenarios:

(i) the mothership being towed by the tug, (ii) independent motion of the tug and the mothership, and (iii) the tug pushing the mothership. For each situation, a modular approach was adopted to construct the respective models by rearranging coefficient and component vectors in block matrices. Specifically, in the context of the pushing situation, a mathematical model was formulated to represent the multibody dynamics of the tug and mothership (Figure 18; Equations (1)–(8)).

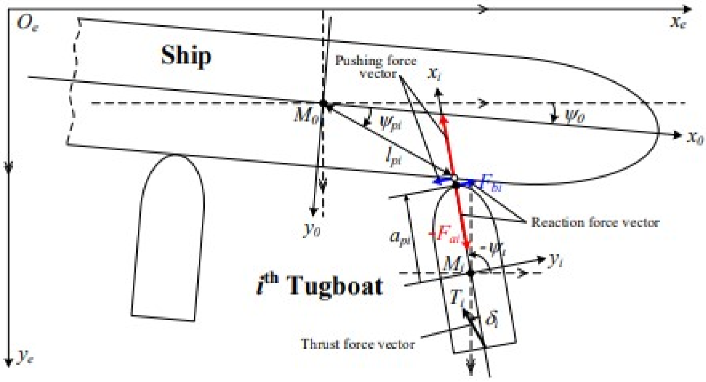

Figure 18. Coordinate systems in the case of pushing assistance [30].

$$\begin{bmatrix} A_0 & \cdots & A_{p0n} \\ \vdots & \ddots & \vdots \\ A_{pn0} & \cdots & A_{pn} \end{bmatrix} \begin{bmatrix} B_0 \\ \vdots \\ B_{pn} \end{bmatrix} = \begin{bmatrix} C_0 \\ \vdots \\ C_{pn} \end{bmatrix} \tag{1}$$

Equation (1) is an equation organized as a matrix equation by considering the equation for the ship and the geometrical positional relationship for n tugboats as a linear system of equations.

$$\begin{aligned} B_0 &= [\dot{u}_0 \quad \dot{v}_0 \quad \dot{r}_0 \quad \dot{u}_{eo} \quad \dot{v}_{eo}]^T \\ B_{pi} &= [\dot{u}_i \quad \dot{v}_i \quad \dot{r}_i \quad \dot{u}_{ei} \quad \dot{v}_{ei} \quad F_{ai} \quad F_{bi}]^T \end{aligned} \tag{2}$$

$$C_0 = \begin{bmatrix} (m_0 + m_{y0})v_0 r_0 + m_0 x_{G0} r_0 + X_{H0} \\ -(m_0 + m_{x0})u_0 r_0 + Y_{H0} \\ -m_0 x_G u_0 r_0 + N_{H0} \\ u_0 r_0 sin(\psi_0) + v_0 r_0 cos(\psi_0) \\ -u_0 r_0 cos(\psi_0) + v_0 r_0 sin(\psi_0) \end{bmatrix} \tag{3}$$

$$C_{pi} = \begin{bmatrix} (m_i + m_{yi})v_i r_i + m_i x_{Gi} r_i^2 + X_{Hi} + (1 - t_i)T_i cos(\delta_i) \\ -(m_i + m_{xi})u_i r_i + Y_{Hi} - T_i sin(\delta_i) \\ -m_i x_{Gi} u_i r_i + N_{Hi} - x_{Ti} T_i sin(\delta_i) \\ u_i r_i sin(\psi_i) + v_i r_i cos(\psi_i) \\ -u_i r_i cos(\psi_i) + v_i r_i sin(\psi_i) \\ r_0^2 l_{pi} cos(\psi_0 + \psi_{pi}) - r_i^2 a_{pi} cos(\psi_i) \\ r_0^2 l_{pi} sin(\psi_0 + \psi_{pi}) - r_i^2 a_{pi} sin(\psi_i) \end{bmatrix} \tag{4}$$

Equation (2) to (4) consists of the component vector B_0 of the vessel, each containing five variables related to the motion of the vessel, and the component vector B_{pi} of each tugboat, each containing seven variables related to the motion and pushing force of the tugboat; when n tugboats push the ship, a matrix equation of size 5 + 7n is solved. The constant vector consists of the component vector C_0 of the ship and the component vector C_{pi} of each tugboat. Additionally, X_H, Y_H, and N_H inside the matrix are expressed to represent the hydrodynamic surge force, sway force, and yaw moment due to the maneuvering motions, respectively; m_0 is the mass and m_{x0} and m_{y0} are the added masses in the surge and sway of the ship, respectively. I_{zG0} is the moment of inertia, and I_{zG0} is the added moment of inertia. The $x_{Ti}T_i sin(\delta_i)$ term gives an azimuth thruster located at (x_{Ti}, 0) of $m_i - x_i y_i z_i$, representing the assumed thrust. Lastly, $\dot{u}, \dot{v}$, and $\dot{r}$ are the surge, sway accelerations, and angular acceleration in the yaw direction, respectively, and F_{ai}, F_{bi} means the force at the contact point.

$$A_0 = \begin{bmatrix} m_0 + m_{x0} & 0 & 0 & 0 & 0 \\ 0 & m_0 + m_{y0} & m_0 x_{G0} & 0 & 0 \\ 0 & m_0 x_{G0} & I_{zG0} + I_{zG0} + m_0 x_{G0}^2 & 0 & 0 \\ cos(\psi_0) & -sin(\psi_0) & 0 & -1 & 0 \\ sin(\psi_0) & cos(\psi_0) & 0 & 0 & -1 \end{bmatrix} \tag{5}$$

$$A_{pi} = \begin{bmatrix} m_0 + m_{xi} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_i + m_{yi} & m_i x_{Gi} & 0 & 0 & 0 & 0 \\ 0 & m_i x_{Gi} & I_{zGi} + J_{zi} + m_i x_{Gi}^2 & 0 & 0 & 0 & 0 \\ cos(\psi_i) & -sin(\psi_i) & 0 & -1 & 0 & 0 & 0 \\ sin(\psi_i) & cos(\psi_i) & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & a_{pi} sin(\psi_i) & -1 & 0 & 0 & 0 \\ 0 & 0 & -a_{pi} cos(\psi_i) & 0 & -1 & 0 & 0 \end{bmatrix} \tag{6}$$

$$A_{p0i} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & cos(\psi_i - \psi_0) & -sin(\psi_i - \psi_0) \\ 0 & 0 & 0 & 0 & 0 & sin(\psi_i - \psi_0) & cos(\psi_i - \psi_0) \\ 0 & 0 & 0 & 0 & 0 & l_{pi} sin(\psi_i - \psi_0 - \psi_{pi}) & l_{pi} cos(\psi_i - \psi_0 - \psi_{pi}) \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

$$A_{p0i} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -l_{pi} sin(\psi_0 + \psi_{pi}) & 1 & 0 \\ 0 & 0 & l_{pi} cos(\psi_0 + \psi_{pi}) & 0 & 1 \end{bmatrix} \tag{8}$$

Finally, Equations (5) to (8) represent a 5 × 5 A_0 matrix composed of ship variables, a 7 × 7 A_{pi} matrix composed of variables of the ith tugboat, and the geometric dependence between the ship and the ith tugboat, meaning A_{p0i} (5 × 7) and A_{Pi0} (7 × 5) columns. The A_0, A_{pi} and A_{p0i}, A_{Pi0} matrices are arranged diagonally, respectively. Then, it is assumed that there is no dependency between the tugboats, and an A_{pij} matrix representing direct interference from the j-th tugboat to the i-th tugboat is set to a zero matrix.

System modelings that include both tugboats and motherships were conducted initially in the form of thrusters and considered as a single system, which was different from the actual operation method of berthing, which includes pushing and pulling mechanisms of multiple tugboats. However, as research progressed, modeling techniques that incorporated environmental disturbances and the use of a towline were developed. In the most recent study [29], different multibody dynamic modeling techniques were introduced for both the towing and berthing modes, and modeling techniques for autonomous tugboat swarm and motherships for automatic berthing were developed. Future studies should consider the dynamics of towlines, individual tugboats, and motherships.

4.4. Control Technology

Control technology can be said to be a core technology, to the extent that control technology is mentioned the most in research on ship berthing. Since tugboats and large ships perform cooperative work in a relatively close distance environment, accurate position and attitude control performance is required. In the study in [52], an empirical experiment was conducted to maintain a fixed position while offsetting the influence of tidal current or wind by implementing a dynamic position control algorithm for an autonomous tugboat.

In order to berth a large-scale merchant ship, it is necessary to control a group of at least two or more tugboats instead of one tugboat, so research on control technology using a group of tugboats is being actively conducted.

In the study in [18], a distributed control approach was employed to independently control each tugboat instead of using a centralized control method. The study focused on investigating the tracking control of the towed vessel using a robust control strategy. However, the study only addressed the issue of controlling the vessel's simple direction without taking into account the effects of hydrodynamic forces or environmental disturbances.

The study by Braganza [19] assumed that tugboats are strategically placed close enough so that information transmission between them is not necessary. An adaptive control technique was used to compensate for the force on the contact point between the main ship and the tugboat when it cannot be accurately known. Other studies [2,21] have used adaptive control techniques to compensate for changes in fluid dynamic parameters, such as drag force and mass coefficient when passing through narrow channels or open sea. Another study [23] dealt with maneuvering a target vessel using an autonomous surface vessel with an overactuated system equipped with six propellers. The study designed a tracking controller using an adaptive control technique to match the desired trajectory. This tracking controller can be applied to a scenario in which the motion of a mothership is manipulated using an autonomous tugboat (Figure 19). In Figure 19 a traceable desired trajectory (p_d) is generated that reflects the actuator configuration and constraints, model uncertainties, and controller structure and generates the desired forces and moments(τ_{net}) through the tracking controller. Given τ_{net}, we are given the commands for individual actuators τ_1, τ_2, etc., as well as the barge's position and yaw angle in the inertial frame (p), the barge's velocity in the body frame(v), heading(ψ), and rr of the ship.

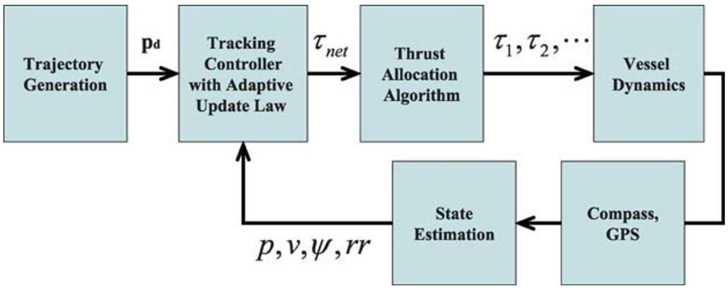

Figure 19. Trajectory tracking framework proposed by Feemster et al. [23].

In a subsequent study [24], the authors considered modeling disturbances such as wind, current, and waves, which are types of environmental disturbances. They applied the Sliding Mode Control (SMC) technique, a robust control method, instead of the adaptive control method. SMC can handle not only uncertainties in quickly changing parameters but also disturbances or dynamic components not included in the model. SMC is more resistant to disturbances compared with the adaptive control technique. The effectiveness of these control methods was verified using a 1:70 scale model ship, also known as a "cybership". In another study [3], the authors proposed a new robust controller methodology through matrix decomposition. They arranged the tugboats in a specific configuration, which converted the overall problem into a second-order system with an asymmetric input gain matrix. The studies mentioned above primarily focused on developing control methods for tugboats, but did not address the control of the mothership's attitude, which involves the positioning and orientation of the ship during the berthing process. Moreover, these studies only modeled each tugboat as an azimuth propulsion system and did not consider the actual physical interaction between the tugboats and the mothership, where the tugboats push and pull the mothership. Therefore, there is still a need for research on developing control strategies that take into account the actual physical interaction between the tugboats and the mothership and ensure precise control of the mothership's position and attitude during the berthing process.

In order to better reflect the actual operation method, Tran et al. [53] developed a ship berthing system that utilizes cooperative control between the damper and tugboat, as well as a subsequent study [54] was conducted to design a berthing system considering the ship characteristics and dynamics of the towline. However, the dynamics of the entire system were not taken into account. In actual tugboats, controlling the mothership accurately to the predefined path using a towline is challenging. If the tugboat and the vessel to be towed follow different paths due to waves and complex maneuvering environments, the risk of collision is high, making precise control of the path essential. To address this challenge, Quan [27] proposed a basic mathematical model of a tugboat equipped with three active rudders (see Figure 16). As tugboats are dependent on the towline to pull the vessel or deal with obstacles, Quan proposed a follow-up control for the leader to enhance the tracking performance of the towed vessel along the path of the tugboat.

In the study by [28], the motherships and each tugboat were treated as one system, and the independent variables were controlled by considering multibody dynamics. A pose control method was proposed based on simplified dynamics, excluding the contact force term. Figure 20 shows the simulation result, which was demonstrated using a tracking control technique that can be manipulated to track a straight path while maintaining a desired heading angle.

The problem of autonomy of a tugboat when docking a ship is a problem in which the tugboat's positional movement problem and control problem are complex. Therefore, in order to solve these complex problems, recently, research on reinforcement learning-based control methods using AI artificial intelligence is increasing. If reinforcement learning is used, it has the advantage that it can be applied to complex nonlinear problems or problems that are difficult to solve with existing control methods.

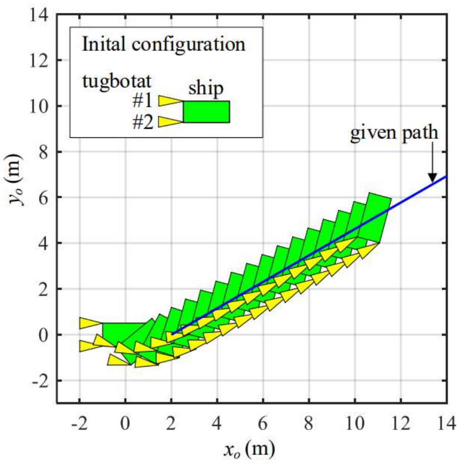

Figure 20. Tracking a given path using two tugboats while maintaining angle between tugboat and mothership [28].

The study in [29] proposes a hybrid control concept that combines a discrete-time dynamic model accounting for the tugboat's position movement and a continuous-time dynamic model representing the tugboat control. A control approach using the policy gradient-based Proximal Policy Optimization (PPO) algorithm is introduced, which is suitable for continuous action spaces and has shown high performance in reinforcement learning. The PPO algorithm is an artificial intelligence technique used to determine the optimal action to take in the current state. In the study in [29], the error between the current state and the state of the target ship is calculated, and the compensation value is obtained to minimize the error, maximizing the outcome. In Figure 21, the output value of the network consists of a total of five values ($\triangle f_1, \triangle f_2, \triangle \alpha_1, \triangle \alpha_2, k$) that select the amount of change in the force of each tugboat, the amount of change in the direction of the force, and the tugboat mode. Among these, the k value was discretized into two continuous action values from -1 to 1 to represent the discretized mode change in the tugboat. If -1 to 0, q_1 (towing mode), and if 0 to 1, q_2 (berthing mode), were used to select the tugboat mode. Network inputs are x, y, ψ, u, v, and r, representing the state of the ship and e_d, and e_ψ, e_v (distance error, heading error, and velocity error), and the output value of the previous step was set as the network input value in the current step.

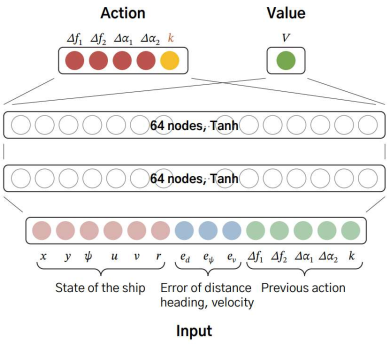

Figure 21. Policy network and value network configuration for reinforcement learning-based controller proposed by Hong and Kim [29].

In the early 2000s, research on control methods for tugboats evolved from simple directional control to adaptive control, which compensates for the positional problem of tugboats and the uncertainty of differential coefficients of hydrodynamic force, as well as robust control methods that take into account environmental disturbances. Recently, research on control methods using artificial intelligence has gained traction. As the actual berthing method is gradually considered, the control methods are also being applied in various ways.

4.5. Infrastructure and Operation

The shipping industry faces many interrelated challenges and opportunities as its role in the global trading system has become increasingly important over the past few decades. On the one hand, a collaboration between port terminals and shipping lines can reduce costs and achieve sustainable supply chains, and on the other hand, optimizing operations and voyage times can reduce bunker consumption and lower fuel costs and air emissions. Therefore, there is a growing need to address the consolidation opportunities and environmental challenges associated with container shipping through optimization. Container port operations can be classified into two categories: landside operations and seaside operations. The landside usually consists of a gate, yard, and quay, while the seaside consists of berth and channel anchorage areas. As shown in Figure 22, container ships require the assistance of tugboats. However, the availability of tugboats and the ability of each tug to serve a ship is limited. Therefore, for tugs to provide effective service to large ships, they must be effectively utilized.

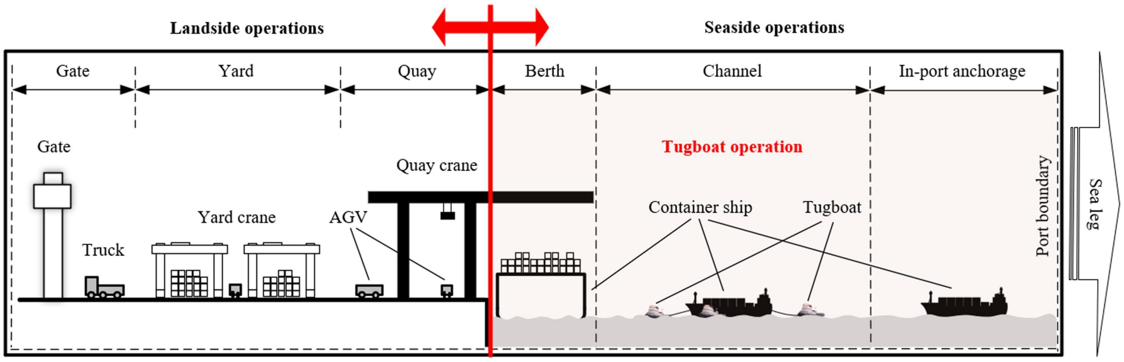

Figure 22. Seaside and landside operations in container ports [44].

A mixed-integer linear programming (MILP) method is developed to solve the tugboat scheduling problem by considering real-world problems such as tugboat flow balance constraints, ship arrival time constraints, sail time limits, tugboat arrival time constraints, service start time constraints, and ship–tugboat compatibility constraints and is applied to the tugboat scheduling problem (Tug-SP) to show efficient scheduling performance [44]. Figure 23 shows a more practical tugboat scheduling strategy, considering a proactive scheduling strategy that takes into account the expected variability and uncertainty during the execution of the tugboat operation schedule and a reactive scheduling strategy that appropriately adjusts the initial schedule to deal with unexpected scenarios with minimum recovery cost [45].

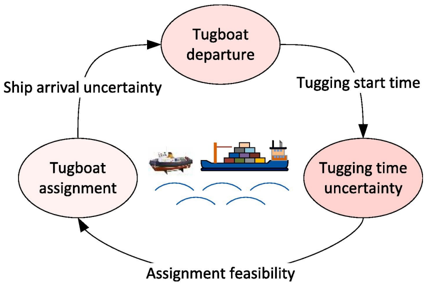

Figure 23. Tugging processes with time uncertainty [45].

In addition to the tugboat scheduling problem, we can focus on the Berth Allocation Problem (BAP), which is a well-known optimization problem for assigning berth times and locations for ships. By considering the speed of ships and their arrival and departure times as decision variables in the problem, we extend the traditional BAP to obtain a better solution by using a higher level of discretization with more accurate speed variables. In addition, fuel and ship GreenHouse Gas (GHG) emissions can be reduced by approximately 40% when comparing the model with a situation where each ship is sailing at its design speed [46]. It also focuses on the Quay Crane Assignment Problem (QCAP). The Berth Allocation and Quay Crane Assignment Problem (BACAP), where each vessel is assigned a berth time and location for a given planning horizon, is solved by assigning cranes considering the marginal productivity loss due to crane interference and the processing time depending on the vessel's berth location [47].

In addition, research in the field of energy efficiency and greening for green ports is increasing, and operational strategies, technologies, and energy management systems for energy efficiency are being reviewed, and all methods, measures, and technologies are being reviewed, quantified, and compared. Through this comparative analysis, energy savings and emission reductions can be expected [49].

Finally, mooring is one of the most dangerous operations on ships and in ports. Currently, as shown in Figure 24, there are various innovations in mooring systems, such as automatic vacuum mooring systems, magnetic mooring systems, and berthing assistance systems. In [48], a study compares the operational reliability, operating costs, maintenance costs, environmental impact, ease of handling, and system limitations of vibration-based automatic mooring systems, magnetic mooring systems, and conventional mooring systems using ropes and windlasses.

As these studies show, many factors are being considered for tugboats, including scheduling, safety, and eco-friendliness. If autonomous tugboats take these factors into account, they will be economical, efficient, and reliable and play an important role in logistics and international trade. They will also help the shipping industry to be sustainable and develop in the future.

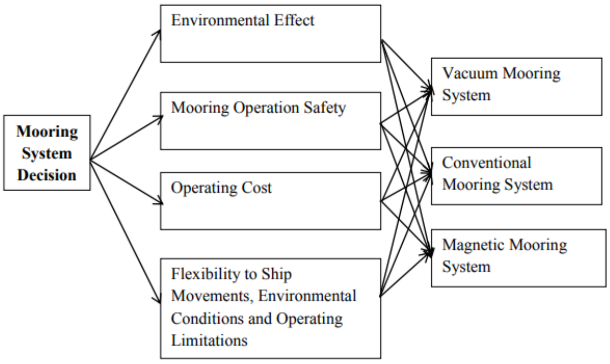

Figure 24. Hierarchical structure for mooring system decision [48].

5. Conclusions

In this paper, we analyzed previous studies on relevant topics to provide engineering knowledge and insights related to autonomous tugboats. Firstly, we explained actual projects being carried out for the autonomous operation of tugboats, and then we conducted an analysis of various required element technologies for constructing autonomous tugboats. Four types of technologies are required for ships using autonomous tugboats: perception, decision-making, modeling, and control technology. We described the necessity and detailed research trends for each technology. Previous studies for each element technology have indicated research trends from the early 2000s to the present.

The analysis of previous studies revealed that many of them assumed the tugboats to be fully autonomous and did not address certain issues, such as determining the formation for operating tugboats as a cluster during mooring and developing algorithms that automatically assign and reassign tasks such as thrust adjustment for each tugboat. There were also few studies that considered the communication issues between the mothership and each tugboat, assuming that they were strategically positioned close enough to eliminate the need for information transmission. Furthermore, most of the studies were limited to simulations in environments such as MATLAB and Pygame [28], without verification in real-world maritime environments.

Research on berthing using a fully autonomous tugboat requires verification of various scenarios in an environment similar to the actual environment, and it is necessary to overcome the limitations of the state of the art. Firstly, research is needed to develop an algorithm that automatically assigns and reassigns tasks to the tugboat swarm for the scenarios of the towing and berthing mode. Each individual tugboat should be reassigned roles to perform a given task by receiving control objectives and methods according to the goals required for each mode. Secondly, precise modeling of the towline, individual tugboats, and mothership must be based on multibody dynamics for the towing and berthing mode. Considering the operational method where the tugboat pushes and pulls the towline, modeling of the entire system that includes tension in the towline, friction between the tugboats and mothership, and the environmental disturbance is necessary. Finally, it is deemed necessary to have communication/network technology that allows each tugboat to exchange information, as well as fault diagnosis and response technology that can immediately detect and respond to any malfunctions in the tugboat's components.

Previous research has made progress in control and modeling techniques, as well as various other technological elements; however, to achieve autonomous berthing of ships using autonomous unmanned tugboats, research is needed not only on individual unmanned tugboats but also on the technologies required to operate them in a swarm manner. If autonomous surface vehicles are successfully employed in ship berthing operations, significant technological ripple effects could reduce personnel costs and save time.

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