Journal of
Marine Science and Engineering

MDPI

Review

A Review of Progress and Applications of Automated Vacuum Mooring Systems

Kaicheng Yan [1], Shengdong Zhang [1,2], Jungkeun Oh [1] and Dae-Won Seo [1,*]

[1] Department of Naval Architecture and Ocean Engineering, Kunsan National University, Gunsan-si 54150, Korea
[2] School of Mechanical and Intelligent Manufacturing, Jiujiang University, Jiujiang 332005, China
* Correspondence: dwseo@kunsan.ac.kr

Abstract: Compared with the traditional mooring system, the automated vacuum mooring system can meet the development needs of large-scale ship automation, port automation, and environmental protection. This review describes the latest research focuses, progress, applications, and future perspectives regarding the automated vacuum mooring system. First, the components, working principles, advantages, limits, and risks of the automated vacuum mooring system are discussed. Secondly, typical application cases of automated vacuum mooring systems are introduced, looking at two aspects of the ship-based system and shore-based system. Then, the routine maintenance of the automated vacuum mooring system is introduced. Finally, a discussion on the challenges and future perspectives of the automated vacuum mooring system is provided in this review. The advantages of an automated vacuum mooring system make it a potentially highly effective and economical option for a wider range of ship mooring than a traditional mooring system.

Keywords: vacuum mooring system; MoorMaster^{TM}; vacuum pads; ship-based system; shore-based system

check for updates

Citation: Yan, K.; Zhang, S.; Oh, J.; Seo, D.-W. A Review of Progress and Applications of Automated Vacuum Mooring Systems. *J. Mar. Sci. Eng.* **2022**, *10*, 1085. https://doi.org/10.3390/jmse10081085

Academic Editor: Mohamed Benbouzid

Received: 26 June 2022
Accepted: 1 August 2022
Published: 8 August 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The number of ships and ports is increasing to accommodate the growing transportation demand and increasing number of mooring operations. For thousands of years, ships were moored by human hands using cables. This traditional mooring method is not only inefficient, but dangerous [1–3]. With the continuous increase in ship tonnage and the development trend of intelligent ships [4,5], the traditional rope mooring method is becoming increasingly difficult and time-consuming. According to incomplete statistics, there are hundreds of accidents due to mooring with ropes every year. Statistics from the European Harbour Master's Committee (EHMC) [6] indicate that, of all registered mooring injuries, 95% are caused by ropes and wires, and 60% of these injuries happen during mooring operations. Losses from major accidents (including injuries to seafarers) caused by mooring equipment exceeded USD 34 million from 1995 to 2016, according to reports. [7] Such accidents mostly occur in the process of rope/wire handling, in which rope/wire breakages account for 53% of the accident rate, and rope/wire jumps/slips from the end of the drum/bite account for 42% of the accident rate, of which 5.0% of accidents are caused by actual equipment failure. (Figure 1) [8–10]. According to the UK P&I Club, about 1/10 of personal injuries in ports are caused by mooring failures, the majority of which are caused by separate ropes and wire ropes [11–14]. According to statistics of the 5 years from 2011 to 2015, the Australian Maritime Safety Authority (AMSA) received a total of 227 mooring-related incident reports, of which 51 incidents resulted in injuries [15]. In the 11 years from 2006 to 2016, a total of 331 mooring reports were collected according to the International Maritime Health Association [16]. Statistics included in the Transportation Safety Board of Canada (TSB) database show that, from 2007 to 2017, 24 mooring incidents were reported involving mooring operations on Canadian and foreign-flag vessels. In these incidents, 24 people were injured and 2 were seriously injured. In the 7 years from 2001 to 2017, other International Maritime Organization (IMO) member states also investigated mooring incidents. A total of 25 marine incidents and 14 very serious marine incidents were reported. The casualties were caused by the buckling or trapping of mooring lines and crews tripping, falling, hitting, or being hit while conducting mooring operations, resulting in a total of 27 injuries and 13 serious injuries [17]. According to a report by CHIRP Maritime, in 2018, 2019, 2020, and 2021, there were 10, 12, 8, and 13 mooring accidents, respectively [18]. From 2019 to 2021, MACI reported the accidents and incidents in mooring operations at 7.14%, 5.26%, and 14.55% [19].

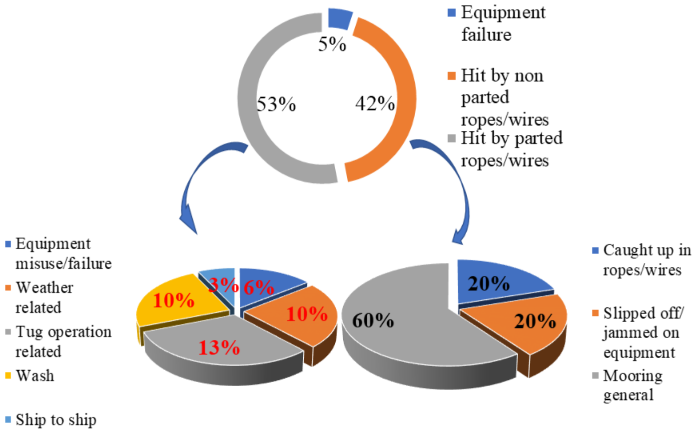


Figure 1. Types of incidents resulting in personal injury from 1995 to 2016 (adapted with permission from Ref. [19]. Copyright 2020 Cayman Registry).

Therefore, there is an urgent need for a safe and effective mooring system to solve the above problems, such as an automated vacuum mooring system. The main companies in possession of automated vacuum moorings at present are Cavotec [20–23] and Trelleborg [24].

Iron Sailor is a range of ship-based systems consisting of three different models: Iron Sailor E, Iron Sailor I, and Iron Sailor T [25] (Figure 2). In 1998, a mooring system, Iron Sailor I, was installed for the first time by Cavotec [23]. It was used for the first time on the Aratere ferry (150 m long). It consists of four 20-ton units. There are two units each near the bow and stern. The device is activated by controlling the bridge, and it then automatically connects to the surface of the steel plate on the wharf.

Figure 2. Iron Sailor devices type showing (**a**) Iron Sailor E, (**b**) Iron Sailor I, (**c**) Iron Sailor T (adapted with permission from Ref. [25]. Copyright 2022 Cavotec. Ref. [26]. Copyright 2013 Cavotec MSL Holdings Limited).

The first automated ship-to-ship docking system (Figures 3 and 4) was developed by Cavotec in 2014, so that two ships could exchange containers in the ocean. The system mainly consists of vacuum pads, robot arms, cables, automated winches, and fenders [27].

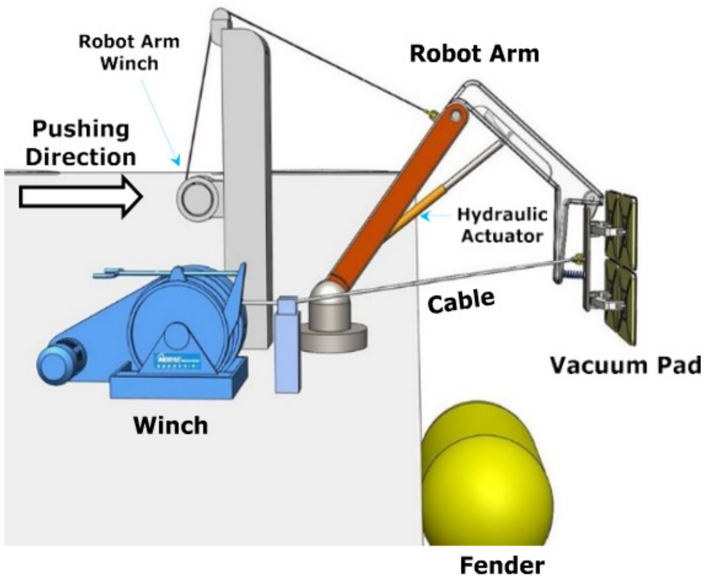


Figure 3. Schematic diagram of the design of the automated ship-to-ship docking system (adapted with permission from Ref. [27]. Copyright 2014 YongYook, Kim).

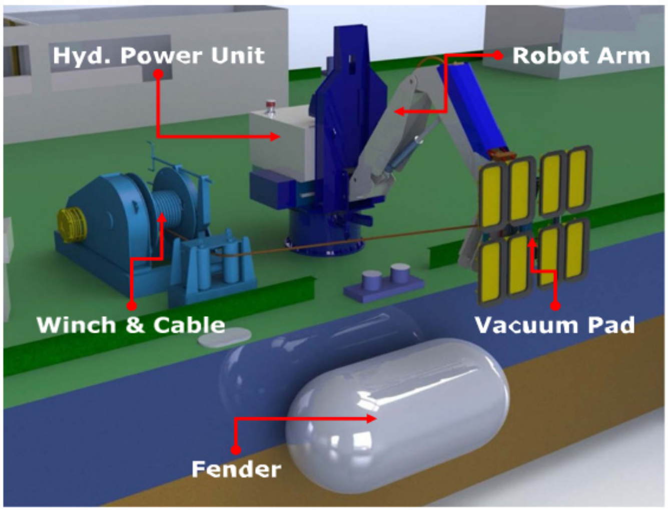


Figure 4. Hardware and arrangement of the automated mooring system (adapted with permission from Ref. [27]. Copyright 2014 YongYook, Kim).

Then, Cavotec developed the MoorMaster^{TM} range of automated mooring units for different applications. The mainframe is a linkage mechanism, and the system uses vacuum technology to generate a suction force of 200 kN per mooring unit during operation, with small movements and rotations at the end (Figure 5).

Trelleborg [24] developed the AutoMoor automated mooring device using the environment detection technology SmartPort and passive damping technology, which uses vacuum technology to quickly and securely fix the vessel to its berth, inhibits vessel movement, and continuously monitors the mooring load of the moored vessel, as shown in Figure 6.

Figure 5. MoorMaster^{TM} vacuum mooring systems type showing (**a**) MM200C, (**b**) MM200E, (**c**) MM200LS, (**d**) MM400, (**e**) MM400A, (**f**) MM400E, (**g**) MM I-400, (**h**) MM600, (**i**) MM800 (adapted with permission from Ref. [28]. Copyright 2014 Cavotec).

(**a**) Single suction cup (**b**) Double suction cup

Figure 6. AutoMoor mooring systems of the Trelleborg company showing (**a**) Single suction cup, (**b**) Double suction cup (adapted with permission from Ref. [24]. Copyright 2022 Trelleborg).

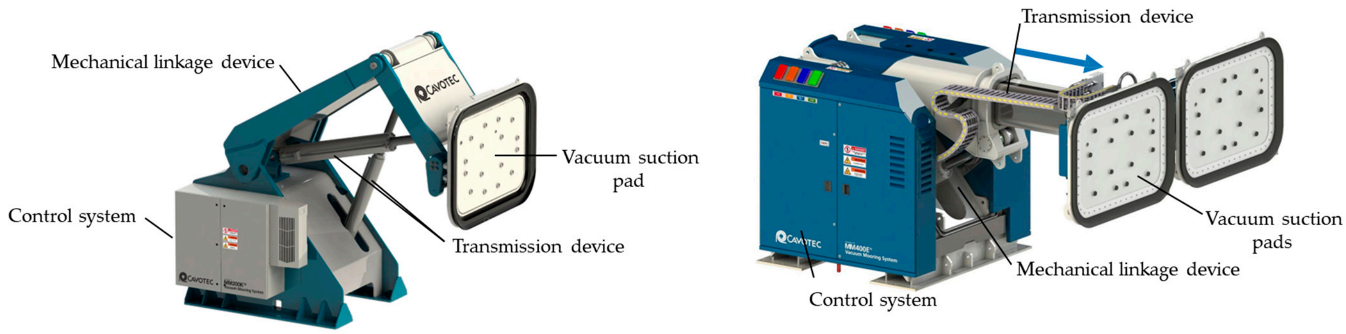
Only one regulation, the British standard BSI 6349-4: 2014 [29], has been introduced to this system at present.

The review aims to present the automated vacuum mooring technologies, especially regarding the latest research focuses, progress, applications, challenges, and future perspectives. In this review, Section 2 covers the automated vacuum mooring system's components, working principles, advantages, limits, and risks; Section 3 presents the applications based on the ship-based system and the shore-based system; Section 4 presents the routine maintenance; Section 5 presents the discussion, challenges, and future perspectives; and Section 6 presents concluding remarks. Compared with traditional mooring systems, the automated vacuum mooring system can meet the development needs of large-scale ship automation, port automation, and environmental protection. These advantages make it a potentially highly effective and economical option for a wider range of ship mooring than a traditional mooring system.

2. Automated Vacuum Mooring System

2.1. Components

The automated vacuum mooring system mainly includes the following components: 1. the vacuum suction pad; 2. the mechanical linkage device; 3. the transmission device; and 4. the control system. This is shown in Figure 7. The main principle of the vacuum suction pad is to evacuate the air in the suction pad through a vacuum pump, so that negative air pressure is generated in the suction pad and the object is adsorbed. The vacuum suction pad is in contact with the hull, the edge is sealed by rubber, and the suction pad is connected with the vacuum pump equipment through the nozzle [30].



(**a**) (**b**)

Figure 7. The components of automated vacuum mooring systems showing (**a**) two transmission devices & single pad, (**b**) one transmission device & two pads (adapted with permission from Ref. [31]. Copyright 2022 Cavotec).

2.2. Working Principles

The automated vacuum mooring system is an innovative mooring system for seagoing vessels. The working principle of the system is as follows: when the ship sails close to the wharf, generally a few meters, the vacuum pump of the automated mooring system is turned on. The ship is slowly pulled into the wharf by the vacuum pad until mooring is complete. During the mooring of the ship, the ship is subjected to a constant suction force from the vacuum pad. After the ship is moored, the safety system of the automated vacuum mooring system can ensure a constant suction force between the ship and the automated vacuum mooring system. Even if the system is powered off, the automated mooring system can guarantee the suction power force for 2 h [31]. The automated vacuum mooring system can compensate for the movement of the ship in real time and automatically adjust the position of the ship. Sensors are integrated into the vacuum pad and hydraulic system to provide information to the system. Among them, the vacuum percentage and the suction force acting on the ship are provided by sensors in the vacuum pad; the motion information of the ship is provided by sensors in the hydraulic system. All the above information is displayed on the computer.

2.3. Advantages

1. Works with virtually all vessels. The vacuum pad has a modular design and can be attached to the plane of the hull [32].

2. Faster. Traditional rope mooring takes half an hour to an hour to complete a mooring, whereas an automated vacuum mooring system can moor a ship within 30 s [33–35].
3. High degree of automation and more safety. The operator only needs to press the control button to complete the automated mooring operation through the remote-control system. Since there are no snap-back zones in this mode of operation, personnel do not need to work in hazardous areas, thus this system can guarantee zero accidents for personnel (Figure 8).

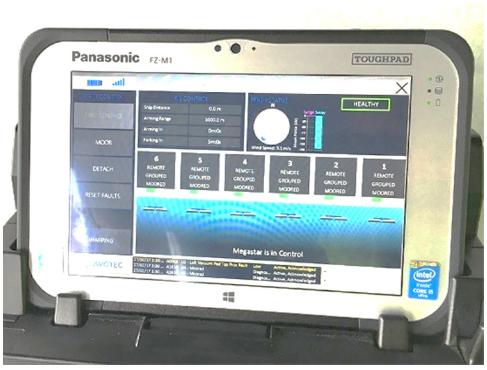


Figure 8. Operation system.

4. Vessel overhang. Since the birth of the MoorMaster^{TM}, the berthing of large ships no longer requires additional infrastructure investment in the port, only the addition of some automated vacuum mooring systems. Dock length can easily be changed by increasing the number of devices. Ships of any tonnage can use these berths.
5. Stability. There is reduced vessel motion due to the advanced control system. Research shows that the range of the vessel motion in surge and sway when using mooring lines is 1.1 m and 0.77 m, respectively, when using 6 × T40′s and 12 × T40′s of an automated vacuum mooring system. The range of the vessel motion in the surge is 0.64 m and 0.29 m, respectively, and in sway this range is 0.7 m and 0.44 m, respectively [24].
6. Economy. At present, the automated vacuum mooring system is installed in 23 docks in 12 different countries [31], and the system does not require ropes and mooring persons. Time loading and unloading can be saved, and the turnover rate of ships is accelerated, thus more ships can be berthed in the port per unit time. This saves the start time during transfer and reduces the workload of mooring personnel. The application of an automated vacuum mooring system reduces injury to mooring personnel and avoids the need for large amounts of compensation, thereby producing good economic benefits.
7. Environment. Emissions of polluting gases, especially carbon dioxide, are reduced as the automated vacuum mooring system can berth in less time [36]. At present, new European regulations [37,38] impose restrictions on the emissions of greenhouse gases (CO_2) and harmful pollutants from ships. In traditional mooring systems, ship emissions are affected by the following factors: the machine regime or the speed control [39–41], the quality of the fuel used, the conservation of the ship and the hull [42,43], and the time taken to carry out the maneuvers. However, with the installation of an automatic vacuum mooring system, CO_2 emissions were reduced by 97%. There are two methods for analyzing the reduction of CO_2 emissions in ports where automatic mooring systems are installed, namely, the EPA methodology [44] and the ENTEC methodology [45–48]. Both methods are considered suitable [49,50]. Taking the Salalah, Beirut, and Ngqura ports as examples, the CO_2 emissions of conventional mooring and automated vacuum mooring systems were calculated using both ENTEC and EPA methods (Table 1). From 2009 to 2019, CO_2 emissions from ports worldwide have decreased by 944,241,2160 tons due to the adoption of

automated vacuum mooring system technology. With the installation of an automatic vacuum mooring system, CO_2 emissions were reduced by 98% (Table 2) [34].

Table 1. Emissions of CO_2 in tons/year during mooring operations with ropes (ROPE) and with automated vacuum mooring systems, and reduction in CO_2 emissions (R) in tons/year and CO_2 emissions (RP) in % using the ENTEC and EPA methods in 2017 (adapted with permission from Ref. [34]. Copyright 2021 Díaz-Ruiz-Navamuel, E.).

PORTS	Ropes/Tons		Automated Vacuum Mooring System/Tons		Reduction/Tons		Reduced Percentage/% RP = (R − ROPE)/ROPE	
	$ROPE_{ENTEC}$	$ROPE_{EPA}$	A_{ENTEC}	A_{EPA}	R_{ENTEC}	R_{EPA}	RP_{ENTEC}	RP_{EPA}
Salalah	7815.3	9509.7	130.3	158.5	7685.1	9351.2	98.3	98.3
Beirut	2568.0	3333.5	42.8	55.6	2525.2	3277.9	98.3	98.3
Ngqura	2574.9	3477.1	42.9	58.0	2532.0	3419.1	98.3	98.3

Table 2. Emissions of CO_2 from 2009 to 2019 (adapted with permission from Ref. [34]. Copyright 2021 Díaz-Ruiz-Navamuel, E.).

Year	E Ropes/Tons	E Automated Vacuum Mooring System/Tons	AE = E Ropes − E Automated Vacuum Mooring System	AE/E Ropes
2009	593,452,606	11,869,052	581,583,554	
2010	701,869,239	14,037,385	687,831,854	
2011	760,884,972	15,217,699	745,667,273	
2012	809,222,136	16,184,443	793,037,693	
2013	855,160,921	17,103,218	838,057,703	
2014	898,484,577	17,969,691	880,514,885	
2015	919,340,019	18,386,800	900,953,218	
2016	935,487,080	18,709,742	916,777,339	
2017	1,011,662,659	20,233,253	991,429,406	
2018	1,065,516,031	21,310,321	1,044,205,710	
2019	1,084,034,210	21,680,684	1,062,353,526	
Total	9,635,114,449	192,702,289	9,442,412,160	98%

Figures 9 and 10 show the contribution of each country to the annual reduction in CO_2 using the ENTEC methodology and the EPA methodology, respectively. It can be seen that the countries with the most significant CO_2 reductions are those with automated vacuum mooring systems installed in busy ports, such as Finland, the Netherlands, and Denmark.

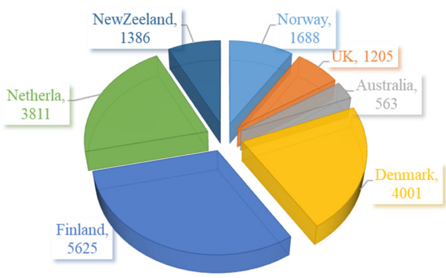


Figure 9. Reduction in CO_2 in tonnes per country and year with ENTEC (adapted with permission from Ref. [34]. Copyright 2021 Díaz-Ruiz-Navamuel, E.).

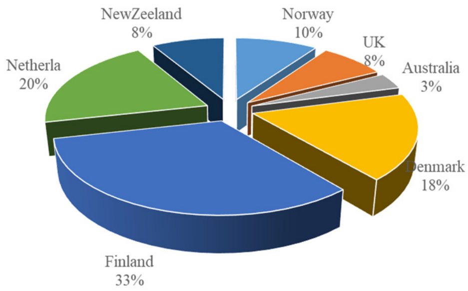


Figure 10. Reduction in CO_2 in tonnes per country and year with EPA (adapted with permission from Ref. [34]. Copyright 2021 Díaz-Ruiz-Navamuel, E.).

2.4. Limits and Risks

Although the automated vacuum mooring system itself does not have many limitations, if a ship needs to be anchored to the dock, the thickness of the hull can be an issue. When the thickness of the hull is less than 9.8 mm, the hull can be bent by the automated vacuum mooring system. Pads are not allowed to suck to the glass. The total force of the automated vacuum mooring system needs to be lower than the maximum force acting on the fenders. If the total force of the automated vacuum mooring system is greater, the fenders may be damaged or even broken. Each automated vacuum mooring system can only move 0.5 m in the horizontal direction. It is impossible for the automated vacuum mooring system to move vertically [51,52]. To obtain an 80% vacuum, a vacuum pad must have at least 2.5 m^2 of adsorption area. The vacuum pad must be attached to the flat hull or the vacuum will be lost.

3. Applications

At present, the MoorMaster™ is a widely accepted technology, with more than 300 MoorMaster^{TM} units in service at some 100 unique sites worldwide, which have performed more than 500,000 mooring operations with a 100 percent safety record, including ferry, bulk handling, RoPax and RoRo, container, and lock applications, all around the world by 2020 [28,29].

Two possibilities are available for the system: the ship-based system and the shore-based system. Both systems have their advantages.

3.1. Ship-Based System

The ship can be moored in a port without a shore-based system, which is the greatest advantage of the automated vacuum mooring system. The ship only needs to prepare a stable foundation and a flat, large steel plate to facilitate the adsorption of the vacuum suction pad to the steel plate [25,31]. All types of ship-based systems are shown in Figure 2.

The ship-based system includes three different types: their models are the Iron Sailor E, Iron Sailor I, and Iron Sailor T.

The Iron Sailor E type (Figure 2a) is an external automated vacuum mooring system mounted on the vessel's sidewall. When it is not used, it is placed at the sheer strake level. When it is in use, it tracks down the ship's sidewall until it couples with the suction plate on the shore.

The Iron Sailor I type (Figure 2b) has a total of four units installed on the "Aratere". Each unit has a rated suction capacity of 20 tons and is paired with two units. A pair of units are installed at the bow of the ship and a pair of units are installed at the stern of the ship. When the ship is moored, the controller activates these units on the bridge wing of the ship's wheelhouse, and the automated vacuum mooring system is extended out of the hull under the thrust of the hydraulic cylinder and is connected to the steel plate of the berth.

The Iron Sailor T type (Figure 2c) is primarily designed for barges and inland waterways. This type of mooring system is geometrically similar to the QuaySailor series and can secure smaller ships to larger ships.

3.2. Shore-Based System

When the automatic vacuum mooring system is used to berth a ship, there is no need to make additional adjustments and modifications to the ship. It is only necessary to provide a power supply and solid foundation for the system. The applications of a shore-based system of vacuum mooring are listed in Table 3.

The application of the automated vacuum mooring system to the shore-based system is mainly concentrated in six aspects: Ropax and RoRo, electric vessels, container, bulk, locks, and ship to ship.

RoPax and RoRo [28]. Cavotec's automated vacuum mooring system, MoorMaster™, can be installed on a variety of Ropax and RoRo systems; this system can significantly reduce the mooring time of the ships and reduce the cruising speed, thus providing ample time for passengers and vehicles. Since the ship's mooring time is shortened, the ship can save more fuel, reduce pollutant emissions, and reduce noise.

Electric Vessels [53]. The research and development of e-vessels started in 2014 by Cavotec and its customers. Cavotec's automated vacuum mooring systems and charging solutions are used in more than 60 ports. The automated mooring technology and Automatic Plug-in System (APS) of Cavotec is a single revolutionary platform that can moore and charge electric vessels safely, quickly, and efficiently. This composite system has an integrated user interface and communication architecture. This combined system was applied to the world's first electric ferry in 2015 by Cavotec. The APS developed by Cavotec can realize the fast connection and disconnection for e-vessels with the following characteristics: a short charging time, safe operation, low installation cost, easy maintenance, and no extensive modification of vehicles and ships.

Container [54]. The MoorMaster™ automated vacuum mooring system bridges the technology gap between container ships and today's highly automated facilities, and it is recognized by more and more ports, as well as being seen as part of the fully automated port design. The MoorMaster™ automated vacuum mooring system can protect Super Post-Panamax vessels (over 20,000 TEUs). It can reduce the surge motion of the ship to a certain extent through the smart control algorithm.

Bulk [55]. The MoorMaster™ automated vacuum mooring system has been working normally for more than ten years. In bulk carrier ports of Australia and Europe, this system can provide safer mooring for bulk carriers, LNG ships, and oil tankers, improve loading and unloading efficiency, and reduce the investment in port infrastructure.

Locks [56]. The automated vacuum mooring system can be applied to locks. It is installed on vertical rails inside the lock chamber walls of locks and automatically rises and sinks as the ship rises and sinks. The surge and oscillating roll motion of the ship can be controlled by this.

Ship-to-ship [57]. Mooring is the most challenging part of the job, sometimes, when many ships have to be moored together due to the lack of a haven. The automated vacuum mooring system avoids the difficulties of traditional rope mooring and can make ship-to-ship mooring simpler, making mooring work faster, safer, and more efficient.

Table 3. Application of the shore-based system of vacuum mooring.

	Port, Country	Berths	Since (Year)	Moorings	LOA (m)	Owner	Operator	Figure
RoPax and RoRo [28]	Port of Helsinki, Finland (RoPax)	LJ7 and LJ8	2017	9/day	up to 212 m	Port of Helsinki	Tallink and Eckerö Line	Figure A1(A-1)
	Wightlink, UK (RoPax)	Portsmouth–Fishbourne	2017	30/day	62 to 89	Wightlink	Wightlink	Figure A1(A-2)
	Searoad, Australia (RoRo)	Melbourne–Devonport	2003	2/day	182 to 210	SeaRoad	SeaRoad	Figure A1(A-3)
	Samsø Rederi, Denmark (RoPax)	Hou–Sælvig	2015	7/day	99	Samsø Kommune	Samsø Rederi	Figure A1(A-4)
	Molslinjen, Denmark (RoPax)	Spodsbjerg–Taars and Ballen–Kalundborg	2009	5/day 18/day	99	Molslinjen	Molslinjen	Figure A1(A-5)
	Interislander, New Zealand (RoPax)	Picton–Wellington	2005	3/day	180 to 181	KiwiRail	Interislander	Figure A1(A-6)
	Teso, The Netherlands (RoPax)	Den Helder	2014	16/day	110 to 130	Teso	Teso	Figure A1(A-7)
	Port of Turku, Finland (RoPax)	Viking Line berth	2020	-	up to 222	Port of Turku	-	-
	Port of Tallinn, Estonia (RoPax)	-	2020	9/day	up to 212	Port of Tallinn	Tallink and Eckerö Line	-
Electric Vessels [53]	Norled, Norway (Two Routes)	Lavik–Oppedal and Sydnes–Utbøya	2015	52/day	67 to 114	Norled	Norled	Figure A1(B-1)
	Asko Maritime, Norway	Horten–Moss	2022	7/day	58	ASKO	ASKO	Figure A1(B-2)
	Fjord1, Norway (Multiple Routes)	-	2018	50/day	70 to 110	Fjord1	Fjord1	Figure A1(B-3)
	Finferries, Finland (One Route)	Parainen–Nauvo	2017	61/day	98	Finferries	Finferries	Figure A1(B-4)
	Ærø Ferries, Denmark	Søby–Fynshav–Faaborg	2019	6/day	60	Ærø Kommune	Ærø Kommune	Figure A1(B-5)
	Ontario Transport, Canada (One Route)	Amherst, Millhaven, Kingston, Marysville and Wolf Island	2019	10/day	95	Ontario Transport	Ontario Transport	-
	Boreal, Norway (Two Routes)	Kinsarvik–Utne–Kvanndal and Skånevik–Matre–Utåker	2019	11/day	67 to 75	Boreal	Boreal	-
	FosenNamsos Sjö, Norway (One Route)	Flakk–Rørvik	2019	39/day	107	STFK	FosenNamsos Sjö	-
Container [54]	Port of Salalah, Oman	Transshipment	2006	2–3/day	400	Port of Salalah	Port of Salalah	Figure A1(C-1)
	Port of Beirut, Lebanon	-	2014	4–5/day	350	Port of Beirut	Port of Beirut	Figure A1(C-2)
	Port of Ngqura, South Africa	-	2015	4–5/week	366	Transnet	Transnet	Figure A1(C-3)
	Napier Port, New Zealand		2022			Napier	Napier	-
Bulk [55]	Port Hedland, Australia	Iron ore loading	2010	3–4/week	295	Pilbara Ports Authority (PPA)	Pilbara Ports Authority (PPA)	Figure A1(D-1)
	Port of Narvik, Norway (Lkab)	Iron ore loading	2016	2–4/week	305	LKAB	LKAB	Figure A1(D-2)
	Econnect Energy (Connect LNG), Norway	LNG transfer	2017	-	Vessels with various LOA	Gas Natural	Gas Natural	-
Locks [56]	St. Lawrence Seaway, US and Canada	Lockage	2014	4–5/day	225	SLSMC	SLSMC	Figure A1(E-1)
Ship-to-ship [57]	US Navy, USA	Navy	2016	-	Military vessels	US Navy	US Navy	Figure A1(F-1)
	Econnect Energy (Connect LNG), Norway	LNG transfer	2017	-	Vessels with various LOA	Gas Natural	Gas Natural	Figure A1(F-2)

4. Routine Maintenance

The monitor in the automated vacuum mooring system is used for the prediction phase. Sensors in the hydraulic system and vacuum pad continuously monitor the vacuum mooring system. The vacuum degree in the vacuum pad is measured by the sensor, and the sensor sends the signal to the control system and then controls the hydraulic device to realize the application of the ship's physical force.

Since the role of the sensors is very important, their maintenance is a priority. If the sensors fail, there is no way to send a heartbeat to the monitor. This will cause the ship to move and cause major failures. Therefore, to avoid such accidents, the sensors must be checked before each mooring.

A standard LCD monitor has a lifetime of 35,000 h [58]. This means it will collapse in about 4 years. This is predictive and the monitor should be replaced every 3.5 years to ensure the monitor does not fail. However, when a monitor fails before that, the vendor must provide a new monitor.

After the boat is moored, the pads must remain attached to the hull at all times; therefore, the pads must always work. When the useful life of the pads is known, it is possible to calculate how much and when to replace these shims, but corrective maintenance is better because the shims can fail before the end of their useful life.

The hydraulic power unit is the power output source of the system and plays an important role in the normal operation of the automated vacuum mooring system. The hydraulic power unit must be kept clean. In the surrounding environment, the power unit, piping connections, and components must be kept clean and washed. Regarding hydraulic fluids, contamination and moisture should be observed to prevent contaminants from the surrounding environment entering the tank; refueling the tank can only be carried out through a filter, preferably through a system filter or a portable filter cart equipped with a precision filter. If there is a protective coating, its compatibility with the added oil should be checked. The hydraulic system requires regular checks, including for the level of the oil tank, the efficiency of the cooler, the leakage of components and pipelines, the oil temperature when the system is working, the main circuit and the control circuit, the cleanliness of the oil, the filter element or filter alarm (device) signal, the pipeline, the noises, the equipment performance and speed, the accumulator station, etc.

5. Discussion, Challenges, and Future Perspectives

5.1. Discussion

In the automated vacuum mooring system, the sensors play a vital role. In addition to the tasks of measuring the distance from the ship to the dock, the hydraulic pressure of the hydraulic system, the suction of the vacuum suction cup, and the ship's motion, they also need to measure the speed of the ship, wind speed, etc. Therefore, determining whether various sensors are perfectly qualified for the working environment of automated mooring ports is challenging.

Most ships use the internal combustion engine as the power source; of course, some ships may be equipped with bow thrusters, and it is difficult for these ships to complete automatic berthing. The main reason for this phenomenon is that ships near the wharf cannot make slight turns or sharp turns, let alone move in the direction of the wharf. Therefore, ships with several propulsion systems have been considered, which may be a good way to solve this problem: for example, equipping a ship with several directional thrusters, or with the main propulsion system, and having jet thrusters installed elsewhere on the ship.

In the actual mooring process and mooring state, the motion of the ship is very complicated. After the ship is docked, it is affected by various external environments, such as wind, wave, current, tide, ballast water, deballast water, and the amount of cargo loaded. Under the action of these influencing factors, the movements that the ship generates are heave, sway, surge, pitch, roll, and yaw. For such complex movements, the automated vacuum mooring system's movement mechanism needs to be improved to adapt to the complex ship-berthing movements.

5.2. Automated Vacuum Mooring Systems Face Many Challenges

On the dock, the initial installation costs are relatively high. Generally speaking, the terminal needs to install at least four units, which increases expenses.

The maintenance of automated vacuum mooring systems is much more complicated than that of iron bollards. The structure of the automatic vacuum mooring system is more complicated than the traditional rope mooring system. In addition to its structure, it is also equipped with auxiliary equipment, such as power stations, hydraulic workstations, etc.

At present, ships are designed according to the traditional mooring method of mooring cables, thus there are strong supporting structures at the ship's bollards. The automated vacuum mooring system is a new type of equipment, and the entire adsorption force acts completely on the hull steel plate. The hull steel plate is not specifically designed for the automated vacuum mooring system, and the hull steel plate has no reinforcement structure. Taking the MoorMaster 200 as an example, the suction force of the suction pad is 20 tons, and the force on the hull plate reaches 10 t/m^2. Although the company claims that this will not cause damage to the ship, the strong suction force acts on the hull plate and the hull of the ship. Whether the strength of the ship meets the design requirements requires further discussion and research.

When the ship is subjected to external force, movement tends to be generated; the automatic vacuum mooring system prevents this movement, thus the external force is transferred to the placement position of the system through the system support frame. Therefore, there are certain requirements for the strength of this system's placement on the wharf.

When a certain rolling angle occurs during ship loading and unloading, the allowable rolling range of the automated vacuum mooring system is worth considering. Compared to mooring with cables, it is more necessary for the ship to keep floating as much as possible.

In some ports, when the ship is docking or leaving the dock, the pilot uses the cable to complete the bow or stern leaving/docking first, thereby reducing the use of tugboats. If fully automated mooring systems are used without ropes, tug assistance is required.

When most ports adopt this automatic vacuum mooring system, new requirements will be put forward for ship design. For example, the number of winches on the bow and stern may be reduced or even eliminated. The change in the cable machine requires adjustments to the ship's bow and stern structure.

5.3. Future Perspectives

As far as the current mooring situation is concerned, an automated vacuum mooring system is a very good mooring alternative. It breaks the traditional mooring mode and can complete mooring in 30 s through remote control without mooring cables. It has the advantages of safety, reliability, economy, efficiency, saving manpower, and improving the utilization rate of the wharf.

In this automated mooring system, to ensure the normal operation of the system, it needs to be equipped with a continuous and stable power supply. To ensure that the suction pads closely fit with the ship's outer side and move only slightly with the ship's dynamics, high-precision displacement is required. Displacement sensors, pressure sensors, precise control systems, and adsorption units can provide sufficient adsorption force. Compared with traditional mooring, the position of the mooring force on the ship is changed from the bollard on the deck to the side shell. Corresponding reinforcement is required when designing the strength of the ship's structure.

Replacing traditional mooring systems with automated vacuum mooring systems will increase port construction costs; however, in the long term, automated vacuum mooring systems can increase port utilization and mooring efficiency, reduce personnel costs, and generate considerable economic benefits for ports.

Although automated vacuum mooring systems have practical applications and have been installed in ports for many years, due to the complexity of the problem, in theory, only Trelleborg [23] uses DHI's truly dynamic mooring analysis software, MIKE 21 MA, at present, to conduct a comparative simulation of ships fitted with traditional moorings and automated vacuum moorings. The results show that, when considering the range of the vessel motion in surge and sway, the berth operability of a ship with an automated vacuum mooring system is increased from 65% to 95%.

5.3.1. Theoretical Mathematic Models of Automated Vacuum Mooring Systems

It is understood that, in projects where this equipment has been adopted, the equipment manufacturer usually cooperates with the owner and the design unit to determine the number and specifications of the required equipment. Therefore, it is necessary to establish a theoretical calculation model for the automated vacuum mooring system.

Based on the analysis of the force characteristics of the automated mooring system, the mechanical model is assumed, and the force calculation formula of the automated vacuum mooring system is deduced in combination with the external force calculation under the relevant ship mooring conditions in the current code. This allows for designers to calculate the force of the automated vacuum mooring system in the early stages of the project and to estimate the specifications and quantity of the automated mooring systems.

5.3.2. Structurally Improved Automated Vacuum Mooring System to Suit Various Port and Marine Conditions

The automated vacuum mooring system has some problems, such as restricted lateral movement, and pads cannot be attached to the bow and stern.

From a technical perspective, this system cannot move laterally. In a port with many ebbs and flood currents, this system cannot be used at present. A guide rail could move in the lateral direction on the base of the automated vacuum mooring system to solve the above problems.

The pads can only connect to a flat surface. The pads cannot connect at an angle, which makes it impossible to connect on the bow or stern of the vessel. To solve this problem, we can change the structure of the pads and divide the original pad into 4–16 or more pieces (Figure 11). Each small pad piece is controlled by an independent hydraulic link, which can adjust the angle according to the irregular hull surface shape of the bow and stern, thereby realizing the adsorption of the irregular surface.

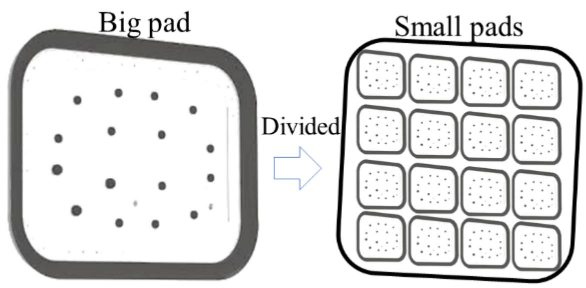


Figure 11. Pads with some small pads.

6. Conclusions

As a revolutionary innovation in mooring systems, the automated vacuum mooring system overcomes disadvantages inherent in traditional mooring. Two companies have developed automated vacuum mooring systems, but few have disclosed the design and control of vacuum pads, mechanical linkage devices, transmission devices, the control system, and other key technical data due to commercial confidentiality. The extant research and data show that the adjust of the vertical movements with the automated vacuum mooring systems are relatively easy to be achieved, but automated vacuum mooring system vacuum pads with both vertical and horizontal movements or with six degrees of freedom are difficult to produce. To adapt to the irregular curved surfaces of the bow and stern, the vacuum pads that can be connected at an angle to the bow and/or stern of the vessel have yet to be fully developed.; in terms of theoretical research, the theoretical mathematical model of the automated vacuum mooring system has not been established and studied.

Again, the automated vacuum mooring system has several notable advantages compared to traditional mooring (e.g., speed, safety, stability, environment, and economy). As this technology continues to develop and improve, automated vacuum mooring systems are expected to play an increasingly critical role in future ship mooring systems and may have a profound impact on the green shipping industry.

Author Contributions: Conceptualization, S.Z. and K.Y.; methodology, J.O. and D.-W.S.; data curation, S.Z.; writing—original draft preparation, S.Z.; writing—review and editing, K.Y., J.O. and D.-W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research and APC were funded by the Ministry of Oceans and Fisheries, Korea.

Institutional Review Board Statement: Not applicable.

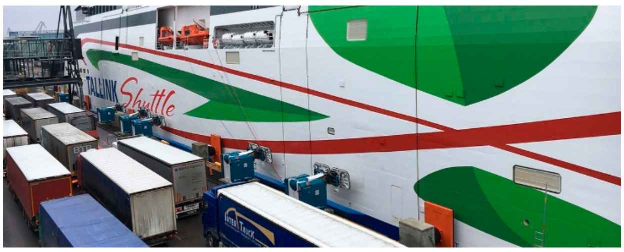
Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Acknowledgments: This review paper was a part of the project titled "Development of Smart Port-Autonomous Ships Linkage Technology", funded by the Ministry of Oceans and Fisheries, Korea.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Appendix A



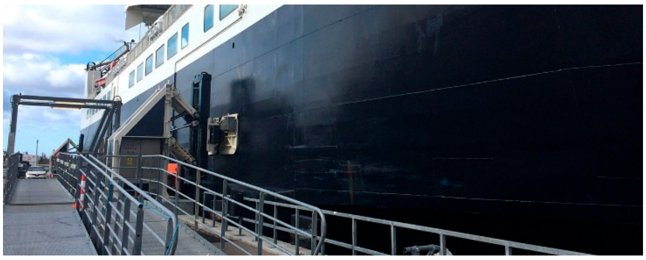
A-1

A-2

A-3

A-4

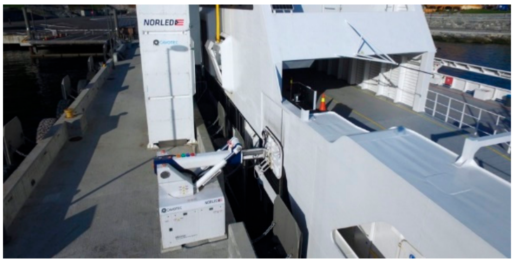
Figure A1. *Cont*.



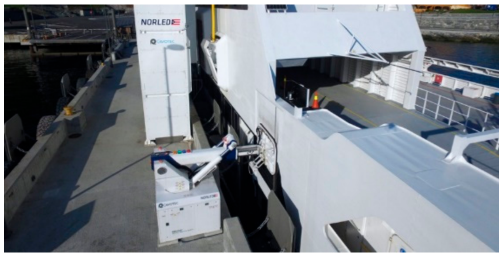
A-5

A-6

A-7

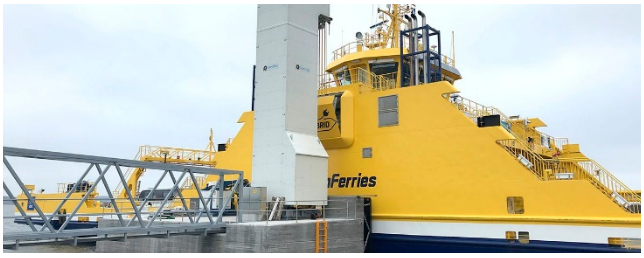


B-1



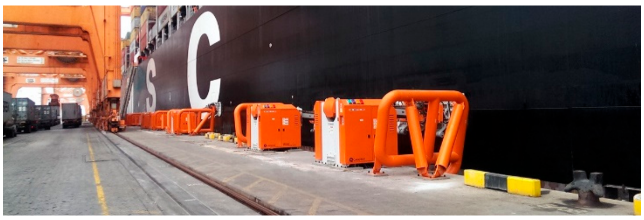
B-2

B-3



B-4

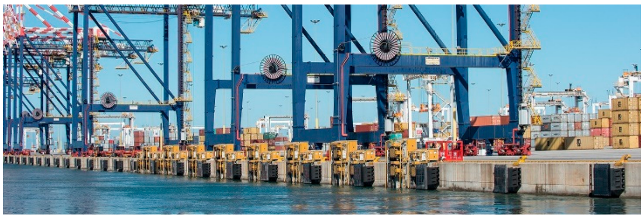
B-5



C-1

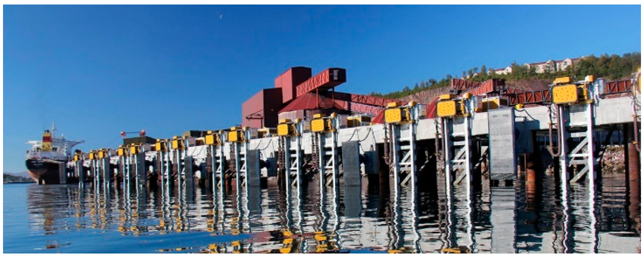
C-2

Figure A1. *Cont.*

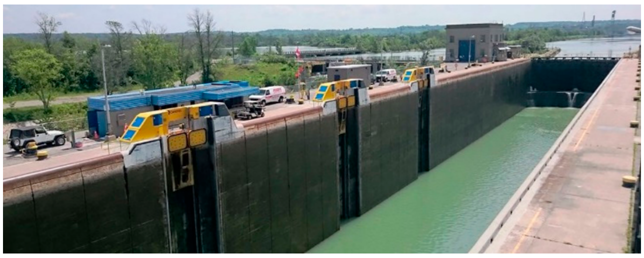


C-3

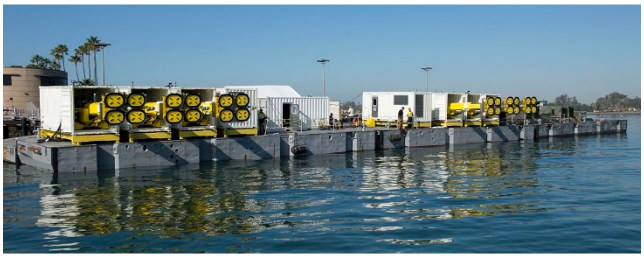
D-1



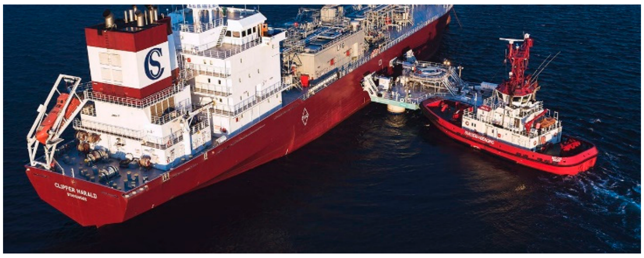
D-2



E-1



F-1



F-2

Figure A1. Application of shore-based system of automated vacuum mooring showing, application of RoPax and RoRo on (**A-1**) Port of Helsinki, Finland, (**A-2**) Wightlink, UK, (**A-3**) Searoad, Australia, (**A-4**) Samsø Rederi, Denmark, (**A-5**) Molslinjen, Denmark, (**A-6**) Interislander, New Zealand, (**A-7**) Teso, The Netherlands; application of Electric Vessels on (**B-1**) Norled, Norway,(**B-2**) Asko Maritime, Norway, (**B-3**) Fjord1, Norway, (**B-4**) Finferries, Finland, (**B-5**) Ærø Ferries, Denmark; application of Container on (**C-1**) Port of Salalah, Oman, (**C-2**) Port of Beirut, Lebanon, (**C-3**) Port of Ngqura, South Africa; application of Bulk on (**D-1**) Port Hedland, Australia, (**D-2**) Port of Narvik, Norway; application of Locks on (**E-1**) St. Lawrence Seaway, US and Canada; application of Ship-to-ship on (**F-1**) US Navy, USA, (**F-2**) Econnect Energy (Connect LNG), Norway.

References

1. Amaechi, C.V.; Wang, F.; Ye, J. Mathematical Modelling of Bonded Marine Hoses for Single Point Mooring (SPM) Systems, with Catenary Anchor Leg Mooring (CALM) buoy application—A review. *J. Mar. Sci. Eng.* **2021**, *9*, 1179. [CrossRef]
2. He, S.; Wang, A. Time and Frequency Domain Dynamic Analysis of Offshore Mooring. *J. Mar. Sci. Eng.* **2021**, *9*, 781. [CrossRef]
3. Huang, W.-H.; Yang, R.-Y. Water Depth Variation Influence on the Mooring Line Design for FOWT within Shallow Water Region. *J. Mar. Sci. Eng.* **2021**, *9*, 409. [CrossRef]
4. Shakhov, V.V.; Yurgenson, A.N.; Shakhov, V.V.; Yurgenson, A.N. Towards Edge Computing Based Monitoring for Smart Ports. In Proceedings of the International Conference on Computational Science and Its Applications—ICCSA 2021, Cagliari, Italy, 13–16 September 2021; Lecture Notes in Computer Science. Springer: Cham, Switzerland, 2021; Volume 12958, pp. 262–271. [CrossRef]
5. Üzel, M. Cavotec Wins Breakthrough Automated Vacuum Mooring Order in Far East. 2021. Available online: https://www.mynewsdesk.com/cavotec/pressreleases/cavotec-wins-breakthrough-automated-vacuum-mooring-order-in-far-east-3101459 (accessed on 20 July 2022).

6. DNV; Li, Y. A New Look at Safe Mooring. 2020. Available online: https://www.dnv.com/expert-story/maritime-impact/A-new-look-at-safe-mooring.html (accessed on 20 July 2022).
7. UK P&I Club. Risk Focus Consolidated 2016: Identifying Major Areas of Risk. 2016. Available online: https://www.ukpandi.com/news-and-resources/articles/2016/risk-focus-consolidated-2016/ (accessed on 20 July 2022).
8. Kuzu, A.C.; Arslan, Ö. Analytic Comparison of Different Mooring Systems. In Proceedings of the Global Perspectives in MET: Towards Sustainable, Green and Integrated Maritime Transport, Varna, Bulgaria, 11–14 October 2017; pp. 265–274.
9. Popesco, O. Automating the Mooring Process. 2009. Available online: https://aapa.files.cms-plus.com/SeminarPresentations/2009Seminars/09Facilities/09FACENG_Popesco_Ottonel1.pdf (accessed on 20 July 2022).
10. Ma, K.; Shu, H.; Smedley, P.; L'hostis, D.; Duggal, A.S. A Historical Review on Integrity Issues of Perma Permanent Mooring Systems. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 2013. [CrossRef]
11. Van Bonifacio, J.; Van der Meijden, F.; Sprenger, G.; Sproot, D. *Alternative Berthing: Improvement and Innovation*; Maritime Symposium: Roterdam, The Netherlands, 2014.
12. Gao, F.; Hu, K.; Shen, W.; Li, Y. Study on the Safety Guarantee of Ship Mooring from Frequent Cable Accidents. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *621*, 012007. [CrossRef]
13. Brindley, W. Mooring Rope Snapback Simulation. 2022. Available online: https://ore.catapult.org.uk/blog/mooring-rope-snapback-simulation/ (accessed on 20 July 2022).
14. Shapovalov, K.A.; Shapovalova, P.K. Traumatism During Mooring Operations on Vessels. *Ann. Mar. Sci.* **2020**, *4*, 030–034. [CrossRef]
15. The Maritime Executive. Majority of Mooring Accidents Caused by Lines Parting. 2015. Available online: https://maritime-executive.com/article/majority-of-mooring-accidents-caused-by-lines-parting (accessed on 20 July 2022).
16. Erkan, Ç. Fatal and Serious Injuries on Board Merchant Cargo Ships. *Int. Marit. Health* **2019**, *70*, 113–118. [CrossRef]
17. Poisson, M. Safety Issues Associated with Mooring Operations in the Maritime Industry. 2017. Available online: https://www.tsb.gc.ca/eng/securite-safety/marine/2018/m17c0060/m17c0060.html (accessed on 20 July 2022).
18. CHIRP Maritime. Maib Accident Reports Reference Library. 2022. Available online: https://www.chirpmaritime.org/reference-library/ (accessed on 20 July 2022).
19. Registry, C. Accidents and Incidents Reported to MACI (2020). 2021, pp. 1–12. Available online: https://www.cishipping.com/policy-advice/casualty-investigations (accessed on 20 July 2022).
20. Cavotec. Automated Mooring. 2022. Available online: https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring (accessed on 20 July 2022).
21. Cavotec. MoorMaster Automated Vacuum Mooring System. 2022. Available online: https://www.cavotec.com/en/video/moormaster-automated-vacuum-mooring-system (accessed on 20 July 2022).
22. Cavotec. MoorMaster NxG. It's Time to Rediscover Vacuum Mooring. 2022. Available online: https://www.cavotec.com/en/video/moormaster-nxg-its-time-to-rediscover-vacuum-mooring (accessed on 20 July 2022).
23. Villa-Caro, R. Sistemas De Amarre En Buques: Situación Actual y Evolución Futura. Ph.D. Thesis, Universidade da Coruña, Coruña, Spain, 2015.
24. Trelleborg. AutoMoor. 2022. Available online: https://www.trelleborg.com/en/marine-and-infrastructure/products-solutions-and-services/marine/docking-and-mooring/automated-mooring-systems/automoor (accessed on 20 July 2022).
25. Cavotec. Automated Mooring Systems. 2022. Available online: http://www.cavotec.com.ua/download/cat9/AMS.pdf (accessed on 20 July 2022).
26. Cavotec MSL Holdings Limited. Automated Mooring Method and Mooring System. Patent Registration No. US-8408153B2, 2013. (Application date 24 March 2010; Granted date 2 April 2013).
27. Kim, Y.Y.; Choi, K.-J.; Chung, H.; Han, S.; Lee, P.-S. A ship-to-Ship Automatic Docking System for Ocean Cargo Transfer. *J. Mar. Sci. Technol.* **2014**, *19*, 360–375. [CrossRef]
28. Cavotec. Automated Mooring. 2014. Available online: https://www.cavotec.com/zh/your-applications/ports-maritime/automated-mooring/ropax-roro (accessed on 20 July 2022).
29. *BS 6349-4: 2014*; BSI Standards Publication Code of Practice for Design of Fendering and Mooring Systems, 3rd ed. BSI: London, UK, 2014.
30. Son, Y.; Kim, M.S.; Jang, H.; Kim, S.; Kim, Y. Study on Temperature Dependent Mechanical Properties of Chloroprene Rubber for Finite Element Analysis of Rubber Seal in an Automatic Mooring System. *J. Soc. Nav. Archit. Korea* **2022**, *59*, 157–163. [CrossRef]
31. Cavotec. Alternative Berthing Improvement and Innovatiaon. 2022. Available online: https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring (accessed on 20 July 2022).
32. Ignacio, H.S. *Sistema Automático De Amarre Por Vacío: Implementación y Análisis Para el Buque Volcán del Teide*; Atribución-NoComercial-SinDerivadas, Creative Commons Corporation: Los Angeles, CA, USA, 2021.
33. Vedin, N. Parking Up Safely. Maritime Risk International. 2020. Available online: https://www.standard-club.com/fileadmin/uploads/standardclub/Documents/Import/news/2020-news/3376591-mri-2020-dec-jan.pdf (accessed on 20 July 2022).
34. Díaz-Ruiz-Navamuel, E.; Ortega Piris, A.; López-Diaz, A.I.; Gutiérrez Miguel, A.; Andres Roiz, M.; Oria Chaveli, J.M. Influence of Ships Docking System in the Reduction of CO_2 Emissions in Container Ports. *Sustainability* **2021**, *13*, 5051. [CrossRef]
35. Laura, H. Alternative Mooring Systems. Bachelor's Thesis, Kymenlaakso University of Applied Sciences, Kotka, Finland, 2016.

36. Cullinane, K.; Cullinane, S. Atmospheric Emissions from Shipping: The Need for Regulation and Approaches to Compliance. *Transp. Rev.* **2013**, *33*, 377–401. [CrossRef]
37. Kalli, J.; Jalkanen, J.-P.; Johansson, L.; Repka, S. Atmospheric Emissions of European SECA Shipping: Long-term Projections. *WMU J. Marit. Aff.* **2013**, *12*, 129–145. [CrossRef]
38. Chang, C.-C.; Chang, C.-H. Energy Conservation for International Dry Bulk Carriers Via Vessel Speed Reduction. *Energy Policy* **2013**, *59*, 710–715. [CrossRef]
39. Eide, M.S.; Longva, T.; Hoffmann, P.; Endresen, O.; Dalsoren, S.B. Future Cost Scenarios for Reduction of Ship CO_2 Emissions. *Marit. Policy Manag.* **2011**, *38*, 11–37. [CrossRef]
40. Eide, M.S.; Dalsoren, S.B.; Endresen, O.; Samset, B.; Myhre, G.; Fuglestvedt, J.; Berntsen, T. Reducing CO_2 from Shipping—Do non-CO_2 Effects Matter? *Atmos. Chem. Phys.* **2013**, *13*, 4183–4201. [CrossRef]
41. Bocchetti, D.; Lepore, A.; Palumbo, B.; Vitiello, L. A Statistical Approach to Ship Duel Consumption Monitoring. *J. Ship Res.* **2015**, *59*, 162–171. [CrossRef]
42. Celo, V.; Dabek-Zlotorzynska, E.; McCurdy, M. Chemical Characterization of Exhaust Emissions from Selected Canadian Marine Vessels: The Case of Trace Metals and Lanthanoids. *Environ. Sci. Technol.* **2015**, *49*, 5220–5226. [CrossRef] [PubMed]
43. U.S. Environmental Protection Agency. *Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data Paperback*; Office of Transportation and Air Quality, U.S. Environmental Protection Agency: Washington, DC, USA, 2000; ISBN -13.
44. Grebot, B.; Scarbrough, T.; Ritchie, A. *Study to Review Assessments Undertaken of the Revised MARPOL Annex VI Regulations*; Entec UK Limited: London, UK, 2010. [CrossRef]
45. Llorca, J.; Gonza lez Herrero, J.M.; Ametller, S.; Pin~eiro Díaz, E. *Recomendaciones Para el Proyecto y Ejecución en Obras de Atraque y Amarre*; Puertos del Estado: Madrid, Spain, 2012; Available online: https://www.puertos.es/es-es/BibliotecaV2/ROM%202.0-11.pdf (accessed on 20 July 2022).
46. Whall, C.; Cooper, D.; Archer, K.; Twigger, L.; Thurston, N.; Ockwell, D.; McIntyre, A.; Ritchie, A. *Quantification of Emissions from Ships Associated with Ship Movements between Ports in the European Community*; Report for the European Commission; Entec UK Limited: Northwich, UK, 2010.
47. Díaz, J.M. Un Enfoque Regional Unificado de Respuesta Contra la Contaminacion Marina Por Petroleo en el Pacifico Nordeste. In Proceedings of the International Oil Spill Conference Proceedings, Miami Beach, FL, USA, 15–19 May 2005; pp. 507–511. [CrossRef]
48. Gonzalez, C.; Pe rez-Labajos, C.A.; Oria, J.M.; Andres, M.A. Methodology Bottom-up for Estimation of the Air Emissions Inventory and Carbon Footprint for Tugboats. *J. Marit. Res.* **2015**, *12*, 103–107.
49. Ortega Piris, A.; Díaz-Ruiz-Navamuel, E.; Pe rez-Labajos, C.A.; Oria Chaveli, J. Reduction of CO_2 Emissions with Automatic Mooring Systems. The case of the Port of Santander. *Atmos. Pollut. Res.* **2018**, *9*, 76–83. [CrossRef]
50. Díaz-Ruiz-Navamuel, E.; Piris, A.O.; Pérez-Labajos, C.A. Reduction in CO_2 Emissions in RoRo/Pax Ports Equipped with Automatic Mooring Systems. *Environ. Pollut.* **2018**, *241*, 879–886. [CrossRef] [PubMed]
51. Tolsgaard, J. The Modern Port Automate the Mooring Handling. 2022. Available online: https://docplayer.net/167485431-The-modern-port-automate-the-mooring-handling-presenter-jakob-tolsgaard.html (accessed on 20 July 2022).
52. Díaz-Ruiz-Navamuel, E.; Ortega-Piris, A.; Pérez-Labajos, C.A.; Andrés, M.A. Wind Safety Limits on Ships Docked with Two Different Mooring Systems. In *Developments in Maritime Technology and Engineering*; CRC Press: London, UK, 2021; pp. 351–360.
53. Cavotec. Electric Vessels. 2022. Available online: https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring/electric-vessels (accessed on 20 July 2022).
54. Cavotec. Container. 2022. Available online: https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring/container (accessed on 20 July 2022).
55. Cavotec. Bulk. 2022. Available online: https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring/bulk (accessed on 20 July 2022).
56. Cavotec. Locks. 2022. Available online: https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring/locks (accessed on 20 July 2022).
57. Cavotec. Ship-to-Ship. 2022. Available online: https://www.cavotec.com/en/your-applications/ports-maritime/automated-mooring/ship-to-ship (accessed on 20 July 2022).
58. ICT Loket. Monitor. 2015. Available online: http://www.ictloket.nl/kennisbank/monitoren/ (accessed on 20 July 2022).