
Photo: Safety4Sea.

Report

Automatic Mooring: Technical Gap Analysis

Author(s):
Pauline Røstum Bellingmo, Ulrik Jørgensen

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Client(s):
SFI Autoship

SINTEF Ocean AS
Postal address:
Postboks 4762 Torgarden
7465 Trondheim, Norway
Switchboard: +47 46415000

Enterprise /VAT No:
NO 937 357 370 MVA

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AUTHOR(S)
Pauline Røstum Bellingmo, Ulrik Jørgensen

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This technical report on automatic mooring systems is a part of Work Package 5 Sustainable Operations in SFI Autoship. This study has investigated if existing automated mooring systems are technically suited for the following three use cases: ferry, short-sea container ship, and deep-sea bulk ship. The report presents automated mooring system that exists today. They are either vacuum based, magnetic based, or robotic arms. For the ferry use case, the existing quayside mounted automated mooring systems are currently commercially available, thoroughly tested and well suited for the use case, but there are some reports about unstable system performance. This is also the case for deep-sea bulk ships, under the assumption that the ships operate between ports where automatic vacuum mooring systems are available. For short-sea container ships however, it is assumed that the ship operates between ports without any auto-mooring infrastructure. For this use case, the vessel needs to bring the automated mooring system themselves. This is solved by use of robotic arms; however, these systems are currently in the testing phase and has not been thoroughly tested in normal operation yet.

PREPARED BY
Ulrik Jørgensen

SIGNATURE
Ulrik Jørgensen (14. des. 2022 16:04 GMT+1)

CHECKED BY
Even Ambros Holte

SIGNATURE
Even Ambros Holte (15. des. 2022 09:26 GMT+1)

APPROVED BY
Odd Erik Mørkrid

SIGNATURE
Odd Erik Mørkrid (14. des. 2022 22:53 GMT+1)

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Table of contents

Abbreviations

AMS	AutoMooring Systems
SFI	"Senter for Forskningsdrevet Innovasjon". Translated: Centre for research-driven innovation
LOA	Length overall
DWT	Deadweight
RPR	Rope Picker Robot
SWL	Safe Working Load

Report Context

This report on automatic mooring systems is a part of Work Package 5 Sustainable Operations in SFI Autoship. SFI Autoship is an 8-years research-based innovation center that will contribute to Norwegian players taking a leading role in the development of autonomous ships for safe and sustainable operations. The focus areas include:

1. Enabling technologies like situational awareness, artificial intelligence, autonomous control, and digital infrastructure.
2. New business models and operational concepts like the adaptation of shore control centers and development cost-effective solutions for logistics and port solutions.
3. Methods and models for monitoring risk and the clarification of the legal aspects of liability when a captain is not on board.

The results from this report will be used as input for further studies related to mooring in the SFI Autoship project.

1 Introduction

1.1 Motivation

To get a fully autonomous ship, all the processes need to be autonomous, including mooring of the ship. Conventional mooring is performed by attaching mooring lines from the ship on the bollards on the quay. The heaviest cargo ships may require more than a dozen mooring lines. Shoremen on the quayside manually attach the mooring lines to bollards, see Figure 1. There can be large forces acting on the ship caused by waves, winds, and currents. The mooring lines must be tight to keep the ship steady, but at the same time, avoid too large tensions in the lines. An unsteady ship or large ship motions can cause damage on the cargo, ship, and quay and cause mooring lines to break, imposing a large danger on the shoremen. Additionally, the mooring lines must be adjusted due to changing tides and ship drafts, but also because of onloading and offloading operations (MacGregor, 2018). 95 percent of the registered mooring injuries are caused by ropes and wires according to the European Harbour Master's Committee[1]. With automated mooring systems, the shoremen are moved away from dangerous operations which greatly increase the safety of the docking operation.

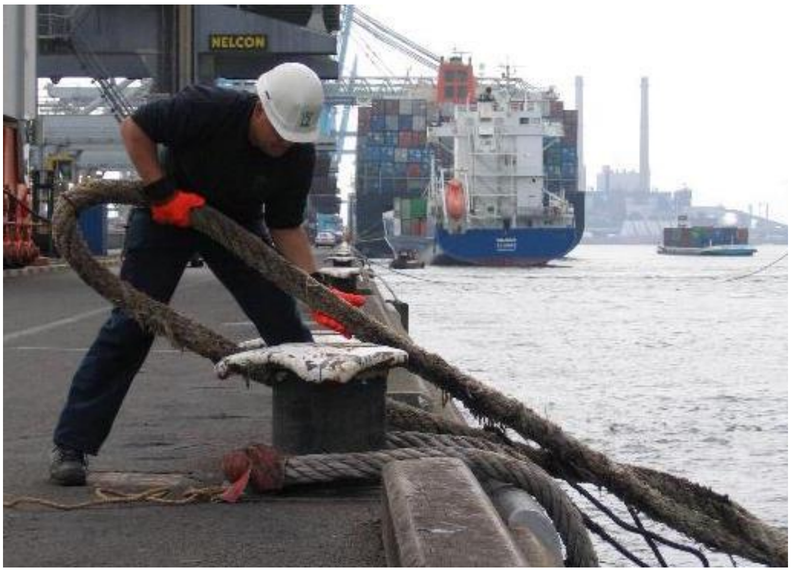


Figure 1: Shoremen handling mooring lines. Image source (Wikipedia, 2022).

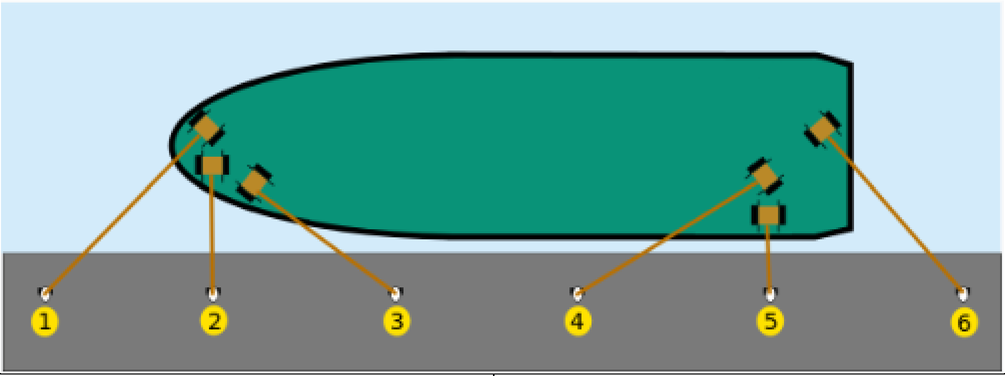
1.2 Scope

Currently there exist some solutions in the market that allow for automatic mooring. This report will investigate if **it is possible to automatically moor ferries, container ships, and bulk ships.** To properly answer this question, this report contains input for the system providers and users. The system providers Trelleborg, Cavotec, MacGregor and AMS have contributed with their input in Chapter 4 and 5. The ferry operator Torghatten Midt and bulk ship operator LKAB have elaborated on their experience on using automated mooring systems. The inputs from the automated mooring system users are used as a basis for the benefits and challenges described in Chapter 5. This is a technical gap analysis and do not consider economical and regulatory aspects.

[1] https://www.dnv.com/expert-story/maritime-impact/A-new-look-at-safe-mooring.html

2 Conventional Mooring

According to (Wikipedia, 2022), a mooring is any permanent structure to which a ship may be secured. A ship is secured to a mooring to prevent free movement of the ship on the water. Mooring is often accomplished using thick ropes called mooring lines. The lines are fixed to deck fittings on the ship at one end and to fittings such as bollards and rings on the other end. The heaviest cargo ships may require more than a dozen mooring lines. Smaller ships can generally be moored by four to six mooring lines. A typical mooring configuration is shown in Figure 2.



1	Headline	Keep forward part of the ship against the dock
2	Forward breast line	Keep close to pier
3	Forward or head spring	Prevent forward movement
4	Back or aft spring	Prevent back movement
5	Aft breast line	Keep close to pier
6	Stern line	Prevent forwards movement

Figure 2: Main fastening ropes for merchant ship. Image source (Wikipedia, 2022).

Mooring of ships has remained largely unchanged for thousands of years. This, despite that the procedure poses considerable safety risks to personnel both onboard and quayside. Mooring the ship is currently mainly manual work. As the ship approaches, the captain decides which side of the ship to be moored. After that, deck hands are preparing mooring lines, and enough slack is released from the coil. This is needed for easy rope handling. Anchor stoppers are removed so that in case anchors are needed it is easy to let them go. When approaching the quay, all seamen are in standby. When approaching the quay, cast line is thrown ashore from bow of the ship, and spring line is fastened to allow easy stern-in operation. The cast lines for all ropes are thrown or fired to shore from the ship. Typically, one or two shoremen are working on the quayside. Earlier, the onboard crew jumped to the quayside for mooring, but this is considered too dangerous and hence not done any more. After shoremen have received the cast line, they pull the actual mooring rope and make it fast with a bollard. Hydraulic onboard winches, with an auto-tension system, achieve the correct tightening of the rope. The auto-tension system is very important for two main reasons; firstly, to hold the ship steady at its location, and secondly, to avoid too much tension in the rope. In case the ropes are loose, or tension increases too much, persons working in the area might be severely injured and the ship might leave its position unintentionally.

Although not common, it is also possible that the mooring equipment is at the quayside, and the coupling is done onboard. In this case, all the work is done by shoremen, as the assumption is that the mooring bollard on the ship can be accessed directly from the quay. In this case the bollards are accessible by the shoremen, and the automatic tension equipment is located at the quayside. This increases safety and enables automation as there is less need for onboard crew and remote operation and supervision is possible.

All the mooring solutions described so far require mooring ropes, but there are also solutions without mooring ropes. One of these systems has equipment mounted on the quay and connects directly to the bollards on the shipside. This requires that the position of the system matches with the onboard bollards. Since the mooring forces area always kept horizontally, this reduces the required force to hold the ship in addition to accurately maintain the ship position. An example of this is seen in Figure 3.

Figure 3: Mooring solution that does not require ropes. Courtesy: MacGregor.

3 Ship characteristics and operational conditions

To find out if automatic mooring is possible for ferries, short-sea container ships, and deep-sea bulk ships, it is important to understand how the different ships operate. This is presented below.

3.1 Ferry

A ferry typically operates between a few fixed terminals. This makes it convenient to install a mooring system on the quayside at the terminals. A ferry is typically moored using a ramp that attaches to the quay and thrusters on the ship to keep the ship side into the quay.

Figure 4: Torghatten Midt MF Lagatun ferry. Courtesy: Torghatten Midt.

In this study relatively small vehicle and passenger ferries are studied. More specifically, the Torghatten Midt's MF Lagatun ferry[2] is used as an example case. See Figure 4. The characteristics[3] of this ferry is given in Table 1.

3.2 Short-sea container ship

Container ship typically operates between many different ports, both large and small. Some small ports are without infrastructure quayside such as cranes. One solution is to carry necessary equipment onboard the ship, e.g., cranes (geared ship). The height above water level can vary a lot for a container ship due to varying draught during loading and discharging of cargo. This study is based on the short-sea container ship NCL Averøy as an example, see Figure 5. This ship has two cranes with an SWL of 45 mt each. The characteristics[4] of this ship is given in Table 1. The ships mainly dock by themselves without the use of tugboats but may need assistance for the docking when the weather is rough.

Figure 5: NCL Averøy. Courtesy: NCL.

3.3 Deep-sea bulk ship

As for container ships, bulk ships can also operate between both large and small ports, which might make it necessary to carry cargo handling equipment onboard (geared ship). Typical equipment that is carried along are cranes and rope based mooring systems. Deep-sea ships are however often of considerable size and usually operating between large ports where some infrastructures are expected. The height above water level can vary a lot for a bulk ship due to varying draught during loading and discharging of cargo. Docking time might also be long, which further increases the likelihood of high height variations due to the tidal water. This study uses the Grieg Star deep-sea bulk ship Star Lysefjord as an

Figure 6: Star Lysefjord. Courtesy: Wolfgang Plapp

[2] http://www.torghatten-midt.no/sor-i-trondelag-more-og-romsdal/mf-lagatun-article14561-894.html
[3] https://www.marinetraffic.com/en/ais/details/ships/shipid:5739728/mmsi:257057960/imo:9820398/vessel:LAGATUN
[4] https://griegstar.com/vessels/

example case, see Figure 6. This bulk ship is equipped with four cranes with an SWL of 75 mt each. The characteristics[5] of this bulk ship is given in Table 1.

3.4 Ship characteristics

Table 1 shows typical values for these characteristics for the Torghatten ferry, the NCL's container ship, and the Grieg Star's bulk ship.

Table 1: Typical ship characteristics for a ferry, container ship, and bulk ship.

Characteristics	Ferry	Container ship	Bulk ship
Deadweight	750 mt	11 200 mt	51 000 mt
LOA	108 m	134 m	204 m
Beam	17 m	23 m	32 m
Draught	4.5 m	9 m	13 m

[5] https://griegstar.com/vessels/

4 Which automatic mooring systems exist today?

Today, several systems offering automated mooring are commercially available. The mooring system can either be installed on shore, i.e., shore-based system, or on the ship, i.e., ship-based system. This chapter will give an overview of the existing solutions.

4.1 MoorMaster by Cavotec

MoorMaster uses automated vacuum pads to moor the ship (Cavotec, 2022). The mooring system can either be installed on top of or in front of a quay, see Figure 7 and Figure 8 respectively. The vacuum pads attach to the hull of the ship. This mooring system does not require any mooring lines. The automatic mooring is remotely operated, often by means of a remote-control panel. The mooring system has a maximum suction force of 200 kN in sway and 100 kN in surge per mooring unit and a 1.6 m outreach (Cavotec, 2021). Additionally, the vacuum pads can rotate about a pivot point with up to 6° in roll angle. MoorMaster can adjust to different draughts and tides by being installed on vertical rails, or by utilizing the stepping feature where the vacuum pads one by one detach and reattach in a new position. The mooring system uses active controls to dampen surge motions. Near to 400 MoorMaster units are installed globally.

Figure 7: MoorMaster on top of quay. Courtesy: Cavotec.

Figure 8: MoorMaster in front of quay. Courtesy: Cavotec.

MoorMaster is used for ferries, the largest container ships, general cargo ships and +300 m bulk ships. The MoorMaster is faster than conventional mooring and can reduce the turnaround time for ships. The mooring takes about 30 seconds, and the release time is about 15 seconds (Cavotec, 2021). For a ferry using automated mooring, the mooring and unmooring phase takes less than a minute, while with conventional mooring this takes about 6-8 minutes (Tolsgaard, 2020) depending on application. This means that a ferry can save 5-7 minutes where ship engines can be shut down earlier reducing CO_2 and NO_X emissions, also allowing for more time to be spent on charging, energy efficient sailing, as well as cargo and passenger transfer. For a container ship, conventional mooring and unmooring may take 30 minutes, while with the automated mooring it can take less than a minute, saving about half an hour (Tolsgaard, 2020). The number of mooring units needed to moor a ship depends on the ship characteristics and environmental conditions at the port. For a small ferry, only one mooring unit may be needed, but for a large container ship 16-20 mooring units may be necessary (Cavotec, 2021).

4.2 AutoMoor by Trelleborg

AutoMoor uses the same principle as MoorMaster and uses vacuum pads to automatically moor the ship (Trelleborg, 2021), see Figure 9. This mooring system is installed on the shore side and does not require the use of mooring lines. This mooring system uses a passive damping technology that limit ship motions in surge and sway, ensuring safe operation in berth during different environmental and berthing conditions. By using passive damping, the mooring system can restore energy from the ship movement. The mooring system include environmental sensors to adapt to the current environment.

AutoMoor can be installed with up to two arms with vacuum pads. AutoMoor has an active outreach of 1.45 m and a vacuum holding capacity of 40 mt using two vacuum pads (2 x 20 mt) (Trelleborg, 2018). This auto mooring system can moor in less than 1 minute and unmoor in less than 30 seconds. The mooring system is mostly used for ferries and container ships, for instance at the Port of Tallinn serving large passenger ferries[6]. The system has also been installed for a bulk ship. There are over 100 installations of vacuum based automated mooring systems by Trelleborg globally.

Figure 9: AutoMoor by Trelleborg. Courtesy: Trelleborg

4.3 StS vacuum mooring system by AMS

AMS has developed an automatic mooring system series that is designed to be used in Ship-to-Ship (StS) operations, see Figure 10. However, due to its modularity, it is also possible to use the StS series for conventional mooring operations by installing the system on shore. The StS series uses vacuum pads and has hydraulic telescopic arms that can reach out 12 m and pull the receiving ship into a predetermined distance between 2 and 8 m. This will speed up mooring and make the operation safer. The telescopic arms that can control mooring forces up to 1000 kN and uses active damping technology that limit ship motions in surge and sway, ensuring safe operation in berth during different environmental and berthing conditions. The system is designed to enable mooring of ships without need for fenders. The mooring system include environmental sensors to adapt to the current environment.

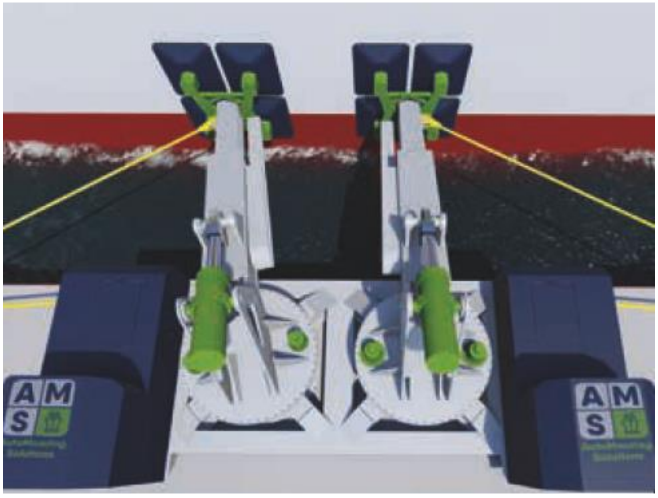


Figure 10: StS mooring system by AMS. Courtesy: AMS

[6] https://www.trelleborg.com/en/media/products-and-solutions-news/automoor-future-proofs-mooring-performance

4.4 Magnetic mooring system by AMS

The magnetic mooring system by AutoMooring Solutions (AMS) is an automated solution consisting of an arm with magnetic pads, see Figure 11. The magnets attract two plates that have been welded into the hull of the ferry. The mooring unit itself is located on the shore side, with a maximum holding capacity of 1000 kN. This mooring system is not widely used but an example of usage is the Wollwich ferry in London[7].

Note that the magnetic mooring system for the Woolwich ferry is built by Mampaey Offshore Industries and that AMS is a spin-off from Mampaey.

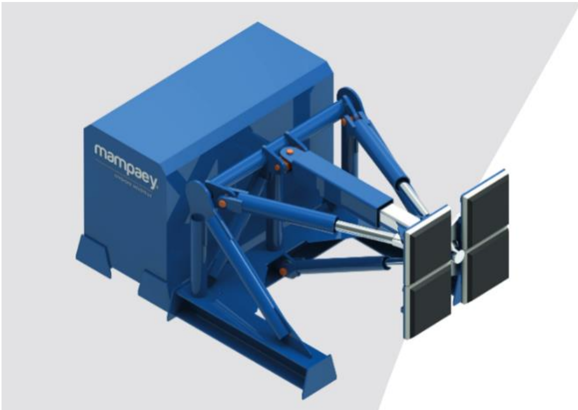


Figure 11: Magnetic mooring system. Courtesy: AMS

4.5 Rope Picker Robot by AMS

AutoMooring Solutions (AMS) is developing a robotic arm that can be used to automatically moor ships (AutoMooring Solutions, 2021), see Figure 12. The Rope Picker Robot (RPR) consists of a compact hydraulic telescopic arm with a stereo camera, usually mounted on the ship. The RPR can automatically place the mooring rope's eye on a selected bollard on shore. Once the rope is in place, standard winch mooring systems can be used to securely keep the ship moored. For un-mooring, the RPR will automatically find the connected bollard and release the rope from it. The system uses Artificial Intelligence (AI) to automatically recognize the quay and bollards. A self-learning system is included for cases where the system does not recognize a bollard. Using the learning system, the operator can add and confirm the new bollard such that it is prepared and recognizable for the next time. The RPR has an outreach of up to 15 m with typically makes it possible to handle heights between -4 to 10 m. The working load is 50-600 kN.

Figure 12: Rope Picker Robot. Courtesy: AMS.

[7] https://www.goudsmitmagnets.com/announcements/news/ferry-in-London-moors-magnetically

4.6 Robotic Arm by MacGregor

MacGregor has developed a fully electric seven-axis robotic arm to be used for automatic mooring (MacGregor, 2022). The ship is moored by stretching mooring ropes with loops from the ship and place them around bollards on the quayside using the robotic arm as see Figure 13. The robotic arm has a 21 m range. The mooring system is equipped with a compensation system to position the robotic arm correctly independent on ship movements. There is a camera at the end of the robotic arm which is used to detect where the mooring lines are. This mooring system is installed in the autonomous container ship Yara Birkeland, and it is planned to be operational in Q4 2022. Yara Birkeland has two robotic arms, one is installed in the bow of the ship and one in the stern.

Figure 13: Robot arm by MacGregor Courtesy: MacGregor

5 Benefits and challenges for automatic mooring

This section describes the overall benefits and challenges for the different types of automated mooring systems, i.e., vacuum (e.g., Cavotec and Trelleborg), magnetic (e.g., AMS), and robotic arm (e.g. MacGregor and AMS). To complement the inputs from the systems providers, benefits and challenges have been identified from interviews with some users of the automated mooring systems. More specifically, Section 5.1 contains input from the ferry operator Torghatten Midt and the bulk ship operator LKAB who both use Cavotec's MoorMaster.

5.1 Vacuum and magnetic automated mooring systems

Since there are many common benefits and challenges of the vacuum and magnetic automated mooring system, these are presented together.

5.1.1 Benefits

Some of the benefits of the shore-based automated mooring systems are listed below:

- **Faster**. One benefit of these automated mooring systems (vacuum and magnetic) is that it is faster than conventional mooring. For instance, a ferry can save about 6 minutes and a container ship can save up to half an hour during mooring using an automated mooring system (Tolsgaard, 2020). Ships can use the time save to sailing at a lower speed, which will reduce operational costs and emissions. For the ports, the reduced turnaround time will increase the availability at the port and thus increase efficiency and earnings.
- **Shorter dock.** With the automated mooring systems, the ship can overhang the dock by adding additional automatic mooring devices. Thus, automated mooring enables the use of shorter docks compared to conventional mooring.
- **Reduced manning.** Crew used in traditional mooring operations quayside and on board the ship are not needed, hence cost can be reduced.
- **Varying heights.** In some ports the difference between high- and low tide can be as much as 7.5 m, and ship draught can vary with up to 12 meters (Cavotec, 2021) due to on- and off-loading of cargo. The automated mooring systems can adapt to different draughts of the ship by installing the units on vertical rails. This allows the units to move both below and above the height of the quay depending on the draught and tides. If no vertical rails are present, the vacuum mooring systems have a stepping feature where the vacuum pads one by one detach and reattach in a new position to adapt to varying heights.
- **Stability.** The automated mooring system can reduce the ship motions when moored. This simplifies the task of loading and offloading cargo as the ship is more stable.
- **Environment.** Automated vacuum mooring reduces the CO_2 emissions related to mooring operations by 90-98 % compared to conventional mooring operations due to reduced use of tugs and ship engines (Cavotec, 2021; Díaz-Ruiz-Navamuel et al., 2021).
- **Enable full autonomy.** Automatic mooring systems enables possibilities for use of fully autonomous transportation operations.
- **Safety.** No ropes are needed, i.e., eliminating hazards associated with rope brakeage and failure.
- **Accurate ship positioning.** It is possible to adjust the ship position accurately after the ship has been moored. This could for instance be important for ferries that need to line up accurately to use land mounted gangways or equipment.

5.1.2 Challenges

Some of the challenges of the shore-based automated mooring systems are listed below:

- **Small ships.** The environmental loads can be very large compared to the weight of the ship, creating large movements on the ship. These ship motions makes it challenging for the mooring system to keep the ship in place.
- **Hull thickness.** The suction force from the automated mooring system on the hull requires that the hull thickness is above 10 mm and that the hull is made of steel. If not, the hull might be bent by the suction force. Consequently, it cannot attach to other hull types like aluminum, fiberglass, or windows. The automated mooring can restrain most of the motion of the moored ship. However, this will wear out the mechanical components of the mooring system, so the ship must be allowed some movements while moored. Additionally, the total force from the automatic mooring system can never exceed the force acting on the fenders (Yan et al., 2022), as the fenders can be damaged. Moreover, automated mooring requires a relatively flat surface on the hull to attach to. For the magnetic mooring solution, a metallic plate is usually welded into the hull since this solution requires a thicker hull than the vacuum solution.
- **Wrong connection point.** These automated mooring systems does not restrict motions in heave, pitch, or roll. If the ship is rolling and the mooring is attached high on the hull, the bottom of the ship can act on the quay which will cause a large moment on the mooring units. The pads should ideally be attached about 2 m above the water line.
- **Pre-mooring positioning.** Using these automated mooring systems adds additional requirements to the docking. The ship needs to be at the fenders and at stand-still before the automated mooring can start, because the mechanical arm has a maximum outreach of 2.6 m. The arm can be extended but to a higher price. For conventional mooring, the mooring can start 5 m away by throwing the ropes to shore. Additionally, with conventional mooring, the ship can simplify the docking and undocking procedure by being attached to a rope in one end of the ship and thrusting with the other end. Without ropes, this requires that the ship is fully actuated and can dock independently or uses tugboats to assist the docking.
- **Power loss.** What happens to the automated mooring systems when there is a loss of power? For the vacuum system, it is not possible to release the vacuum, so the pads will be stuck to the hull. Backup power is needed to release the ship. For the magnetic system, the pads will drop the ship if power is lost, meaning that power is always required to ensure safe mooring.
- **Complex systems.** Automated mooring systems are complex, and all subsystems need to work for the overall system to function properly. Users have experienced several issues, for instance vacuum loss, vacuum release issues, control signal issues, communication losses, latency, and non-consistent behavior of the system. These issues can lead to down time and reduce the trust in the system.
- **Service**. Issues may occur for all mooring systems. However, since automatic mooring systems are in general more complex and not designed for manual intervention, unforeseen issues and failures usually needs to be handled by the specialized system provider service team. This might result in downtime for the equipment which in turn may lead to downtime for the ship. Consequently, automatic mooring systems generally have higher requirements to the service system than traditional mooring.
- **Shore installation.** A downside of these automated mooring systems is that they are installed on shore. This means that the mooring system must be installed in every port the ship visits. Some quays are small and may not have power available. This challenge can be solved with an automated mooring system installed on the ship. Pros and cons for this is described in Section 5.2.
- **Crane operations.** If cargo is handled with cranes mounted on the ship, unwanted roll motion might be an issue. This is illustrated in Section 5.1.3.

5.1.3 Use case example: Geared ship

A geared ship can have multiple cranes onboard, as described in Section 3.2 and 3.3. This example looks at a bulk ship with four cranes, each with an outreach of 26 m and a maximum SWL of 75 mt each. Can an automated vacuum mooring handle this operation while the ship is moored?

The example is illustrated in Figure 14 where one can see a ship that is moored using an automated vacuum mooring system. The ship starts rolling when cargo is being loaded on or off the ship. The size of the roll angle depends on the operation. For a Greig Star bulk ship, the maximum allowed listing (rolling) angles for the cranes are 5° for lifting loads below 40 mt, while the limit is 4° for loads above 40 mt. As mentioned in Section 4.1, the vacuum mooring system can handle roll angles up to 6°. This means that the vacuum mooring systems can always be used when operating within the limits of the crane.

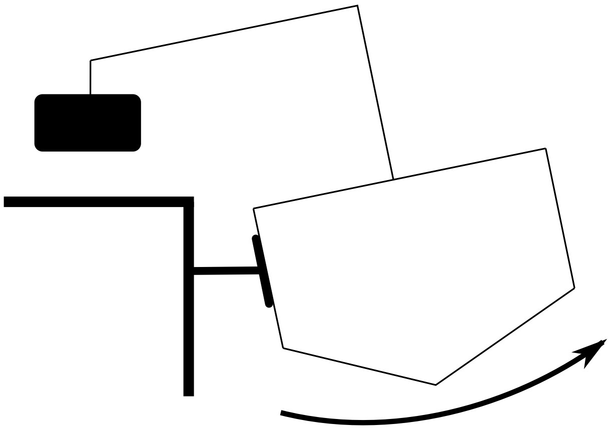


Figure 14: Illustration of a ship handling cargo while being mooring with vacuum pads. This cargo handling causes the ship to roll.

5.2 Robotic arm mooring systems

Robotic arm mooring (on board the ships) is currently in the testing phase and has not been tested in commercial operation yet. Pros and cons are therefore not well established but nevertheless, benefits and challenges for robotic arm mooring manipulators are presented in the following sub sections.

5.2.1 Benefits

- **Safety.** The solution moves the crew away from the dangerous mooring process (ropes, lines, etc.)
- **Enable full autonomy.** Automatic mooring systems enables possibilities for use of fully autonomous ships.
- **Flexible.** No quayside infrastructure is needed, and the system can moor at "any" port.
- **Reduced manning.** Crew used in traditional mooring operations quayside and on board the ship is not needed, hence cost can be reduced.
- **Positioning requirements.** Using robotic arms makes it possible to utilize traditional docking techniques. For instance, using robotic arm mooring, it is possible to be connected at the bow and use the thrusters to align with the quay. Hence, ship positioning requirements may be lower than for automatic vacuum mooring systems.

5.2.2 Challenges

- **Locating bollards.** The camera on the robotic arm must detect where the bollards on the quayside are located. Camera systems suffer from typical limitations like high contrast light, darkness, and fog. Alternatively, the exact location of the bollard must be given as an input to the control system of the robotic arm.
- **Locating mooring lines.** The camera on the robotic arm must detect where the mooring lines are.
- **Identify objects in the way.** Objects that can be in the way for the robotic arm must be detected and avoided by the robotic arm.
- **More weight.** A robotic arm installed on the ship increases the overall weight and this in turn increases the energy consumption of the ship.
- **Reduces space.** The robotic arms occupy space on the ship that could have been used to carry cargo. It may also be challenging to place the robotic arms optimally, especially in retrofit cases.
- **Varying heights.** As for vacuum mooring systems, varying ship draught and tides can be a challenge. Based on the existing robotic arm solutions, MacGregor has the longest range of 21 m. If the total distance between the bollard on the quay and the robotic arm installation on the ship is larger than the range, the ship cannot be moored using the robotic arm.
- **Performance.** Since these types of mooring systems have not been exhaustively tested in commercial operation, one does not know exactly how well these systems perform. For instance, the robotic arm depends on the compensation system used to correctly position the arm relative to the ship and the quay. If the compensation system performs poorly, the mooring system will suffer.
- **Weather challenges.** Since the robotic arm is transported along with the ship, it will be subject to a wider range of weather situations. This might impact system performance.
- **Complex systems.** Automated mooring systems are complex, and all subsystems need to work for the overall system to function properly. Issues may lead to down time and reduce the trust in the system.

6 Are the existing automatic mooring systems suited for ferries, container, and bulk ships?

This section describes if the existing auto mooring systems are suited for the three use cases ferries, short-sea container ships, and deep-sea bulk ships. A traffic light model is utilized to define different levels as seen in Table 2.

Table 2: Technical traffic light levels.

🔴	A red color indicates that the technical aspect of existing auto-mooring solutions is not commercially available for the corresponding use case.
🟡	A yellow color indicates that the technical aspect of existing auto-mooring solutions is currently under development, is not sufficiently stable during operation, or is not tested sufficiently in normal operation for the corresponding use case.
🟢	A green color indicates that the technical aspect of existing auto-mooring solutions is currently commercially available, is sufficiently stable in operation, and well tested for the corresponding use case.

6.1 Ferry

As described in Section 3.1, a ferry typically operates between a few fixed ports, making it convenient for mooring systems to be installed on the quay at each port. For ferries that loads vehicles and/or passengers from the bow or stern of the ship, operational experience shows that it is sufficient with only one automatic vacuum unit to moor the ship. This is achieved by using the ferry limb as a mooring point to the quay at one end and the vacuum unit, located at the quayside, as the other mooring point at the other end of the ferry. This solution has been thoroughly tested in varying setups and in varying situations and weather conditions. Based on this and seen from a technical point of view, the currently available auto mooring solutions work satisfactorily. However, according to the auto mooring operators, there are some issues with general system stability due to the complexity of the system. To maintain an adequate level of uptime, an easily accessible and well-established service system is required.

Given the above arguments and seen from a technical point of view for the ferry case, it is concluded that auto mooring systems are workings satisfactorily, are well tested, are commercially available, but with some stability issues. Hence, a yellow light is given for the ferry case.

6.2 Short-sea container ship

As described in Section 3.2, short-sea container ships frequently operate between many different ports where infrastructure on quayside might be missing. To automatically moor the ship in such ports, the mooring system must be carried with the ship, meaning the robotic arm mooring systems. As discussed in Section 5.2, the robotic arm mooring systems are in the testing phase and have not been tested thoroughly in daily operation. Hence, a container ship cannot be automatically moored at every possible port yet. However, at some larger ports automated mooring is today performed for container ships using vacuum mooring systems. Additionally, container ships can experience huge draught variations due to loading and off-loading, in addition to varying tides. As mentioned in Section 5.2, this will be an issue if the distance between the quay and ship deck is larger than the outreach of the robotic arm (21 m). Some geared container ships might experience ship roll motions induced by the cranes during cargo loading and unloading operations. For the robotic arm mooring system, this roll angle is not an issue. To conclude, are automated mooring systems suited for short-sea container ships? Since container ships visiting many small ports without infrastructure, a robotic arm must be used which is not thoroughly tested in operation. According to Table 2, this results in a yellow light for short sea container ships. However, for a container ship operating between selected ports where infrastructure is available, vacuum mooring systems can be used. Vacuum mooring systems are commercially available and is used on some container ships today.

6.3 Deep-sea bulk ships

As described in Section 3.3, deep-sea bulk ships typically operate between large ports where some infrastructures of various kinds are expected. However, for convenience and since cranes are not always installed at the ports, bulk ships may as well be geared. Moreover, a large bulk ship can experience large height differences due to shifting loading conditions. Docking time might also be long, increasing the likelihood of high tidal variations. Because of this and the benefits and challenges presented in Section 5.1-5.2, automatic vacuum mooring systems seem like the best auto mooring solution for deep-sea bulk ships.

Consequently, it is assumed that auto vacuum mooring systems are installed at the ports which the ship visits. This assumption is justified since deep-sea bulk ships are assumed to operate at large ports with resources to invest in auto mooring equipment. Under this assumption, the automatic vacuum mooring systems have been well tested in various weather conditions, can handle large ships, are able to cope with large height variations due to draught and tide changes, and is thoroughly tested in operation. However, there are some reports of issues with system operation stability due to the complexity of the system and the corresponding need of specialized service personnel. Therefore, a yellow light is given for the deep-sea bulk ship case.

6.4 Summary

Table 3 summarizes if automatic mooring is possible today for the use cases ferry, short-sea container ship, and deep-sea bulk ship as defined in Chapter 3. The coloring schema is defined in Table 2.

Table 3: Summarizes if automatic mooring is possible today for the different ship types.

Ship type	Is automatic mooring possible today?	Comments
Ferry		The principle works satisfactorily, but there are some concerns with daily operational stability.
Short-sea container ship		The prinsiple looks promising, but it is not thourogly tested in operation yet.
Deep-sea bulk ship		The principle works satisfactorily, but there are some concerns with daily operational stability.

7 What is missing?

This chapter describes what is missing for the existing auto-mooring systems to get a green light according to Table 2 for the three use cases: ferries, short-sea container ships, and deep-sea bulk ships.

Ferries

Based on the assumptions and arguments in Section 6.1, the ferry case has commercially available auto-mooring systems installed at the quayside. These systems are thoroughly tested in operation and are well suited for the case. The only aspect that is missing to get a green light according to Table 2, is due to reported challenges with daily operation stability.

Short-sea container ships

Based on the assumptions and arguments in Section 6.2, the short-sea container ship case has commercially available auto-mooring systems that is installed on the vessel, i.e., robotic arms. The prinsiple looks promising, but the solutions have not been tested thoroughly in operation yet. Hence, for this case to get the green light according to Table 2, the available solutions need to demonstrate that the principle is working satisfactorily in daily operation with sufficiently low level of downtime.

Deep-sea bulk ships

Based on the assumptions and arguments in Section 6.3, the deep-sea bulk ship case has commercially available auto-mooring systems installed at the quayside. These systems are thoroughly tested in operation and are well suited for the case. The only aspect that is missing to get a green light according to Table 2, is due to reported challenges with daily operation stability.

8 Conclusions

This study has investigated if existing automated mooring systems are technically suited for the following three use cases: ferries, short-sea container ships, and deep-sea bulk ships. The existing automated mooring systems are either vacuum based, magnetic based, or robotic arms. For ferries, the existing automated mooring systems are commercially available, well suited, and thoroughly tested, but some issues are reported regarding daily operation stability. This is also the case for deep-sea bulk ships, assuming that ships operate between ports where automatic vacuum mooring systems are available. For short-sea container ships however, it is assumed that the ship operates between ports without any auto mooring infrastructure. Hence robotic arms on board are the only option and these are currently in the testing phase and have not been thoroughly tested in normal operation yet.

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