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A gap analysis for automated cargo handling operations with geared vessels frequenting small sized ports

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ABSTRACT

With the Yara Birkeland, the world's first autonomous cargo ship developed for commercial use, nearing regular unmanned operation, it is crucial to assess the availability and readiness of unmanned cargo handling solutions. While there are already fully automated container terminals at large international ports, the purpose of this study is to consider solutions to support autonomous ships for small sized ports with little infrastructure, typical of coastal harbors in Norway. The analysis centers on geared cargo vessels that can navigate such ports with minimal or no crew onboard, and the primary method used involved workshops and interviews with personnel from relevant industries. An important finding is the lack of skilled crane operators that are willing to follow the ship. The study concludes that it is important to address the following 3 key technological gaps: (1) the autonomous connection and release of break-bulk, (2) automatic securing and lashing of onboard cargo, and (3) shipboard cranes that can operate without an onsite crane operator.

1. Introduction

Maritime transportation plays a critical role in global trade, necessitating the development of more cost-effective and efficient solutions within the maritime industry to align with the UN Sustainable Development Goals. Increasing levels of autonomy is a crucial step in this direction. By reducing or eliminating crew members from vessels, ships can be designed with reduced crew-specific infrastructure, equipment, and systems, creating more cargo space and ultimately leading to a reduction in fuel consumption. Kretschmann et al. estimated that this could reduce fuel use by approximately 6 % (Kretschmann et al., 2017) for a bulk carrier. Moreover, autonomy enables the optimization of sea routes and travel times without the constraints associated with crew salaries, safety considerations, welfare concerns, and fresh food supplies. This flexibility opens up possibilities for new transport systems, supporting point-to-point sailing between smaller ports, leading to further emissions reduction. Additionally, automated cargo handling systems improves logistics by accurately estimating the required time at ports, thereby reducing waiting times and associated pollution. However, realizing these benefits requires mature and proven autonomous solutions for all operational phases, where some, such as unmanned loading and unloading operations, may involve significant upfront costs for the ports involved.

A recent study reveals that a mere 3% (62 terminals) of global container terminals are fully or semi-automated (only vertical movements automated) (Knatz et al., 2022). This highlights substantial untapped market potential for port automation. Particularly, further research and investment are required to develop and implement automation solutions relevant to a broader range of ports,

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Fig. 1. Open hatch jib crane (wire-luffing crane) onboard a G2 Ocean ship.
Source: Image credit: G2 Ocean.

including small sized, rural ports with regional influence that are commonly found along the coast of Norway. These ports typically handle less than 500,000 tonnes of freight per year and have marginal port infrastructure. Not classified as *Core ports* under the Trans-European Transport Network (TEN-T) (Anon, 2013), they face constraints in securing adequate funding for near-term efficiency enhancements.Consequently, such ports are typically frequented by geared vessels that rely on their own loading equipment, such as onboard cranes as shown in Fig. 1. Typically, vessels serving these ports are tasked with the handling of both containers and other types of individually counted units of goods, the latter is referred to as break-bulk cargo.

This study aims to review current and emerging cargo handling solutions applicable to geared vessels in small sized ports and to identify the need for new automated solutions. Specifically, the study will (1) assess the readiness of maritime cargo infrastructure to support higher levels of autonomy in geared vessels, (2) explore and discuss new and emerging technologies relevant to automating shipboard crane handling of containers and break-bulk cargo, and (3) identify key technological gaps that must be addressed to facilitate the transition towards unmanned operation of geared cargo ships.

The paper will first present a brief overview of the state-of-the-art solutions and recent academic research for autonomous ships and automated cargo handling solutions (Section 2), before moving on to the methodology used to achieve the study's objectives (Section 3). Then, the key results will be summarized for each step of the shoreside-to-ship cargo operation (Section 4), before discussing the identified challenges (Section 5). Finally, we will provide conclusions and propose ideas for further research (Section 6).

2. State-of-the-art solutions and literature review

The field of autonomous ship technology is rapidly evolving as more organizations and countries invest in research, trials, and commercial implementation of autonomous shipping solutions. This momentum is further accelerated by international, national, and class society initiatives aimed at developing regulatory frameworks specifically tailored for Maritime Autonomous Surface Ships (MASS) (IMO, 2019, 2021; Norwegian Maritime Authority, 2020; DNV, 2021).

2.1. A brief overview of autonomous ships

The Yara (2023) and the Asko Maritime Sea Drones (Anon, 2020) are among the first crewless ships currently undergoing testing under the supervision of onboard crew. These vessels are the tangible results of over a decade of research initiatives, marking significant milestones in the field of autonomous maritime operations.

One notable project, the "Maritime Unmanned Navigation through Intelligence in Networks" (MUNIN), received funding through the EU Seventh Framework Programme from 2012 to 2015. MUNIN was one of the pioneering efforts to explore the concept of autonomous ships by integrating onboard decision support with remote control from a shore-based station (MUNIN, 2016).

In 2015, Rolls-Royce launched the "Advanced Autonomous Waterborne Applications Initiative" (AAWA), with the objective of developing specifications and preliminary designs for the next generation of advanced ships. The initiative reached a significant milestone in 2018 when the world's first fully autonomous ferry demonstration took place with the Finferries car ferry named "Falco" (Rolls-Royce, 2018). Continuing the progress in autonomous shipping, the "Autonomous Shipping Initiative for European Waters" (AUTOSHIP) project commenced in 2019 and is scheduled to run until November 2023. The primary aim of AUTOSHIP is to develop and demonstrate two self-navigating ships that will serve as prototypes for a future fleet of fully autonomous vessels. The project encompasses various aspects such as the development of a shore control network and secure communication systems. A notable achievement thus far has been the creation of a novel cyber risk assessment method for ship systems (Bolbot et al., 2020). There are several other notable endeavors that have emerged to advance the realm of autonomous ships, such as the Mayflower Autonomous Ship (BBC New, 2022) and the MEGURI2040 project (The Nippon Foundation, 2023). Moreover, certain companies have already embarked on operating the main engine(s) and other systems for tankers from shore-based operation centers, as referenced in the Application provision of the latest draft of the IMO MASS code (IMO MSC 107/WP.9, 2023).

While the projects mentioned in this section have contributed significantly to the advancement of autonomous ships, it is important to note that they primarily focused on the technological aspects of ship operation. These projects did not specifically address cargo operations.

2.2. A brief overview of autonomous cargo handling

The conventional methods of cargo handling at ports heavily rely on human involvement, which poses risks such as human errors, personal injuries, and occupational health issues (Chu et al., 2018; Darbra et al., 2005; Cezar-Vaz et al., 2014). The loading of standardized shipping containers is easier to automate than the loading of more varied break-bulk cargo. The first automated container terminal was established in Rotterdam in 1992 (Kon et al., 2020), and since then, various automated technologies for cranes have been implemented at ports worldwide. A notable example is the introduction of unmanned Ship-To-Shore (STS) cranes, which can be operated remotely from a control room. ABB Crane Systems deployed the world's first such cranes at Manzanillo International Terminal in Panama in 2011 (Holmgren, 2011). Manufacturers like Konecranes now offer retrofit solutions to enable remote control for existing STS cranes (Lapin, 2020).

However, existing port automation technologies primarily target container terminals at major ports classified as *Core ports* according to the Trans-European Transport Network (TEN-T) (Anon, 2013). These ports have high traffic volumes, national or international influence, and larger budgets. In contrast, several ongoing autonomous ship projects, such as the Yara Birkeland and Asko Maritime Sea Drones, are designed as zero-emission alternatives for existing trucking routes, involving small-sized ports with limited infrastructure.

The ongoing EU Horizon 2020 project "Advanced, Efficient, and Green Intermodal Systems" (AEGIS), aims to design a more flexible and autonomous waterborne logistics system. The project presents a concept that suggests autonomy can overcome the limitations of the "economy of scale" by advocating for an increased number of smaller ships (Rødseth et al., 2020). While AEGIS emphasizes automated cargo handling, specific discussions regarding crane handling solutions are currently lacking. Gattuso and Pellicanò (2023) provide a comprehensive overview of automated container handling technologies. While several fully automated or remotely controlled options exist, the authors note that "automation involves changes to all areas of the terminal". They highlight that achieving a significant reduction in average per unit cargo handling cost requires a substantial level of port automation alongside a high volume of containers. Kurt and Aymelek (2022) assess the impact of Maritime Autonomous Surface Ships (MASS) on the shipping industry, including ship-port interoperability. Although they discuss the role of onboard crew in cargo handling preparations, they do not provide a detailed analysis of the specific automation challenges or technology gaps.

The specific focus of this study, which examines the operation of geared vessels in small-sized ports, remains unexplored within the referenced work.

3. Materials and methods

The study was conducted as part of SFI Autoship, a Norwegian center for research-based innovation that aims to leverage the competencies of the entire Norwegian maritime cluster to establish Norway as a leading global actor within autonomous ships. The project gathered information from key representatives from SFI Autoship, covering the entire cargo handling chain.

The main objective of the study was to review existing procedures and infrastructure to identify technology gaps and opportunities for automation that could support the operation of autonomous ships and enhance safety and efficiency in cargo handling. Discussions with stakeholders, including shipowners and port operators, provided valuable insights into the urgency of specific solutions and the willingness to invest in new technology and infrastructure. Literature reviews were conducted on particular obstacles to automation, in order to determine the present state of knowledge and technology among the broader industrial and academic communities. Fig. 2 illustrates the overall approach of the study.

The workshops and interviews conducted for this study have been summarized in Table 1. In this paper, participant identities have been kept anonymous. However, the following general descriptions and corresponding abbreviations are used to represent each organization or company involved: Research and technology organization (RTO), university (UNI), operator of general cargo ships with shipboard cranes (OGCS), shipowner of general cargo vessels (SGC), major offshore energy company (OEC), provider of shipboard cranes (PSC), short-sea container ship operator (CSO), major provider of autonomous ship solutions (PASS), telecommunication provider (TP), global maritime industry group (MIG), marine insurance company (MIC), company owning an

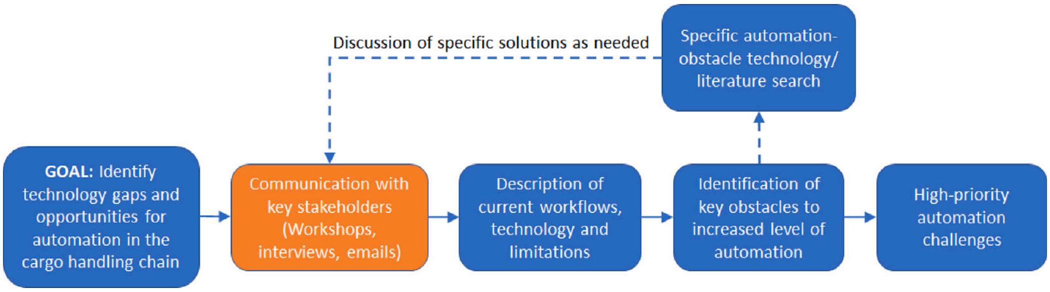

Fig. 2. Flowchart for identification of key challenges in cargo handling automation.

Table 1
Summary of the information gathered as part of the study.

#	Activity	Main discussion topic
1	Workshop	Deep sea shipping use case with relevant SFI Autoship partners.
2	Workshop	Short sea container shipping use case with relevant SFI Autoship partners.
3	Workshop	Why automate? With cargo handling focus involving relevant SFI Autoship partners
4	Workshop	Cargo handling state of the art with relevant SFI Autoship partners.
5	Workshop	Emerging cargo handling technologies and current gaps. With SFI Autoship partners
6	Interview with OGCS	State-of-the-art in cargo handling operations, motivation for automation, current challenges.
7	Interview with NCL	State-of-the-art in cargo handling operations, motivation for automation, current challenges.
8	Interview with PSC	Focus on crane operation technologies and crane simulation technologies.
9	Interview with DCH	Sensing and decision support in cargo handling, ideas for offshore automated container handling.
10	Interview with PCS2	Focus on technologies for automated break-bulk handling.
11	Interview with PACH	Focus on technologies for automated break-bulk handling.
12	Interview with CMS	Focus on spreader technologies.
13	Interview with PCS3	Focus on crane operation technologies.

autonomous ship undergoing sea-trials (OAS), digital cargo handling (DCH), provider of automatic crane hooks (PACH), crane spreader manufacturer (CSM), major classification society (CLASS), provider of maritime autonomous solutions (MAS), national maritime authority (NMA), autonomous ship operator (ASO), national coastal administration (NCA), port authority (PORT). To denote instances of similar companies, numbers are added, e.g., RTO1 and RTO2. Although the specific experience level and titles of the individuals involved in the activities are not explicitly mentioned, it is important to note that all participants were appointed as senior experts in their respective organizations regarding the relevant topics.

To facilitate a well-prepared and productive session, a team of researchers crafted the agenda, questionnaires, and other relevant materials for all activities. This information was shared with the participants in advance, ensuring the presence of a suitable skill mix. Each session featured multiple researchers with diverse expertise in the relevant areas. Refer to Table 2 for more specific information about the participants and the format of each activity.

4. Results

4.1. Analysis of typical cargo operations at small sized ports

This section focuses on the cargo operations involved in transferring goods between a ship and the quay side, assuming the use of mostly manual shipboard cranes. The different steps of a cargo operation are shown in Fig. 3. Each step will be discussed in the following subsections, by first describing the traditional way of performing the operation, then presenting new or emerging technologies. It is important to note that the detailed interactions involved in each step will depend on factors such as the type of cargo, its location onboard the ship, and the available shoreside infrastructure. As most small sized ports have a limited number of vessel calls, the vessels tend to carry a mix of standardized containers and break-bulk cargo, requiring consideration of both types.

Table 2
Activity format and participant summary.

#	Format	Participant information
1	1 h presentations of Use Case an 1 h discussions.	24 participants including RTO1 (3), UNI (9), OGCS (2), SGC (1), PSC1 (3), MIC (1), PASS (1), CLASS (4),
2	1 h presentations of Use Case an 1 h discussions.	33 participants including RTO1 (6), RTO2 (1), UNI (9), OEC (1), PSC1 (3), CSO (1), PASS (2), MAS (2), CLASS (2), NMA (1), MIC (1), ASO (1) TP (1), NCA (1), PORT (1)
3	30 min short industry presentations and 30 min open discussion.	22 participants including RTO1 (5), UNI (2), OGCS (2), SGC (2), OEC (3), PSC1 (1), CSO (1), PASS (1)
4	45 min short industry presentations and 45 min open discussion.	16 participants including RTO1 (6), UNI (3), OGCS (2), SGC (1), OEC (1), CSO (1), PASS (1), TP (1)
5	45 min short industry presentations and 45 min open discussion.	19 participants including RTO1 (8), UNI (2), OGCS (1), SGC (1), OEC (2), CSO (1), PASS (1), MIG (1), MIC (1), OAS (1)
6	1.5 h Q&A session	Questions: RTO1, Answers: OGCS
7	1.5 h Q&A session	Questions: RTO1, Answers: CSO
8	1.5 h Q&A session	Questions: RTO1, Answers: PSC1
9	1.5 h Q&A session	Questions: RTO1, Answers: DCH
10	1.0 h Q&A session	Questions: RTO1, Answers: PSC2 Operator perspectives: OGCS
11	1.5 h Q&A session	Questions: RTO1, Answers: PACH
12	1.0 h Q&A session	Questions: RTO1, Answers: CSM
13	1.5 h Q&A session	Questions: RTO1, Answers: PSC3

Fig. 3. Cargo handling operations: loading process.

Typically, break-bulk cargo is stored in a hold beneath the main deck, whereas containers can be stored in holds or lashed together on top of the main deck.

4.1.1. Prepare and connect the cargo

The required preparation of cargo depends on the cargo type. Standardized shipping containers have become increasingly popular due to their ability to streamline cargo handling processes. However, there remains a significant volume of cargo that is transported without being containerized. Goods shipped as individually counted units are referred to as break-bulk. One popular option consists of large, inexpensive, lightweight bags that require minimal return effort. Other goods may require unitization, where individual bales or bundles are secured together for efficient loading and unloading. This study does not cover bulk goods, which are transported in large quantities, such as tons, using specialized bulk carriers.

Once the cargo is appropriately packaged and available at the quay-side, it is ready to be loaded onto the ship. This process typically involves preparing the cargo for lifting by connecting it to the lifting mechanism of the crane onboard the ship. In traditional cargo loading scenarios, dock workers or stevedores manually connect the cargo to the crane. For break-bulk cargo, this may require attaching hoisting gear that the crane hook can be connected to, as the hoisting gear is often not pre-installed on the cargo unit. While manual cargo handling at small sized ports today presents risks to personnel and results in inefficient use of resources, it is worth noting that it also provides a certain level of resiliency due to the insight and experience of human operators. For example, human operators can help determine the optimal loading order and attachment method for each individual piece of cargo.

For certain types of cargo, there exist options for (partially) automated connect and release mechanisms. Vacuum clamps, for example, utilize vacuum suction to connect to the cargo, and several clamps can be mounted to one lifting frame to make it possible to lift multiple cargo units at the same time. Vacuum clamps are ideal for handling break-bulk cargo, such as bale pulp, which is lightweight and has a suitable flat area for the clamp to connect to. They can have automatic connection and offer automatic release. Another option is magnetic connection devices, which can be used to lift steel plates and similar cargo. These devices also support automatic connection and release, but their use is limited to ferromagnetic cargo with suitable surfaces for connection. Fig. 4 illustrates examples of break-bulk cargo and commonly utilized connection devices.

Recently, a few automated hooks have become available, such as the “evo” range of hooks produced by Elebia, which enable remote-controlled or automatic operation when using big bags or slings. However, humans are still required to guide the hooks efficiently into the lifting eye or loop, both on the quay when loading the ship at the departure port and onboard the ship when

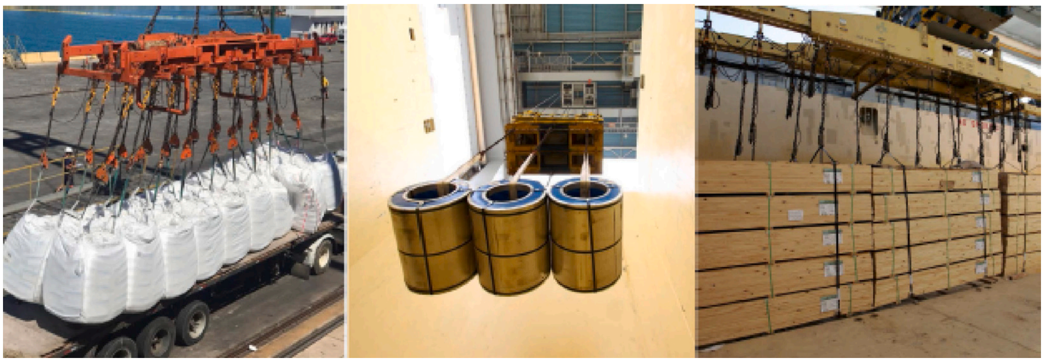

Fig. 4. Illustration of break-bulk cargoes and typical connection devices (left: Big bags, middle: steel coils, right: plywood).
Source: Image credit: G2 Ocean.

unloading at the arrival port. It should be noted that none of the options presented so far provide the flexibility needed to efficiently handle all types of break-bulk cargo, and manual cargo operations involving humans cannot be completely eliminated. The presence of workers in the cargo hold poses a significant safety hazard, as accidents can be caused by falling objects or by workers getting crushed between heavy equipment or cargo.

Containers are one of the most commonly handled cargo types, and their standardized sizes make them easier to automate than other types of cargo. They are typically lifted using spreaders equipped with twist-locks, which are mechanical locking devices attached to each corner of the container to secure it onboard the ship. However, twist-locks usually need to be manually inserted into the corner castings of the container. This is either performed by quay-side workers immediately after the container is lifted off the dock (with twist-locks inserted into the bottom corner castings), or after the container has been placed on the deck (with twist-locks inserted into the top corner castings). Unfortunately, neither of these options is ideal from a worker safety perspective. Some twist-lock systems can be operated manually, while others are semi-automatic or fully automatic.

The fusion of machine vision and Artificial Intelligence (AI) represents a promising and emerging technology with significant potential to address the challenge of achieving complete automation in cargo handling. By replacing human decision-making in various aspects of cargo handling, such as selection of loading order, hoisting preparation, and crane attachment, this technology facilitates safer and more efficient operations. However, to realize these benefits, the AI system must consider several factors during the loading operation, such as the stability of the ship and the precise positioning of the crane's connection mechanism for non-standard break-bulk units. Large sized ports will likely be supported by a fully automated cargo handling system with real-time access to information about all cargo units and ships. Based on data such as geographical placement, destination, dimensions, weight, cargo unit IDs, map of the cargo holds, and ship stability models these systems can determine the loading and unloading sequence as well as the exact placement of each cargo unit onboard the ship. For smaller ports that lack this level of automation, it is important to develop high-quality manual procedures for cargo logistics handling. This can help to support the (partly) autonomous crane in an optimal way and ensure that cargo handling operations are performed safely and efficiently.

Significant advancements are required to achieve a higher degree of autonomy in cargo preparation and attachment for crane hoisting. These include: (1) the development of robust automatic attachment mechanisms for break-bulk cargo, (2) technology to eliminate the need for manual insertion of container twist-locks, and (3) the implementation of procedures, sensors, and algorithms that provide precise positioning information for the cargo unit, attachment points, and crane mechanism. These improvements must be tailored to meet the specific needs and resource constraints of small sized ports.

4.1.2. Lift and slew the cargo

The next steps of the cargo handling operation involve lifting (vertical movement) and slewing (horizontal rotation) of the cargo along a sensible trajectory towards the designated placement position. It is crucial to perform these operations correctly to mitigate risks to personnel and infrastructure in the vicinity of the crane. The shipboard cranes currently in use are usually wire-luffing cranes or cylinder luffing cranes (depicted in Fig. 1), and the lifting and slewing are typically carried out by the crane operator. Once the cargo is securely connected, the stevedores step away from the cargo and signal to the crane operator to start lifting. Alternatively, the crane operator can make his or her own observation and decide that it is safe to start lifting. Although some crane displays may show the cargo's height above the ground, the operator still relies on visual information or communication with the ground crew to control the lifting process. Crane movements or external disturbances can cause unwanted cargo rotation. On a fully manual crane there is no way to control this rotation beyond the use of stevedores or deck-crew to guide the cargo using e.g., attached wires. Lifting, slewing, and lowering operations are frequently executed concurrently, such as initiating slewing before the lifting process concludes.

Automated functionality is commonly available for other types of maritime cranes. STS cranes at some fully automated container terminals, including those at the ports of Rotterdam, Shanghai and Qingdao, are operated from a remote control room located a distance away from the actual crane (Knatz et al., 2022). Most STS cranes at major ports include automated functionality, such as heave compensation, pendulum compensation, load rotation compensation, ship motion compensation, technology to enhance situational awareness, and various types of collision avoidance solutions. Additionally, there are fully autonomous discharging cranes available for bulk carriers (MacGregor, 2023) that feature pendulum-free motion and collision avoidance.

Although the available crane technologies provide a solid foundation for achieving a high degree of automation for shipboard cranes, there are two major operational challenges that must be addressed. The first and most important hurdle is the inherent risk of operating remotely controlled STS cranes with humans in the operating area. As a result, fully automated container terminals have emerged, with advanced logistics planning and tracking as well as additional autonomous transportation solutions to move cargo units around the port area as needed. However, for small sized ports with limited budgets for new infrastructure, achieving a hard separation between humans and machines is challenging.

Second, a human operator will need to monitor and assist the autonomous crane for an extended period until the system is proven in service. Based on the workshop discussions with the SFI Autoship partners, the favored approach is to remotely control shipboard cranes from a shore-based operation center. This solution would enable a gradual and safe adoption of automation, assuming a reliable communication solution is available.

In large sized ports, communication between the cranes and the control room can take place in the terminal's own controlled network, ensuring acceptable bandwidth and speed of commands and data-feeds. However, safety requirements for communication restrict the distance between the remote operator and the crane. The emergency stop function must be available at all times and provide a sufficiently fast response. This presents a challenge for the remote operation of a shipboard crane in small sized ports where the business case will only materialize once several ports can be serviced from the same remote operation center. However, as the systems become more robust and further automated, the need for time-critical information exchange between the crane and operator will decrease, enabling remote monitoring from further away.

In summary, there are two main obstacles to overcome for the acceptance of autonomous manoeuvring of shipboard cranes. The first obstacle is establishing and maintaining a sufficiently large safety zone around the moving crane, which can be addressed by adapting sensor technologies, collision avoidance algorithms, and new operational procedures to provide an additional protection layer if the "forbidden" perimeter is infringed upon. The second obstacle is building trust in the autonomous solutions by gradually adopting technology with human assistance and supervision as needed. This obstacle relies heavily on developing high-capacity and reliable long-distance communication solutions, and 5G technology will be discussed as a possible option in Section 5.3.

4.1.3. Lower, place and release the cargo

The final steps of the cargo handling operation involve lowering the cargo into the desired position and disconnecting the cargo once it is securely positioned. Currently, the crane operator lowers the cargo manually while crew onboard the ship assists by communicating through hand gestures and two-way radios. If the cargo is out of sight for the crane operator, he or she must fully rely on information from the crew. Moreover, the majority of cranes lack rotation control, necessitating manual intervention from the onboard crew to achieve the desired orientation of the load. This is commonly accomplished by directly interacting with the cargo or by utilizing ropes or wires attached to the load for rotational adjustments.

As discussed in Section 4.1.1, use of machine vision will be key to succeed with increasing levels of crane automation. This technology plays a vital role in accurately tracking the real-time positioning of both the moving crane and the load. It serves three important goals: first, enable autonomous connection of crane to cargo per the previous discussion, second, to ensure the required placement accuracy (orientation and position) of the cargo, and third, to maintain a safe distance to persons and relevant objects and infrastructure. Several recent studies have highlighted the potential of machine vision technology in this regard (Grudziński et al., 2020; Yoshida, 2014; Lourakis and Pateraki, 2021; Mi et al., 2021). This technology is especially critical when it comes to the automatic loading and unloading of break-bulk cargo units, which can have uncertain dimensions and non-rigid structures, making it difficult to determine the exact position of the crane's connect- and release-mechanism.

Although some initial solutions for machine vision are emerging, further research is needed to optimize the efficiency and reliability of these systems. Key areas of study include:

- Selecting an appropriate sensor configuration (e.g., cameras, lidars) that can operate effectively in diverse environmental and lighting conditions (e.g., fog, rain, snow, sunlight) while also being robust and easy to maintain.
- Determining whether marker-based technology, which uses static images to trigger additional information, should be used to simplify the identification, position, and orientation estimation of cargo.
- Identifying the best placement of sensors and markers, taking into account the constraints in sensing range, field of view, and line-of-sight, as well as their potential to be lost or damaged.

The method for physically releasing the cargo depends on the connect- and release-mechanism used for the crane, which was discussed in Section 4.1.1. In many cases, release is handled manually by the crew, such as unhooking hooks. However, for connect- and release-mechanisms based on magnetic or vacuum lifting, the release process can be performed automatically and without the direct assistance of the crew.

It is also important to note that the stowage plan of the ship has to adhere to established stability criteria, safeguarding against hazardous situations during loading and transit. The stowage plan is crucial for maintaining the integrity and protection of cargo throughout the journey, optimizing loading operations and effectively utilizing the available stowage space. A key goal is to ensure regulatory compliance, while also contributing to the overall efficiency of the ship during its voyage.

Table 3
Summary of current automation status for cargo handling with geared vessels.

Operation	Cargo type	Key tasks and current status
Prepare, connect, and release	Break-bulk	Attach hoisting gear if not pre-installed. Manual attachment of hoisting gear and crane hook typically required. Automatic hooks and vacuum clamps are available for some cargo. Emerging machine vision to enable automatic connection.
	Containers	Inserting twist locks into castings. Fully automatic container spreaders available but typically not at small sized ports. Emerging machine vision for precise connection.
Lift and slew	All cargo	Typically manually operated, some automated functions to help stabilize the load are available. Increased automation requires securing crane perimeter and reliable communication for remote controlled intervention.
Lower and place	All cargo	Typically manually operated with assistance from crew via hand gestures and two-way radios. Emerging machine vision to help place the cargo and maintain safety perimeter.
Secure	Break-bulk	Manual application of dunnage and lashings. Automation is needed.
	Containers	Automated twist-locks available, but manual permanent deck twist-locks. Challenging and costly to automate lashing. Use of cell guides reduces the need for lashing.

4.1.4. Secure the cargo (add dunnage and lashings)

Once the break-bulk cargo has been placed, the crew onboard the ship manually protects it with dunnage, which includes padding and other materials to fix the cargo in place. The cargo is further secured with lashings, which can be wire, rope or webbing used to tie several cargo units together or to tie a cargo unit to the ship's structure. While some automated securing devices for containers are available, such as fully automatic twist-locks and hull or deck storage space specifically designed for standardized containers (e.g., through use of cell guides), containers stored on deck depend on lashings for external stabilization and secure fastening to withstand the seagoing forces they may encounter. Crew members need to inspect the cargo frequently, often daily, while the ship is underway to check and re-tighten the lashing straps as they tend to loosen due to the constant motion of the ship. For autonomous ships, securing the cargo without having onboard crew available to inspect and tighten the lashings as environmental forces stress the ship structure is a critical aspect.

However, the emergence of autonomous ships can also be viewed as an opportunity to develop new and safer methods for securing cargo that do not rely on crew involvement. This will require further exploration of factors such as selecting the optimal sensor configuration for monitoring the cargo, designing cargo storage spaces with reduced motion, and developing automated securing systems that can withstand environmental stresses, such as winds and waves. While the Yara Birkeland has been designed with cell guides in the cargo hold and no container storage on-deck, which eliminates the need for lashings, such an arrangement may not always be feasible for all types of ship cargo transportation. Therefore, further research is needed to identify innovative solutions that can be applied across different cargo types and transportation contexts.

Until a viable alternative that can fully replace manually performed cargo handling operations onboard the ship is available, the presence of the crew remains necessary, eliminating the economic incentive for automating any of these operations.

4.2. Summary of cargo handling challenges

It is evident that certain operations lend themselves more readily to automation compared to others, and there are specific challenges where automation possibilities are limited. For instance, achieving full automation in break-bulk cargo connection is particularly challenging due to the diverse range of goods and the lack of standardization. For an overview of the current automation status pertaining to cargo handling with geared vessels, please refer to Table 3.

5. Discussion

The main drivers behind the automation of cargo handling are safety enhancement, improved efficiency (both in terms of time and cost), and reduced environmental impact. Based on the literature review, workshops and interviews, the following specific challenges associated with the operation of vessels into small sized ports were perceived as the most critical to address with use of automated solutions:

- Manual operations requiring crew presence in the cargo hold during cargo handling.
- Manual securing of containers, both at the port and while underway.
- Shortage of skilled crane operators willing to accompany the ship.

In the subsequent sections, we will delve into each of these challenges, examining them in more detail. Furthermore, we will provide insights into the business case for increased autonomy in shipboard cranes.

5.1. The presence of crew in cargo hold during cargo handling

As we have observed, the presence of personnel in the cargo hold is primarily required for assisting with the connection, placement, securing, and release operations of break-bulk cargo. Despite the emergence of connection mechanisms that simplify operations and reduce the need for human involvement, the lack of fully automated break-bulk terminals, even in large-sized ports, highlights the challenges in achieving complete elimination of human presence from the process. This difficulty arises from the diverse range of cargo types and the multiple attachment points for hooks and clamps, which introduce complexities that impede full automation. In the near term, a realistic goal for break-bulk cargo loading and offloading operations should be to develop efficient work processes that minimize human involvement while utilizing available automation. By responsibly reducing the number of individuals participating in cargo handling, we not only reduce the risk of personal injuries and fatalities but also create opportunities for additional automation and remote control of large machinery like shipboard cranes.

Looking towards long-term solutions, exploring the potential use of mobile robots to handle tasks such as attaching the crane hook to break-bulk cargo could be considered. However, such technology would involve substantial development costs and might require the leadership of large sized ports seeking to enhance the efficiency and throughput of their break-bulk terminals through full automation. More feasible long-term solutions include innovative cargo hold designs that eliminate the need for human assistance in cargo placement and securing. Additionally, increased standardization of break-bulk cargo can prove beneficial, whether through greater container usage or standardized lifting eye and loop designs that facilitate automatic crane hook attachment.

An essential aspect to consider when striving to remove the crew from cargo handling operations is the necessity of inspecting and adjusting lashings while the ship is in transit. Although the safety advantages of eliminating crew members from cargo handling are indisputable, there is no economic incentive to automate only some manual tasks if the crew still needs to perform other tasks. Labor costs are low in certain countries, further hindering the economic drive for more automated solutions. This situation is particularly relevant in deep-sea shipping, where salaries constitute a small fraction of the overall operating costs.

5.2. Manual securing of containers

Containers stored within the hull of conventional cargo ships can be effectively secured using cell guides, ensuring their stability. However, containers stored above deck typically require lashings for securing. This task is physically demanding, and if not properly installed, the lashings can become loose. The absence of automation in this process is primarily due to its inherently manual nature. Lashing involves inserting long metal lashing rods vertically into designated holes or openings on the containers at various heights in the container stack, connecting the lashing rods to a turnbuckle on deck or on the lashing bridge, and tensioning the lashings using the turnbuckles to achieve the desired level of tightness and stability. To automate this task, it would be necessary to devise an innovative method for securely fastening the containers to the ship while also attaining the required rigidity of the container stack. Potential options include new ship designs as well as sufficiently rigid above deck cell-guide solutions. However, both of these approaches tend to reduce the ship’s flexibility in carrying non-standard cargo and are not feasible for existing cargo fleets. Additionally, for ships that carry containers both below and above deck, it is crucial to ensure that any new structures designed to secure containers above deck do not impede the opening and closing of hatch covers.

5.3. Lack of skilled crane operators

The cargo handling workshops conducted as part of this study have highlighted the challenge of recruiting a sufficient number of skilled crane operators willing to follow the geared vessel. To address this issue, one potential solution is to transition the best operators to a centralized control center, from which they can operate multiple cranes. While this approach may result in operators losing some sensory information by not being physically present at the site, advancements in technology such as situational awareness tools, decision support systems, augmented and virtual reality, and digital twins have the potential to enhance crane operators’ performance in cargo operations. These technological advancements can contribute to safer and more efficient practices compared to the existing methods. However, there are several challenges associated with this approach that extend beyond the technological readiness of the crane itself. These challenges include:

- Opposition from strong labor unions, who are concerned about potential job losses for their members due to the introduction of remote-controlled cranes and other automated technologies.
- Ensuring high reliability and redundancy in critical communication links between ports and remote control centers to maintain seamless operations.

- Lack of regulations governing the remote operation of shipboard cranes, leading to significant uncertainty and financial risk for implementing such systems.
- The presence of personnel in close proximity to remotely operated cranes may not be feasible, necessitating the development of new working methods.

Addressing these challenges will be essential for the successful implementation of remote-controlled crane systems and similar automated technologies, enabling improved efficiency and safety in cargo handling operations while also managing concerns from labor unions and regulatory compliance.

With the introduction of 5G networks, new opportunities emerge for supporting safe remote operation of equipment through hybrid and private networks, as well as network slicing. Network slicing, a network architecture feature of 5G, allows the physical network infrastructure to be divided into separate virtual logical networks. This technology holds potential for ensuring reliability and speed, especially for mission-critical and safety-critical applications, even during peak usage of 5G networks (Roddy et al., 2019). However, network slicing is still in the trial phase and not yet fully developed. Additionally, the deployment rate of 5G varies across countries, with some still focusing on 4G deployment (Rahman et al., 2021). Another possibility for enabling remote crane operation is the implementation of a fail-to-safe-state feature. This would involve an automated safety system on the crane side, which monitors the communication channel and can force the crane into a safe state (such as cutting power) if a fault or excessive lag is detected in the communication between the crane and the operator. However, this solution may prove cumbersome if the network quality is not sufficiently high, leading to frequent or lengthy disruptions in the loading and offloading process.

A comprehensive risk analysis of long-distance remote crane operation, particularly use of centralized operating centers, is crucial to understanding the technical and operational challenges linked to this form of operation. It is essential to identify and address the following key requirements:

- Data Feeds: Given the transportation of data over much longer distances than usual, it is imperative to define acceptable requirements for data interruptions and latency. This becomes particularly relevant for visual data feeds that rely on large data streams.
- (Instrumented) Safety Functions: Robust safety systems, including emergency stop mechanisms, must be implemented to ensure that the system can promptly transition to a safe state in the event of faults and unforeseen circumstances.
- Operational Risk Mitigations: Well-defined operational procedures need to be developed to mitigate risks effectively. For instance, protocols for removing crew members from the vicinity of the crane should be established to enhance safety measures.

Ultimately, all the identified requirements should undergo rigorous testing and verification within a realistic operating environment to ensure their feasibility and effectiveness.

5.4. Business case considerations

The limited availability of automated functions for shipboard cranes can be attributed primarily to the high initial investment costs and the varied approach taken by different ports regarding this equipment. During the workshops conducted as part of this study, stakeholders highlighted that certain ports mandate the involvement of port employees in shipboard crane operations due to local regulations or demands from labor unions. This requirement raises concerns that inexperienced operators may inadvertently damage equipment if more sophisticated cranes are installed. However, the main obstacle to consider is the expected financial benefit that end users can attain through crane automation. In the case of STS cranes at large sized ports, the enhanced throughput achieved by increased autonomy justifies the significant upfront investments required for developing the necessary technologies (Zrnić et al., 2005). Operating a shipboard crane for bulk cargo and containers entails additional complexities compared to discharging cranes for bulk or STS cranes. However, it is likely the narrower profit margins associated with cargo transportation into small-sized ports that have impeded the development of autonomous functionalities for shipboard cranes. Notably, MacGregor, the developer of the world's first autonomous discharging bulk crane, has emphasized that the progression of their autonomous portfolio is driven by customer demands (MacGregor, 2019). As discussed in the previous section, the development of a sufficiently reliable communication solution combined with acceptably safe crane perimeter monitoring technologies can enable remote operation of shipboard cranes at several ports from a centralized location. Such a solution may provide the required incentive for shipowners to invest in the needed technologies.

6. Conclusions and further research

This paper presents an analysis of cargo handling operations at small sized ports, with a focus on the process of transferring goods between a ship and the quay using a shipboard crane. It discusses both traditional manual methods and emerging technologies for automation. One key finding is that remote operation of shipboard cranes from a centralized location onshore can help attract and retain skilled crane operators, while facilitating more direct transportation of goods to and from small sized ports with limited infrastructure. However, there are several challenges that need to be addressed, requiring further research and development in the following areas:

- Break-bulk cargo handling: It is crucial to develop robust automatic attachment mechanisms for break-bulk cargo. Additionally, implementing computer vision and AI-based algorithms for precise positioning of cranes and cargo placement is necessary.

- Container handling: Automation of container handling is more feasible due to standardized sizes. However, safety concerns arise from the need for manual insertion of container twist-locks. Research should focus on eliminating the need for manual twist-lock insertion.
- Machine vision and AI: The combination of machine vision and AI has great potential to help automate cargo handling operations by enhancing the localization and positioning of cranes, cargo, and relevant objects in the surrounding area to ensure a safe operating perimeter. Further research is needed to optimize the efficiency and reliability of these systems, including selecting appropriate sensor configurations and placements.
- Autonomous and remote crane operation: Developing autonomous functionality for shipboard cranes requires addressing operational challenges, such as establishing a safety zone around the crane and building trust in autonomous solutions. This involves adapting sensor technologies, collision avoidance algorithms, and developing reliable long-distance communication solutions for remote control of multiple shipboard cranes from a centralized location. Until fully automated cargo handling operations become viable for small sized ports, it is essential to establish a comprehensive and efficient alternative based on manual procedures to ensure the safe operation of partially autonomous crane systems.
- Securing cargo with minimal crew presence: Automation of cargo securing, including the use of dunnage and lashings, requires innovative solutions. Research should focus on developing automated securing systems that can withstand environmental stresses and reduce the complexity of cargo securing without requiring crew involvement.

By effectively tackling these challenges, small sized ports can enhance their appeal as ports of call, thereby facilitating the development of a more flexible maritime transport network.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

All original ideas contained in the manuscript were generated and developed by the authors. The corresponding author used ChatGPT from OpenAI in order to improve the language and readability of the revised version of the paper. After using this tool/service, the corresponding author reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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