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Analyzing the Feasibility of an Unmanned Cargo Ship for Different Operational Phases

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ABSTRACT: The maritime industry has begun to look into autonomous ships as an alternative to conventional ships due to growing pressure to reduce the environmental impact of maritime transportation, to increase safety, to mitigate the growing challenges in recruiting seafarers, and to increase profit margins. There is a lot of research on the challenges and feasibilities of an autonomous ship. However, there is less discussion on the transition from manned to unmanned ships and the tasks that are feasible to automate before the whole ship is unmanned. This paper investigates the technical and regulatory feasibility of automating different tasks for different operational phases for a large cargo ship. This study shows that a fully unmanned cargo ship is not feasible today, but that some tasks can be automated within the next five years.

1 INTRODUCTION

The maritime transportation sector is under pressure to make improvements in several areas. Firstly, the environmental footprint must be reduced to achieve the goal of 70% reduction of greenhouse gas emissions by 2050 [1]. Secondly, the sector is facing increasing challenges in the recruitment of seafarers. Thirdly, the sector needs to increase safety, both in terms of the crew and valuable assets. Fourthly, the sector needs to increase competitiveness to meet the goal of a modal shift towards waterborne transportation. Finally, there is a need to increase resilience in the maritime transport towards situations such as the COVID-19 pandemic which deteriorated seafarers work life and created difficulties with accessing ports. In this context, the maritime industry is investigating autonomous ships as an alternative to conventional ships. Automation can improve safety by removing people from potentially dangerous tasks like cargo handling. Another benefit of automation is the potential to reduce manning, which can remedy the shortage of seafarers and reduce the crew cost. Moreover, for a fully unmanned ship, the superstructure can be removed, increasing the cargo carrying capacity, lowering energy usage, and enabling new ship designs. By automating different tasks on a ship, the needed manning can be reduced. However, operating a large cargo ship unmanned is not straight forward. One of the biggest challenges for operating a large cargo ship unmanned today is the frequent need for maintenance on the power and propulsion system and international regulations.

The autonomous container ship YARA Birkeland, ASKO's autonomous vessels, and MEGURI2040 are just some of the commercial initiatives that aim to operate autonomous ships in the near future. There exists a lot of research on the challenges and feasibilities of autonomous ships, e.g., [2]–[9]. However, there is less discussion on the transition from manned to unmanned ships, as pointed out in [7]. This study will investigate the technical and regulatory feasibility of automating different tasks for different operational phases. As such, it will serve as a guidance to taking the steps towards unmanned ships by identifying what autonomous operations are feasible today, and which remaining challenges must be solved to take the final steps. The scope is limited to unmanned cargo ships operating internationally, e.g., ships operating within European trade or in the deep sea segment. This paper uses the term unmanned ship to refer to a ship without any people on board and operating under constrained autonomy. A constrained autonomous ship is defined as an "uncrewed operation with constrained autonomy onboard but with operators in Remote Operation Center (ROC) that can handle more complex situations." [10].

2 METHOD

The methodology in this study follows the work in [11]. The study investigates the technical and regulatory feasibility of an unmanned cargo ship. The evaluation is performed by looking into specific tasks and operational phases. The tasks and phases have been determined based on feedback from shipping companies. The operational phases include 1) at port, the ship is stationary at a port, 2) near port, the ship is arriving or leaving a port, 3) coastal, the ship is in a highly trafficked area or narrow waters, and 4) deep sea, the ship is in open sea. This study covers the following tasks: navigation, propulsion, communication, cargo handling, and mooring. To narrow the scope of this study, additional tasks that are required to operate a cargo ship are not included.

A traffic light is used to indicate the feasibility with the colors defined in Figure 1. A color of feasibility status is given for each task for each operational phase.

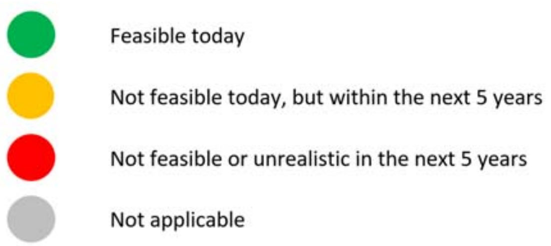

Figure 1: Colors defining feasibility.

If all the tasks can be performed at all the operational phases, the ship can operate unmanned. The assessment of feasibility is based on a combination of literature study and semi-structured interviews with technical and service providers, authorities, and classification society in the maritime industry. Details on this can be found in [9], [11].

3 TECHNICAL FEASIBILITY

In terms of evaluating the technical feasibility of realizing unmanned cargo ship operations, this paper takes a closer look at navigation, propulsion, communication, mooring, and cargo handling.

3.1 *Navigation*

Navigation is the act of getting a ship from one location to another in a safe and efficient manner. To navigate a ship with no crew on board, it is necessary to establish situational awareness, i.e., observe, detect, and classify objects in the surroundings of the ship and predict the behavior of the objects. Next, the navigation system must plan a path for the unmanned ship and steer the ship accordingly while ensuring the safety of the ship, cargo, and the environment of its operation.

3.1.1 *Automatic Navigation in Congested and Confined Waters*

Today, several solutions for autonomous navigation are available on the market, e.g., [12]–[17], where some have been tested for large cargo ships [15], [18], [19]. Based on interviews with leading technology and service providers in the maritime industry, one of the biggest hurdles to overcome towards realizing unmanned navigation of ships is object classification. It is crucial for the navigation system to know what type of objects are in the surroundings, for instance if it is a ship or shore. A lot of high-quality data is needed to develop an accurate object detection algorithm, which is currently lacking [9]. Another challenge is for the automatic navigation system to know its own limitations, that is, when to call for assistance from an ROC or go into a safe state. This is also a challenge for all other automated tasks. Moreover, behavioral prediction and path planning will be a challenge when the unmanned ship must interact with other ships [20].

3.1.2 *No Physical Pilotage on Board*

In specific areas, such as in port areas or highly trafficked areas, a pilot is required to safely guide a ship [21]. Today, this operation requires that the pilot physically boards the ship. As outlined in [22], this becomes an issue in the case of an unmanned ship, as the pilot will not have a bridge to perform its tasks from. As a possible solution to this issue, Porathe [22] suggests a digital pilot service with the same local knowledge and expertise as a conventional pilot. However, solutions for digital pilotage are not yet realized. Another possible solution is for the ROC operators to have a pilotage certificate for the area of operation. However, for international voyages, this can be a challenge due to the large area of operation.

3.1.3 *Automatic Docking Without Assistance From Tugboats*

When a ship approaches a quay, it must prepare for and carry out the docking operation, i.e., sailing from the fairway area to the quay. When leaving the quay, the operation is reversed, and un-docking is performed before the ship returns to the fairway. Some actors have already demonstrated autonomous docking [23]–[25]. However, information on the actual performance of these docking systems, for example the operational stability, is not publicly available.

3.1.4 *Feasibility*

Based on the above, it is reasonable to assume that the ability of an oceangoing cargo ship to perform autonomous navigation in a safe and efficient manner is not feasible today, but within the next 5 years (giving a yellow traffic light). The main reason is the existing operational limitations of today's autonomous navigation systems related to object detection and classification. Nevertheless, automated navigation is considered less challenging in the deep sea operational phase compared to the other operational phases, mainly due to the limited traffic and lack of congested areas.

3.2 *Propulsion*

For a conventional ship, there is crew on board to handle any potential failures and maintenance needed with the propulsion and support system (Nedcon Maritime, 2013). However, for an unmanned ship, there is no crew on board, meaning that the propulsion system must be able to operate without need for intervention or repairs for the entire voyage (i.e., sailing between two ports). Cargo ships operating internationally are typically equipped with low-cost fossil fuel propulsion systems, e.g., a diesel engine using VLSFO, which requires a lot of maintenance. However, there exists alternative propulsion systems and cleaner fuels which require less maintenance. For shorter voyages (e.g., 15-30 nm as for Yara Birkeland), electrical engines with batteries can be used, which require less maintenance. Unfortunately, for cargo ships operating long distances, maintenance free propulsion systems have a low level of technical maturity. There exist solutions for maintenance and fault prediction, however, this would still require a power and propulsion system that could operate without failures between ports.

3.2.1 *Feasibility*

Automated propulsion systems for cargo ships sailing long voyages are not considered feasible within the next 5 years, due to the human intervention needed with today's propulsion system. Further development of new propulsion systems without need for maintenance on long voyages is necessary. However, for shorter voyages, where for instance electrical engines can be used, automated propulsion system is possible within the next 5 years. Thus, a red traffic light is given for the feasibility in deep sea, while a yellow traffic light is given for the at port, near port and coastal phases due to the shorter distances.

3.3 *Communication*

For a cargo ship, communication with other ships, ports, and authorities is required. Additionally, for an unmanned ship, communication with an ROC is needed. Moving the responsibility from the ship to an ROC creates new requirements for communication.

3.3.1 *Gain Situational Awareness Around the Unmanned Ship*

Communication requirements for an ROC operating an unmanned ship are not easily available as this is still under development. Operators at an ROC need to gain sufficient situational awareness to safely operate the unmanned ship. A challenge is to determine the needed data to gain situational awareness, which is limited by the available bandwidth. Thus, the ROC must prioritize what should be communicated. Regardless, the ROC will utilize all available bandwidth. The communication bandwidth available depends on where the ship is located. Near shore, terrestrial communication with high bandwidth is typically available. In deep sea, only satellite communication is available, which has limited bandwidth. Low bandwidth limits the amount of sensor data that can be transferred to an ROC from an unmanned ship. This means that it might not be sufficient bandwidth to gain full situational awareness at the ROC in some areas. In the next years, satellite communication systems with higher capacity and lower latency are expected, such as Starlink. Moreover, as the level of autonomy rises on the ship, the amount of data needed in an ROC is expected to decrease.

Another challenge is to ensure the data quality and reliability, as faulty data can impact the safety and efficiency of the operation. If communication with the ROC is lost, the ship should enter a minimum risk condition if the situation is challenging. Further information on communication challenges and possible data requirements for an ROC is discussed in [27], however the study is some years old.

3.3.2 *Possible to Remotely Control the Unmanned Ship*

The ROC must be able to remotely control the unmanned ship if the automation system cannot handle the situation. Low latency is crucial when operating the ship remotely. When the ship is close to shore, there are communication systems with low latency available, e.g., 5G. When far from shore (i.e., deep sea), only satellite communication is available, which has a high latency. However, when operating deep sea, decisions will be less time critical and thus a larger latency can be accepted. As mentioned earlier, when Starlink is up and running globally, communication with low latency should be available.

3.3.3 *Communication With Other Ships, Authorities, and Ports in Real-Time*

Even for an unmanned ship, communication with nearby ships, ports, and authorities is needed. All ships must follow the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs), i.e., the rules of traffic at sea. However, in some traffic situations these rules are not explicit on what action should be taken, which makes it hard for the automated navigation system to determine the proper action. In such situations, ships must communicate with each other and decide who takes what action (to avoid a collision). Until new COLREGs are in place, communication with other ships must be handled by the ROC [20]. Route exchange between ships has been proposed as another possible solution to avoid unclear traffic situations. However, for this to work, all operating ships must be equipped with route exchange systems, which is a comprehensive task [20]. Even more, with route exchange systems in place on all ships, there is still need for explicit rules on how to behave if these routes intersect. This means that the COLREGs needs to be altered or amended to make them explicit.

Today, this type of communication is done over radio. Voice communication from the unmanned ship can be transferred to an ROC using Voice over Internet Protocol (VoIP). It is assumed that limited bandwidth is needed to communicate with ports, authorities, and ships. However, the latency cannot be too high. This should not be a problem according to [28], as for instance Iridium Certus offers voice communication without noticeable delay.

3.3.4 *Feasibility*

For the phases at port, near port, and coastal, terrestrial communication systems are typically available with high bandwidth and low latency, allowing the ROC to gain situational awareness and remotely control the ship, giving a green traffic light. In deep sea, gaining full situational awareness and remotely control the ship can be a challenge due to the limited bandwidth and high latency. However, for an unmanned cargo ship, communication with an ROC cannot be safety critical as the ship must maintain safety in the event of a communication system failure (it must have fallback solutions). Moreover, due to the expected improvements of satellite communication in the next years, e.g. Starlink, a yellow traffic light has been given.

3.4 *Mooring*

Traditional mooring requires crew to secure the ship using ropes. With large forces in place, this traditional method poses a large danger for the crew involved. When discussing mooring in this paper, it is assumed that the ship is stationary at port. This section summarizes the outcomes from a gap analysis on automated mooring systems [29] with highlights on the main challenges.

3.4.1 *Automatically Mooring a Cargo Ship*

There exist different solutions to automatically moor a ship in the market today, including vacuum mooring (e.g. [30]–[32]), magnetic mooring (e.g. [30]), and robot arms (e.g., [30], [33]). The vacuum based mooring system is the most established solution in the market and in use on many different types of ships, ranging from large cargo ships (< 300m) to smaller car and passenger ferries. The typical installation consists of multiple vacuum pads installed at port, where the number of pads depends on the size of the ship it should be able to moor. The automated vacuum mooring system can reduce the mooring time and the human risk compared with manual mooring. A downside of the vacuum mooring is that it requires installations at every port the ship visits. The robotic arm mooring system, if placed on the ship, can visit any port without requiring any other on-site infrastructure than the conventional bollard. However, the robotic arm mooring systems are still under development and have not been extensively tested during operation. Therefore, it is unclear how well this mooring system actually performs.

3.4.2 *Automatic Mooring with Draught and Tidal Changes and Rolling Motions*

Mooring systems must be able to handle tidal changes and draught difference when loading cargo. Tidal changes can be up to 7.5 m in some ports and ship draught can differ with 12 m between an empty ship and a fully loaded ship [34]. By mounting the mooring units on vertical rails, the vacuum and magnetic automated mooring systems can adjust to changes in tide and ship draughts. Another option for adapting to varying heights is to use the different vacuum pads to step along the hull. The vacuum based automated mooring systems can handle roll motions induced by cargo handling up to 6°, which is adequate for most situations.

3.4.3 *Feasibility*

Automated mooring systems are in use on cargo ships today and are thus considered feasible (giving a green traffic light). There are, however, some challenges with the operational stability of today's systems.

3.5 *Cargo Handling*

When the ship is at port, the cargo must be loaded on and off the ship. Additionally, it is important to secure the cargo on board the ship. Cargo ships can carry many different types of cargo, e.g., containers, dry bulk, wet bulk, and break bulk, and the difficulty of automating the cargo handling varies between the different cargo types. Today, there exist cranes that can automatically on- and off-load containers. This is available on large, advanced ports today, but not on smaller ports. For containers, the biggest challenge is securing the containers on board the ship [11]. When the containers are stacked above deck, lashing is required to avoid movement of the containers. The lashing is manual work and difficult to automate. A possible solution is to use cell guides to secure the containers. However, this is not possible for large container ships due to the height of the container stacks. For smaller container ships, like Yara Birkeland, this is not an issue since the containers can be stored below deck. For break-bulk, automated cargo handling is challenging, particularly the connection (hooking) of the cargo [11]. This is mostly due to the wide variety of goods and packaging, complicating the automation task. There exist some semi-automated solutions for connection in the market, but a lack of fully automated solutions for any type of goods. This is a topic for further research. Wet and dry bulk are easier to automate as the collection, transferring, releasing, and securing of the cargo is simpler. There already exist some solutions for this in the market, such as [35].

3.5.1 *Feasibility*

The feasibility to automate cargo handling depends on the type of cargo. Break-bulk is difficult to automate, while for containers and wet and dry bulk there already exist some solution for automation. Thus, a yellow traffic light is given for the feasibility of automated cargo handling. However, to sail a cargo ship unmanned, it is not strictly necessary to automate the cargo handling, as crew can board the ship at port. However, this does not solve the challenge of securing cargo during the voyage.

4 REGULATORY FEASIBILITY

The regulatory feasibility of an unmanned cargo ship will be evaluated based on the different tasks navigation, propulsion, communication, mooring, and cargo handling. Existing regulations for approval and operation of ships have been developed under the basic assumption that important tasks are performed by humans on board the ship. Although automation has taken over more and more human tasks in recent decades, conventional ships always have a human on board with the operational responsibility. Hence, a shift towards unmanned ships creates gaps in existing rules, regulations, and standards, since these typically require explicit human presence.

Current autonomous ship initiatives mainly involve relatively short routes, such that only domestic regulations and authorities are relevant. This allows the involved actors (developers, authorities, etc.) to focus on a limited and well-defined concept of operation (CONOPS). In support of a "standardized" approval process, some maritime authorities such as the NMA have established a case-by-case approval procedure [36]. These case-by-case approvals are very demanding when it comes to documenting how the autonomous systems perform and how responsibilities are distributed between the automation systems and ROC in different situations. It is necessary to verify that equivalent safety is provided with the automation systems and the process becomes more demanding as the area of operation increases. When expanding the operation to arbitrary and global routes, the ship and its supporting infrastructure (such as ROC), must also comply with international regulations. There are also certain legal questions which require clarification, especially when it comes to the jurisdiction of flag states, ports, and coastal states. Currently, there are no common international regulations for unmanned ships, but IMO is working on a 'MASS Code' which is expected to be released in the mid 2020's [37]. Until the MASS Code is released and in force, any international unmanned voyage will require specific agreements between the ship owner and all involved authorities.

Other conventions, such as the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) and The International Search and Rescue Convention (SAR), have been left out to limit the scope of the study.

4.1 *Navigation*

Autonomous navigation is particularly challenging from a regulatory perspective because it involves extensive decision-making and interaction with other seafarers. Rules for navigation at sea are determined by COLREGs, which has been written for a world of manned ships and are not straightforward for algorithms to interpret. For example, terms such as "good seamanship" and "safe speed" require subjective interpretations based on context. Another example which is difficult for autonomous systems to handle is that the COLREGs specify that a ship must give way to another ship if it is crossing its path. It is not always clear how a ship should determine if it is crossing the path of another ship, especially in crowded waterways. Another challenge is to make an autonomous system "behave" in a way that makes its intentions clear to other seafarers.

While it is feasible to demonstrate and document equivalent safety levels for autonomous navigation systems for a limited operational domain, it is not trivial to get such systems approved for "free sailing" between arbitrary ports. Hence, international operations for unmanned ships are not considered feasible within the next 5 years, indicating a red traffic light for deep sea. However, for coastal and near port phases a yellow traffic light is given, as unmanned navigation along specific routes is considered feasible on a case-by-case basis.

4.2 *Propulsion*

Requirements regarding reliability and fault tolerance for systems related to propulsion and steering are particularly demanding to comply with for unmanned ships sailing long distances. For instance, DNV's class guideline DNV-CG-0264 for autonomous ships [38] mentions, with reference to SOLAS Ch. II-1, that "Means shall be provided whereby normal operation of the propulsion machinery can be sustained or restored even though one of the essential auxiliaries becomes inoperative" and that a navigable speed must be maintained in case of potential failures of single systems or components. DNV-CG-0264 further states that unmanned ships should be arranged with a minimum of two independent propulsion lines. Based on the strict redundancy requirements for propulsion systems, a red traffic light is given for the deep sea phase, as meeting such requirements does not seem feasible for long journeys within the next 5 years. For the coastal and near port phases, however, it should already be feasible to get case-by-case approval for specific routes, while approval for free sailing is assumed to be realistic within the next 5 years (giving a yellow traffic light for these phases).

4.3 *Communication*

According to the regulatory scoping exercise conducted by IMO [39], the requirements in SOLAS chapter IV (Radiocommunications) do not take into account remote operations and on-shore control centers, and the most appropriate way of addressing this issue is to develop a new instrument to properly address MASS operations. Such a MASS instrument is not expected to be in place and in force within the next 5 years, giving a red traffic light for the deep sea phase. For the near port and coastal phases, a yellow light is given, since limited operation is considered feasible based on case-by-case approval following the NMA circular [36]. For the at port phase, a green light is given since this phase does not involve any navigation or maneuvering and any applicable requirements are expected to be met by state-of-the-art technology.

4.4 *Mooring*

Unmanned mooring operations do not appear to introduce any requirements which can't be met with today's state-of-the-art technology, and mooring is therefore given a green traffic light for regulatory feasibility.

4.5 *Cargo handling*

The regulatory feasibility of unmanned cargo handling has not been evaluated in detail, partly because the main challenges appear to be technical rather than regulatory. However, the following rules and standards from DNV have been identified as relevant:

- DNV-RU-SHIP Pt.5 Ch.1 Bulk carriers and dry cargo ships
- DNV-RU-SHIP Pt.6 Ch.4 Cargo operations
- DNVGL-ST-0377 Standard for shipboard lifting appliances

The above doesn't seem to have specific requirements for autonomous cargo handling, but a yellow traffic light is given since such systems have not yet been tested (or approved), and it is expected that regulatory hurdles may be met during development and approval of unmanned cargo handling systems.

5 RESULTS AND DISCUSSION

Figure 2 gives a summary of the technical and regulatory feasibility for operating an unmanned cargo ship internationally. The findings of this work indicate that, over the next five years, it will not be possible to operate an unmanned cargo ship on international waters. The main challenges are the high frequent maintenance required with today's propulsion and sub systems and regulatory challenges for international operations of cargo ships. However, specific tasks for specific operational phases can be automated today or within the next five years. This can reduce the needed manning for that phase or related to the specific task. For instance, automatically mooring cargo ships is possible today. Moreover, automatic handling of some types of cargo is expected within the next five years. Autonomous navigation should be technically feasible in deep sea and areas with low operational complexity within the next five years since the traffic challenges are limited. From a regulatory point of view, periodically unmanned navigation should be possible in the near future as there are large cargo ships today that are allowed to operate without proper view due to large cargo stacks blocking the bridge. However, exceptions on the lookout rules need to be approved for each specific voyage. Nevertheless, it is not straight forward to reduce the overall manning of a cargo ship. The crew are typically involved in multiple different tasks for different operational phases. An analysis of crew reduction is discussed in [7].

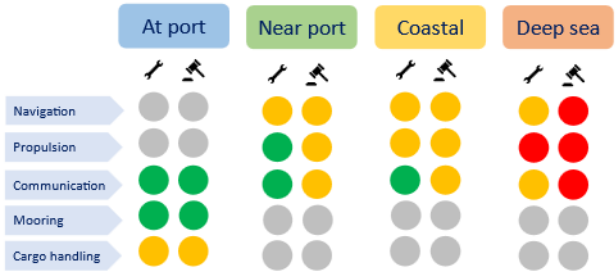

Figure 2. Technical and regulatory feasibility of an unmanned cargo ship.

6 CONCLUSION

Before cargo ships can operate completely unmanned internationally, there are still several issues that need to be resolved. The biggest challenges are the high frequent maintenance related to the power and propulsion systems for large cargo ships and the international regulations for "free" sailing between arbitrary ports. For a small or medium sized ship operating short distances within national waters, these challenges can be overcome by using electric propulsion with less maintenance needed, and by obtaining national permits for unmanned operations in limited areas. However, for a cargo ship operating internationally, it is possible to automate some tasks for certain operational phases within the next five years, for instance mooring, cargo handling (cargo dependent), and navigation in deep sea. Further research is needed on maintenance free propulsion systems and data and information needs of an ROC. Moreover, on the regulatory side, it is necessary to review the COLREGs and examine the implications of the MASS code under development.

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