Marine Design XIII – Kujala & Lu (Eds)
© 2018 Taylor & Francis Group, London, ISBN 978-1-138-34076-3

Towards autonomous shipping: Operational challenges of unmanned short sea cargo vessels

C. Kooij, M. Loonstijn, R.G. Hekkenberg & K. Visser
Delft University of Technology, Delft, The Netherlands

ABSTRACT: Autonomous shipping is considered a highly promising development in the shipping industry. Technologically it is believed to be possible, but there are several challenges that still need to be solved before autonomous shipping can become a reality. In this paper the main challenges for autonomous shipping are identified. This is done by taking the main functions of the ship and combining them with the crew tasks. That way it is possible to identify where problems occur when the crew is no longer on board. Combining the challenges found with prior research on autonomous shipping leads to three elements into which little to no research has been conducted. However, they are important for the operation of an autonomous ship. The elements that need to be further investigated are; navigation and situational awareness, ship-to-ship communication, physical intervention of the crew on the ship and its systems, and maintenance and repair.

1 INTRODUCTION

With the technology for autonomous vehicles evolving rapidly, the shipping industry has also started to research its potential. There are several projects completed and in the works which all come to the same conclusion: the technological building blocks to build an autonomously navigating ship are available. However turning these building blocks into actual systems and control algorithms still requires significant development. At this point there are several small vessel that can operate autonomously or via remote control, but there are no functioning cargo vessels yet (Israel Aerospace Industries, no date; Naveltechnology.com, no date).

This paper looks at the direct problems that arise from the removal of all crewmembers from a conventional short sea cargo vessel. This allows for the identification of the biggest challenges that lie ahead. Finally these challenges are compared to information and articles about research that has already been done to find the remaining challenges. These results are the starting point for further research.

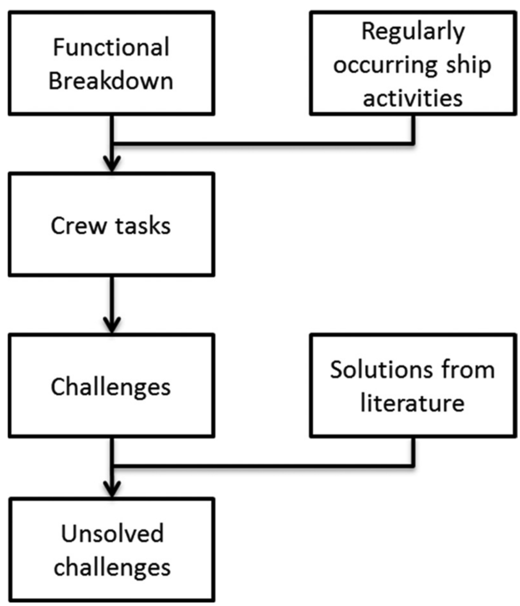

Figure 1. Graphical overview of the method followed.

2 METHOD

This section discusses the method by which the unsolved challenges have been found. Figure 1 gives a graphical representation of the method followed.

The first step in identifying the aforementioned challenges is making a functional breakdown of the ship. In the functional breakdown, every function of the ship and crew which is relevant to fulfil the ship's mission is identified. This is done by analyzing what functions need to be fulfilled in order to accomplish certain operations such as 'move'. This analysis is repeated until basic functions, i.e. functions that can be split further and can be performed by a single system, can be found (Viola *et al.*, 2012). For example: the function 'communicate' can be split into two functions 'to allow for external communication' and 'to allow for internal communication'. The function 'to allow for external communication' can then be split into the functions 'communicate with other ships' and 'communicate with the shore'.

In his book *Practical Ship Design* (Watson, 1998), Watson states that in war ship design there are three main functions (in order of importance): float, move and fight. But if 'fight' is identified as 'perform the ships main mission', this method can be applied to any ship type.

During the course of making the functional breakdown, it was found that in addition to these three functions, two additional functions play an important role in the operation of the ship. The first is communication. This is a part of almost every function the ship can perform, from communication between two ships to the communication for a sensor to a computer. To better identify the different communication types, communication is added as a main function.

It was also found that the three main functions identified by Watson do not cover what happens in case of failure. This is an interesting area for autonomous ships, since the crew is now the first line of defense in many cases. Therefore it is important to know how failures are prevented or currently solved, what systems exist to prevent or mitigate these failures and what role the crew plays. For this reason this function is also added as a main function.

To summarize: the main functions of the ship identified in this paper are:

- Float
- Move
- Communicate
- Perform mission
- Prevent and mitigate failure

The next step is to identify which role the crew plays in the operation of the ship. A ship is a complicated system of which the operational profile differs depending on the situation and the environment. To get a good view of the crew involvement their tasks and actions are identified in six key activities that take place during a ship's journey. These activities are ordered chronologically to ensure that every aspect of the journey is covered. Additionally, the processes that take place during specific parts of the journey in each department are documented, although they differ between ships and companies. These six activities are:

- Preparing for the mission
- Quayside operations (e.g. loading and unloading, bunkering and taking on stores)
- Preparing for arrival and departure
- Near and in port sailing (arrival and departure)
- Normal sailing in open sea
- Emergency situations

For each of the activities mentioned, the relevant functions from the functional breakdown are identified. The functional breakdown allows for an identification of which functions are performed by systems and which functions require human interference or a human to perform the function completely. The human involvement is determined from handbooks, observations in practice and expert interviews. Together these elements give a good overview of the level of human involvement. As this paper focusses on the general operational aspects of shipping where challenges can arise, no further details are required within the functions or the crew tasks.

From there, it is possible to identify what would happen if the crew is no longer on board. This is determined by expert interviews.

The final step in this paper is to combine the identified problems with the challenges and solutions found in literature. That way the challenges that have not been identified or solved in previous research can be found, thus showing where further research is required.

3 FUNCTIONAL BREAKDOWN AND CREW TASKS

The first step is to identify which functions a short sea cargo vessel must have, to perform its mission. Next, the crew tasks for each of the identified key activities are identified.

3.1 *Functional breakdown*

The developed functional breakdown consists of the five main functions of the ship. Each of these five functions in broken down into smaller functions until a function can be defined that can be performed by a single system. A graphical representation of the functional breakdown, showing the first two levels, can be found in Figure 2.

3.1.1 *Float*

The function 'float' covers sub functions such as have structural integrity and be watertight. While these functions are not performed by a system per se, they are an important element in the ship's functions.

3.1.2 *Move*

The function 'move' not only covers the physical movement of the ship, but also the planning of this movement: navigation.

The physical moving of the ship consists of functions covering the movement of the ship in

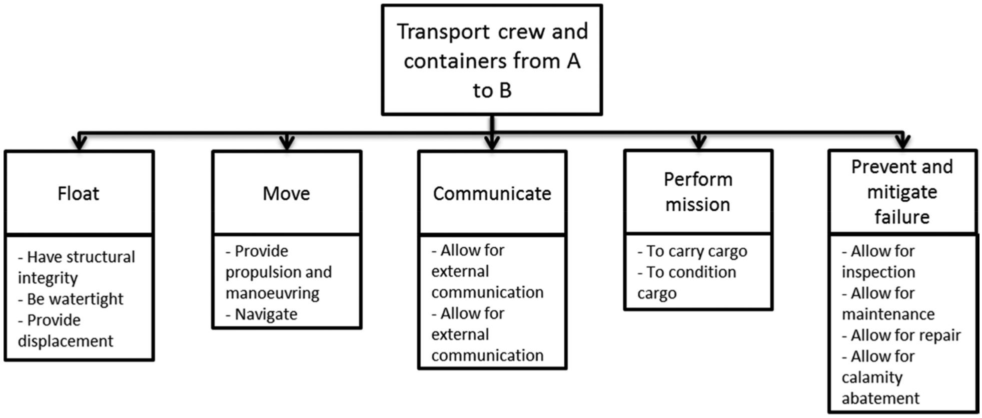

Figure 2. Functional breakdown showing the first two levels of the identified functions.

all directions, for example, proving lateral thrust at slow speeds, which can be performed by the bowthruster.

The navigational part of the 'move' function mostly consist of planning the route and being able to follow it without any problems. This includes functions such as 'to display navigational data' which can be performed by several systems alone or a combination of them.

3.1.3 *Communicate*

There are several forms of communication that take place during a mission. There is internal communication between different crewmembers, external communication with the shore (e.g. the vessel owner, port authorities, and terminals) and communication between ships. Additionally the ship is able to send out several different emergency signals.

Internally the most used methods of communication are verbal communication between crew and data transfer between systems. Finally the systems also communicate with the crew, for example by showing data on a screen or giving alarms.

In external communication verbal communication and data transfer are also important, additionally communication happens via lights and sound signals. Each of these manners of communication takes place in both ship-to-ship and ship-to-shore communication.

3.1.4 *Perform mission*

This function includes all elements that are required to move cargo from a to be. Therefore it not only includes the ability to load and unload cargo, but also all elements that are required for safe and comfortable passage of the crew, such as providing HVAC and electricity.

3.1.5 *Prevent and mitigate failure*

The final main function of the ship is the ability to solves problems if something breaks down as well as maintenance to decrease the possibility of a failure. This is a very broad function as it covers many potential problems that can occur on board of a ship. In general it covers the ability of each system and space to be inspected and be repaired if required as well as calamity abatement for every possible calamity.

3.2 *Crew tasks*

For this paper a only a general overview of the crew tasks is required. A general understanding of what the crew does is enough to determine if problems will arise when the crew is no longer available. Further details can always be added if they are required. Commonly, the crew of a ship is subdivided into four departments:

- The bridge crew
- The deck crew
- The engine room crew
- The catering crew

The bridge crew is responsible for the general operation of the ship. This means that they steer the ship, determine the precise route and make decisions to deviate from this plan, if necessary. Since the bridge crew steers the ship, they are also responsible for navigational safety and situational awareness of the ship.

The deck crew is responsible for planned maintenance and general upkeep of the deck equipment. Additionally they operate the equipment and handle the lines during mooring and anchoring operations.

The engine room crew spends most of their time on inspection and planned maintenance to keep the equipment in good condition.

Table 1. Crew involvement for functions during different operational activities. (The checkmarks show crew involvement).

	Preparing for journey	Quayside operations	Preparing for arrival and departure	Near and in port sailing	Normal sailing in open sea	Emergency situations
Float	X	X	X	X	X	X
Move	✓	✓	✓	✓	✓	✓
Communicate	✓	✓	✓	✓	✓	✓
Perform mission	✓	✓	✓	✓	✓	✓
Prevent and mitigate failure	✓	✓	✓	✓	✓	✓

Finally, the catering crew is responsible for the food on board of the ship

For each of the six identified key activities, the crew tasks were identified. Table 1 shows whether crew is required for the performance of a specific function during different operational activities.

3.2.1 *Preparing for the journey*

The preparation for the journey is done by the bridge officers prior to departure. The whole route is planned and elements such as traffic conditions and weather reports are reviewed (International Chamber of Shipping, 2016). The exact list of steps that are taken during the preparation of the trip depends on the company, the ship and the mission it will execute.

During the trip preparation, the ship also undergoes basic maintenance and repairs if required.

3.2.2 *Quayside operations*

The most important part of the quayside operations is the loading or unloading of the ship. In most cases, the cargo is handled by the port crew, leaving the ship's crew free to perform other tasks. Labor organizations even advise against working on a ship where loading and unloading operations fall under the crews authority (ITF, 2015). Some other operations during the loading and unloading, such as ballasting, are already fully automated.

Not only mission-specific items (e.g. cargo) are loaded onto the ship, the ship also takes in bunkers and stores. According to industry experts this task is performed by the crew from the responsible department. For example, a member from the engine room crew would oversee the bunkering of the fuel.

3.2.3 *Preparing for arrival and departure*

The final preparations for arrival and departure are listed on a checklist, to ensure that no tasks are forgotten. However, these procedures are not standardized, they differ from ship to ship. In general the following elements can be expected to be listed on the checklist (International Chamber of Shipping, 2016):

- Check main engines and rudder control
- Check navigational equipment
- Check cargo and cargo handling systems
- Check communication systems

Each of the departments has their own checklists and a required number of people required for the tasks. Generally, this is a higher number than is required for normal sailing to assist in case of an incident.

3.2.4 *Near and in port sailing*

Near port sailing differs from normal sailing in several key points. The first is the amount of traffic, different ships with different functions are moving around the port. This does not only include cargo vessels but also smaller vessels such as yachts and pleasure crafts. This means that the communication density with other ships and shore is much higher. The second area where the two differ is the fact that the water depth is limited and the domain in which the ship can sail safely becomes more confined. This means that some procedures on board change. For example, the watertight doors are closed, as the chance of grounding increases near shore.

These elements cause more crew to be involved in the operation of this ship during near port sailing than is required for normal sailing. In the engine room the number of crew members on standby increases, allowing for quick intervention should the situation call for it. The additional crewmembers have no specific additional tasks, they are mainly there to decrease the consequences should something go wrong.

On the bridge, there are two main tasks for the crew, communicating and traffic identification and processing. Communication is required between the ship and both port control and other ships.

Additionally, contact between the different areas of the ship and between the ship and its pilots might be required. In addition to the communication, the crew is using both equipment and their own visual capabilities to determine if the selected route is clear of traffic and how to respond if it is not. Experts agree that in busy waters the navigational equipment, such as the radar, AIS and electronic charts, is not sufficient to identify all other traffic. This means that human intervention is required.

The deck crew is responsible for the maintenance and operation of the deck equipment, such as mooring winches and lines and anchors. During arrival and departure the deck crew is on deck to operate the equipment and afterwards secure it and prepare it for later use.

3.2.5 *Normal sailing*

During normal sailing the crew works on their normal duties. In the engine department this means inspection, planned maintenance and, in some rare cases, unplanned repairs.

The deck crew also performs planned maintenance on the equipment on the deck and also on the hull and superstructure of the ship. Additionally they monitor the cargo; should some of the cargo shift or become loose they are tasked with re-securing the lashings if possible.

The bridge department navigates the ship. There is a continuous watch on the bridge as well as a crewmember tasked with steering the ship. Additionally each of the officers have specific responsibilities such as keeping the navigational charts up to date or periodically checking the safety equipment.

3.2.6 *Emergency situations*

There are many emergency situations that could occur during sailing. This means that it is also very difficult to detail what the crew does during those situations. Each situation is different and has its own procedures. However, in most situations, the crew is heavily involved, for example by fighting the fire or by navigating the ship to a safer location.

4 IDENTIFICATION OF CHALLENGES

The crew tasks are combined with the functional breakdown of the ship. This gives an overview of the challenges that arise on an unmanned vessel during the different phases of the mission. The largest challenges for each of the main functions are discussed here. A summary of the findings can be found in Table 2.

4.1 *Float*

The functions that are listed under float are all ship functions that can be performed without human intervention. The prevention and mitigation of failures with respect to these functions of the ship are discussed in paragraph 4.5.

4.2 *Move*

The function move can be divided into two parts, the first is the actual propulsion of the ship, the second the navigation of the ship. In the following paragraphs, the challenges for each part are discussed.

4.2.1 *Provide propulsion and maneuvering*

Most of the propulsion and maneuvering equipment requires very little interaction with the crew after starting up. The crew only steps in to maintain the equipment and monitor its state.

4.2.2 *Navigation and situational awareness*

The second part of the main function move consists of navigation. A large part of the navigation is already automated. For example; Meteo Group offers a service where weather data is used to find the optimal route for a ship, sending a route to the ship that only needs to be followed (MeteoGroup, no date).

Table 2. Operational challenges found the defined activities. (The checkmarks show that there is a challenge to be found).

	Preparing for journey	Quayside operations	Preparing for arrival and departure	Near and in port sailing	Normal sailing in open sea	Emergency situations
Float	X	X	X	X	X	X
Move – Provide propulsion	X	X	X	X	X	X
Move – Navigation and situational awareness	X	X	✓	✓	✓	✓
Communicate – external	X	X	✓	✓	✓	✓
Communicate – internal	X	X	X	X	X	X
Perform mission[1]	X	✓	✓	✓	✓	✓
Prevent and mitigate failures[2]	✓	✓	✓	✓	✓	✓

[1]Due to physical interaction with the system.
[2]Due to physical interaction with the system and current maintenance strategies.

It is the situational awareness where the crew plays an important role. Much of the navigational and steering equipment can help with the following of a route, for example by using the autopilot function, which can not only go in a straight line but can also use waypoints. However, the crew is still required for the observation of the environment. While radar and AIS do provide a good view of what obstacles are around the ship, these systems are not infallible. AIS updates in intervals and radar does not pick up all ships in the area, especially smaller ones like recreational crafts. In this case a human serving as lookout is relied upon to identify potential hazards that the ship might encounter. Experts feel that at this point in time it is not possible to sail the ship blindly on the navigational instruments, the crew is required.

4.3 *Communicate*

As mentioned before, the ship's communication can be divided into two parts, internal and external communication. Both parts are discussed separately.

4.3.1 *Internal communication*

As stated above the internal communication consists of either verbal communication or data transfer. The verbal communication is no longer relevant if there are no crewmembers left on board. The data communication between systems remains in operation as long as no problems occur, repairing the systems will pose a problem, which is discussed further in paragraph 4.5.

The communication of the systems with the crew are also no longer required onboard. However, these systems could be required in a shore control station, which is discussed in paragraph 4.3.3.

4.3.2 *Ship-to-shore communication*

When the ship is sailing, the crew keeps in regular contact with the owner or main office, updating them on their location and any situations that might have occurred. On a crewed ship, this contact takes place approximately once a day, depending on company policy. In case of an unmanned ship the number of updates as well as the amount of information might increase, to ensure that the ship remains safe.

In the AWAA and MUNIN projects it is suggested that the ships are monitored or controlled from a shore control system (Jokionen, 2015; MacKinnon, Man and Baldauf, 2015). This would mean that a lot of information would have to be sent from shore to the ship via satellite communication, which is currently expensive. The MUNIN project has estimated that communicating all the data collected by sensors on the ship to the shore by satellite, would cost approximately 150.000 US dollars a month (Porathe, Prison and Man, 2014).

4.3.3 *Ship-to-ship communication*

The other important form of communication is between ships. This contact is both active, by the crew on one ship talking to the crew on another ship by VHF, and passive, for example by using navigation lights or sound signals.

The active communication is expected to be a challenge, especially between a manned and an unmanned vessel, as humans and computers have very different ways of communicating. While speech recognition is getting increasingly better, mistakes are still made and the technology does not allow for a full conversation.

The passive communication from the autonomous ship is relatively simple, the ship shall be equipped with navigational lights and horn to produce the required signals at the required time. However, interpreting the signals that other ships and structures are giving might pose a larger challenge. For example, registering a sound signal might pose a problem for a system, especially when it is important to determine the direction.

Taking these elements into account it is clear that communication could pose a major challenge in autonomous shipping.

4.4 *Perform the mission*

As mentioned, the mission 'transport of cargo' requires very little human intervention outside of the observation of cargo and intervention if there is a problem with the cargo. Both these tasks require a physical interaction between the crew and the ship which is very difficult to recreate on an unmanned ship at this point in time.

In addition to transporting the cargo, one of the ships functions is also to transport the crew, with all of the provisions required to do so. However, with no crew, these provisions are no longer required.

4.5 *Prevent and mitigate failures*

In case of a failure or an emergency the crew has a large role to play. Once again a large part of this is the crew interacting with the ship and its systems, something that might by difficult to do on an unmanned ship.

The state of the equipment is monitored closely. This is mostly done by sensors, which inform the crew if something is amiss. Should the sensor indicate a problem someone is send to investigate and solve the problem. The ability of the crew to physically interact with the ship and its systems is one of the big challenges to solve.

Experts also expect planned maintenance to be a challenge. While a lot of the equipment is self-regulating (e.g. switching to a second filter if the first does not function anymore), a lot of planned maintenance still occurs during normal sailing. This would mean that the entire maintenance plan for the ships would have to be restructured.

4.6 *Summary of the challenges found*

To summarize; the following primary challenges arise with the removal of the crew from the ship;

- Situational awareness
- External communication
- Physical interaction of the crew with the systems and the ship
- Maintenance and repair

5 PROMISSING SOLUTIONS

The next step is to find the promising solutions within literature that provide solutions for the challenges identified above. The effects of the found solutions on the challenges from section 4 can be found in Table 3.

5.1 *Autonomous navigation and situational awareness*

As concluded in the previous section, the crew plays an important role in the identification of hazards and in the positioning of the ship. Fully autonomously navigating ships are not yet a possibility. Most projects propose the use of some form of a shore control station. In this station an operator has the ability to directly control the ship and steer it away from danger if necessary. This does mean that enough information has to be send to the shore control station for the operator to see what is happening to the ship.

In the AAWA project's white paper (Poikonen *et al.*, 2017) an analysis is performed on the different sensor types that are available to provide the ship with situational awareness. In that paper it is stated that a wide variety of sensors is required to

Table 3. The operational challenges that are not solved in previous research. (The symbol explanation can be found below).

	Preparing for journey	Quayside operations	Preparing for arrival and departure	Near and in port sailing	Normal sailing in open sea	Emergency situations
Move – Provide propulsion	–	–	–	–	–	–
Move – Navigation and situational awareness	–	–	/ AAWA: Sensors and remote control require further research	/ AAWA: Sensors and remote control require further research	/ AAWA: Sensors and remote control require further research	/ AAWA: Sensors and remote control require further research
Communicate – External	–	–	X Ship-to-ship communication not investigated	X Ship-to-ship communication not investigated	/ Ship-to-ship communication and data transfer needs further investigation	/ Ship-to-ship communication and data transfer needs further investigation
Perform mission	–	✓ Port crew	✓ AAWA and Lloyds: Use of sensors and cameras	X Physical interaction has not been researched	X Physical interaction has not been researched	X Physical interaction has not been researched
Prevent and mitigate failures	✓ MAN: CBM	✓ MAN: CBM	X Physical interaction has not been researched	X Physical interaction has not been researched	X Physical interaction has not been researched	X Physical interaction has not been researched

–: no challenges found.
✓: Challenges solved in research.
/: Partially solved in research, further research is required.
X: No solutions found.

get a complete view of the landscape around the ship. A combination of high frequency radar, infrared cameras and normal cameras, as well as the standard navigational equipment such as AIS and ECDIS should give a good overview of the world around the ship. Additionally it is suggested that the ship is outfitted with sound sensors to allow the ship to capture sound signals that are produced by other ships as a means of communication.

Lloyds register goes even further in their booklet *Global Marine Technology Trends 2030* (Lloyds Register, QinetiQ and University of Southhampton, 2017), focused on autonomous systems. They suggest the use of a Global Positioning System (GPS), an Inertial Navigation System (INS), optical and infrared cameras, radar, Lidar, high-resolution sonar, microphones and wind and pressure systems.

Both Lloyds Register and the AAWA project conclude that with sensors, the ship could have a situational awareness that is at least as good as the situational awareness of a human crew, they do however, both expect a challenge in the communication of this information.

The level of detail in the situational awareness is determined by the phase of the journey in which the ship is operating. During the journey preparation and quayside operations it is not necessary to know exactly what is going on around the ship. The ship might only need a watch to ensure that it remains moored. During the arrival and departure preparation and the near and in port sailing the level of detail needs to be very high due to the difficult navigational situation and the presence of other traffic. On the other hand the communication of the relevant data will be easier due to the proximity to land where the coverage of different communication methods is much better than out at sea.

During normal sailing the reverse is true. It might be possible to decrease the level of detail in the situational awareness due to the lower number of possible obstacles however, it will be more difficult to send the required data to shore.

Autonomous navigation and situational awareness are considered partly solved. The largest challenge that remain is the sensor types that are required for a complete view of the area around the ship.

5.2 *External communication*

5.2.1 *Ship-to-ship communication*

Communication is an element that is discussed in many different autonomous shipping projects (Rødseth *et al.*, 2013; Poikonen *et al.*, 2017). However, these mostly covers the communication between the ship and the shore control station as discussed above. There are no solutions given for ship to ship communication.

The ship to ship communication is mostly important during near and in port sailing due to the high traffic density.

5.2.2 *Ship-to-shore communication*

With regards to the communication between the ship and shore the biggest challenge lies within the data transfer. To cut down on the cost of this data transfer several solutions have been suggested, especially for the transfer of the camera images. In the AWAA white paper (Poikonen *et al.*, 2017) it is suggested to use traditional methods of decreasing the file size; such as a lower frame rate as well as efficient compression of the data. Part of the data could be processed on board, for example by using horizon detection to remove the irrelevant parts of the image before it is send to an observer in a shore control station. It is stated that this should give a remote observer enough information in non-critical situations. As mentioned above this solution is more relevant during normal sailing when the ship is far from shore with limited communication options.

For critical situations, such as near and in port navigation and emergencies, a shore control station with direct control is required (MacKinnon, Man and Baldauf, 2015).

Neither forms of communication can be considered a solved area within autonomous shipping. There has been no research into ship-to-ship communication and ship to shore communication is too expensive to be feasible.

5.3 *Physical interaction of the crew with the system and the ship*

There are many occasions where the crew physically interacts with the systems or the ship. For some problems, a specific solution has been found. For example, research has been done into automatic mooring, either by a magnetic connection or by vacuum suction cup (Port of Rotterdam, 2014; Cavotec, 2017). These systems means that no deck crew is required to assist with the mooring operations. However, these systems are currently only available on certain locations and for certain ship types.

For inspection work, drones are suggested as a good alternative to human inspectors. DNV GL has used drones to inspected the tanks on ships (DNV GL, 2015). This method could perhaps be expanded towards inspections of other areas and at different moments.

However, these solutions are stand alone and solve only a part of the interaction challenge. There are other elements that do not have a solution yet. For example, when the anchor is used, a human operator is used to determine how much anchor cable is fed into the water. This cannot be done by remote observation due to the speed of the release and the limited view due to airborne rust particles.

Additionally the integration of all these solutions could also lead to additional challenges. Therefore this subject is considered partly solved.

5.4 *Maintenance and repair*

There are no clear solutions to the challenges in maintenance and repair that are currently applied in shipping. There are some promising techniques used in system maintenance that could also work on board of unmanned ships, and specifically unmanned machinery spaces. Modern propulsion plants use Condition Based Maintenance (CBM). This means that systems are used to monitor the health of the propulsion system and send a signal to the engine room crew in case of degradation of performance.

This system is slowly being integrated into the Marine Diesel engine market (Oskam, 2014; Basurko and Uriondo, 2015). The systems can help provide information that could allow for a completely unmanned machinery space, for example by sending the information not to the engine room crew but to a monitoring system on shore.

Full CBM systems already exist in the shipping industry (Rolsted, no date), however they are monitored by a full crew which is on board of the ship.

A wider adoption of CBM systems can improve the technology, increasing, for example, the reliability of both the system and the machinery space it monitors. However, the problem of fixing a broken system due to an unforeseen event still remains. CBM only allows for better planning of planned maintenance, which will have to be done while the ship is in port.

In the MUNIN project a different solution is suggested. They feel it might be beneficial to switch from a diesel engine to a less complicated system that is easier to maintain. They propose LNG as a solution. Additionally it is proposed to increase the redundancy of the system by having two main engines (Rødseth *et al.*, 2013). However, this solution does carry a very high cost with it.

6 DISCUSSION: UNSOLVED CHALLENGES

With the analysis of the challenges the solutions in literature, a few challenges remain that have no clear solution at this point in time. These challenges are discussed in this part of the paper.

6.1 *Navigation and situational awareness*

At this point, the solutions suggested for autonomous or remote navigation and situational awareness are not a feasible option. They are simply too costly to implement on a large scale. Further research as well as a steady advancement in imaging and data transfer capabilities should make this technology more widely available and useable in the future.

6.2 *Ship-to-ship communication*

While communication between the ship and the shore, mostly in the way of data transfer, is a topic that is frequently discussed and researched the communication between two ships is not addressed. There are some intricacies not easily solved, such as the communication via sound signals or spoken communication.

In case of the shore control station, communication is possible between a manned ship and an operator on shore, or between two operators on shore. This way clear communication between two humans is still possible.

Later on in the process the communication between two autonomous ships should also pose no further challenges, as once again the ships speak the same language. The largest challenge will be when both autonomous ships and manned ships interact with each other.

6.3 *Physical interaction of the crew with the systems and the ship*

It has become clear that a large part of the identified challenges are related to the physical interaction of the crew with the ship. While there are some isolated solutions, such as the automatic mooring systems mentioned above, there is no good complete solution.

This element comes into play in a lot of different areas, from standard everyday tasks to emergencies. Because it is so diverse, finding an all-encompassing solution seems unlikely. Each problem has to be looked at individually to find which solution is the most suitable.

6.4 *Maintenance and repair*

As mentioned there is very little solved about how maintenance will look on an autonomous ship. The maintenance strategy mentioned above provide a partial solution but it does not solve all the problems. Additionally, the repairs that have to be executed in case of problems are not covered in any research.

In the MUNIN project (Rødseth *et al.*, 2013) it is suggested that redundancy is a good solution to decrease the potential for failures. However, it does mean that there is a large additional cost in the building of the ship. Additionally this solution is difficult for conversions.

They also suggest using a simpler propulsion system, as a diesel engine has a lot of different part that can break. While this is a valid point, their solution, LNG, comes with its own challenges and elements that can fail. It is also less well known, making predicting the probability of failure more difficult.

7 CONCLUSIONS

Based on the performed analysis there are four elements that are barely researched or only researched in part:

- Navigation and situational awareness
- Ship-to-ship communication
- Physical interaction of the crew with the systems and the ship
- Maintenance and repair

These four elements will be a starting point for further research as they are critical elements in the operation of the ship that need to be solved before autonomous shipping can become a reality.

ACKNOWLEDGEMENTS

This paper would not have been possible without the input of several people with significant experience on board of ships. We would like to thank Harmen van der Ende of the Maritiem Insituut Willem Barentsz, Gaby Steentjes of MARIN, and the crew of the training ship the Delfshaven, who were kind enough to share their experience and ideas on our analysis.

REFERENCES

Basurko, O.C. and Uriondo, Z. (2015) 'Condition-based maintenance for medium speed diesel engines used in vessels in operation', *Applied Thermal Engineering*. Elsevier Ltd, 80(x), pp. 404–412. doi: 10.1016/j.applthermaleng.2015.01.075.

Cavotec (2017) *MoorMasterTM Automated Mooring systems*.

DNV GL (2015) *Surveys without scaffolds – DNV GL conducts drone inspection of ship tanks – DNV GL*. Available at: https://www.dnvgl.com/news/surveys-without-scaffolds-dnv-gl-conducts-drone-inspection-of-ship-tanks-51628 (Accessed: 8 December 2017).

International Chamber of Shipping (2016) *Bridge procedure Guide*, *Release 9.1.3*.

Israel Aerospace Industries (no date) *Katana USV System*. Available at: http://www.iai.co.il/2013/36781-46402-en/BusinessAreas_NavalSystems.aspx (Accessed: 2 January 2018).

ITF (2015) 'ITF UNIFORM "TCC" COLLECTIVE AGREEMENT'. Available at: http://www.itfseafarers.org/files/seealsodocs/33560/itfuniformtcccba20122014.pdf.

Jokionen, E. (2015) 'Introduction'. AAWA.

Lloyds Register, QinetiQ and University of Southhampton (2017) *Global Marine Technology Trends 2030 – Autonomous Systems*.

MacKinnon, S., Man, Y. and Baldauf, M. (2015) 'D8. 8 : Final Report : Shore Control Centre'.

MeteoGroup (no date) *RouteGuard*.

Naveltechnology.com (no date) *Fleet Class Common Unmanned Surface Vessel (CUSV) – Naval Technology*. Available at: https://www.naval-technology.com/projects/fleet-class-common-unmanned-surface-vessel-cusv/ (Accessed: 2 January 2018).

Oskam, G.J.. (2014) *Optimizing diesel engine condition monitoring*. Tu Delft. Available at: https://repository.tudelft.nl/islandora/object/uuid:037a6a9d-8655-429d-a361-bb5d9caf9c7f.

Poikonen, J. *et al.* (2017) 'Technologies for Marine Situational Awareness and Autonomous Navigation.pdf'. AAWA.

Porathe, T., Prison, J. and Man, Y. (2014) 'Situation awareness in remote control centres for unmanned ships', *Human Factors in Ship Design & Operation*, (February), pp. 1–9.

Port of Rotterdam (2014) *Are magnets taking mooring into the future*?

Rødseth, O.J. *et al.* (2013) 'Communication architecture for an unmanned merchant ship', *OCEANS 2013 MTS/IEEE Bergen: The Challenges of the Northern Dimension*, (314286). doi: 10.1109/OCEANS-Bergen.2013.6608075.

Rolsted, H. (no date) 'On board diagnostic, a web-based engine information management system', pp. 1–32. Available at: http://marine.man.eu/docs/librariesprovider6/marketing-publications/chalmers-universary-of-technolgy-2016/09-time-between-overhaul-condition-monitoring.pdf?sfvrsn=4.

Viola, N. *et al.* (2012) 'Functional Analysis in Systems Engineering: Methodology and Applications', in *Systems Engineering- Practice and Theory*, pp. 71–96.

Watson, D.G.M. (1998) *Practical Ship Design*. Elsevier.