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A pre-analysis on autonomous ships

Summary

The Danish Maritime Authority has requested the assistance of the Technical University of Denmark (DTU) for connecting and planning a number of tasks to be included in coming efforts to shed light on the importance of unmanned ships to Blue Denmark. The Danish Maritime Authority considers technological developments to be at the core of these projects and has asked the DTU to assist with the identification of research and innovation activities that would be important to acquire this insight.

This report is a pre-investigation, the purpose of which is to describe the potentials of autonomous ships, on the basis of international activities of direct relevance to the investigation. It briefly summarises how to define various levels of autonomy. From the lowest level with completely manual operation, where the navigating officer gets his information from electronic charts and where he gets information about his own position, course and speed as well as an overview from radar that also presents other ships' course and speed; over various levels of decision-support, where automatics take care of still more tasks; to levels of actual autonomy.

This part is based on the experience and knowledge gained from so-called self-propelled cars and unmanned aircraft and refers to ongoing reflections from similar ship projects. Eventually, the report presents proposals for specific research and innovation projects that are expected to be of benefit to the Danish maritime industry and Blue Denmark.[1]

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[1] The report has been made with support from the Danish Maritime Fund.

Autonomy versus automation

In everyday talk and in the general public, the term autonomy is used indiscriminately. Therefore, this report starts by summarising how autonomy and steps on the way from manual control to fully automatic control and autonomous navigation are defined and perceived by experts.

Cars

The car industry is far advanced when it comes to implementing and testing self-propelled cars at various levels. In addition to being smart and trendy and, thus, a sales promoting functionality, the ability to enhance road safety is driving this development. At the same time, it is possible to reduce the distance to cars ahead without increasing the risk of collisions. The vision for autonomous vehicles on the roads is, inter alia, to be able to increase the frequency and flexibility of public transport and of the carriage of goods by road, and to be able to prevent the risk of having a human driver and accidents caused by human error. Reduced wage costs is another argument. In order to have a common understanding in the industry of levels of automation, the Society of Automative Engineers has described six levels of autonomy (AAWA), which are presented in table 1.

Table 1. SAE definition of level of autonomy for cars

Level of autonomy for cars (SAE definition)
SAE 0: No automation. The driver performs all driving and navigation without any aids.
SAE 1: Driver assistance: The car can keep a distance to other similar cars.
SAE 2: Partial automation: The car can perform simple tasks on its own, such as driving in the road system where it is located.
SAE 3: Conditional automation: The car can drive on its own in specific situation (e.g. on motorways). The driver does not need to control the car actively or to keep a lookout, but must be able to intervene at short notice.
SAE 4: High automation: The car can drive on its own in specific surroundings, but the driver does not need to be ready to take over control.
SAE 5: Full automation: Driverless cars in all surroundings and in all potential situations.

At SAE levels 0 to 3, the driver is present in the car and can and must do the driving. At level 4, the driver need not be ready to take over the driving since the car can stop by itself in unexpected situations or in case of defective equipment. At level SAE 5, the car can react autonomously and, in principle, be unmanned.

For cars at level 0 to 4, the surroundings are defined by marked roadsides and conditions for the conduct of the traffic. At level SAE 5, the car must be able to operate in all surroundings and handle other road users in complex situations. A safe condition for a car is when it stops at the roadside. In emergencies, such as fires, the passengers leave the car on their own.

The technology behind high-level autonomy includes RADAR and LIDAR[2] as well as computer vision in visible and infrared areas. The information from these sensors is interpreted by software that recognises elements in the surroundings, can interpret a situation and can take over the steering and braking of the car. From SAE level 3 and onwards, the automatics are capable of intervening without the driver's participation. In 2016, cars are at level SAE 3.

For ships, both navigation and the safety and reliability issues are more complicated.

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[2] Sensors measuring the distance and direction to an object by means of electro-magnetic microwaves (RADAR) and laser light in the near-infrared area (LIDAR).

Ships

Initially, this section provides a general introduction to the terminology on the operation of ships at various levels of automation. We use the terminology summarised in Lloyds Register, 2016).

Commercial ships are fitted with electronic navigation instruments that inform about the ship's position (GPS etc.), the distance to other ships, their course and speed as well as the predicted trajectory (from ARPA,[3] radar and AIS[4]), and electronic charts are used. For ships, a manned navigation bridge is required and, in certain situations, also a person to monitor surrounding waters. Large ships are steered by plotting a route in the electronic chart. An autopilot keeps the ship on this predefined track. Manual control of the rudder and main engine is used for manoeuvring or for handling error events.

Table 2. Terminology for ships

Terminology related to automatic steering, remote operation, remote monitoring and autonomy	
Manual navigation of merchant ships	The navigating officer gives the command for the wanted course and speed, either to a helmsman or as an autopilot setting and for bridge navigation of the ship's main engine. The navigating officer has electronic charts and own position and course. A radar system shows other ships' course and speed.
Automatic course steering	Course steering takes place between encoded positions; the ship's autopilot ensures that the ship goes from position A to B.
Decision-support	Decision-support consists in planning a route and speed profile in order to reach a port at a given time with a prediction of the sea and wind conditions underway. More extensive decision-support could consist in guidance for the navigating officer about the performance of an evasive action in narrow waters.
Remotely operated navigation	Remote operation is used about the possibility of remotely operating a point for the autopilot and the effect on the propulsion machinery.
Remote monitoring	Measured values from sensors in, for example machinery spaces, on course and speed are shown in real time in an operation centre ashore or on board another vessel. Full monitoring includes transmission of TV monitoring and radar picture so that the operation centre has sufficient information about the ship and its surroundings to be able to perform remotely-operated navigation.
Partial autonomy	The ship has systems for assessing the situation as well as the consequences and advising the navigating officer about how to react. The navigating officer is not necessarily present on the ship's bridge in person.
Full autonomy	The situation is perceived and assessed and a decision on which action to take is made without any intervention by human beings.

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[3] ARPA is short for *Automatic Radar Plotting Aid.* The ARPA function calculates other ships' course and speed and transmits a warning if there is a risk of collision.

[4] AIS is short for *Automatic Identification System*. Ships fitted with AIS transmits information about the ship's identification, its position, course and speed.

Safety

Despite the above-mentioned information systems and steering options, there are a large number of collisions and groundings each year, and the accident statistics of the European Maritime Safety Agency point to human error as the triggering factor in 62 per cent of incidents with EU registered ships from 2011 to 2016 (EMSA, 2016). Statistics on fatal accidents have ascertained that work on deck, for example mooring operations, is 5 to 16 times more dangerous than jobs ashore (Primorac & Parunov, 2016; Roberts et al., 2014). Advocates for increased autonomy point to the possibility of increasing safety at sea considerably by means of highly automatised/autonomous ships.

Attempts are made to avoid collisions at sea by all ships observing adopted regulations for preventing collisions at sea (COLREG) (IMO, 2017 (convention from 1972)). Said popularly, this set of regulations describes the duty to keep clear and the signals to be used by shipping. In complicated situations, a set of regulations may, however, become complex and misinterpretations may lead to some of the collisions occurring at sea. The introduction of autonomous navigation is expected to make it possible to reduce the number of these incidents. Correct and reliable interpretation of the provisions for preventing collisions at sea (COLREG) is, however, decisive for achieving enhanced safety by means of autonomously navigating vessels. It is difficult to develop algorithms for compliance with the COLREG set of regulations because COLREG is situation-specific and even open for interpretation in some areas. The need for algorithms has been known for long (Munk, 1989) and quite a lot of studies have been made, just as algorithms have been proposed (see Lazarowska, 2017; Grinyak, 2016; Johansen et al., 2016; Zhang & Furusho, 2016; Naeem et al., 2016; Li & Ma, 2016), but the solution to the COLREG algorithm problem is still only at the level of research.

Validation of the safe performance of an automatic COLREG system is a considerable challenge when it comes to achieving reliable decision-support (Kim et al., 2015) and, ultimately, autonomous navigation. Narrow waters and vessels with limited manoeuvrability, for example due to their size and draught, are especially challenging – both for navigating officers and for algorithms that are to be able to ensure autonomous navigation.

Lookout is a requirement in near-coastal areas. The research project MUNIN (MUNIN, 2016) has shown that camera technology combined with computer vision in a visible and infrared area provides a safer perception of a situation than human lookout. In case of fully or partly unmanned vessels, the lookout can be replaced by a combination of different sensors, including radar and computer vision in various wave length areas (AAWA, 2016; Levander, 2017). Experiments with these systems are ongoing in several contexts. In Herman et al., 2015, sensor fusion by use of car radar technology and computer vision in the visible area is being tested.

Autonomy has been tested on rather small vessels for both civilian and military use for two decades (Bertram, 2008; Manley et al., 2016). Plans for large vessels for military use are known from press clippings, but the documents as such are classified.

Coming trials in Norway (Kongsberg, 2016) with an offshore vessel and in Finland with a ferry (AAWA, 2016) aim at demonstrating technology where remote monitoring is made by means of sensors and, obviously, sensor fusion. The demonstration vessels are to establish that remote operation from an operation centre ashore can monitor the safe and reliable performance of navigation and manoeuvring.

With fully implemented autonomy, the vision is that ship's systems interpret the situation by themselves in relation to the surroundings and are capable of handling all situations. The view has been expressed that total autonomy is not necessarily the most appropriate or best economic solution for all types of surface vessels.

Obviously, there will be a gradual transition from the current degree of navigation automation to fully autonomous navigation. There is a potential for enhanced safety, but also a debate on whether completely unmanned navigation is the solution (Bertram, 2016).

Levels of autonomy for unmanned, remotely operated, remotely monitored and unmanned systems have been defined by Lloyds Register (Lloyds Register, 2016), as shown in table 3. These levels of autonomy concern merely navigation-related aspects.

Table 3. Autonomy levels (AL) adapted from Lloyds Register

Description	Operator role
AL 0: Manual steering. Steering controls or set points for course, etc. are operated manually.	The operator is on board or performs remote control via radio link.
AL 1: Decision-support on board. Automatic steering of course and speed in accordance with the references and route plan given. The course and speed are measured by sensors on board.	The operator inserts the route in the form of "waypoints" and the desired speed. The operator monitors and changes the course and speed, if necessary.
AL 2: On-board or shore-based decision support. Steering of route through a sequence of desired positions. The route is calculated so as to observe a wanted plan. An external system is capable of uploading a new route plan.	Monitoring operation and surroundings. Changing course and speed if a situation necessitates this. Proposals for interventions can be given by algorithms.
AL 3: Execution with human being who monitors and approves. Navigation decisions are proposed by the system based on sensor information from the vessel and its surroundings.	Monitoring the system's function and approving actions before they are executed.
AL 4: Execution with human being who monitors and can intervene. Decisions on navigation and operational actions are calculated by the system which executes what has been calculated according to the operator's approval.	An operator monitors the system's functioning and intervenes if considered necessary. Monitoring can be shore-based.
AL 5: Monitored autonomy. Overall decisions on navigation and operation are calculated by the system. The consequences and risks are countered insofar as possible. Sensors detect relevant elements in the surroundings and the system interprets the situation. The system calculates its own actions and performs these. The operator is contacted in case of uncertainty about the interpretation of the situation.	The system executes the actions calculated by itself. The operator is contacted unless the system is very certain of its interpretation of the surroundings and of its own condition and of the thus calculated actions. Overall goals have been determined by an operator. Monitoring may be shore-based.
AL 6: Full autonomy. Overall decisions on navigation and operation are calculated by the system. Consequences and risks are calculated. The system acts based on its analyses and calculations of its own capability and the surroundings' reaction. Knowledge about the surroundings and previous and typical events are included at a "machine intelligent" level.	The system makes its own decisions and decides on its own actions. Calculations of own capability and prediction of surrounding traffic's expected reaction. The operator is involved in decisions if the system is uncertain. Overall goals may have been established by the system. Shore-based monitoring.

General reliability and operational reliability

Where navigation is mentioned above, the ship's machinery must be both generally reliable and operationally reliable to achieve a well-functioning, highly automatised vessel. The propulsion machinery is decisive for a ship's manoeuvrability and possibility of navigating. Therefore, this section considers which requirements should be made for the general reliability and operational reliability of machinery and auxiliary systems on board.

Ships' propulsion machinery, auxiliary machinery, generators for procuring electricity, separators, pumps, cooling systems, etc. are complex and maintenance-demanding. The major part of commercial ships' crews consists of the engine crews. In case of reduced or no manning, on-board machinery systems are decisive for achieving an acceptable level of reliability.

Methods for achieving reliability have been proposed by DNV-GL in the ReVolt project (Adams, 2014), where redundant propulsion machinery drives two propellers. The project calculates that the time elapsing between defects on considerable electrical propulsion components is considerably longer than on conventional machinery.

Table 4. Levels of fault tolerance and redundancy

Fault tolerance and redundancy	Functionality
FT 5: Fault operational: No single fault prevents navigation, safe monitoring and complete normal propulsion.	All main functions are double or triple redundant. All other functions are fault operational towards single faults and fault tolerant towards double faults. Fault diagnosis and fault management are autonomous.
FT 4: Fault tolerant: It is possible to handle all single faults without the operator's intervention, but reduced capacity is permitted.	Main functions are redundant. All functions are fault tolerant towards single faults. Built-in fault diagnosis and fault management ensure autonomous fault handling.
FT 3: Fault tolerant: It is possible to handle all single faults through the operator's assistance. Reduced capacity is permitted in case of faults.	Main functions are redundant. All functions that are necessary to execute redeployment are fault tolerant towards single faults. Built-in fault diagnosis and remote control permit fault handling via an on-board or shore-based operator.
FT 2: Propulsion and steering are redundant. Other sub-systems are not necessarily redundant, but can be re-coupled to handle faults.	Re-coupling for fault handling is made on board or remotely controlled from land.
FT 1: Propulsion and steering are redundant. Other sub-systems are not necessarily redundant.	Fault diagnosis secures information about necessary fault handling measures. Handling is made by persons on board or ashore. Redundancy in functions for propulsion and navigation, but not in other auxiliary systems.
FT 0: Systems are not fault tolerant. In case of faults, re-coupling/replacement must be made by personnel on board.	No redundancy.

Reliability is also achieved by replacing a fault in a sub-system with a redundant function. Redundancy is easy and, thus, inexpensive to acquire in electrically propelled ships. Consequently, there are strong arguments in favour of electrical propulsion for autonomous ships. The energy supply may consist in battery capacity or hybrid solutions with combustion engines with generators that produce electricity for direct use and/or for recharging batteries.

Reliable operation despite faults can be acquired by means of technology and methods known from, inter alia, vehicles ashore. A methodological approach to handling any single fault in electrical steering was shown in Blanke & Thomsen, 2006, and was demonstrated in an industrial context.

In order to be able to identify the functionality required to acquire the necessary general reliability and operational reliability, it may be necessary to categorise the level of functional safety. Such a categorisation of the levels of redundancy and fault tolerance is presented in table 4.

Table 5. Overall method for selecting the desired level of autonomy

	Overall method for selecting the desired level of autonomy
A	Describe the business model that would be relevant in the short and long term. Define objective needs both within a few years and a decade or longer ahead. Let the description of the needs include scenarios of how to use the vessel focusing on the tasks to be performed.
B	Describe the level of autonomy that it would be appropriate to implement to acquire the desired properties. Examine the economy and safety in this connection and specify whether it is desirable to execute the functions.
C	Evaluate the technology readiness level of solutions to decide whether to achieve the final level of autonomy gradually or at once. Examine which modularity to use in order to make possible any extension to a higher level of autonomy. In this connection, special focus should be on software modularity since ships in the merchant fleet and for commercial use are only rarely fitted with new hardware during the lifetime. Examine the economic consequences (cost over lifetime) for various levels of autonomy.

Choice of technology and level of automation

The choice of technological level is, first and foremost, dependent on the business model used and the functional and operational capacity needed. The US Navy uses a three-level model to analyse and select future needs (United States Navy, 2004). Table 5 rewrites and adapts this method to commercial maritime conditions.

When selecting the business model and assessing the economy, some sources point out that reduced expenses for sailing personnel is an important element. Others stress that the lack of qualified personnel is a considerable risk. Accident statistics (Roberts et al., 2014; EMSA, 2016) and a ship design company (Allan, 2016) stress that minimising the number of persons in dangerous work areas is itself a major argument in favour of the introduction of remotely controlled or autonomous work vessels and refer to the very high accident frequency.

Unmanned aircraft

Within airborne technology, remotely controlled technology is developing rapidly and several levels of autonomy (Kendoul, 2012) are used on a daily basis (Watts et al., 2012). The interaction between remotely controlled or autonomous drones has been an object of massive research (Dalamagkidis et al., 2012, 2nd edition) and regulations on approved use exist at some levels of use in civil air space and are being developed for more extensive integration of unmanned system (Unmanned Aerial Systems (UAS)) with manned aircraft in civil air space (Drone Advisory Committee, 2017).

Aircraft benefit from an AIS-like system, *traffic collision avoidance system (TCAS)*, that transmits information about the position and the planned route. Aircraft use two-way TCAS to avoid collisions with other aircraft.

Political and competitive considerations

This section outlines the most important elements of a political and competitive nature that we expect will form the basis of the coming introduction of autonomous vessels within various segments of maritime tasks.

Introduction

Various levels of autonomy are really starting to gain ground in the transport sector. For many years, ships and aircraft have benefitted from various forms of self-steering technologies, in the form of either autonomous or partly monitored systems. As regards trains, the technology is known from, for example, the Danish Metro, where the trains are unmanned, but monitored and controlled from a control centre.

On the roads, autonomous cars have started to gain ground in recent years. As regards trucks, not least *platooning*, i.e. bumper-to-bumper driving, has been tested for a number of years and will presumably be able to engage in commercial operation within a relatively short period of time.

As regards passenger cars, recent years have presented a number of auxiliary technologies in the form of warning systems when changing lanes (lane assistant/warning), automatic distance and braking control and parking assistance. And recently, Tesla and Mercedes have launched models that are, to a wide extent, capable of driving by themselves – in any case on, for example, motorways and motorway-like stretches.

This development has contributed strongly to the Ministry of Transport's idea of making Denmark the centre of autonomous car testing from 1 July 2017. The background for this is a desire to test the user-related and commercial potentials of opening up for new technologies capable of supporting autonomous driving. The tests will presumably to a lesser degree focus on the development of new technologies and far more on analyses of what the use of the technologies could result in and where they could advantageously be implemented. As a spinoff, the analyses could also have an impact on, for example, traffic safety and help map "regimes" for handling the distribution of responsibility, etc.

The measures taken within road traffic have opened up for the other means of transport's focus on the potentials of autonomous technologies, including of course the competitive challenges that could be the result of this development. In a goods transport context, this means, for example, that the competitiveness of trucks could be improved distinctly vis-à-vis other means of transport if the need for and costs of the driver can be reduced. In a current set-up, where the costs for the driver account for approx. 1/3 of total costs,[5] a reduction of these costs will have a not inconsiderable effect on the competitiveness of road transport compared to other means of transport.

The political context – including EU policy

Interest in autonomous transport solutions attracts quite considerable political interest. In addition to distinct cost savings, it is a road towards a solution of expected bottleneck problems in the labour market. On the other hand, these cost reductions could, on the one hand, result in more road traffic, but also in more transport being moved from especially *short sea* to road. Naturally, the latter applies especially to transports over rather long distances, where the EU has the goal that 30 per cent of goods transports over distances above 300 km should be by either sea or railroad as the main means of transport in 2030. And since developments towards more expressed degrees of autonomous solutions must be expected to increase, it is in other words necessary to introduce these solutions at sea and on railroad.

Competition interface with trucks

A decisive element in the analysis of the suitability of autonomous ships for goods transport is associated with the competition interface with transport by truck. For a number of years, not least international transport by truck in Europe has undergone a relatively distinct development. There are a number of reasons for this. Among the most important is a market and product development that, more often than not, focuses on fast delivery of small quantities – a market that is well-suited for trucks.

At the same time, technological developments of trucks and infrastructure have increased their reliability. And in a market that focuses on speed and flexibility, trucks capable of carrying out many transports directly between the consignor and the recipient have a strong stand compared to, for example, ships. The latter requires many operations and re-loadings, including expensive pre- and post-transports. To this should be added a not inconsiderable document handling process, which goes far beyond the CMR document of truck transport.

Logistics and document handling form part of the business models to be considered as part of the introduction of autonomy at a given level.

Developments in truck technology

In its report (Shoer & Murray, 2016), the *American Transportation Research Institute* (ATRI) has pointed to the following completely decisive aspects of importance to the use of and benefits of autonomous trucks:

- Increased productivity since the driving and rest time conditions are relaxed.
- Increased safety.
- Reductions in the lack of drivers (since the number of drivers needed is reduced).
- Retaining drivers in autonomous units since the job contents is improved.
- Reduced need for motorway service areas as well as reduced driver absence from their homes in the longer term.
- Improved driver health since it will be possible to reduce sedentary, monotonous work.
- Improved economy for truck operators (more kilometres and fewer costs for drivers).
- Reduced congestion by trucks due to more driving at odd hours.

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[5] Applicable to a typical national transportation, which we consider the most relevant basis for comparison here.

- Improved safety because distraction of the driver will not have the same consequences as today.

The bottom line is that, in the short term, the competitiveness of trucks will be improved distinctly. Some of these considerations of operational and economic benefits could be transferred to partly manned ships.

Congestion

Self-propelled trucks (and passenger cars) could result in a smoother conduct of traffic, especially when the total number of vehicles is replaced by self-propelled units. However, this process is not expected to have been finalised until in 20-30 years. At the same time, self-propelled units at both levels SA4 and 5 are expected to open up for far more individual mobility, which will, eventually, result in more traffic and consequently more congestion.

The environment

New means of propulsion, including electricity, will have a clearly positive influence on the energy consumption of both trucks and ships. Electricity has already been introduced in the road sector for delivery vans where it is feasible to use it on cars where the need for a range of 100-150 km suffices. As regards trucks, battery technology and weight present a challenge of high priority.

Electrically powered ferries are just about to be introduced, which the coming vessels on the Elsinore-Helsingborg crossing and to and from the island of Ærø are also expected to show. A transition to electrical propulsion of ships will radically reduce the need to monitor the machinery and, furthermore, probably result in a larger degree of operational reliability and, thus, reduced operation costs.

Other analyses

Autonomous ships have, to some extent, been analysed in a number of projects, inter alia in an EU context. The main project is MUNIN (*Maritime Unmanned Navigation Through Intelligence in Networks*), which is an EU-funded study. Focus of the study is on the unveiling of the potentials for using autonomous ships, initially for transport in bulk over long distances (handymax dry bulker of 75,000 deadweight tonnes). The reason for this choice is that, on long free distances, the autonomous technology can really unfold and result in large profits. The profit is especially available because of reduced crew costs and better fuel economy. These elements are to counterbalance higher construction costs.

The MUNIN analysis shows in general that it will be possible to insert autonomous ships in a number of voyage phases, for example so that night-time voyages are autonomous. Some also point to solutions where monitoring systems are capable of monitoring the machinery and other parts of the ship.

Regulations and legal conditions

The analysis points out that, generally speaking, the handling of an autonomous vessel does not seem to present any marked challenges. Naturally, a number of aspects related to the legal responsibility of using autonomous vessels need to be clarified. From a safety point of view, the challenges seem to be easy to handle since, for example, the number of collisions and groundings with autonomous vessels will be drastically reduced compared to those of conventional ships. However, during a rather long transition phase problems could arise in situations where autonomous ships are operating "side-by-side" with non-autonomous ships. In such situations, the two types of ships must be expected to react in different ways.

Consequently, especially autonomous vessels must have navigation routines capable of compensating for these differences.

Therefore, the legal elements are especially related to the more classic distribution of responsibility, inter alia between operators and masters in the so-called shore control centre (SCC). Currently, similar problems are being analysed in connection with tests of autonomous vehicles, for which reason it may be possible to be inspired by this work. However, a quite fundamental and similar problem, which is found ashore as well as at sea, will be the co-existence of autonomous and manual units in the same environment. This aspect needs to be subject to closer scrutiny. However, future tests with partly autonomous vehicles, which can be initiated in the summer of 2017, must be expected to provide valuable information in this respect.

Autonomous ships are not mentioned in the international codes and conventions that have been drawn up during the last 200 years because it has been presumed that all ships are always manned and exactly this fact presents us with a major challenge. It may result in the legal framework lagging behind the technological development, thus excluding some of the ways in which autonomous ships are capable of operating internationally. On the other hand, the initial conclusion is that it is not necessary to wait for United Nations' International Maritime Organization (IMO) because national regulation permits autonomous ships in domestic waters.

However, there is a compelling need for the IMO to engage in the work promoting remotely-controlled and autonomous ships. The challenge consists in ensuring that the legal challenges are handled carefully so that the issue is promoted in the IMO in the long term.

In recent years, we have observed a tendency for the IMO to no longer adopt especially detailed regulation stipulating exact technical solutions based on tradition and experience. Today, the IMO has the ambition to adopt regulation which is, inter alia, based on research and physical principles and making it possible to construct unprecedented new solutions.

The Danish Maritime Authority is in line with the IMO and is actively striving to make regulations goal-based and function-based so that Blue Denmark gets the very best possibilities of using its competences in global competition – also when it comes to autonomous ships.

The International Association of Lighthouse Authorities and Aids to Navigation (IALA) is also preparing for future work on autonomous ships and will, in its future work, include autonomous ships' impact on provisions and services related to aids to navigation.

Communication with the vessel

Another aspect associated with the handling and steering of autonomous vessels is data and communication security, including security in relation to cyber attacks and hacking. The MUNIN study does not attach great importance to this aspect and assesses that it is possible to secure oneself against this type of attack. Furthermore, it is uncertain whether these ships are attractive at all when it comes to these types of attacks.

We must confess that we do not share the assessment made by MUNIN; just as Lloyds Register, we attach great importance to cyber security aspects. Whether vessels are attractive goals depends on the cargo carried as well as the purpose of the attack (ransom, using the ship for hostile actions, or something entirely different). There is a direct need to include cyber risks in the consideration of the design of autonomous systems.

MUNIN'S analytical elements

The MUNIN project has focused in detail on the following elements and technologies:

- ”Advanced sensor module” covers infrared and "visual spectrum" cameras supplemented by radar and AIS, all of which supply data for navigation use. These data are supplied with a view to executing the best possible actions under the given conditions (p. 8).
- ”Deep sea navigation systems” secure data for handling ships' overall behaviour and approach. This is done by establishing the "COLREG" conditions in relation to other ships and securing that autonomous vessels navigate in accordance with these regulations. Furthermore, the following is ensured:
    - That meteorological information is used to optimise trans-ocean voyages.
    - That the ship is handled safely under the given weather conditions in accordance with IMO weather standards.

The systems are capable of operating fully autonomously, but can also allow the operator at the "shore control centre" to take over and assist with the navigation in the form of remote steering of the vessel. Naturally, the latter requires a possibility of establishing safe electronic contact with the vessel.

- ”Remote Manoeuvring Support System”: This is an auxiliary system that helps manoeuvre the ship in difficult conditions/narrow straits, etc., based on the collection and analysis of data from similar previous manoeuvres. Thus, the ship can be autonomous; the system supports manoeuvring routines that the ship would otherwise make on the basis of available "here and now" data.
- ”Engine monitoring systems” ensure continuous monitoring of ships' machinery. In addition to preventing breakdowns, the system can ensure improved maintenance planning. The ship's own systems handle data, but there is also contact to a "shore control centre" that can adjust the information level.[6]
- ”Maintenance Interaction system” is very similar to the above with focus on maintenance; that is, maintenance that ensures that the machinery, etc. does not fail.
- ”Energy efficiency System” ensures that the ship is energy efficient. The ship is expected to be far more automatised than today, that it has two engines, and that all vital systems are duplicated, including with diesel-electrical equipment.
- ”Shore control centre” supplements the ship's automatic/autonomous systems and is capable of intervening in case of major incidents, including securing a certain degree of "supervision" in connection with, inter alia, legal issues that are normally handled by the captain and an engineer officer. The system can also set the ship for the so-called "fail to safe" mode in case of communication failure. The Shore Control Center is capable of intervening in complex situations that the autonomous system cannot handle. This balances the project between technological complexity and economic rationality.

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[6] The concept is, in many respects, similar to the Rolls Royce concept, where continuous monitoring takes place in a number of areas. It should be noted that the vessel is assumed to be fitted with two engines.

AAWA consortium analyses

The AAWA consortium (*Advanced Autonomous Waterborne Applications)* is a national Finnish project. The white book (AAWA, 2016) presents the results gained during the first project year:

- Vision for remotely operated/autonomous operation.
- Situational awareness and autonomous navigation technologies.
- Legal issues and consequences.
- Safety and security of autonomous shipping.
- From innovation to market – shipping redefined.

The participating companies aim to spread remotely monitored and remotely operated technology to the market and to continue to higher levels of autonomy within a number of years (Levander, 2017).

The project plans to demonstrate various levels of autonomous technology on a Finnish ferry in approx. 2020.

Ship types to be further analysed in the autonomous ship project

The choice of ship type for further analyses and investigations is considered decisive for getting good results, including identifying focus areas that may help Denmark take a leading position. Consequently, it would make sense to adjust the areas of analysis to areas where a demand for new tonnage or a desire for adjusting existing tonnage may be expected also in a relatively short perspective.

In their presentation video, Rolls Royce has focused on a medium-sized bulk carrier engaged in voyages on, inter alia, the Atlantic Ocean and/or the Pacific Ocean. This type of ship is characterised by having a rather modest number of crew quite a few of whom work in the engine room. We do not expect this fact to change markedly right away as long as the ship is fitted with a conventional combustion engine. Furthermore, we expect the cost savings in the form of a reduced crew to be rather modest for this type of ship.

Consequently, we have estimated that efforts made on other and, especially, smaller types of ships in local traffic would be far more relevant; not least because this will make it possible to combine autonomy with electrical propulsion, which may reduce the manning requirements drastically. Among the obvious types of tonnage, especially the following deserves to be mentioned:

- Small/minor island ferries.
- Tugs.
- Barges.
- Supply/service vessels for drilling platforms, wind turbines, etc.
- Autonomous surface vessel for servicing underwater and drone units for offshore inspection.

These types of ships distinguish themselves by being obvious for use in the development of autonomous systems as well as electrically-propelled systems and any other alternative types of energy.

But, why these specific recommendations? Considered one by one, the arguments are as follows:

Island ferries: Small ferries to many Danish islands are the life nerve of these societies and their only real connection to the surrounding world. The costs for operating these, often municipally owned, ferries are relatively high. Consequently, they are often the object of savings – or of attempts at savings. Savings will often result in a negative spiral where people move away from the islands, which would, thus, be drifting in the direction of the outskirts. Therefore, solutions capable of reducing the operational costs (the crossings) are sought for since reduced costs could result in improved accessibility to the islands – something that would have a positive impact both in terms of personal finances and the national economy. It seems, thus, to be possible to combine electrical propulsion (which will form part of the coming Ærø island ferries) with some degree of autonomy.

"Some degree of autonomy" covers the fact that ferry crews, on the one hand, handle the technical and navigational aspects of ferry operation and, on the other hand, have a safety-related role in relation to the passengers. So, it is a decisive question how this role can be handled if the crew is reduced or disappears entirely from the ferry. A simple solution could be to keep the crew during the daytime when the number of passengers must be assumed to be the highest, and subsequently reduce or remove the crew entirely at times when the number of passengers is more modest.

As an example of this, we could point to the possibilities of issuing island inhabitants with a certificate of competency or proficiency enabling them to operate the ferry under special conditions. Thus, it becomes possible for the inhabitants to have jobs at odd hours. The certificate could also be issued to, for example, ambulance drivers and others so that an ambulance driver can transport an ambulance between the mainland and the island on his or her own, thus ensuring a far better and cheaper safety preparedness for a number of island communities. And, of course, the model could be extended to other means of transport with a limited number of persons.

Tugs: Typically, these vessels operate for limited periods of time in specific geographic areas and could be autonomous or remotely controlled (Allan, 2016). Based on the arguments in favour of the Canadian design, there could be market-related potentials for Danish companies and shipyards in this connection.

Barges and lighters, etc.: Based on the Norwegian design (Adams, 2014), self-propelled barges for use in short-sea shipping or for other goods and equipment transport could also turn out to be an interesting area of development.

Supply vessels: Rather small supply vessels that transport supplies and personnel/technicians to drilling platforms and offshore wind farms can presumably be made autonomous and fitted with electrical propulsion (Kongsberg, 2016).

The economy of autonomous solutions

A very important argument in favour of autonomous ships is the cost savings that this technology could result in over time. The cost savings should be considered in a general perspective where focus is on reduced costs in all parts of the production chain, including transportation.

Furthermore, it must be stressed that the emergence of autonomous vehicles, including autonomous trucks, increases the competition interface with maritime transport considerably. Thus, there are also major reasons for working with the autonomous technology within maritime transport in order not to be lagging behind.

It is not possible to make a definite account of the cost reductions to be achieved through the introduction of autonomous ships compared to traditional ships. It is evident, however, that the crew costs account for a relatively large proportion of total costs on passenger ships compared to similar figures for cargo ships. The explanation is the simple one that today passenger ships require considerable crew resources for passenger-related tasks, such as the direction and support of passengers as well as general on-board service. Initially, any reductions will be associated with the part of the crew who perform tasks related to ferry navigation. In the longer term, this could also be extended to crew members having safety-related tasks if this is compatible with automatised service on board ferries.

According to a rough estimate, personnel on board ferries and ashore account for 50 to 65 per cent of total costs for an island ferry. If it is possible for new technology in the form of autonomous solutions to do away with some of the costs in the long term, it would be very relevant to consider this in more detail. High personnel costs constitute the most important factor in this connection.

It is not unusual for the gross costs per employee to amount to DKK 1 million annually, which is a considerable amount. Consequently, we estimate that autonomous solutions could reduce these costs considerably and, thus, allow for more cost efficient new solutions and new markets. Therefore, autonomy will cover retention as well as development of existing operation, but also potentials for developing a market – also internationally – for new solutions and technologies. This would be of great interest to various manufacturers and Danish Maritime as an organisation.

In this connection, it is of course a question of gradual phasing in that takes account of the nature of the tasks, the crew's tasks other than those that are related to navigation, terms of agreement and, not least, technological developments. There is, however, hardly any doubt that autonomous technologies could help develop new types of ferries in a safe and cost efficient manner.

When focusing on island ferries, it is important to bear in mind that they cover a wide spectrum in terms of geography, voyage distance and size of ferries. The Ferry Secretariat covers approx. 30 routes with crossings that take from 20 minutes to three hours. Thus, they cover a wide array of types and services. However, a considerable part of the ferries are engaged on routes with crossings that take between 4 and 12 minutes.

Furthermore, the island ferry market is characterised by having a considerable number of ferries that need to be replaced in the near future. At the same time, efforts are being made to introduce electrical propulsion on these ferry crossings, just as there will be a possibility of combining autonomy with electrical propulsion and/or hybrid technologies.

Autonomous ships and the interface with other means of transport

One important reason for working with autonomous technologies is, of course, their emergence. By now, a number of possibilities are available that could strengthen maritime transport, which is in itself of great relevance.

To this should be added the fact that autonomous technologies strengthen the competitiveness of other means of transport considerably. In the future, drones could perform a number of tasks that have so far been performed by rather small ships, including to some extent for example feeder vessels. But not least a strengthening of road transport could result in the unwanted "modality swing back" effect, i.e. that goods that have been moved from road to sea is moved back to the road again. In the short term, this could be the situation when truck platooning is, very likely, introduced in coming years.

Activities related to unmanned voyages

This chapter lists a number of activities that would be desirable steps on the road towards unmanned voyages. Some of the activities could generate the knowledge and experience necessary to make a safety assessment and approval of autonomous vessels at sea; others could contribute to knowledge generation in Denmark in areas that are quite essential to autonomy at sea; and finally proposals for demo projects are listed. Some of the outlined projects are based on a gradual introduction of high automation and it will be possible to launch tests within a rather short period of time. The most visionary projects are based on totally autonomous units and will require technology that needs to be matured first through research and small-scale testing.

The catalogue of ideas contains the following subjects, of which 1-3 cover research and knowledge generation, and 4-6 concern demonstration and generation of experience with the use of autonomous technology.

1. Electronic lookout – how can sensor technology and computer recognition of objects at sea be used to achieve a correct recognition of a ship's surroundings?
2. Situational interpretation and anti-collision – how can information from on-board sensors be fused and interpreted so as to build a machine-understandable picture of the situation for one's own and surrounding vessels? How is it possible to manoeuvre so that the regulations for preventing collisions at sea are complied with and collisions are avoided – even if a vessel in the surroundings does not observe these regulations?
3. Design, monitoring and validation of systems for autonomous navigation – how can an autonomous navigation system be tested and validated so that it can be certified as being safe and reliable?
4. Autonomous island ferries – how can autonomous technology be used to improve the transport services offered to island communities?
5. Autonomous service and work vessels.
6. Autonomous service vessels for underwater and drone inspection.

Electronic lookout

Idea

Sensor technology can make it possible to change the lookout procedures on board ships. Such a paradigm shift could open up for the possibility of drastically changing ships' design, arrangement and mode of operation, and it could also affect the operating economy.

A vessel with sensor-based lookout would not necessarily require a navigation bridge, whereas the ship's accommodation could be optimised on the basis of the need for cargo and cargo handling, rather than the need for lookout from a bridge.

The mode of operation could potentially be changed so that lookout duty is not performed through physical presence on board the ship, but through a data link to shore, where monitoring – and possibly remote control – could take place.

Reduced manning with navigating officers could be achieved through electronic lookout as a basic element in order to achieve an unmanned bridge function where computer interpretations of the ship's situation and of its surroundings are to secure autonomous navigation except in complex situations where a navigating officer would be required to take decisions and steer the ship.

Safety

On the road towards unmanned ships, the introduction of autonomous navigation – supplemented by advanced automation – will require extremely reliable sensor information about the ship's surroundings in order to ensure safe and reliable navigation.

The Danish Maritime Authority will need to be able to make requirements for functionality, reliability, level of redundancy and fault handling.

Research in sensor fusion, mechanical recognition and classification of objects in the surroundings is essential for achieving the necessary level of reliability and safety. An autonomous system must be capable of functioning though one single sensor fails and it must be capable of functioning in all weather conditions.

Method

Practical testing of sensor types and sensor fusion technologies in all relevant weather conditions.

Assessment of the role of the navigating officer and the functionality of the autonomous system at various levels of automation:

- For decision support and for use when calling navigating officers (AL 1-3).
- For decision making with monitoring (AL 2-4).
- Monitored autonomy (AL 5).

Simulation of system-operator interaction in normal and special situations.

Monitoring and validation of systems for autonomous navigation

Idea

Situational awareness and interpretation are decisive for how an automatic anti-collision system can and must function. Research measures taken so far have focused a lot on compliance with the COLREG set of regulations, and this problem presents considerable challenges in itself. In connection with vehicles, techniques from "Deep Learning" are used to make an algorithm learn from its own situations and to update it with situations from other similar units so as to achieve collective learning of best practice.

The following measures will be feasible if the general public is to feel confident that such a COLREG algorithm will always act in a predictable and reliable manner:

- That COLREG algorithms are certified for correct functioning when they come straight from the factory.
- That these algorithms keep acting correctly – in other words, that they do not navigate contrary to regulations or exceptions even when they learn from own or other units' situation in the course of the process.
- That monitoring of test vessels' behaviour is established and that AIS data, etc. are used to calculate the collision risk of manned and autonomously controlled ship traffic.

The risk-oriented approach could be used to draw up regulations in this area.

Method

In the design phase, validation of a learning system contains *monte carlo* simulations, where situational parameters are varied over an area and results are analysed. Correct and predictable behaviour means that resulting manoeuvres remain within the normal are when the input situation is perturbed.

The design of most of the COLREG algorithms reported in literature uses situational pictures from radar and AIS together with navigation chart information to calculate deviations from the planned route in order to avoid collisions. Monitoring of whether other vessels navigate correctly on the basis of their local situation could be a key to manoeuvre planning and to joint decision-taking by autonomous units in the longer term. The point of departure should be a set of normal behavioural patterns for all individual vessels within the relevant distance, and algorithms could detect whether each individual vessel acts correctly and appropriately. Vessels with deviating behaviour could be identified early, thus making it possible to keep a distance to vessels with technical problems or with other reasons for lacking navigation quality. Such a monitoring method could be implemented both as a shore-based solution and on board the autonomous vessel.

It is possible to assess the risk of collisions and groundings on the basis of existing AIS data. As regards cars, the approach consists in calculating an extreme distribution of distance on the basis of a large number of measurements of the distance, where no accidents have occurred. An extreme distribution can be used to estimate the probable number of collisions, and data on the number of actual collisions are used to validate the quality of the extreme value estimate. Similar methods could be used to assess the risks in all phases of the development, implementation and operation of autonomously navigated vessels.

Small/minor island ferries

Idea: Isolation presents a challenge to Danish island communities. One of the main reasons for this is the lack of frequent transportation. In a society where easy transportation of both persons and goods is part of our infrastructure and way of living, there is a need for inexpensive and frequent transportation to/from the islands. Autonomous technology could make it possible to book an electrically powered ferry when needed. The ferry could optimise its timetable by itself and inform the passengers when they will be picked up.

The ferry would prioritise its crossings. If an ambulance with the sirens on is underway from the mainland to the island, the ferry could be ready at the mainland port when the ambulance arrives at the port. Autonomous solutions must be capable of competing with helicopter assistance in terms of price and time. The helicopter rescue capacity is limited and, if incidents occur simultaneously in more places throughout the country, the waiting time for island assistance may be so long that complications arise or the outcome may be even worse.

Autonomous ferries can be small. The smallest of them need only carry one single vehicle, and larger autonomous ferries can be brought in for periods with predicted intensified traffic.

Safety and reliability

The ferry will be safely navigated and manoeuvred by the autonomous autopilot which will use supervision based on radar, lidar and camera to monitor surrounding waters. The system will interpret the ferry's situation and surroundings based on sensor information, on electronic charts and on updates from land containing data of importance.

Intelligent monitoring of on-board conditions will be able to alarm locally as well as a shore-based monitoring centre. Live video and sound will support the monitoring centre's decision-making. It is possible for the shore-based centre to remotely operate the ferry if necessary.

Technical safety and reliability is achieved through a built-in fault tolerance of machinery and automation and is supported by intelligent supervision, with the possibility of calling a shore-based operational centre.

Personal safety presents a special challenge on board ships. It could be considered how to permit unmanned voyages in case one or more passengers on board have completed a special safety course. This information could be encoded in the relevant person's "ticket". If a pre-school class intends to take the ferry, the autonomous ferry or its land support system will call for professional assistance from one or more crew members who have completed safety training, and the ferry will not depart until they have checked in.

Method

The routes to be included in the analysis could be selected in close cooperation between the Danish Maritime Authority and the Ferry Secretariat. It could be an advantage to include the experience gained with the electrically powered ferry to the island of Ærø, which is currently under construction (2017). The same applies to the experience gained applying for funding of demonstration projects (EU funding from Horizon 2020).

It must be unveiled which types of ferries it would be relevant to include in autonomous solutions. The Ferry Secretariat has developed a replacement ferry that can be used on a wide number of crossings, and perhaps this ship could be used as the basis for any new solutions.

Potential beyond a demonstration project

New and/or existing ferries: The advantages/disadvantages/potentials of altering existing ferries for autonomous operation must be unveiled and compared to those of new-built ferries. This area should be scrutinised in cooperation with the yard industry, marine equipment manufacturers and the customers, and we propose to establish a working group with participants from the Danish Maritime Authority to carry out this work.

Connecting autonomy and electricity: The possibilities of connecting the two technologies should be analysed. At present, it is our assessment that electricity is primarily suitable for rather short crossings and, perhaps initially, as a part of hybrid solutions, i.e. solutions where electricity is reserved for auxiliary machinery. The current project does not consider the connection between electricity for propulsion and autonomy in more detail. This issue should be examined by a specific project.

Replacement potential: It is difficult to establish the exact potential for replacing diesel powered ferries by electrically powered ones and, consequently, the installation of autonomous manoeuvring technologies. The ferries have been constructed in the period 1956-2006, and a considerable proportion of them are 20 to 30 years old and are about to be replaced. In other words, there is a basis for taking action now. A possible solution could be to build and put in service more standardised ferries, possibly of various sizes. Then, these ferries could be developed with both different technologies as regards electrical power and with different degrees of autonomy. Especially as regards autonomy, it could presumably be installed subsequently on existing ferries with a (considerable) remaining lifetime in a number of situations.

Project proposal: On the basis of the above-mentioned issues related to the number, types and age of the island ferries, we propose a project for a ferry engaged on a short crossing (4 to 12 minutes) in an area presenting relatively modest navigation challenges, and where the population density and the current frequency of crossings make fewer demands for a 100 per cent system-related operating period for the ferry. If possible, this should be combined with a crossing where it is easy to call for back-up assistance in case of technical problems and where there is real support for a project of this nature.

As regards the ferry as such, it should be of a standard that makes such updating possible, including the possibility of replacing the ferry with the replacement ferry during the construction process and in case of any unavailability. Consequently, the project should be carried out in close cooperation with the Ferry Secretariat.

One decisive issue is of course related to the reduced costs of using an autonomous ferry compared to the costs of using a traditional ferry. The savings will primarily derive from reduced wages for the crew. The savings should be related to the investments in new technology that will have to be made to achieve the desired level of autonomy. A payback period for the project should be established and the feasibility of this should be analysed. In general, the analysis will have the form of a purely financial analysis, but – if requested – any socio-economic elements could be added (safety, the environment, reliability, etc.).

Autonomous work and service vessels

Idea

Autonomous technology could be useful in connection with different types of work vessels:

- Service vessels for offshore wind farms and oil/gas production.
- Engine-driven barges and lighters for the carriage of goods and equipment.
- Tugboats.
- Unmanned vessels used by the Navy for exercises.

A Canadian project assesses that crew costs account for a considerable part of the operating costs of tugboats and, thus, proposes a design based on a high degree of automation (Allan, 2016). There could be operational advantages and better logistical support offshore if one or more autonomous vessels could handle spare parts and the carriage of persons from one place to another offshore. They could remain in the area, thereby avoiding shore-to-offshore transportation unless voyages to land are required.

Certain types of motor barges perform many voyages between given positions. In the ReVolt project, DNV-GL examines coastal goods transport between ports. These voyages would be relatively complicated with port calls, whereas other vessels carry out simpler voyages.

For naval purposes, unmanned vessels are used for exercises, minesweeping, hydrographic surveys and perhaps submarine chases, and vessels have also been mentioned as unmanned supply vessels. Details about unmanned military vessels are not available to the general public.

Safety and reliability

The safety and reliability aspects of the work vessels mentioned will be like those applicable to a similar level of autonomy, and the technical equipment for situational monitoring would correspond to what has already been described. The choice of sensor systems may depend on the specific tasks of the vessel and on the surroundings in which it is to operate.

As is the case with other vessels, reliability and the availability of propulsion and manoeuvring machinery are decisive for safety and availability. In the ReVolt project, DNV-GL concludes that motor barges for "short-sea shipping" are best at achieving the reliability and availability necessary for full autonomy by means of electrical propulsion.

Method

A project is to analyse the navigational manoeuvres made by a vessel of this type today and the navigational and other steering-related challenges related to this. In cooperation with one or more specialised shipping companies, a relevant project is described that focuses on the cost savings of autonomous vessels, on the costs for construction/retrofitting of these vessels compared to those of traditional vessels as well as on the performance of an autonomous vessel compared to that of a manned vessel.

Autonomous service vessel with combined underwater and drone inspection

Idea

Offshore installations undergo the following phases: construction, ongoing inspection, ongoing maintenance, decommissioning.

During the maintenance phase of autonomous technology, it will be possible to offer price efficient and regular inspections without any persons being present. Inspections below the surface of the water and from the air are necessary elements. Autonomous underwater robots could perform regular inspections and, subsequently, swim to an unmanned mother ship to hand over the video and other sensor signals from the inspection, and be provided with energy for resuming the inspections. Modular robot technology could perform maintenance in the form of the replacement of units/components, if needed. Airborne units could land on the mother ship in order to be supplied with energy for continued operation in a similar fashion.

For long periods of time, such an autonomous cluster would not have any other contact with human beings than the one related to the reporting of inspection data to shore and the receipt of instructions about the overall inspection plan, if relevant.

An autonomous cluster as the one mentioned would not only report data about the condition of the technical installations, but also about the surrounding marine environment. Any spillages could be detected very fast, and it would be possible to continuously and intensively monitor the ecosystems' biosphere.

In connection with the decommissioning of offshore installations, there are many inspection tasks. On offshore wind turbines, the nacelle securing bolts may have rusted solidly so that special tools are needed to separate the nacelle from the tower. Exact knowledge about the condition of the unit that has been acquired through autonomous inspection from the air and below the surface of the water would help allocate exactly the crane equipment needed for the dismounting. Thus, it would be possible to save costs for the carriage of unnecessary equipment.

During the maintenance phase, it would be necessary to inspect for corrosion in the zone where waves are breaking against the structure – both above and below the surface of the water.

Safety

The safety of unmanned units means, first of all, that they must not harm persons or vital equipment when used in an offshore field. Reduced weight is a very considerable element when trying to achieve this type of safety, but it is not sufficient.

As regards airborne units, the type of certification that the FAA would refer to in the expected regulation could be adhered to, which would also contain requirements for equipment certification (Drone Advisory Committee, 2017).

As regards underwater units, similar regulation is not in place, but the operational requirements and safety procedures must be adapted to the current requirements for the operation of ROV (Remotely Operated Vehicles) underwater units.

The autonomous surface vessel would have to be designed and operated in accordance with future regulation applicable to small unmanned vessels.

Method

An autonomous service vessel will be permanently present in an area and function as a mother ship from which autonomous underwater vessels and airborne units can tank energy and to which they can deliver data from the inspection of an area. Airborne and submerged units have a relatively limited period of operation due to the energy supply issue. A possibility of frequent tanking/recharging would minimise the consequences of this problem and make airborne/submerged units considerably more inexpensive.

Each individual autonomous unit carries dedicated equipment (a sensor package) for monitoring the parts that need this.

The presence of a host of inexpensive autonomous units for use below and above the surface of the water and in the air will secure continuous inspection and monitoring. Data will be analysed mechanically, and a shore-based operational centre will be advised in case of signs of changes that need to be assessed by a human expert.

The cooperation of land- and shore-based supervision will, thus, be much like the solution that will be implemented on unmanned ships so that research and development will have synergies with both types of use.

The technology and methods are already known, to some extent, from the UAS (Unmanned Aerial System) technology so developments need not be started from zero.

The business idea must be developed by or in cooperation with offshore operators and owners within the areas of offshore wind farms and oil/gas extraction.

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