Ship Intelligence

Marine

AAWA
REDEFINING SHIPPING

Remote and Autonomous Ships
The next steps

Introduction

Esa Jokioinen – Rolls-Royce – Head of Blue Ocean Team

1. Background

"*Autonomous shipping is the future of the maritime industry. As disruptive as the smart phone, the smart ship will revolutionise the landscape of ship design and operations*"

Mikael Makinen, President Rolls-Royce Marine

Ten years ago the very idea that you could manage your life through a small glass screen, was considered almost impossible. Now few of us would want to be without one. Two years ago talk of intelligent ships was considered by many as a futuristic fantasy. Today, the prospect of a remote controlled ship in commercial use by the end of the decade is a reality.

The technologies, particularly sensor technologies, needed to make remote and autonomous ships a reality already exist. The challenge is to find the optimum way to combine them reliably and cost effectively. The decision algorithms which will help such vessels decide what action to take in the light of that sensor information are being perfected. This requires an interpretation of maritime rules and regulations leading to challenges of interpretation for the programmer. The development of decision support systems will be a gradual and iterative process subject to extensive testing and simulation.

To secure regulatory approval; as well as industry support and public acceptance, remote and autonomous ships will need to be as least as safe as existing vessels. They have the potential to reduce human based errors but at the same time new types of risk will arise and will need to be addressed. A comprehensive and structured way to identify and address these risks is required.

Unmanned ships open up exciting possibilities to redefine the way a ship is designed and functions. When there are no people on board, many constraints on the ship layout are removed. One of the most obvious is the removal of the accommodation and with that the entire deckhouse. This will save cost, weight and space, as well as enabling the ship to carry more cargo. A ship contains systems that are only there to serve the crew. Their removal will simplify the entire ship, which should improve reliability and productivity while reducing build and operating costs.

Future vessels will still need human input from land making connectivity between the ship and the shore crucial. Such communication will need to be bidirectional, accurate, scalable and supported by multiple systems creating redundancy and minimising risk. Sufficient communication link capacity for ship sensor monitoring and remote control, when necessary, has to be guaranteed. Continuous, guaranteed connectivity gives us the ability to monitor equipment in service in real time detecting, diagnosing and prioritising issues with critical equipment helping customers get the most out of their assets by optimising both operations and maintenance schedules.

Such a rich stream of data and more standardised ships will have enormous consequences for the shipping industry.

It will allow ship owners to manage their fleet to optimise operations and maximise profit. By looking at data from individual ships together they will be able to identify the best combination of route, cargo, maintenance schedule and fuel price for the fleet as a whole getting the maximum value from a set of very expensive assets.

In this ship owners will not be alone. Increased digitalisation will create new shipping services, such as more efficient pooling and alliances, leasing of assets, online cargo service marketplaces, etc. Some of these services will support existing market players and some will be disruptive – allowing a new player to enter the market and take over large shares of the business in the same way as Uber, Spotify and Airbnb have done in other industry sectors.

Rolls-Royce together with the other partners in the AAWA project, DNV GL, Inmarsat, Deltamarin, NAPA, Brighthouse Intelligence, Finferries and ESL Shipping – and with the support of Tekes Rolls-Royce – is leading this revolution.

2. AAWA Initiative

The Advanced Autonomous Waterborne Applications (AAWA) Initiative is a €6.6 million project funded by Tekes (Finnish Funding Agency for Technology and Innovation) aims to produce the specification and preliminary designs for the next generation of advanced ship solutions.

It brings together universities, ship designers, equipment manufacturers, and classification societies to explore the economic, social, legal, regulatory and technological factors, which need to be addressed to make autonomous ships a reality.

The project will run until the end of 2017 and will pave the way for solutions - designed to validate the project's research. The project will combine the expertise of some of Finland's top academic researchers from Tampere University of Technology; VTT Technical Research Centre of Finland Ltd; Åbo Akademi University; Aalto University; the University of Turku; and leading members of the maritime cluster including Rolls-Royce, DNV GL, Inmarsat, Deltamarin, NAPA, Brighthouse Intelligence, Finferries and ESL Shipping.

The wide ranging project looks at research carried out to date before exploring the business case for autonomous applications, the safety and security implications of designing and operating remotely operated ships, the legal and regulatory implications and the existence and readiness of a supplier network able to deliver commercially applicable products in the short to medium term. The technological work stream, led by Rolls-Royce, encompasses the implications of remote control and autonomy of ships for propulsion, deck machinery and automation and control, using, where possible, established technology for rapid commercialisation.

For remote controlled and autonomous ships to become a reality a number of critical questions need to be answered:

- What technology is needed and how can it be best combined to allow a vessel to operate autonomously and miles from shore;
- How can an autonomous vessel be made at least as safe as existing ships, what new risks will it face and how can they be mitigated;
- What will be the incentive for ship owners and operators to invest in autonomous vessels and
- Are autonomous ships legal and who is liable in the event of an accident?

In 2015 the first phase of the project has examined the current state of the maritime industry and what can be learnt from other industries – from aviation's drones and driverless cars to the smartphone. The project has explored the current state of understanding of the technological, safety, legal and economic aspects of remote and autonomous operation. The findings of this research can be found in this whitepaper.

The next two phases of AAWA will build on the findings from the first phase to develop the technical, legal and safety specifications for a proof of concept demonstrator by the end of 2017.

3. Vision of remote controlled ship operation

The concept of dynamic autonomy

There are number of different definitions of autonomy and machine intelligence in the literature. Levels of autonomy (LOA) are often used to describe to what degree the machine can act on its own. Probably the most well-known descriptions for LOA are developed by Thomas Sheridan. The Sheridan scale includes a continuous range of definitions from a machine being completely controlled by human (i.e. tele-operated) through the machine being fully autonomous and not requiring any input from the human before taking actions.

Level	Description
10	The computer does everything autonomously, ignores human
9	The computer informes human only if it (the computer) decides so
8	The computer informes human only if asked
7	The computer executes automatically, when neccssary informing human
6	The computer allows human a restricted time to veto before automatic execution
5	The computer executes the suggested action if human approves
4	Computer suggests single alternative
3	Computer narrows aleternatives down to a few
2	The computer offers a complete set of decision alternatives
1	The computer offers no assistance, human in charge of all decisions and actions

Table 1 – Sheridan levels of autonomy

Different variations of this types of scale have been developed in the research. A common conclusion is that such scales may not be applicable to entire operation but are most useful when applied to different subtasks of the autonomous machine.

This conclusion is also highly relevant for autonomous ships as the behaviour of the vessel (i.e. LOA) and required amount of human interaction will dependent on the state of the vessel and subtask being executed. This type of “adjustable” or “dynamic” autonomy is a concept which is often discussed in context of mobile robots in which the machine can be operated for periods of time on its own depending on the limits given for the decision making tolerance. The robot can handle simple tasks autonomously but when the tasks are getting more complex increasing interaction with the human operator is needed.

Remote controlled ships will follow this type of dynamic autonomy approach depending on the state of the vessel and mission being executed. In some cases, such as navigation in the open seas, the ship can be nearly fully autonomous whereas for some parts of the voyage it will require close supervision and decision making, or even full tele-operation from the human operator.

In order to understand how autonomous ships would work, an example of general cargo vessel operating between two ports is described in the following. The example will show examples of different levels of autonomy during different phases of the voyage. For simplicity a single vessel operated by one human operator is presented.

4. Voyage planning and initiation

There are certain things which are related to remote control operation that have to be taken into account by the operator while planning the voyage or mission for the vessel. Autonomous vessels will use a mix of different satellite and land based communication networks depending on their availability, quality and price. High bandwidth satellite communication systems provide the capability to operate an autonomous vessel despite the location in vast majority of autonomous operation modes. However some of the remote control or remote supervision modes might require a latency and bandwidth that exceeds the capability of the satellite systems in adverse weather conditions. The operator will have to ensure that there is sufficient connectivity for the intended mission. Even if data transfer of autonomous ships has highest priority in these networks the operator will have to review the traffic and weather conditions in order to decide what is the primary operation strategy for each leg.

From voyage planning point of view this means defining which legs shall be operated in remote control and which are executed autonomously. Once this decision has been made, the operator will have to further define navigational strategies along with fallback strategies for each leg. The fallback strategy sequence is executed only if the ship experiences an unexpected reduction in connectivity simultaneously with operational challenge which would normally require operator intervention.

The fallback strategy could include: asking operator to take manual control (if failed), slow down and proceed to following waypoint (if failed), stop the vessel and stay in DP mode (if failed), navigate to previous waypoint (if failed), navigate back to preset safe location. The commands and their execution sequence is obviously not same in all parts of the voyage. For example trying to maintain its position in the middle of a congested and narrow fairway in harsh weather might not be a feasible strategy. The voyage plan as well as the fallback strategies can always be modified during the voyage using the satellite communication link.

The ship will also need to have an automatic system for verifying the sea readiness before starting the voyage. Most of the systems can be checked remotely by the operator while in some areas (such as securing cargo) shore based crew can also be used to check that voyage can be started.

5. Unmooring and manoeuvring out of harbour

The mooring systems for an autonomous vessel can be fully or semi-automatic. In the case of a fully automatic mooring system the complete mooring and unmooring operation can be remote controlled or is automatically executed by the autonomous vessel. Semi-automatic mooring means that connection to the quay can be made automatically but crew is needed to secure the docking (i.e. using conventional rope-based systems). Both of these require potentially some modifications to the dockside infrastructure which means that the economic feasibility of the mooring system will depend on how many vessels are able to use the same docking system. Solutions for this exist in the market and AAWA explores their feasibility for autonomous vessels along with development of new potential automatic mooring arrangements.

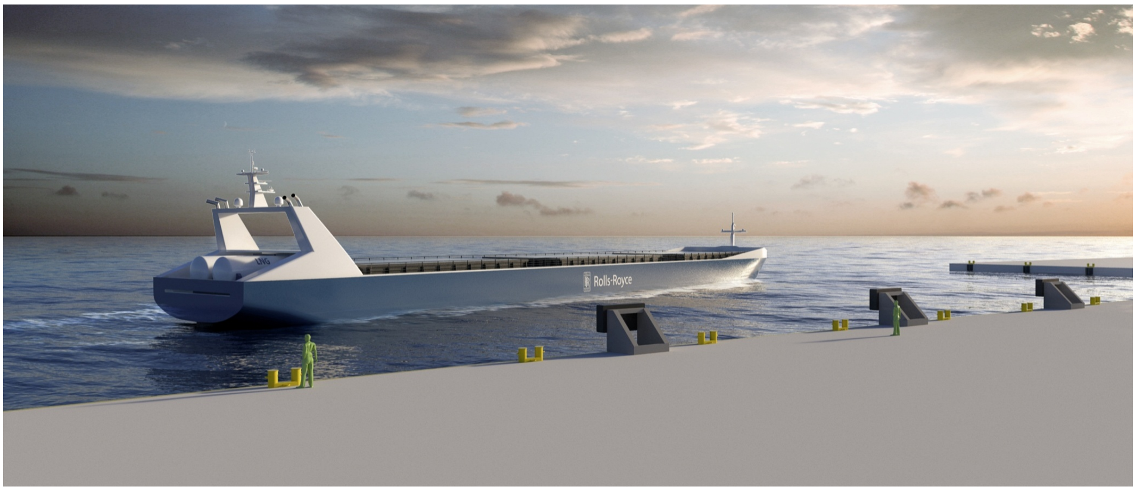


Figure 1 – Semi-automated mooring system

When the ship is manoeuvred out of the congested harbour area the operator can either have direct remote control or supervisory control which is supported by the onboard situation awareness systems. In this type of operation a high bandwidth and low latency communication link is needed. In certain areas this can be provided by the land-based communication networks and satellite communication systems remain as back-up.

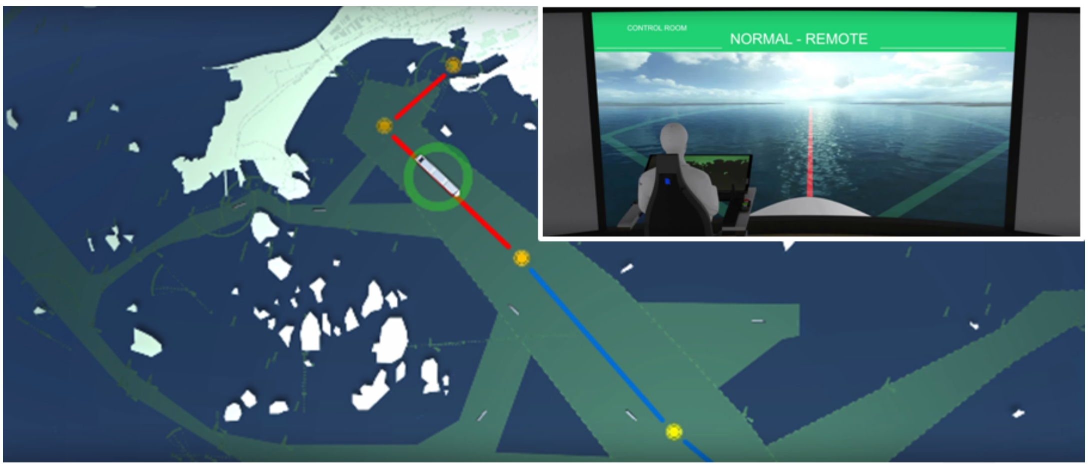


Figure 2 – Supervisory teleoperation

Remote control can mean direct joystick-type operation modes already existing in the dynamic positioning solutions such as locking speed, heading or relative position to an object are available. However, a more practical way in case of most ship types is controlling the vessel by sending waypoint and the dynamic positioning control computer and autonomous control system takes care of actual propulsion controls. In some areas it is potentially also feasible to go directly to autonomous mode instead of starting with teleoperation or supervisory control.

6. Operation modes at open sea

In normal autonomous mode the ship executes the planned mission (e.g. navigation to the next waypoint) according to the defined plan. In this mode the data transfer between the ship and operator is minimised and limited to only relevant status data such as ship's location, heading, speed, ETA to next waypoint (or area of closer supervision) and key information from the situational awareness systems as well as critical ship systems. While the interaction requirement between the ship and operator is minimal in this normal state, it is possible for the operator to supervise more than one vessel at the time. This means that the autonomy level of the vessel is high as long as the mission execution is proceeding according to the plan made by the operator.

Additional information will be provided automatically in case the situational awareness systems and the autonomous navigation system autonomous decision making threshold is exceeded and user notification, confirmation or intervention is required. This means that the autonomy level is dynamically adjusted if the mission execution is not proceeding according to the original plan and the autonomous navigation system sees that adjustments are needed.

Different levels of operator interaction will be requested depending on the operational scenario. For example if the vessel is deviating from the planned course between the two waypoints but stays within specified margins the autonomous navigation system only notifies the operator about planned evasion and gives the operator a possibility to veto for a limited time. One example of such evasion could be taking automatic action to keep out of the way of another vessel by slightly changing the heading or speed. The operator could choose to use VHF radio to communicate with the other vessel and confirm that action taken by the vessel is safe for both parties, and if modifications are needed the operator can take the vessel in manual control.

A more complicated case requiring user decision making is when the vessel needs to change the course in such a way that complete waypoint has to be re-planned (e.g. evasion or offset from the planned path is not enough to solve the navigational challenge). In order to ensure that changes to the plan are made in a safe way operator confirmation will be requested. The autonomous navigation system will offer one or more alternatives of how the waypoint could be modified but the operator will finally make the decision how to continue the voyage.

It can also be expected that there will be complex scenarios where the autonomous navigation system path planning and algorithms cannot unambiguously solve the situation. Example of this could be if extremely large number of crafts or other objects are detected and the path planning algorithms are not capable to identify them and thereby the system cannot determine how the navigation should proceed. In this type of scenario the vessel will immediately send a "pan-pan" message to the operator indicating that it is in urgent need of assistance. The ship has predefined set of fallback strategies that it will start to execute in the planned order if user response is not received, and in "pan-pan"-depending on the urgency, automatic fallback strategy execution can also be started immediately.

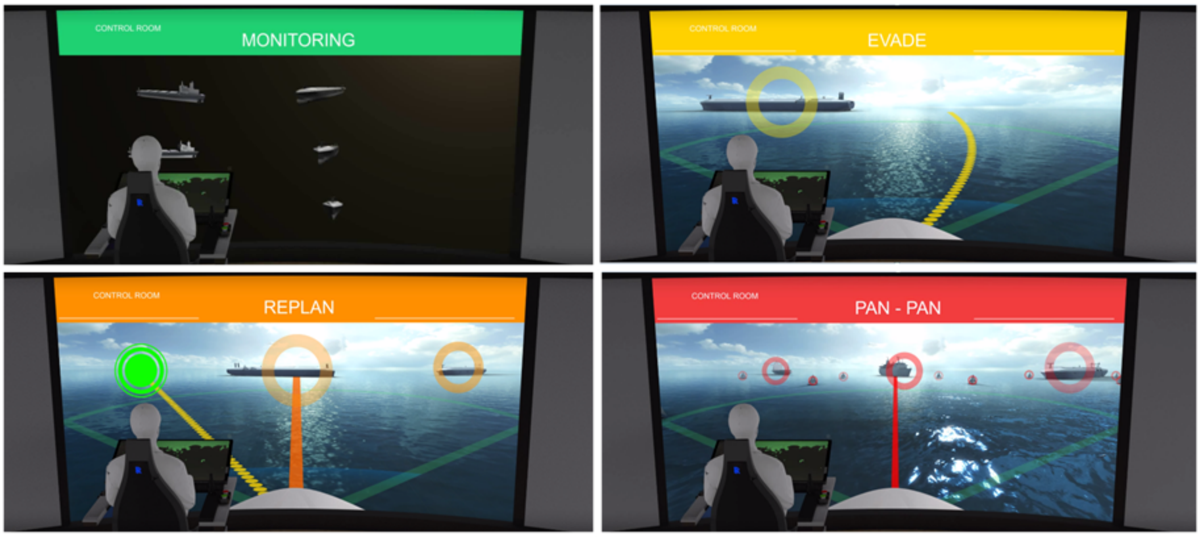


Figure 3 – Different scenarios require different levels of operator involvement

Operation of the autonomous vessel will combine different autonomy levels dynamically depending on the state of the vessel and external conditions. Obviously as the control algorithms will evolve and mature over time, the ships will be capable of handling increasingly complex situations on their own. When the autonomous ship fleet increases it will also be possible that the autonomous ships share voyage plans and communicate with each other automatically which reduces the operator load. However, there will always be manned vessels sailing along with autonomous ships which means that human operator will be necessary for quite some time to interpret this information until clear standards for information sharing between manned and unmanned vessels are developed.

7. Port approach and docking

When approaching the port area the operator can again choose to take teleoperation type control or increase the supervision level of the vessel. This might be necessary from VTS point of view, but also because piloting might be required.

Piloting can in the future be organised in number of different ways for autonomous vessels. One alternative is that the pilot has capabilities to take control of the autonomous vessel, or alternatively the autonomous vessel operator can hold a pilot license for the intended operation areas. Implementation of autonomous vessels will most likely start from national or regional waters and frequent routes which means that piloting procedures and practicalities with VTS can be agreed case-by-case for the first vessels.

When operating the vessel in proximity of the shore it is again possible to rely on the land-based systems for communication. Additionally the navigation system can use land based external reference systems for positioning which will be useful especially in port areas. In addition land based camera and radar systems can be used to navigate the vessel safely alongside the dock.

8. Applicability for different ship types

The example described in the earlier chapter gives an idea of how dynamic autonomy would work for ship operations. Obviously type and level of autonomy will be also highly dependent on the ship type, size, operational area and conditions. For example an autonomous tug would follow the same principles but as the operation is much more focused around the towing mission, the control and autonomy principles have to be defined from a different point of view.

Generally speaking the more variations and complexity the mission has, the more the ship will have to rely on operator assistance and remote control at least in the first phases of the implementation. Another example could be an inland ferry making tens of identical crossings every day. In this case the mission in itself has much less variation and the autonomy level in executing the task can be much higher. At the same time it is important to keep in mind that even though the basic mission is not varied too much, the conditions such as weather and traffic can change considerably. Onboard crew might still be needed in these cases to supervise safety of the operations even if the ship executes the basic mission nearly autonomously.

In addition to differences in operation and conditions, there are also big differences in how the ships will react to control commands. A large container vessel and small general cargo vessel will need to have their own ship-specific models of control algorithms even though the fundamentals of how they react autonomously to different navigational conditions would be following the same principles. Technically this also means that the situational awareness system will have to be different as the reaction distance (time) of a large vessel is considerably higher and higher predictability levels are needed.

9. Conclusion

The first phase of the AAWA project has examined the current state of the maritime industry and what can be learnt from other industries. The project has explored the current state of understanding of the technological, safety, legal and economic aspects of remote and autonomous operation.

The initial conclusions are:

1. There will be no single remote or autonomous ship solution but rather a hybrid of the two which will depend on the type and function of the vessel.
2. The technologies needed to make remote and autonomous ships a reality exist. The challenge is to find the optimum way to combine them reliably and cost effectively. The development of decision support systems for autonomous vessels will be a gradual and iterative process and subject to extensive testing and simulation.
3. The operation of remote and autonomous ships will be as least as safe as existing vessels. There is potential to reduce human based errors but at the same time new types of risk will arise and will need to be identified and addressed.
4. Legislation can be changed if there is a political will. For remote and autonomous shipping to become a reality effort is needed at all regulatory levels. The legal challenges of constructing and operating a demonstration vessel at a national level need to be explored whilst simultaneously considering appropriate rule changes at the IMO. Questions of liability for autonomous ships are subject to national variations, but generally it seems that there is less need for regulatory change in this field. What needs to be explored, however, is to what extent other liability rules, such as product liability, would affect traditional rules of maritime liability and insurance.
5. Remote and autonomous ships have the potential to redefine the maritime industry and the roles of players in it with implications for shipping companies, shipbuilders, maritime systems

providers and technology companies from other (especially the automotive) sectors.

The next steps are:

- the development and testing of specific technological solutions for autonomous operations using both simulators as well as tests at sea across a variety of environmental conditions - the optimum way to combine the different sensor technologies in a range of operating and climatic conditions will be the subject of a series of tests this year on board the FinFerries vessel, the Stella, operating between Korpo and Houtskär;
- research to understand the changed and new risks (a variety of known and unknown hazards) presented by new and emerging technology, building on the marine industry's experience of systematic and comprehensive risk assessments, to develop new approaches;
- exploring the legal challenges of constructing and operating a demonstration vessel at a national level whilst simultaneously considering appropriate rule changes at the IMO;
- exploring stakeholder views of remote and autonomous shipping to establish cost and revenue models of autonomous operation for different ship types.

The outcome Phase II will be the technical, legal and safety specifications for a full scale proof of concept demonstrator by the end of 2017 and a remote controlled ship in commercial use by the end of the decade.

The revolution has begun.

Technology

Jonne Poikonen, Senior Research Fellow, D.Sc.(Tech.), University of Turku

Mika Hyvönen, Senior Research Fellow, D.Sc.(Tech.), Tampere University of Technology

Antti Kolu, Doctoral Student, M.Sc.(Tech.), Tampere University of Technology

Tero Jokela, Senior Research Fellow, D.Sc.(Tech.), University of Turku

Jari Tissari, Project Researcher, M.Sc.(Tech.), University of Turku

Ari Paasio, Professor, D.Sc.(Tech.), University of Turku

Technologies for marine situational awareness and autonomous navigation

Technologies for realising remote and autonomous ships exist. The task is to find the optimum way to combine them reliably and cost effectively.

The development of autonomous vehicles, either on land, air or sea has seen great progress during the last 10 years. This has been enabled by advances in technologies, which enable perception of the surrounding environment, path planning and vehicle control in real time. With a combination of an array of advanced sensor technologies – becoming available also beyond earlier military and scientific use – and rapidly increasing data processing performance, we have reached a technological level on which full vehicular autonomy is indeed feasible.

The most progress has been demonstrated in the field of autonomous cars. This is natural due to the large mass-market potential and the global need for increased traffic safety. For military applications, significant research and development has been carried out in the fields of autonomous land vehicles, aviation and also marine vessels, such as small patrol and attack boats [Elkins, 2010]. Recently, efforts to create solutions also for civilian autonomous marine vessels have seen a significant increase, e.g. in the form of many new research programs in co-operation with academia and marine technology companies, including AAWA.

One of the key technologies for any reliable autonomous vehicle navigation is sensor fusion. When creating Situational Awareness (SA) for an autonomous vehicle, no single sensor technology can provide sufficient performance under all possible conditions. Therefore, in order to guarantee that the information on the vehicle's surroundings is sufficiently accurate at all times, the input from multiple sensors has to be combined and analysed. The sensor data processing should then be seamlessly integrated with subsequent path planning and reactive collision avoidance systems, which maintain a constantly updated detailed map of the vehicle's environment, allowing the vehicle to plan its route and avoid any collisions with objects or other vehicles. The map gathered from sensor data can also be augmented with data from static map databases such as Google Maps for cars or electronic nautical charts (ECDIS) for ships, which present static objects of the surrounding area.

Research on autonomous cars offers the most extensive source of publicly available information on technologies developed for autonomous vehicles. The top part of Figure 1 illustrates a typical sensing and processing pipeline applied in autonomous cars. Multiple sensors are used to extract data from the surroundings of the vehicle. The preference on different sensor types varies: Google applies LIDAR as the main sensor source, which is supported by other devices, while the approach taken by Tesla or Mercedes Benz is based on the fusion of cameras and short range automotive radars. The selection of the optimal sensor platform is a question of performance, reliability and cost. The data from the SA-sensors is used to create a local map of the surroundings of the car, which is compared to very detailed maps or even 3D models of the area where the vehicle is moving. This enables extracting the position and pose of the vehicle with more accuracy than is possible with just GPS-based localisation. The local map of obstacles surrounding the car is also used for reactive collision avoidance. [Franke, 2013], [Guizzo, 2011]

The bottom part of Figure 1 illustrates the ship autonomy approach currently being developed in AAWA. Many existing technological solutions from automotive development can be directly, or through some adjustment, applied also to autonomous marine navigation. The main question is therefore not whether the implementation of autonomous ship navigation is technically possible, but what is the combination of technologies and methods that provides the level of performance and reliability that is required for practical operation of large vessels, and at a reasonable cost.

The key aspect to successful vehicular autonomy is reliability and safety. Despite all of the recent technological advances, conclusive demonstrations of sufficiently reliable autonomous car navigation in varying real-world conditions have not been presented. Even the most advanced and widely tested automotive solutions such as Google's autonomous cars still struggle to cope with unknown environments and unexpected events, thus requiring human intervention from time to time. Even more importantly, tolerance to extreme weather conditions is a significant challenge, which so far has not been fully resolved.

Published marine solutions have so far been demonstrated on small boats and with only e.g. a limited use of sensory fusion and autonomy and typically under fairly easy weather conditions. In the AAWA project, the focus is from the start on harsh, but still realistic, conditions and on the particular challenges of autonomy and remote control implementation for even large ocean-going ships. This is made possible by close co-operation between researchers and industrial partners.

For the implementation of autonomous navigation and reactive collision avoidance, the marine application presents both advantages and challenges compared to other autonomous vehicles. Because the speed of a ship is fairly slow, the interpretation of SA-sensor data and navigation manoeuvres do not have to be as fast as in e.g. automotive applications. The ship is also not confined to e.g. a narrow road, which makes avoiding other vessels easier. On the other hand, the inertia of a ship is large and it is not possible to e.g. make a sharp turn or to stop quickly. An important aspect to also take into account is that the number of autonomous ships will, in any future scenario, be orders of magnitude lower than what is envisioned for autonomous cars. While it is not feasible to apply remote human monitoring (control centre) for billions of autonomous cars, shore control centres dedicated to autonomous ships are feasible. Such centres can oversee the performance of multiple ships, and apply remote controls if necessary.

This report will take a closer look at the available technologies that can be applied for ship autonomy and the remaining challenges ahead to reach required technological readiness for a proof-of-concept demonstrator by the year 2017.

1. Autonomous navigation of the vessel

1.1. Reactive control and path planning for collision free navigation

Collision avoidance for ships has seen great interest after World War II, due to the development of radar and the rapid rise of the traffic in the seas. Collision avoidance plays a major role in the mariner's daily work and because critical decisions of humans are highly subjective, international rules for maritime collision avoidance (COLREGs) are developed by International Marine Organization (IMO) to help navigation.

Collision-free motion techniques can be divided into either global methods, based on path planning using a priori information, or local methods which are based on reactive navigation using sensory information. In motion planning the path is solved by computing a geometrical trajectory avoiding known obstacles, which, in real-world uncertain environments, will easily lead to collision. In reactive navigation the reality of the environment during motion is taken into account using a rapidly repeated perception-action process. [Statheros, 2008], [Pietrzykowski, 2009], [Tam, 2009], [Campbell, 2012].

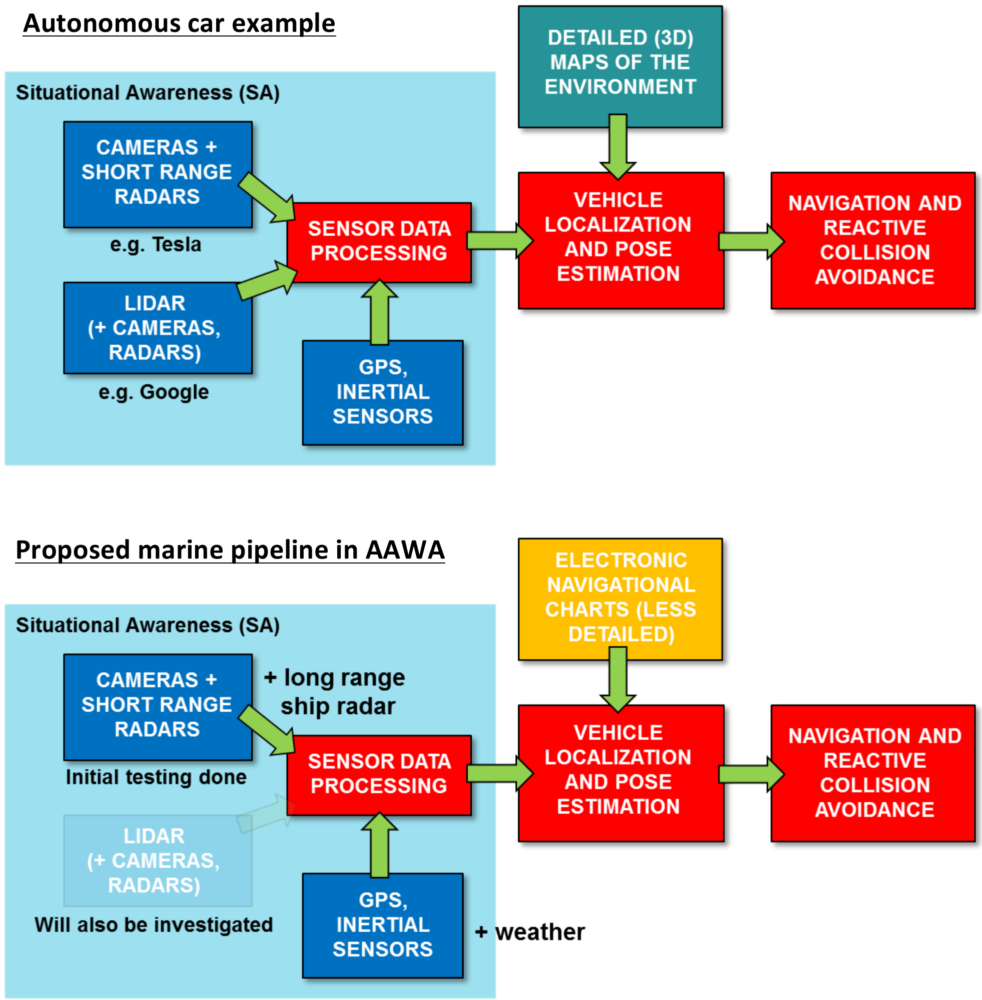


Figure 1. Comparison between automotive and marine navigation pipelines.

Planning a collision free path for an autonomous machine through an environment containing static or moving obstacles, in this case a vessel moving in both harbour area and open sea, is a problem that has been extensively studied during the past decades. Different systems require different planning strategies. Also, the kinematic and dynamic constraints of the vessel have to be taken into consideration when planning the path, so that the planned manoeuvres can be executed. For example, the turning radius of the vessel limits the minimum turning angle allowed for the path. Also, the dynamics of the vessel need to be taken into account, i.e. the vessel turning radius also depends on speed of the vehicle. For autonomous ships, also the environmental elements need to be taken into account when planning a path. Weather conditions have also a large effect on the selection of the best path. The challenges related to reactive navigation are mainly due to instability of the closed loop control due to the dynamic properties of the ship and surrounding environment (waves, wind, sea currents) and in getting the proper information from the ship's situational awareness sensors. [Statheros, 2008], [Pietrzykowski, 2009], [Tam, 2009], [Campbell, 2012], [Elkins 2010].

Two of the most common path planning approaches are graph-based and sampling-based approaches. Graph based approaches such as A* and D* and their numerous variants have been the most studied algorithms for optimal path planning problems. The main advantage of sampling-based approaches, such as probabilistic roadmap (PRM) and rapidly exploring random tree (RRT) and their variants, is the ability to easily include dynamic and kinematic constraints of the vehicle. For reactive obstacle avoidance, these optimal path planning approaches may not be efficient enough. Therefore, algorithms such as velocity obstacles are commonly used. [Campbell, 2012], [Casalino, 2009], [Lalish, 2012], [Evans, 2008], [Sharma, 2012], [Statheros, 2008] and [Tam, 2009]

1.2. Autonomous Navigation System (ANS) of AAWA

In AAWA, a solution for the integration of a complete autonomous ship navigation architecture is being developed, which takes advantage of a Rolls-Royce Dynamic Positioning (DP) system developed for future autonomous ships and links it with an Automatic Navigation System (ANS), including Situational Awareness (SA), Collision Avoidance (CA), Route Planning (RP), and Ship State Definition (SSD) modules developed in the AAWA project. Figure 2 shows a schematic of the ANS architecture.

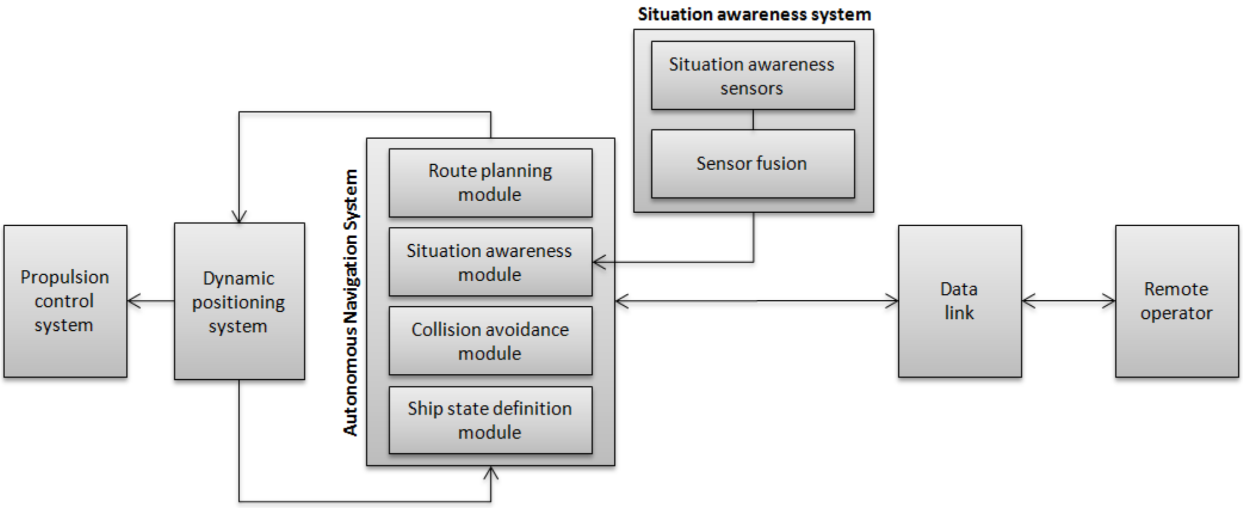


Figure 2. Autonomous Navigation System (ANS) architecture.

The highest level in the ANS system is the Ship State Definition (SSD) module or "Virtual Captain" (VC), which combines information from different ANS sub-systems (SA, DP, RP and CA), as well as from other ship automation systems and the operator to determine the current state of the ship's systems. The state of the ship determines the allowed ship operation mode, such as autonomous, remote-control or failsafe. The state information from the VC is also used to continuously inform the operator about the stage of the ship.

Dynamic positioning systems allow the ship to automatically maintain its position or heading by using its propellers, rudders and thrusters. When combined with a global or local positioning reference such as Global Navigation Satellite System (GNSS), and with wind sensors and Inertial Measurement Units (IMUs), the ship is able to keep its position even in rough weather conditions. Modern DP systems, such as Rolls Royce Icon DP, are able to also manoeuvre the ship at slow speed. This allows the integration of autonomous behaviour in ship control. As the DP system already has information of the ship's manoeuvring capabilities, it is able to calculate where the ship is can to move in the future. These dynamic constraints on the ship's movement are transmitted to the CA module to enable more efficient local path planning.

Route Planning (RP) module is a software module that is responsible for planning the path from start to finish, via predefined waypoints, while avoiding static obstacles defined in electronic navigational charts and following shipping lanes when advisable. This module is closely related to voyage planning that is nowadays done by the ship crew. However, the RP module uses the planned voyage as information when planning the actual route for the ship. Route consists of waypoints, headings and speed for the ship. The RP module does not plan routes in real time as the CA module is responsible for manoeuvres done to avoid obstacles.

The Collision Avoidance (CA) module is responsible for safe and collision free navigation. It uses information from the Route Planning module to follow a path that leads to the destination but can deviate from the course if a risk of collision detected. The SA module supplies the local map and obstacle information that shows the current obstacles near the ship. The DP module supplies the CA module with an area where the ship is able to manoeuvre and thus creates boundaries for new waypoints that can be realistically assigned. The CA module has two main functionalities, the first is an assessment of the collision risk and the second is to navigate the ship safely both in the harbour and in the open sea. When a collision risk is detected, a suitable state is requested from the SSD module, in which a final definition of the ship state is made based on all given data from different sub-systems.

The situational awareness (SA) module of the ANS is connected to multiple sensor devices of different types. The SA module fuses the sensor data and extracts relevant information on the ship's surroundings to be used by the CA system. The SA module can also perform reduction of sensor data for more efficient off-ship data communication. Technology development issues related to the SA system and the ship sensors are discussed in Sections 2 and 3.

1.3. Environmental mapping and obstacle detection for autonomous ship navigation

Mapping means the creation of a representation of the world. There are multiple ways the mapping process can be performed and what kind of a presentation of the world is created. These are dependent on the application, where the maps are needed and what sensors are used for perceiving the environment. Map information is used in for path planning, obstacle avoidance, and localisation of the autonomous ship.

On sea and harbour area, it is possible to use nautical and terrain charts to obtain information about shipping lanes, shoals and coastal terrain. Dynamic obstacles, such as other vessels, are mapped by using the ship's situational awareness system, combined with e.g. AIS data. Many methods have been developed for processing perception data for modelling and representing a 2D or 3D world, to mention for example occupancy grid maps, height grid and Quadtree type of maps. [Mooney]

Two of the most common approaches for presenting the world are topological and metric maps. Topological approaches describe the connectivity of spatial locations in the environment, whereas metric maps describe the world through a geometric presentation. Topological maps are best suited for high-level path and mission planning. Metric maps contain geometric information that is necessary to plan and execute trajectories safely while avoiding collisions. The mapping process creates a representation of the surrounding world. [Elfes, 1987], [Broten 2012].

Obstacles can be presented as parts of the map, but it can also be beneficial to present dynamic obstacles separately. Object detection and tracking is closely related to obstacle avoidance procedures and together they ensure collision free navigation of the vessel. There are several methods developed for obstacle tracking, commonly used are particle and extended Kalman filters. When a separate presentation is used for dynamic obstacles, using novel sensor fusion techniques and commercial ship object tracking functionalities (ARPA), their movements and actions can be easier to predict. For example, obstacles can have speed or a predefined path, as well as kinematic properties that can be used to predict their positions in the future. [Sinisterra, 2014]

2. Situational Awareness (SA) for autonomous ships

2.1.Sensoring the ship environment

Methods for the fusion of multiple sensor types, such as LIDARs, cameras and radars have been actively studied for automotive applications [Herpel, 2008], [Mukhtar, 2015]. For example, a short-range radar or LIDAR can provide accurate range, velocity and angular measurement of objects, while cheaper and smaller cameras can provide better spatial resolution for object classification. Near-IR (NIR) cameras, with active illumination, or thermal LWIR cameras can be used also for night-time imaging. On the other hand, the use of a radar allows operation also under difficult weather conditions (e.g. heavy rain or snow) where the cameras (including IR) may fail. The same issues apply also to marine SA sensors.

The main task of sensor fusion is to combine the data from different sensor source in such a way that optimal SA perception is guaranteed under all conditions and in all situations. SA data is then used to map local obstacles to enable reactive collision avoidance.

2.1.1 Sensor technologies for Situational Awareness

Cameras

Cameras are a natural choice for SA. They are cheap (with some exceptions), small in size and durable, and can provide very high spatial resolution with colour information for object identification. True night-vision is possible with thermal IR imagers and a pair of cameras can be used in a stereoscopic configuration for (limited) 3D sensing. Due to the huge range of both commercial and niche applications, camera technology is still constantly improving. The large existing knowledge-base on visual analysis algorithms provides many potential solutions also for marine Situational Awareness. Normal visual spectrum HD cameras are seen as an important technology to be fused with other sensory data. High spatial resolution allows for recognition of objects and obstacles, either by a human remote operator or through automated analysis algorithms, and colour information can be used to help the separation (segmentation) of relevant objects from the background (sea surface).

A disadvantage of cameras is the massive amounts of data generated by high-resolution sensors, which requires extensive processing performance and high-bandwidth data links for analysis and transmission. However, when considering a marine SA implementation on a large ship, the requirements e.g. in terms of the small size or low power consumption of processing hardware, are much less strict than for many other autonomous platforms, such as cars or aircraft.

Visual spectrum cameras have some severe limitations: they cannot be used in the dark (apart from detecting lights) and their seeing distance drops very quickly in bad weather, such as fog or heavy rain. Better performance can be obtained with cameras operating in the Infrared (IR) range. Near-IR (NIR) sensing is commonly used for night-vision in security cameras, because NIR signals can be captured with inexpensive CMOS/CCD camera sensors. This, however, requires active IR illumination of the scene, which is not practical for ship SA. True passive night-vision can be realized with Long-Wave IR (LWIR) cameras, which are sensitive to IR radiation in the 8-14 μm wavelength range. Because thermal LWIR radiation is passively emitted by all objects, LWIR sensors can be used for imaging in total darkness. Due to the varying thermal emittance properties, depending on e.g. surface materials and surface geometry, a visually meaningful image can be created even from objects and scenes, where the average temperature is effectively uniform. As can be seen from Figure 3, thermal imaging can be beneficial even in daylight conditions, e.g. in difficult illumination conditions.

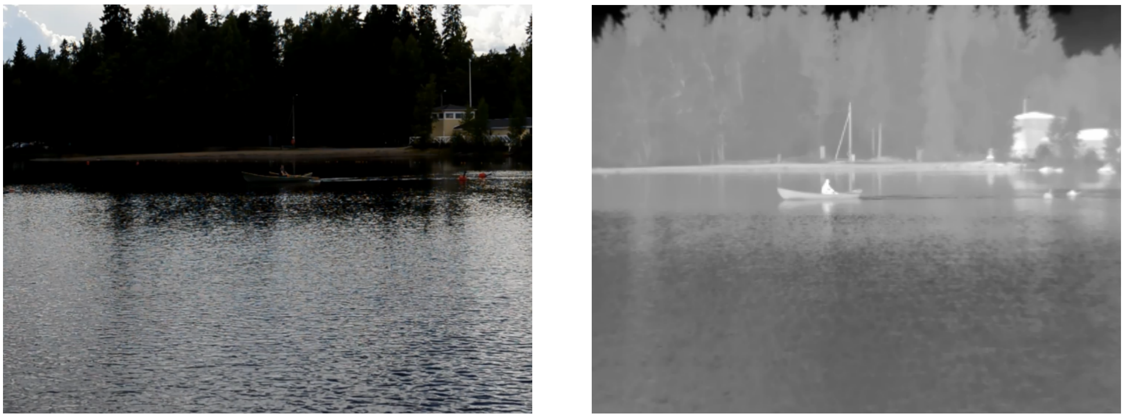


Figure 3. Daylight Scene captured with a normal camera and a thermal camera.

Microbolometer-based LWIR cameras are the most affordable thermal imaging technology. Furthermore, unlike some other IR technologies, bolometer sensors do not require cryogenic cooling, leading to simpler (more robust) camera hardware. The disadvantage of bolometer-based LWIR sensors is their low resolution (typically 640x480 pixels, megapixel sensors are available but very expensive), i.e. for the same spatial accuracy, the field-of-view (FOV) is narrower than in a normal HD camera, as can be seen from Figure 4.

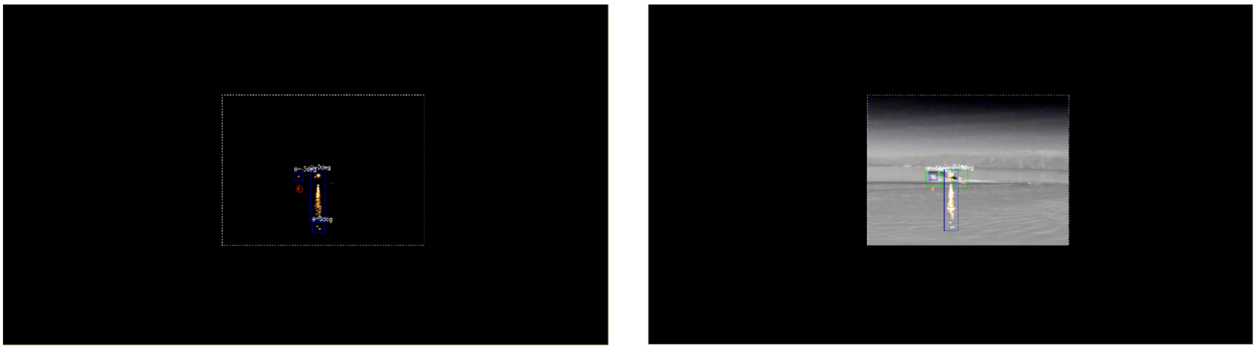


Figure 4. Fusion of visual light and thermal imaging at night.

More recently, Short-Wave IR (SWIR) camera technology has become available also for non-military and or scientific applications [Stark, 2015]. SWIR sensors operate in the 1-3 µm wavelength region, where the detected signal is not passively emitted (thermal), but reflected radiation. SWIR sensors provide better visibility through haze or fog than visual spectrum cameras and they also work well in very low light conditions, but not in total darkness. It has been stated that SWIR enables better detection range under humid and foggy conditions than LWIR [Wallace, 2013]. However, SWIR technology is currently more expensive than e.g. LWIR, and does not improve on the spatial resolution.

While IR sensors offer better visibility than visual range cameras, their performance is also degraded in bad weather. For example, different IR-bands are attenuated differently depending on the level of humidity in the atmosphere, which can lead to greatly varying seeing ranges depending on weather conditions [Beier, 2004]. This is why a sensor source which is robust against weather effects, such as radar, has to be fused with the less reliable camera data.

Radar and LIDAR

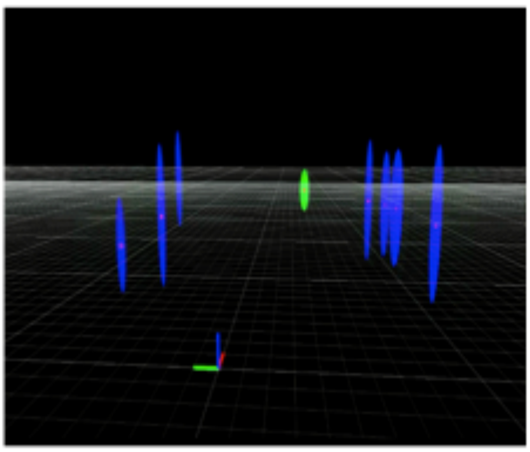
Camera-based sensing (fusion of visual and thermal imaging) has two significant disadvantages regarding to SA extraction in autonomous vehicles 1) insufficient weather tolerance and 2) lack of an easy way to extract object distance information.

A combination of two monocular cameras can be used to implement stereo imaging, i.e. create a 3D map of the visual scene through disparity mapping between two images. The drawback of stereo imaging is the computational complexity related to large amounts of image data applied to stereo matching algorithm. Also, the choice of camera baseline, i.e. the physical separation of the two sensors, effectively sets constraints on the distance resolving capability of the system. Much better performance can be obtained by using active sensor technologies, such as radar or LIDAR.

In maritime applications the use of radar has a long history. Therefore, several radar system suppliers can be found in the market for obstacle detection and mapping. Radar capability is influenced by the operating frequency band of the radar, so that typically higher frequencies offer better angle and range resolution. There is a wide variety of radars in the market, intended for different purposes, having specific carrier frequencies, bandwidths, transmit durations, waveforms, antennas etc. Typically, marine radars are microwave radars using S- or X- bands, which are robust in different weather conditions. [Heuel, 2013]

However, the resolution of traditional marine radar may not be sufficient for reactive collision avoidance. For example, considering an autonomous ship in a harbour area or approaching the dock, the resolution of the radar in the very near field, i.e. some hundreds of meters, needs to be good enough to be able to detect, and maybe also track, even small stationary and moving objects. New Ka and W – band radars, originally developed for automotive applications, could be beneficial in autonomous ship applications, especially for very close range obstacle detection. They offer much better angular and distance resolution than traditional ship radars, at the cost of reduced range. These new type of radars together with modern S- and X -band radars and several different type of cameras are exploited in the development to enable near-field reactive collision avoidance, as well as autonomous navigation in e.g. harbour areas. [Skolnik, 2008], [Seliga, 2010]

LIght Detection And Ranging, LIDAR (or LAser Detection And Ranging, LADAR) is a scanning laser sensor technology, which can provide very accurate distance measurements. Multichannel devices (e.g. with a 64 laser array), such as those used in Google's autonomous test cars, can create a very detailed 3D map of the surroundings of the vehicle. LIDAR-based marine navigation has been proposed and demonstrated e.g. in [Jimenez, 2009], [Pastore, 2010] and [Halterman, 2010].



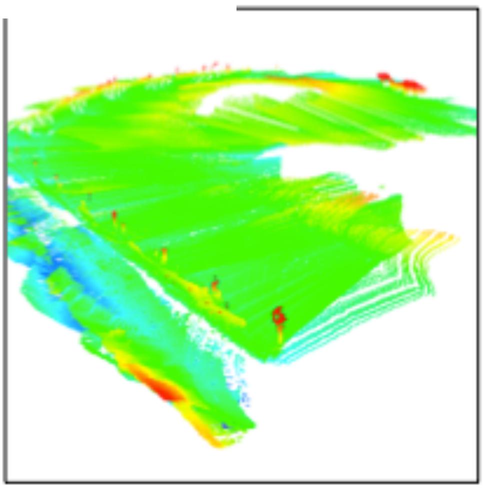


Figure 5. Left: radar view of object. Right: 3D LIDAR scanning data

One possible disadvantage of LIDAR is that it uses rapidly moving mechanical components for the scanning operation, which could be prone to malfunctions, especially over longer periods of time in a harsh marine environment. Because LIDAR employs a laser beam (typically a pulsed IR laser), its range and accuracy is also affected by adverse weather, such as heavy fog, rain and snow, similarly to IR cameras.

2.2. Sensor data fusion and processing

In practically all fields of vehicle autonomy, utilisation sensor fusion has been seen as the key for achieving sufficient situational awareness reliability. Each separate sensor type exhibits particular weaknesses and limitations under some conditions (weather) or detection setups (range, field of view, identification). Also, both false positive and false negative detections can never be completely prevented for a single sensor; optimising one leads to a trade off against the other. By combining the capabilities of multiple sensor modalities, individual errors and weaknesses can be averaged out and better overall performance can be reached. Table 1 roughly compares different potential sensor types in terms of performance aspects relevant to marine SA.

Table 1. Comparison of different marine SA sensors.

	Visual HD cameras	IR cameras	Ship radar	Short-range radar	LIDAR	Sound
Spatial Accuracy	++	+	- -	-	++	- -
Field of view	+	-	++	-	+	++
Distance measurement	-	-	++	++	++	- -
Object identification	++	+	- -	- -	+	+
24H, all weather operation	- -	+	++	++	+ (?)	- (?)
Computational load of analysis	- -	-	++	++	- -	+
Marine robustness	++	++	++	+(?)	(?)	(?)
Price	++	-	+-	++	- -	+

Based on the review of existing solutions reported in various fields of autonomy and the testing of sensor technologies already done in AAWA, the fusion of different types of radars and visual sensors, including thermal IR cameras is seen as a feasible solution for marine situational awareness. Radars enable easy tracking of target distance and can provide the required tolerance to bad weather. The application of new high-GHz radars developed for automotive collision avoidance can also provide sufficient object detection accuracy for ranges which are too short and too inaccurate for conventional ship radar. Cameras can augment radar data by providing more detailed information on detected objects. Furthermore, the fusion of cameras and radar can also increase detection robustness. Thermal IR cameras can see objects also in total darkness, while colour information from normal HD cameras can be used for segmenting objects in the water. A significant consideration is also the affordability of the sensory system. While many high-end sensor devices could provide a valuable addition to the SA-system, a solution which takes advantage of affordable technology should be preferred. In this sense, the combination of radar and imaging has an advantage over e.g. LIDAR sensors.

Sound signalling (e.g. by horns) is also an integral part of the current maritime navigation process. Therefore, in order to realise a SA system which is at least as capable as a human crew, sound capture and data analysis should also be included. While loud and clear sounds such as e.g. horns and whistles could be fairly easily detected, their sources should also be accurately localised relative to the ship, to help reactive collision avoidance. This requires more than just capture and detection of sound, the sound source also has to be spatially localised, e.g. via an array of microphones, and the sound data fused with other sensor modalities. Sound sensors could also be applied in a more general manner in the SA system, for detecting and identifying other vessels by the sounds that they normally emit.

Sensor data processing

The most computationally intensive part of a sensor fusion pipeline is the analysis of data provided by cameras. The output created by radars is very sparse (objects with some noise) and therefore much easier to process. An important part of image data processing, is the segmentation of the input data. High resolution video cameras provide massive amounts of data, most of which is irrelevant for the process of object detection and image content understanding. The first step in an image analysis process is therefore to segment the raw input data, i.e. to remove all information which is not relevant to the particular task (background) from those features and objects which should be detected (foreground). On the reduced amount of image data, more complex analysis algorithms can then be applied for spatial and temporal object tracking and object classification. For example, a marine scene can be assumed to always consist of three different coarse regions: water in the bottom part of the image, sky in the top part and a horizon area in the middle. By finding the horizon line, a large part of the image data can be discarded from further processing. Sensor fusion can be used to make the process easier by using clues from other sensor modalities to help the image processing pipeline. For example, the detection (or lack thereof) of objects in the view of a radar can be used to guide the image segmentation algorithm to focus more on potential object areas and false detections from image data can be discarded if suitable confidence based on radar data is available.

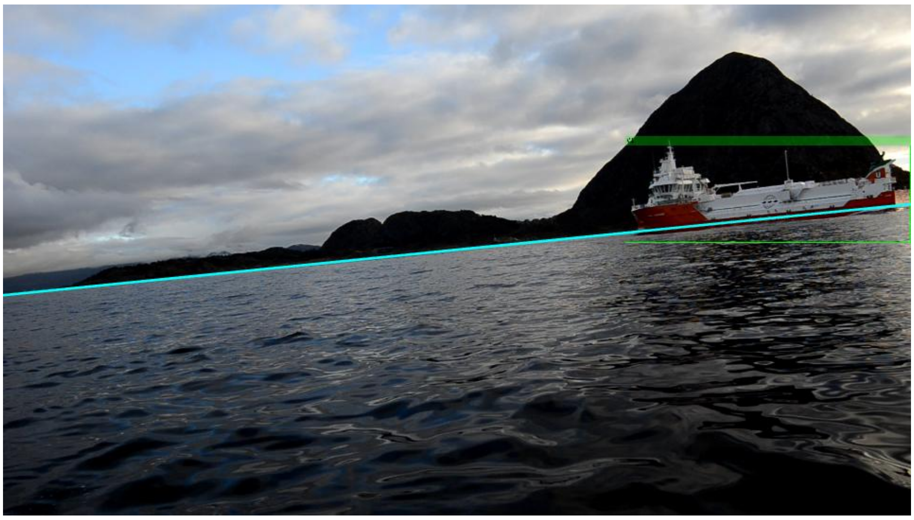


Figure 6. Horizon detection and object segmentation.

Data from multiple sensors can be fused in different ways, as illustrated in Figure 7. Low-level fusion is performed on the raw or nearly unprocessed data from different sensors, while in high-level fusion, the separate data streams are processed individually and the detections from different sensors are combined on object level. The use of low-level fusion is more natural between two different camera types, such as visual and thermal sensors, while the fusion between cameras and radar can be more naturally implemented on a higher object level. In practice, the most efficient way to implement sensor fusion between multiple (>2) different sensor modalities is probably a combination of both low-level and high-level fusion approaches.

In a marine sensor fusion process, radar can be used to provide bearing angles and distances for various objects in the scene. This information can then be mapped to corresponding objects segmented from multiple camera data, to extract more details. The presence of the same object in multiple sensor data provides a more robust detection than a single sensor source, which can always provide noisy or incomplete data. Frame-to-frame analysis results often contain temporal noise, with objects being sometimes lost due to analysis uncertainty. Spatial and temporal object tracking can be applied to provide a continuous situational awareness for reactive collision avoidance.

In order to reach best possible autonomous navigation reliability, all other available data sources which can help the ship navigation and collision avoidance process should also be fused with onboard sensor data. These include already commonly used technologies such as GPS, AIS, ARPA and ECDIS, the outputs of which can be fused with the extracted sensor data via high-level local and global map representations.

3. Off-ship communication

The capability for remote human interaction and control has to be enabled for situations, which the ship autonomy cannot resolve or is not allowed to handle by itself. Relaying the SA information gathered by the ship's sensors to a remote operator may require the transfer of significant amounts of data. Due to practical limitations on e.g. satellite communications at open sea, the same amount of bandwidth may not be available at all times. Methods for reducing the amount of sensor data only to what is absolutely needed for the human operator to perceive the environment of the ship needs to be considered. Also issues such as data security (intentional tampering) and link reliability should be addressed and the possibilities of using multiple alternative communication networks (satellite, VHF, 4G) depending on availability and performance needs should be examined.

Transmission of HD video from the ship to the shore control centre is not required all the time. It may be required only when something unexpected that requires the attention of the shore control centre happens. Such a situation could be for example detecting an obstacle which requires human identification, or a situation in which the ship is unable to calculate a reliable avoidance manoeuvre. It is assumed that for most of the time in the open seas, the autonomous control system is able to handle the situation with the help of the sensory systems on board (collision avoidance, object detection etc.). Thus, most of the time, very minimal amount of outbound data, such as ship state information and reduced sensor data is required. On the other hand, sufficiently high transmission capacity should be available when needed on short notice.

The amount of data to be transmitted grows quickly as more sensors are added to the system, especially with high resolution video. Reduction of the frame-rate, lower image resolution and efficient video compression have traditionally been applied for remote monitoring over low-bandwidth datalinks. However, to even further reduce data transfer requirements, the sensor inputs can be segmented with the onboard SA processing system to extract only the minimal amount of data, which can still be sufficient for human understanding of the scene. Foreground/background segmentation performed by the ship's SA-system, enables transmission of only certain relevant features, objects or regions of interest (ROI), as illustrated in Figure 8. A human operator could, at least in non-critical conditions, extract sufficient situational awareness from very sparse segmented image features, which can require the transfer of very little data.

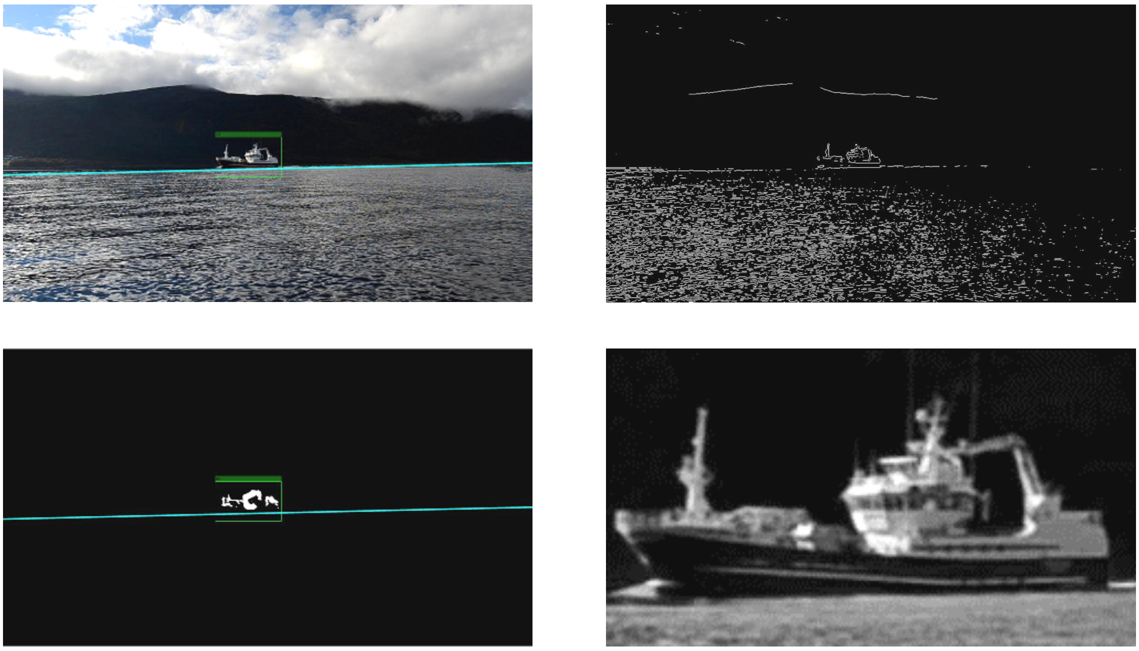


Figure 7:
Image segmentation for reducing data rates. Top-left: Original (1900x1080 px) with segmented objects. Top-right: 1-bit edge data. Bottom-left: 1-bit object data. Bottom-right: Region of interest capture of object area (241x145 px).

On the open sea, the main means of communication is via satellite, however, satellite communication can be disturbed by weather conditions. The amount of attenuation caused by e.g. heavy rain is dependent on the frequency band employed by the satellite network. For example, fading is much more severe at Ka-bands (above 20 GHz) than at the L-band (1 to 2 GHz) [Qingling, 2006]. This means that severe weather may degrade the performance of links operating at Ka-bands. However, combining a Ka-band system with e.g. a less weather sensitive L-band network, as has been done in the Inmarsat Global Xpress system, reduces the risk of losing all communications even if the Ka-band system would be non-operational. The Inmarsat system allows dynamic switching between the two satellite types without user effort. However, the lower capacity offered by the L-band satellites has to be taken into account when allocating bandwidth to off-ship communication.

In the future, there may be a large number of autonomous vessels in the same satellite beam or cellular network cell area. As the total bandwidth within a certain beam or cell area is shared between all users, a shortage of bandwidth may be created if many vessels simultaneously require high bandwidth, for example for HD video transmission. This problem could be leveraged by forming swarms or fleets of vessels where one ship would be the leader. In this way, communication to a shore control centre could be coordinated via the lead ship with line of sight ship-to-ship communication. In this way it could be possible to optimise the use of satellite bandwidth in a certain area by reducing the need for all the ships in the swarm to communicate with the shore control centre simultaneously.

Possible effects of weather or multi-user congestion on communication performance should be considered carefully when implementing the control and "intelligence" of the whole autonomy system through the "Virtual Captain". Difficult situations may arise if poor weather simultaneously causes reduction of SA-system capability, requiring more shore control intervention or decision making, and a reduction in datalink capability required to transfer sensor data from the ship. Correct behaviours and precautions for such situations should be defined. These issues are addressed in the ANS architecture development in AAWA, through the Virtual Captain and the ship state definition discussed earlier.

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Legalities

Henrik Ringbom, Adjunct Professor in Maritime Law and the Law of the Sea

Department of Law, Åbo Akademi University

Felix Collin, Project Researcher, Faculty of Law, University of Turku

Mika Viljanen, Acting Professor of Civil Law, Faculty of Law, University of Turku

Legal Implications of remote and autonomous shipping

1. Introduction

Maritime law is a functional term used for describing a whole range of laws and other legal sources that govern the legal framework related to ships and their operation. It includes a variety of different legal systems, ranging from international law to regional and national rules and down to local rules. It covers issues of public concerns, such as safety, security and environmental protection as well as civil law matters, such as contracts of carriage, liability and compensation for damage, salvage and rules related to marine risks and insurance, to name but a few.

The prospect of unmanned ships addresses a very fundamental feature in shipping – the role of the master and crew on board a ship – and will hence affect a multitude of laws and regulation across the whole range of maritime law. An effort to summarise the different levels and types of rules concerned is made in the table in the annex.

The focus of this paper is on the international (global) rules. Three main kinds of such rules need to be distinguished. First, there are jurisdictional rules, which lay down states' rights and obligations to take measures with respect to ships. These are mainly laid down in the 1982 UN Convention on the Law of the Sea (UNCLOS), which is discussed in section 2. Second, the technical rules covering safety, environment and training and watchkeeping standards etc. are discussed in section 3. They are usually adopted by specialised UN agencies, such as notably the International Maritime Organization (IMO). Third, a series of international rules have been established in the field of private law to harmonise issues such as shipowners' civil liability for pollution, collisions or cargo-related losses and how such claims may be enforced. These rules are not as complete or widely ratified as the public law conventions discussed in sections 2 and 3 and may therefore be subject to greater national variation. The main relationships of these rules to autonomous shipping are discussed in section 4.

2. Law of the Sea

2.1 General

The law of the sea deals with the rights and obligations of states over the seas. As far as shipping is concerned, the key issues addressed by this body of law include: to what extent can ships navigate in different sea areas; what obligations do states have over ships flying their flag; and what rights do other states have to interfere in the navigation of ships in different sea areas?

Today's law of the sea governing navigation is more stable than ever before in history. The 'Constitution for the Oceans', UNCLOS enjoys a widespread formal acceptance worldwide (167 contracting parties) and its provisions concerning navigational rights and duties are widely accepted as representing customary law (and hence apply to non-parties as well). The convention lays down the rules on establishment and delimitation of maritime zones and includes detailed rules on states' rights and obligations, differently for each zone.

A first – and fundamental – question to be resolved is whether ships without a crew on board are 'ships' or 'vessels' within the meaning of the convention at all. The two terms are used interchangeably in UNCLOS, but neither is defined. It does, however, follow from the nature of the activities carried out by the large, self-propelled, cargo-carrying, commercially-operated unmanned ships of interest here that they probably will have to be regarded as vessels/ships by virtue of their size, features and functions. Existing international conventions that define the term ship do not include references to crewing and at national level, too, the definition of a ship is usually disconnected from the question of whether or not the ship is manned.[1] It would also seem unjustified that two ships, one manned and the other unmanned, doing similar tasks involving similar dangers would not be subject to the same rules that have been designed to address those dangers.

From the assumption that unmanned ships are 'ships' and 'vessels' within the meaning of UNCLOS follows that they are subject to the same rules of the law of the sea as any ordinarily crewed ship. The same obligations apply to unmanned ships and their flag states with respect to compliance with international rules. On the other hand, they also enjoy the same passage rights as other ships and cannot be refused access to other states' waters merely because they are not crewed.

2.2 Flag State Jurisdiction

Flag state jurisdiction represents the traditional cornerstone of the regulatory authority over ships. UNCLOS establishes that all states have a right to sail ships flying their flag and to fix the conditions for granting nationality to ships (Articles 90 and 91(1)). However, the convention also includes a number of detailed duties for flag states.

Every state has the obligation to "effectively exercise its jurisdiction and control in administrative,

[1] Study 'Liability for Operations in Unmanned Maritime Vehicles with Differing Levels of Autonomy', performed by the University of Southampton on behalf of the European Defence Agency's Group on Safety and Regulation of Unmanned Maritime Systems (SARUMS), , 2016, Part 1, Chapter 3 (unpublished).

technical and social matters over ships flying its flag" (Article 94(1)), including to "assume jurisdiction under its internal law over each ship flying its flag and its master, officers and crew in respect of administrative, technical and social matters concerning the ship" (Article 94(2)(b)). The flag state shall also "take such measures … as are necessary to ensure safety at sea with regard, inter alia, to … the manning of ships, labour conditions and the training of crews, taking into account the applicable international instruments" (Article 94(3)(b)), including measures necessary to ensure "that each ship is in the charge of a master and officers who possess appropriate qualifications, in particular in seamanship, navigation, communications and marine engineering, and that the crew is appropriate in qualification and numbers for the type, size, machinery and equipment of the ship" (Article 94(4)(b)). When adopting these measures each flag state is required "to conform to generally accepted international regulations, procedures and practices and to take any steps which may be necessary to secure their observance" (Article 94(5)).

UNCLOS, in other words, avoids the need to formulate more precise obligations of flag states by referring to an abstract, and continuously changing, set of international rules to be developed elsewhere. In this way it avoids 'freezing' the requirements at a given point in time or at a given technical level, while still preserving the international character of the rules in question. The more precise extent of flag states' obligations is hence left to be developed by the IMO in particular.

2.3 Port and Coastal State Jurisdiction

While the flag state's jurisdiction applies irrespective of the ship's location, other states' parallel jurisdiction over the same ship depends on the maritime zone concerned. The coastal state's authority over a foreign ship increases with the proximity of the ship to its shores.

If the ship is voluntarily present in one of its **ports or internal waters**, the coastal/port state has broad jurisdiction over foreign ships. Internal waters form part of the sovereignty of the state (Article 2) and in the absence of specific limitations, the jurisdiction over foreign ships in this area is therefore complete. Moreover, ships have no general right to access foreign ports and the port state's wide discretion to place entry conditions for foreign ships is widely acknowledged, including in UNCLOS Articles 25(2), 211(3) and 255. In other words, a port state may (unless it has accepted specific obligations to the contrary) refuse unmanned ships access to its ports or internal waters, provided that the refusal complies with certain more general reasonableness criteria that exist in general international law, such as non-discrimination, proportionality between the measure and its objective and that the prohibition does not constitute an abuse of right (Article 300). This may turn out to be a significant limitation of the free of movement of unmanned ships, but the potential limitation is by no means unique to unmanned ships.

With respect to ships passing through its **territorial sea** (which may extend up to 12 nautical miles from the coastline/baseline), the rights of coastal states are more limited. Under a longstanding principle of the law of the sea, all ships enjoy a right of 'innocent passage' through other states' territorial seas. Passage is deemed to be innocent as long as it is not "prejudicial to the peace, good order or security of the coastal state" (Article 19(1)). A list of activities that meet those criteria is given in Article 19(2), but as the list focuses on ships' *activities* (such as use or threat of force, military activities, fishing activities or wilful and serious pollution) questions related to a ship's manning will not as such render passage non-innocent under the wording of UNCLOS.

Regarding the coastal state's legislative jurisdiction, Article 21(2) provides that a state may not impose its national requirements on the construction, design, equipment or manning of foreign ships in its territorial sea, unless those requirements are giving effect to "generally accepted international rules and standards" (Article 21(2)). Independently of what laws the coastal state has adopted, it may not "impose requirements on foreign ships which have the practical effect of denying or impairing the right of innocent passage" (Article 24(1)(b). The right of innocent passage extends to ships that are deemed to pose a particular risk for the coastal state, such as nuclear-powered ships and ships carrying nuclear or other inherently dangerous or noxious substances (Article 23).

The areas of a coastal state's territorial sea which forms part of a **'strait used for international navigation'** are subject to even more limitations for coastal states (and correspondingly stronger passage rights for ships). There are different kinds of such straits, but many of the most important straits that are completely covered by the bordering straits' territorial seas, such as the Straits of Dover and Malacca, are subject to the regime of 'transit passage', where ships' right of (continuous and expeditious) passage are granted and may not even be temporarily suspended by the bordering states (Articles 37-44). Many other important straits, including the Danish and the Turkish Straits, are governed by long-standing international conventions which guarantee the navigational rights of foreign ships (Article 35(c)).

The jurisdiction to prescribe national requirements is obviously even more limited with respect to ships sailing in the **exclusive economic zone (EEZ)**, which may extend beyond the territorial sea, up to a maximum of 200nm from the coastline/baseline. In this zone freedom of navigation (for all states) applies, subject to having due regard to the interest of other states (Article 58). The most express prescriptive jurisdiction of coastal states over foreign ships in the EEZ concerns laws aiming at the protection of the marine environment and even here, coastal states' jurisdiction is limited to prescribing rules that give effect to international rules while enforcement measures exclude interfering in the passage, save for the most serious cases of pollution and damage (Articled 211(5) and 220).

In sea areas that lie beyond the jurisdiction of any coastal state, **the high seas**, the starting point is that the flag state alone has jurisdiction over the ship. A number of exemptions to this main rule exist, but none of them is relevant for the question of navigational rights of unmanned ships.

2.4 Other relevant provisions in UNCLOS

Apart from the jurisdictional provisions, certain other UNCLOS provisions may turn out to be problematic for unmanned ships. The obligation set out in Article 94(4)(b) that each ship needs to have a (properly qualified) master and a crew was already mentioned above. While this requirement may arguably be met in case of remotely operated ships it is less obvious how a fully automated ship would qualify. Since unmanned shipping operations will often represent a mix between different degrees of automation, depending on sea areas, traffic density etc. further clarifications of this obligation may be needed, at least at the level of the 'generally accepted international rules'.

Another UNCLOS provision, which presumes a crew on board is the obligation of the master to render assistance to persons in danger or distress according to Article 98(1) (as specified in SOLAS Regulation V/33). The communication part of the duty can presumably be met by remotely operated ships with relayed radio communications, but it is less clear how physical assistance can be rendered by a ship without a crew on board. The duties include qualifications by reference to "in so far as he can do so without serious danger to the ship" or "in so far as such action can be reasonably expected of him" which will probably reduce the extent obligations for unmanned ships, as the available options will be fewer. However, the absence of a crew does not in itself do away with the duty to provide assistance to the extent necessary and reasonable.

3. Technical requirements

3.1 General

IMO alone has adopted more than 50 international conventions and protocols aimed at harmonising rules for international shipping. Most of these rules are laid down in the form of obligations imposed on ships' flag state administrations. It is primarily for the individual states parties to the conventions ensure that each ship flying their flag is bound by and complies with the rules. A certificate whereby the administration confirms compliance is often required and this certificate shall be accepted by other states as if it were issued by themselves. In addition, the IMO rules frequently include a possibility for port states to verify that ships that enter into their ports in reality comply with the requirements and – if not – to take corrective measures, including detaining the ship if necessary.

Since it is not possible to cover all IMO conventions here, a selection of the most important instruments with implications for crews has been made here. The selected conventions (SOLAS, MARPOL, STCW and COLREGs) are all widely ratified among the world's (flag) states and hence applicable worldwide. The Maritime Labour Convention (MLC), which was developed by the International Labour Organisation (ILO) in 2006, has already been ratified by more than 70 states.

3.2 The International Convention for the Safety of Life at Sea (SOLAS)

The main convention for maritime safety is the SOLAS Convention, adopted in its first version already in 1914. The convention covers a very wide range of matters, its annex containing the substantive rules consists of fourteen different chapters. Some of the rules of SOLAS are only applicable to ships of a specific type or age while the applicability of others depends on the trading area. The focus here is on rules applicable to a new bulk carrier above 500gt in commercial use in international trade, with a particular emphasis on the rules that may turn out to be challenging for a ship without a crew on board. The brief – and incomplete – review thus focuses on operational and functional requirements that explicitly or implicitly presuppose the presence of crew members.

Chapter I establishes the general application of the regulations in the Annex and an exemptions scheme, which is based on three different categories of exemptions:

1. Certain categories of ships that are completely <u>excepted</u> from the SOLAS rules and hence beyond its scope are listed in Regulation 3. However, none of the listed categories are relevant for present purposes.
2. Regulation 4(b) includes a possibility for flag state administration to <u>exempt</u> "any ship which embodies features of a novel kind" from the requirements of Chapters II-1, II-2, III and IV if their application "might seriously impede research into the development of such features. Such exemption shall be communicated to IMO and do not relieve the ship from the obligation to comply with safety requirements that in the opinion of the administration are adequate for the service and acceptable to the (port) states to be visited by the ship.
3. Administrations have a more general possibility to accept <u>equivalent solutions</u> if they are satisfied that the equivalent is at least as effective as that required by the Convention. More

specifically, this possibility applies where SOLAS requires "that a particular fitting, material, appliance or apparatus, or type thereof, shall be fitted or carried in a ship, or that any particular provision shall be made". In these cases the administration may allow other solutions "if it is satisfied by trial thereof or otherwise that such fitting, material, appliance or apparatus, or type thereof, or provision, is at least as effective as that required by the present regulations." Such equivalents shall be communicated to IMO together with a report of any trials made.

Chapters II-1, II-2 and III contain requirements for ships in the areas of structure, stability, machinery and electrical installations (Chapter II-1), fire protection (Chapter II-2) and life-saving appliances (Chapter III). These chapters mainly cover construction, equipment and materials on board, which does not raise particular issues from the perspective of automated operations. A ship that has to be constructed to meet certain stability requirements or features such as double bottoms will obviously have to do so even if the ship is unmanned, and the unmanned condition does not call for additional requirements in this regard.

However, they all include some degree of operational requirements, relating to information procedures and communication for the crew, alarms, monitoring mechanisms etc., which are obviously difficult to apply on a completely unmanned ships. In some cases alarms, monitoring equipment and system operation may have to be shifted or added to the place where the controller is located, as otherwise the whole purpose of the requirement would be defeated. Similarly, term 'navigating bridge', which features frequently in the rules relating to steering gear, indicators and various types of engine and fire alarms, need to be understood as referring to the place from which the ship is controlled, if the rules are to retain their meaning for remotely controlled ships. Many of the provisions specifically address the possibility to replace of human monitoring by technical equipment, such as unmanned machinery spaces.

For these chapters, the possibility for exemptions and alternative designs is likely to play an important role in facilitating compliance for unmanned ships,[2] which presupposes that the ship's flag state administration is favourable to accepting such exemptions.

The requirements concerning radio communications in **Chapter IV** include functional requirements on the equipment as well as watch-keeping requirements for the crew. The basic functional

[2] In addition to the exemptions provided for in Chapter I, the flag state administration may also under these three chapters exempt individual ships or classes of ships which do not proceed more than 20 nautical miles from the nearest land from the requirements "if it considers that the sheltered nature and conditions of the voyage are such as to render the application of any specific requirements … unreasonable or unnecessary" (Regulations II-1/1.4, II-2/4.1 and III/2.1).

requirements are that a ship at sea shall be capable of transmitting a distress alert by at least two separate independent means, receiving distress alerts, communicating (transmitting and receiving) in distress situations (search and rescue), maritime safety information, general radio communication and bridge-to- bridge communication. While at sea, every ship shall maintain a continuous watch on a number of frequencies as provided for. The rules include limited possibilities for exemptions and alternative designs. Compliance with these rules by unmanned ships presupposes that radio communication can be relayed to a place where a controller with full knowledge of the ship's whereabouts is on call.

Chapter V comprises a very wide range of different regulations, some of which may be quite challenging to implement for unmanned ships, such as the rules on manning of ships (Reg. 14), voyage planning (Reg. 34), bridge visibility requirements (Reg. 22) or pilot transfer arrangements (Reg. 23). The chapter also includes a general obligation for masters to proceed to the assistance of those in distress (Reg. 33) and highlights the master's discretion in decision-making relating to safety of sea or environmental protection, not to be restricted by the owner, charterer or operating company (Reg. 34-1). Many of the rules of Chapter V have wider applicability, in terms of the size of ships and trading areas, than the other SOLAS chapters. The scope for exemptions and equivalences varies from one regulation to another, but is in general terms more limited than generally in SOLAS.

The rules on **manning of ships** are of particular relevance. Generally speaking, decisions on ships' manning are left to the flag state administration. Once the administration is satisfied that the number and qualifications of the crew is adequate for the ship in question, usually assessed on the basis of an estimate and justification proposed by the ship's owner/operator, it will issue a safe manning document for the ship. In terms of substance SOLAS Regulation V/14 essentially only requires that "from the point of view of the safety of life at sea, all ships shall be sufficiently and efficiently manned." The associated guidelines (IMO Resolution A.1047(27)) are more detailed and mention a broader range of objectives with manning, including ship security, safety of cargo and environmental protection, but they are not legally binding.

The key question with respect to unmanned ships is whether the on-board manning could be reduced to the extent that a safe manning document could be issued even if there is not a single crew member on board the ship, i.e. that the safe manning would be zero. This, in turn, is closely linked to the question of whether tasks performed by the crew can be taken over by on-shore controllers or, in the case of highly automated operations, by other parties responsible for the ship's operations.

On the one hand, if a national administration were to decide that the functions required to ensure the safety of operations could be performed from other places than from the ship itself, it is difficult to find a provision that would be directly violated by that decision. 'Manned' is not necessarily the same as 'attended' and land-based controllers of ships might very well be able to perform many of the operational functions remotely while shore-based maintenance staff could undertake the required maintenance and service work. Indeed the guidelines on safe manning specifically provide that technical equipment and level of automation is to be taken into consideration when deciding on the manning levels (Annex 2, paras. 1.1.3 and 1.1.4). Nor would such a decision necessarily be against the purpose underlying the safe manning rules. It is not excluded that the operation of the ship might actually get safer if more functions are transferred to shore, as new types of equipment, redundancy systems etc. are brought on board and new functions will be performed from ashore.

On the other hand, the precise wording of the individual provisions should be considered with some caution in this context, as it is evident that the international and national rules on safe manning are drafted on the understanding that the crew is based on board the ship. The prospect of unmanned ships was not there at the time the rules were developed and one should therefore avoid reading in too much support for that development into existing legal texts. This is all the more true for fully autonomous operations, which stretches the notion of manning even further.

Chapter VI mainly contains operational requirements related to the safe loading and unloading of solid bulk cargoes. The chapter, like EU Directive 2001/96/EC, which makes the application of the 'BLU Code' (IMO Res. 862(20)) mandatory in EU ports, includes a number of loading procedures and requirements which presuppose active communication between the master, the shipper and the terminal operator.

Chapter IX makes mandatory the International Safety Management (ISM) Code, which requires a safety management system to be established by the shipowner or any person who has assumed responsibility for the ship (the "Company"). The main purpose of the ISM Code is to achieve a greater involvement of the shore-side company in the safety management of individual ships. It includes requirements on defining the master's responsibilities, plans for shipboard operations and maintenance, emergency preparedness, documentation etc.

Even if unmanned ship operations will inevitably serve to strengthen the link between shore-based operators and the ship, compliance with the Code poses certain challenges in case the manning of a ship concerned is reduced to zero. This is particularly the case with respect to lines of communication and reporting requirements. It can be further noted that SOLAS includes no possibilities for exemptions from Chapter IX, except for government-operated ships used for non-commercial purposes.

Chapter XI-2 addresses measures to enhance maritime security. It mostly deals with obligations for (flag state) administrations and ship operating companies, but presuppose a close communication between them and the ship. Regulations 11 and 12 specifically provide for the possibility for states parties to agree on alternative security agreements with other states or equivalent arrangements for their own ships provided they are at least as effective as those prescribed in Chapter XI-2.

3.3 International Convention for the Prevention of Pollution from Ships (MARPOL)

MARPOL is the main IMO convention for dealing with various forms of pollution from ships. It includes construction and equipment provisions, e.g. for oil tankers, but also certain operational and procedural requirements, including discharge limits, procedures for ship-to-ship transfers, various reporting obligations in case of spills and requirements to keep different record books. The applicable requirements will no doubt have to be complied with by unmanned ships, but generally speaking the MARPOL requirements are unlikely to present particular challenges in this regard. Record books can presumably be maintained in an electronic format while reporting and notification obligations exist in several conventions and need to be addressed in similar ways. Responses to pollution emergencies as outlined in the 'shipboard oil pollution emergency plan' (SOPEP) will have to be adapted to the response capabilities of unmanned ships.

3.4 Convention on the International Regulations for Preventing Collisions at Sea (COLREGs)

The COLREGs include a variety of 'rules for the road' in shipping, including on safe speed, signals, lights, etc. and rules on priorities and manoeuvring for different types of vessels in different situations. The rules will also apply to an unmanned ship, which represent no special category of ships within the meaning of the COLREGs.

The COLREGs cover both core navigational tasks of the crew on board a ship: situation awareness (including lookout) and operational decision-making when it comes to collision avoidance, priorities, speed etc. Both aspects are likely to pose challenges for unmanned ships.

The **look-out** requirement is provided for in Rule 5:

"Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision."

The purpose of the lookout rule is to make sure that whoever controls the ship are aware of the things around them to make informed decisions with respect to actions in avoiding collisions. The term look-out, as used by the Rules, does not necessarily denote a person, but rather the systematic collection of information. Moreover, the use of vague terms such as "proper" and "appropriate" provides flexibility for how such look-out is organised on board.[3]

The key question for unmanned ships is whether the wording of Rule 5 is broad enough to authorise a replacement of the human lookout by various types of cameras, radar, audio technology and other technical solutions. On the basis of the purpose of the rule and its flexible wording, it is arguable that this could be accepted if the equipment allows the controller to have an adequate overview of the circumstances allowing him take appropriate action in good time, to the same extent or better than if he would be on board. However, in view of the widespread authority of COLREGs and the nature of collision regulation (always involving more than one ship), any such clarification or interpretation should be done at international level rather than by individual states.

A separate question is whether the remote controller could also be in charge of the relevant **operational decisions** on the ship's navigation and manoeuvring. For this matter, COLREGs do not pose any direct textual obstacle. The subjects of the steering and sailing rules are 'vessels', without any further details about the person behind the decisions. The more problematic question arises when operational decisions are automated, without a controller in charge of the complete decision-making. From a technical point of view it is probably feasible to create algorithms that comply very diligently with the steering and sailing rules of COLREGs, even taking into account the sometimes unpredictable actions of other ships. A challenge, however, is that the COLREGs do not offer absolute rules of conduct. The rules for preventing collisions include obligation for both vessels to take avoidance action if it seems that there is a risk of collision. In addition, the COLREGs include a rule which serves to give precedence to good seamanship over its own provisions.[4] What constitutes good seamanship

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[3] See e.g. C. Llana & G. Wisneskey *Handbook of the Nautical Rules of the Road,* 3rd on-line edition, 2006 (updated in 2011), available at http://navruleshandbook.com/Rule5.html

[4] COLREGs Rule 2 provides that:

> (a) Nothing in these Rules shall exonerate any vessel, or the owner, master or crew thereof, from the consequences of any neglect to comply with these Rules or of the neglect of any precaution which may be required by the ordinary practice of seamen, or by the special circumstances of the case.
>
> (b) In construing and complying with these Rules due regard shall be had to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved, which may make a departure from these Rules necessary to avoid immediate danger.

for this purpose is a matter of fact to be assessed after consideration of all relevant prevailing circumstances. It seems clear that the incorporation of 'good seamanship' into any automated navigation programme may be coupled with serious difficulties.

Another question linked to COLREGs is whether unmanned ships should be given a specific signal, light, AIS message or the like to inform mariners on board other ships about their status. The answer to this is probably positive, and although some national solutions in this field could be justified under Rule 1(b), such decisions should preferably be made at international level. By contrast, if the objective is that unmanned ships should be naturally integrated into the environment of manned ships, it does not seem justifiable to maintain that unmanned ships should have a status that would offer it special privileges and priorities over other ships in COLREGs.[5]

3.5 International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW)

The STCW Convention does not strictly speaking apply to persons who are not working on board ships. According to its Article III, the Convention applies "to seafarers serving on board seagoing ships" flying the flag of a state party.

Even if not strictly speaking applicable, it is evident that a corresponding **training** regime will eventually have to be developed for persons operating ships remotely. In the shorter term, national administrations have been granted some discretion to apply equivalent arrangements, including to cater for technical developments. Under Article IX(1):

> The Convention shall not prevent an Administration from retaining or adopting other educational and training arrangements, including those involving seagoing service and shipboard organisation especially adapted to technical developments and to special types of ships and trades, provided that the level of seagoing service, knowledge and efficiency as regards navigational and technical handling of ship and cargo ensures a degree of safety at sea and has a preventive effect as regards pollution at least equivalent to the requirements of the Convention.

The qualification and competences of personnel who are operating ships from a remote location need to be given consideration in view of the combination of maritime and technology skills that is needed for this type of work. In the meantime, it is probably safe to apply (at least) the STCW and other

[5] It has been suggested, for example, that compliance with the COLREGs might be ensured merely by treating unmanned ships as a vessel "not under command" or "restricted in her ability to manoeuvre" under Rule 18, which would require other ships to give way.

national requirements analogically (as if the persons were on board the ship). If and when it is considered that unmanned ship operations require particular training, the relevant provisions would probably need to be amended to accommodate the new requirements for the operation of unmanned or largely automated ships.

The biggest challenges for unmanned ships in relation to STCW probably lie in the field of **watchkeeping**. The responsibilities for safe watchkeeping involve several persons, including the company, the master, the chief engineer officers and the whole watchkeeping personnel, whose responsibility it is to ensure "that a safe continuous watch or watches appropriate to the prevailing and conditions are maintained on all seagoing ships at all times". This, according to Regulation VIII/2(2)(1), includes that "officers in charge of the navigational watch are responsible for navigating the ship safely during their periods of duty, when they shall be physically present on the navigating bridge or in a directly associated location such as the chartroom or bridge control room at all times."

The more detailed requirements are laid down in the STCW Code, which in its mandatory Part A includes detailed provisions for watchkeeping in various conditions, including requirements on lookout, bridge, engine room and radio watches. Provisions for work hours and resting hours are included in the act as well as an obligation to perform route planning ahead of the intended voyage.

It is probably difficult for unmanned ships to meet the watchkeeping requirement as laid down in the STCW Convention and Code, which suggests that some amendment of these instruments will be necessary before commercial ships can operate completely without a crew or even with radically reduced watch arrangements on-board. On the other hand, it should be borne in mind that the reduction of on-board crew will normally be compensated by other functions performed remotely. These land-based functions should at least to some extent alleviate the concerns related to fatigue and reduction of safety levels which are usually associated with reductions of on-board crew.

In the end, the decision of whether a particular manning suffices for maintaining a safe lookout and watchkeeping on the ship will have to be addressed through the process of safe manning where all such factors will have to be taken into account.

3.6 Maritime Labour Convention (MLC)

The principal convention in the field of maritime employment, the 2006 Maritime Labour Convention (MLC) addresses a range of issues relating to labour conditions on board ships, ranging from recruitment and conditions of employment to fundamental rights of seafarers and recreational facilities on board. It applies to all seafarers on ships "ordinarily engaged in commercial activities".

The first point to be noted with respect to unmanned ships is that the scope of the MLC Convention is limited to 'seafarers' (MLC, Article II(2)), which is defined in MLC Article II(1)(f) as "any person who is employed or engaged or works in any capacity on board a ship to which this Convention applies" (emphasis added). Literally speaking, a ship which is entirely unmanned is accordingly not subject to these rules. Yet, for unmanned ships it might not be the last word, as Article II(3) includes a specific procedure for settling whether a particular category of person is to be regarded as a seafarer:

> "In the event of doubt as to whether any categories of persons are to be regarded as seafarers for the purpose of this Convention, the question shall be determined by the competent authority in each Member after consultation with the shipowners' and seafarers' organizations concerned with this question."

Secondly, since the rules mainly target living and working conditions on board ships their content largely lose their relevance if the ship is completely unmanned. It is therefore likely that issues such as employment conditions, working hours etc. for shore-based remote controllers will be subject to relevant land-based rules, possibly to be complemented by separate rules which take into considerations the specific nature of their tasks.

4. Liability rules

4.1 General – Autonomous Systems Challenge Legal Thinking

In view of the projected increase of autonomous vehicle technologies, future accidents will increasingly be caused by defective products and systems, while the role of human error is reduced or at least shifted elsewhere. When there is less human control, the reliability and problem-solving capacity of an autonomous system become crucial. The autonomous system must survive even when human intervention is not possible. This also means a change in legal thinking. Liability for damages cannot be based on human acts or omissions in the same way as today.

Currently law does not provide clear-cut answers to questions on liability for autonomous operations. In theory, several actors may be held liable for accidents caused by an autonomous system. Liability could, for example, be placed with the owner, user or manufacturer of an autonomous device, or even on the manufacturer who has produced the defective component. As autonomous systems become more common, the question of liability needs to be clarified. Some manufacturers of self-driving cars have even voluntarily taken up the question, irrespective of the legal framework involved:

> "We are the suppliers of this technology and we are liable for everything the car is doing in autonomous mode. If you are not ready to make such a statement, you shouldn't try to develop an autonomous system." [6]

From a technology point of view, autonomous vessels and self-driving cars may have many things in common. Nevertheless, legal conclusions applied to road traffic are not directly transferable to autonomous shipping and vice versa. Actors, automation, accidents and context are different. For example, ships are more likely to be operated by companies than by private individuals and automation is more focused on remote control than complete automation, at least in the early phases.

In the following, the basis of the current maritime liability legal framework is presented in section 4.2. After that, some ways in which autonomous technologies may affect the functioning of the existing liability framework are highlighted in section 4.3, followed by some concluding observations in section 4.4. As liability regimes differ in different jurisdictions, the present outline specifically departs from the Nordic and, in particular, Finnish legal perspective.

4.2 Maritime Liability Rules

Maritime law relating to ship operators' liabilities and compensation of damage include a number of peculiarities that are specific for this branch of law. The rules have been developed with the particular features of shipping in mind, often originating in considerations and concepts that have been applied for centuries. Basic issues, such as who is responsible, on what basis, and for what amount have to some extent been harmonised through international conventions. However, significant national variations exist as states' participation to the maritime liability conventions is not as uniform as for the safety conventions discussed above and as liability issues to a larger extent depend on national traditions and the legal system concerned. What laws will be applied in a given case in turn depends on a series of factors, including where the incident took place, the type of incidents and, in some cases, on the nationality of the key players involved, including the ship's flag state.

First, with regard to the liable person, existing maritime liability rules generally channels liability and duties to owners/operators of ships (Finnish: 'laivanisäntä', German: 'Reder', French: 'armateur'),

[6] Håkan Samuelsson, President and CEO of Volvo Car Corporation. See www.autoblog.com/2015/10/09/volvo-accept-autonomous-car-liability/

rather than to individual crew members or other assistants. Like employers generally, the owner/operator has a broad vicarious liability for damage caused in the service by the fault or neglect of the master, crew, pilot or others performing work in the service of the ship. The possibility for aggrieved parties to claim damages from others than the owner/operator is limited, but the owner/operator himself may be able to take subsequent recourse action against the party at fault. Special liability rules for particular cases may alter this starting point, but the broad vicarious liability of the owner/operator remains. In case of liability for collisions, for example, liability is placed on the 'ship(s)' at fault without any mention of the persons actually behind the collision. Environmental liability rules normally channel liability exclusively to the register ship owner, specifically excluding a range of other potentially liable persons. The identity of the person whose fault actually caused the damage will therefore not normally have an impact on the question of liable person from the point of view of claimants, as long as the fault is somehow linked to the operation of the ship.

Second, as to the threshold of fault or negligence required to trigger liability, the rules differ between different types of liability. For certain cases, such as incidents causing pollution or injury to passengers, it's accepted that claimants need not demonstrate negligence on behalf of the owner/operator to be compensated (i.e. owners in these cases have a statutory 'strict' liability). In the absence of such rules, the general rule is that liability of the owner/operator presupposes fault (negligent acts or omissions) on behalf of the owner/operator or his helpers. Fault-based liability is also the sole rule for apportioning liability in case of collisions. Autonomous ship operations may introduce new considerations regarding fault which are discussed in section 4.3 below.

Third, current maritime law grants the liable party with a wide-reaching right to financially limit the liability per incident based on the size of the ship. The right of shipowners/operators to limit liability is lost only in very exceptional cases. Claimants may accordingly not be able to recover full compensation for their losses, however legitimate their claims may be. Limitation of liability applies to faults committed by persons for whom the ship owner/operator is responsible and hence to a broad number of helpers involved in the operation of the ship.

The key elements of the general maritime liability regime are thus a broad vicarious liability placed on the owner/operator of the ship, which is based on fault or neglect and protected by a strong right of limitation. These rules also form the basis for liability insurances and other risk management. For ships above 300gt entering European Union ports there is an obligation to maintain liability insurance up to the applicable financial limits.

4.3 Implications of Autonomous Shipping

Even if there may not be an immediate need to change the foundations of maritime liability for autonomous ships, it is nevertheless important to recognise that the technical development towards increased automation does involve certain challenges to the current liability framework.

While errors committed by persons controlling remotely-operated ships are probably to be treated in the same way as errors committed by on-board crew members, autonomous technology may generate new types of errors and causal relationships. One example is damage caused by malfunction of an autonomous system, e.g. by device failure or faulty software. Even under these circumstances the owner/operator would probably be liable, at least in part, if he (or his assistants) fail to override the autonomous system. However, scenarios where human intervention is not even possible are more complicated. For example, if the connection between the vessel and controller is cut off, the vessel will have to rely exclusively on its autonomous systems. If an accident then occurs due to failures in the autonomous system, due to wrongful programming etc., it is less obvious that the owner/operator would carry the liability under a strictly fault-based liability scheme.

Such drawbacks of a fault-based liability scheme for highly automated systems may advance the argument in favour of a strict liability regime for automated ships. That, on the other hand, would create a significant differentiation between manned and unmanned vessels which might not be justified from a risk point of view and would in any case result in difficult issues of delimitation and definition.

As an alternative, claimants may try to base their claims on other liability systems than the maritime one. If accidents were increasingly caused by defective autonomous systems, the aggrieved parties could try to make claims against the builder of the vessel or the manufacturer of the autonomous system, its software etc. This would mean a shift towards product liability in the maritime context to fill a perceived 'liability gap' in maritime law. The development could be advantageous for claimants, as, for example, the EU directive on product liability is based on a strict liability of the producer and does not include a general financial limitation of liability.

It seems inevitable that pressures for such alternative solutions will grow if it turns out that the existing maritime liability regime is insufficient to cover the concerns of business partners, claimants and the general public relating to the risks involved with autonomous shipping. Autonomous shipping may very well act as a catalyst for this development, as it is easier to appreciate the critical role of the product (liability) in systems where there is no human intervention involved.

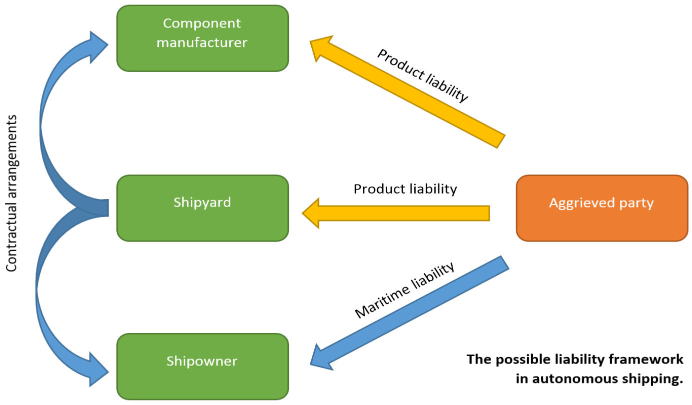

Figure 1: The possible liability framework in autonomous shipping

It should be emphasised, however, that the application of product liability rules to autonomous shipping is by no means straightforward either. The EU Directive on the matter, for example, only covers a limited range of the potentially relevant types of damages. For a fuller picture of role of shipyards and manufacturers of autonomous systems, other supplementary liability systems must also be studied in parallel. The key point at this stage is merely that product and other liability rules may very well operate in parallel with the traditional maritime liability regime in the future and that the prospect of several bases of liability for autonomous shipping needs to be taken seriously from the outset. The presence of parallel liability regimes necessarily involves complex legal questions relating to scope and priorities.

4.4 Concluding Observations

Autonomous shipping might not impose as acute demands for change of the maritime liability rules as is the case for some of the IMO Conventions discussed in section 3. However, it will affect the maritime liability framework, possibly quite significantly, albeit at a slower pace, initially probably driven by national case law. In the longer term, however, autonomous shipping could contribute to the introduction of new legal regimes to supplement the traditional maritime law framework to fill (perceived or real) gaps in the existing maritime law regime. As the rate of automation increases, there needs to be trust not only in the systems as such, but also in the legal regime which is there to make good for any damage caused by the new type of operations.

The increased automation in shipping may also affect maritime risk management more generally. Current insurance and contractual arrangements, for example, are all based on the premise that ships are manned. In autonomous shipping, the players involved, their roles, responsibilities and liabilities will be different, which calls for consequential adjustments in insurance and contractual practices. The legal implications of autonomous shipping accordingly extend beyond the liability rules.

5. Summary

The existing maritime law framework does not anticipate unmanned shipping. A broad range of rules are potentially concerned by a shift to unmanned shipping operations, but the nature of the challenge to accommodate this shift in the existing law differs from one type of rule to another.

Since it is assumed that the vehicles of interest here qualify as 'ships' under the various international and national rules, the regulatory situation is reasonably straightforward. The starting point is that the unmanned ships are subject to the same rights and obligations as their manned counterparts.

The most immediate challenges for ensuring the legality of unmanned shipping operations are found at the level of international technical rules, i.e. the IMO rules. This is not only where the most clear substantive tensions are found in relation to existing rules, but these rules are also decisive for steering the content of the jurisdictional rules of the law of the sea as well as of national maritime laws worldwide. In other words, if IMO rules specifically recognised and authorised unmanned shipping operations, even as an option, the regulatory challenge at the other legal levels would be significantly reduced.

The nature of the challenge also depends on the trading area of the ship and of the level of automation concerned. Ship movements within a single state involves one state's approval only and a large part of the international requirements do not apply to such transports. Autonomous ships involve greater legal challenges than remotely operated ones. The latter ones still have a crew, even if not on board, and may hence more easily comply with a number of today's operational requirements.

The IMO rules international rules accept a significant discretion for the flag state administration to accept alternative and equivalent solutions, which will no doubt be of relevance in the early phases of unmanned shipping. This flexibility for flag states has been somewhat reduced for EU member states by the introduction of EU maritime legislation, but it is clear that unmanned shipping cannot be introduced in the early phases without significant co-operation by the ship's flag state administration.

Maritime liability rules seem less acute to amend, but are also likely to undergo significant changes over time, as new players, new risks and - possibly - new liability systems will enter the scene with unmanned shipping operations. Existing liability rules may need to be interpreted, amended and possibly supplemented by dedicated rules to supplement the traditional maritime liability framework.

New liability rules, in turn, will have repercussions on marine insurance and other business relationships of the ship operators.

The legal challenges discussed here are not insurmountable as laws, at any level, can always be amended to accommodate new developments. The bigger question is whether there is societal acceptance and preparedness in the maritime community and beyond to make changes to accommodate unmanned shipping. If the answer to that question is positive, the legal challenge is reduced to identifying the key rules that are in need of adjustments and make the amendments. The amendments could possibly even be in the form of a generic acceptance of certain key issues of principle, such as the possibility to perform on-board functions from a remote location and the relationship between crew responsibilities and automated functions.

Such international amendments, however, take several years to initiate and formulate and still more years to come into effect. In the interim, non-binding IMO guidelines or best practice codes for unmanned shipping operations may provide important support and assistance for flag states that see the benefits of the development and wish to support it, but are still not prepared to risk the international connection that has inspired maritime regulation for centuries.

Annex: Summary of the different layers and substantive branches of maritime law

	Jurisdictional rules (main target: states)	**Technical req. and standards** (main target: flag states)	**Private law issues** (shipowner and other commercial partners)	**Other rules** (Criminal, social, commercial, public law etc.)
Global (UN)	UNCLOS			
Global (IMO&ILO)		SOLAS, MARPOL, STCW, COLREGS, MLC		
Global (IMO, UNCITRAL, CMI etc.)			Private law conventions on e.g. liability, limitation, arrest, carriage of goods, salvage, etc.	
European Union		Ship safety directives & regulations Limitations on exemptions	Product liability rules, insurance requirements Rules on competent jurisdiction and applicable law	Several issues covered by EU Treaty & legislation
Nordic states			Nordic Maritime Codes, Nordic marine insurance terms	
National (Finland)		National implementing legislation, discretion of flag state administration (Trafi)	Finnish Maritime Code 674/1994, other specified acts on liability, insurance etc.	The entire legislation applies a priori for ships flying its flag

Safety and security

Risto Jalonen, Project manager, senior research scientist, Aalto University

Department of Mechanical Engineering / Marine Technology Group

Risto Tuominen, Senior scientist, VTT Technical Research Centre of Finland Ltd

Mikael Wahlström, Senior scientist, VTT Technical Research Centre of Finland Ltd

Safety and security in autonomous shipping – challenges for research and development

Summary

Safety and security impose essential constraining requirements that need to be fulfilled in the design and implementation of ship automation. In principle, autonomous or tele-operated ships are required to be, at least, as safe as conventional vessels in similar service. However, due to considerable uncertainty concerning new hazards and risks, it may be possible that even more stringent safety goals are needed for future applications with expanded portions of tasks and operations carried out either under remote control or as autonomous operations. Problems can be treated as challenges, and in engineering they may often be solved by creating new technical or sometimes even technological solutions. The questions, what needs to be done to ensure safety and security in ships with continually rising levels of automation and remote control, or up to what level the automation can be increased in ships, have become more relevant than ever before. While addressed initially in a few earlier studies, the impacts of autonomous, unmanned merchant ships on maritime safety have not been studied widely and deeply enough, yet. The gaps in information will be filled to some extent in the AAWA Initiative.

Making something new – something that has not existed before – is central to engineering. According to historical records the concept of failure has quite often been central to the increasing understanding in several areas of the multidisciplinary engineering science. In new designs it has always been an overriding objective to avoid failure. Safety and security need to be taken into account well enough from the beginning of the design to the end of the whole life-cycle of the new design. The socio-technical approach has widened our eyes to possibilities to consider, not only many important technical details, but also wider aspects. This leads us to systemic thinking with the important effects of operational and organisational factors shaping the system design.

Visions of new developments in the field of automation may be identified as heralds of a new technological and operational era. Emergent technology may include many hazards and even some disruptive effects. These features set high demands on the social responsibility of developers to cover all important aspects in their assessments of impacts on safety and security. So, obligations for meticulous and over-arching work before practical test applications and first commercial solutions can

start to spread are high. One of the problems related to the many challenges is to assess the pace of the development. If the technological development seems to be faster than the design and construction of all necessary and feasible safety levers, more efforts should be put on getting them developed at the same pace.

Alongside development of technological solutions to enable higher levels of autonomous operation of ships, the AAWA initiative aims to build up awareness and understanding on safety and security risks relevant to envisioned autonomous concepts, and point out some suggested measures to manage these risks effectively. The risk knowledge will be built up gradually and cumulatively through comprehensive analyses, simulator studies, and finally in pilot demonstrator studies and tests to be executed on actual sea going vessels with some thoroughly considered restrictions. Understanding autonomous or tele-operated ship systems and their embedded complexity grows gradually, but it is also important to form a holistic picture of the new, emergent technology under development. This is what we aim at in AAWA.

1. Introducing of autonomous merchant ships for maritime operation

Design and implementation of merchant ship concepts planned to operate partially or fully autonomously or under remote control from ashore, is still in its infancy. However this vision of new era of marine transportation is gaining increasing interest among the maritime industry and new concepts are developing quickly worldwide. The advances in information and communications technology (ICT) in recent years enable quick development as they make possible the on-board intelligence and data connection capabilities necessary for making ships able to operate even without on-board crew.

The economic benefits of autonomous operation concepts have been hypothesised to capitalize highest in ocean going freight vessels transporting relatively low value cargos on intercontinental routes. However, most likely, the first implementations in commercial traffic, first piloting and then in operational use, could be expected in short sea traffic and special type of applications which operate in national waters. This is because of the associated economic risk, and the need to have high confidence on the performance, reliability and safety of the solutions proposed before taking them into deep sea. Another incentive suggesting this kind of development path comes from the restrictions imposed by the mandatory international maritime regulations which do not currently recognize the concept of unmanned ship operation. Consequently, autonomous operations will initially require exemption permits which a competent flag state administration may issue on a particular ship for national waters if safety and security are not compromised.

Depending on human operators' presence and involvement in monitoring, planning, execution and control of ship operations, different levels of ship autonomy can be identified. However, much work on standardized classifications helping to identify and specify the different autonomy levels in ships may still be expected. In principle, in the lower or medium levels of ship autonomy, the increased intelligence introduced on-board would just provide extra assistance to the bridge operators, or it would take over smaller or larger parts of bridge operator tasks while being under supervisory control by a competent crew member remaining present on-board and able to intervene in case of problems identified by the supervisor or by the automated system.

In higher levels of ship autonomy, the supervisory control part may be transferred to a dedicated Shore Control Centre (SCC) where a supervisor may be able to monitor the operation of several vessels simultaneously and intervene remotely when a specific need is identified. The SCC could also have the responsibility for executing specific operations of a ship, e.g. steering in and out a port, which then would be carried out remotely by tele-operation. In the highest level of ship autonomy, the ships would operate without continuous human supervision present either on-board nor at some onshore control centre. However, the automated system is planned to make contact with an SCC for help when encountering a problem situation it is not able to resolve. Such connectivity, always available with the required capacity when needed, and without any interruptions, is most probably an indispensable feature of applications relying on the support from tele-operation from the SCC. Also important will be the security of the SCCs.

The transition to the autonomous unmanned shipping era can be hypothesized to take place gradually over a period of a few decades. The first applications, especially those being upgrades on existing vessels, could be expected to still carry some, although reduced, crew onboard for specific tasks and available as in situ backup in case of problems encountered at sea. However, single applications with even higher levels of ship autonomy could also be expected already in near future in some local specific services especially well suited for unmanned operation.

2. Are 'unmanned ships' safe?

The presented visions of future autonomous ships sailing unmanned have raised generic concern and questions among some professionals and well-informed laymen about the credibility and safety of such ships as compared to conventional ships operated by a crew on-board. Examples of safety concerns expressed have considered:

- ability of automation to reliably detect small vessels and floating objects on route;
- ability of automation to avoid collisions in case of encounters of multiple ships;
- ability of automation to navigate safely on coastal fairways;

- reductions on preventive and corrective maintenance that are currently largely carried out during voyages;
- ability to handle emergencies, such as firefighting or failure recovery and repairs at sea;
- errors and malfunctions in software;
- disturbances, malfunctions and vulnerabilities in data communication connections;
- undue trust on the capability and flawlessness of ICT systems

From a security point of view concerns have been raised as to the higher vulnerability of envisaged unmanned ships to hijacking or piracy with the purpose of steeling the cargo or kidnaping the vessel for ransom. Similar to the concerns raised regarding cyber security of ICT systems in general, potential vulnerability of unmanned ships to cyber-attacks by different adversaries, allowing them to illegally manipulate or exploit the attacked system, has been especially underlined. This strong concern reflects the roused public awareness on cyber-security and is justified e.g. by the breaches in cyber security pointed out recently on some autonomous road vehicles and in other examples on some other fields of new technology.

Contrary to the feared negative safety and security effects, claims have also been made for the higher safety levels of ships with higher levels of automation and operation autonomy. Such claims have been reasoned e.g. based on high involvement of human error in accidents at sea in the past, and the high crew fatality rate when compared to other industries observed currently. Both of these issues could be hypothesised to be reduced by increased ship autonomy by reducing the human involvement in direct control of ships, and by reducing the size of the crew on-board and exposed to hazards of the hostile sea environment.

While addressed initially in few studies, it appears that the impacts of unmanned merchant ships on maritime safety have not yet been studied comprehensively. Furthermore, there is no experience available on such ships and their safety in everyday use. Therefore it is of high importance in any new development projects that the safety risks are systematically addressed from the beginning, and the knowledge on safety implications are systematically built up, without forgetting the applicable experience from other applications from the past.

3. Preconditions of safety and security

In general autonomous and remotely controlled ships face similar safety threats to conventional ships, i.e. threats arising from the sea environment, other ships operating in close vicinity, and ships' own operations. In case of autonomous or remotely controlled ships, however, the recognition of and response to those threats is transferred, to a certain degree, from the on-board crew to intelligent software and sensor systems operating on-board, or to supervisors monitoring and controlling the ships via data links remotely onshore. In addition, the interconnected ICT systems needed for the autonomous or remotely controlled operation bring along new risks to be addressed and mitigated in the design and commissioning of the systems.

To be safe in its operation, an autonomous or remotely controlled ship shall not produce a safety threat to itself, the surrounding ships and property, or the marine environment. In addition, it needs to be able to adjust its operation if getting threatened e.g. by other ships or unexpected changes in the environment. This implies, in general, that a tele-operated, highly automated, or even unmanned ship must be capable of:

- generating, or at least using, a valid voyage plan for a foreseen sea voyage and assuring the ship's readiness for the voyage before departure;
- navigating accurately according to the predefined voyage plan, and avoiding collisions with other traffic and obstacles – both fixed and floating - encountered during voyage;
- maintaining its sea worthiness and operability over the voyage as carried out in varying sea states;
- responding safely to critical events and adjusting its operation to potentially dangerous changes in the operating environment and ship conditions;
- facilitating emergency interventions for recovery and rescue at sea; and
- resisting unauthorized intrusions into ship systems, either physical or virtual, with the aim of malicious acts or illegal exploitation.

The relative importance of these different aspects obviously depends on the particular application, i.e. ship type and the service it is providing, characteristics of the operating area, etc.

A general requirement commonly stated for autonomous unmanned ships is that, in order to be acceptable to commercial use, they must be approved to be 'at least as safe as the conventional vessels currently in use for similar purpose'. Some claims have also been presented that the level of risk that can be considered acceptable regarding severe casualties should be notably lower for autonomous ships. This would reflect the assumed lower public tolerance of risk in case of autonomous ships due to perceived lower level of control by the people involved on evolution of such situations compared to conventional vessels.

4. Focal areas of risk – some selected examples

In marine technology, risks are often assessed and analysed by categorising them in different types of marine accidents, like: collision, contact, grounding, fire, explosion, capsizing/listing, flooding, foundering, hull failure, loss of control, and in some accident statistics additionally: unknown. However, in case of a new, emergent technology, such an approach may not necessarily be fruitful enough for our purposes, especially, if totally new hazards, risks and risk control options need to be identified and assessed. Therefore, a more holistic view, not limited by the conventional ways of thinking, is considered necessary to obtain a more comprehensive knowledge and understanding.

A review of related literature and preliminary assessment of autonomous and remotely controlled ship operation points out certain impacts of increased autonomy that could become detrimental to safety of shipping unless properly taken into consideration when designing and implementing the systems for such operation. Safety of autonomous ships depends largely on the design and technological implementations. However, in addition to the interactions of the various components and sub-systems in the technology, human operators and the human-technology interaction remain even more important elements in this implementation. In line with this, the risks could be categorised into those related to the technologies needed to implement autonomous ship operations, and those related to operating this technology successfully as part of the maritime transportation system. Selected examples of both are briefly described in the following sub-chapters.

4.1 Reliability of safety critical equipment

There is an increased demand for reliability or dependability[7] in ships applying higher than usual levels of automation. As a matter of fact the development towards tele-operated or autonomous ships demands dependable, safe and secure systems on-board, extending to the ship itself, its systems and its environment, including all services the ships use. Thus, all systems the ship is part of, and all systems and sub-systems the ship uses, are involved.

ICT systems

Shore-based remote monitoring and control obviously relies on the existence of reliable and secure communication links between the control centre and the ships under its supervisory control so that sufficient speed and bandwidth for the needed data transfer is continuously available.

In principle, a fully autonomous vessel could operate successfully for a long time without having an operational data link with the remote Shore Control Centre (SCC). However, if control by an SCC

[7] Dependability is an umbrella term. It includes several sub-terms: reliability performance, availability performance, maintainability performance, supportability performance, integrity, safety etc. For further details, see IEC TC56 standard.

operator is considered necessary as an emergency backup, availability of an operational data link would need to be verified as a prerequisite for the vessel to operate. In other words, starting a sea voyage should not be allowed unless a data link arrangement having sufficient capacity for emergency operations and required reliability over the mission is known to exist. Typically, at least partially redundant, divergent data links to facilitate the needs for communications in the different operational situations would be required.

Similarly, robust, compatible and properly validated ICT structures and software are required both on-board the vessels and at the shore control centre (SCC) in order to avoid risks related to flawed operation of the embedded system intelligence.

Reliability management

Conventional ships appear to rely strongly on the crew on-board as an in situ resource for timely failure recovery at sea and execution of preventive maintenance programs online during the sea voyage. This allows using less costly machinery configurations that require frequent preventive maintenance actions and have lower reliability with respect to failures repairable at sea.

Lack of permanent crew on-board would essentially diminish the capability to perform preventive and corrective manual maintenance tasks on ship equipment during sea voyages. This implies that systems essential for operation need to be designed to be resilient to failure and extended maintenance intervals. Lack of permanent on-board crew also creates higher demands for scheduling of maintenance actions on harbour stays. This calls for the introduction of efficient diagnostics and new predictive prognostic algorithms to help assessing and controlling the risk of failures and prescheduling of required maintenance actions as part of overall ship operation planning. Designing easily maintainable systems would help to minimise the time and resources required and to assure that the actions are correctly performed.

Regarding machinery systems control, a common trend seems to be towards remote monitoring and control from shore-based service centres run often by the manufacturer. In this context, also the control of the status/health of other important equipment than the main machinery needs to be maintained.

Based on experience, revisions and repairs made on existing software intensive systems represent a common risk to errors with immediate or latent impacts on system performance. Consequently, revisions or repairs on such systems need to be thoroughly planned and managed with proper configuration control and comprehensive verification testing procedures to support recommissioning of the systems back to normal use. All changes and modifications should be trackable and thus systematically and truthfully registered in vessel/company logbooks.

4.2 Human factors issues in remote operation and monitoring

There are a variety of potential challenges related to operation and monitoring of the unmanned ships with safety implications. Firstly, the existing literature has pointed out that due to teleoperation there would be no bodily feeling of the ship rocking or ship sense. It is therefore possible that full understanding of the conditions would not be achieved via camera systems. In smaller ships, steering can be adjusted in accordance with the wave formation through bodily sense of the ship.

Automation and remote operation implies that the ships will be equipped and overviewed with multiple sensors. The danger here is that the operator could be exposed to information overload and therefore no longer able to make sense of the situation. The problem would be even graver if one person would monitor several vessels as steering the overview from one vessel to another could be a potential point for mishaps. With UASs (unmanned aircraft system) several mishaps have occurred during changeovers or handoffs, these having been the direct or indirect cause of the incidents. Representing several sources of information in one indication via so-called sensor fusion is a potential solution to this problem. This might be problematic as well as it can be important for the operator to understand each of the sensors. All of the sensors might not always be working and they might even provide conflicting information. To fully understand the situation, the operator would need so-called automation awareness, that is, comprehension of the current and predicted status of automation. Yet, achieving full understanding on what different aspects of automation are doing can be difficult if the sensor data is fused together. This fusion should be done in a manner such that the system is transparent for the operator yet without inducing information overload.

A further complication is potential skill shortage, and skill degradation at a later phase. The first issue here is related to the availability of onboard training vacancies for deck and engine ratings and cadets, if e.g. the number of cabins and trainers onboard get diminished. Assumedly, with reliance on automation and without manual driving activity, it is difficult to maintain skills needed in varying maritime activities. With respect to abnormal situations this could be especially difficult. Maintaining good skills could be especially difficult if monitoring a fleet of different kinds of ships – the operator could have to learn the practical differences of each of the ships and could easily forget or fail to recognize relevant issues when switching the operation from one ship to another.

Driving the unmanned ships remotely by teleoperation could be challenging due to latency. It takes time for a signal to travel via satellites or other means. This implies that in teleoperation there is always latency present. Too much latency can inhibit actualising practical tasks, i.e., with too much distance plus latency the so-called cognitive horizon in teleoperation could be exceeded. According to research, 50 ms delay borders the limit of delay detection for human brain. A delay of 200 ms is considered to be noticeable in practice.

Additionally, boredom has to be considered. For example, in a previous study, 92% of UAS (unmanned aircraft system) operators have reported “moderate” to “total” boredom. Boredom could result~~s~~ as a loss of vigilance and is therefore a risk factor.

As a summary of many potential human factors challenges (excluding security) in automated shipping we may present the following list of issues that need attention:

- Diminished ship sense
- Information overload
- Mishaps during changeovers and handoffs
- Need for automation awareness
- Skill degradation
- Latency and cognitive horizon
- Boredom and vigilance maintenance

4.3 Security

Security refers to unauthorized intentional acts of persons or organisations aimed to cause harm or damage to, or to illegally/criminally exploit, a system for the purposes of the malicious actor. Piracy, theft of cargo, smuggling of goods, human trafficking, damaging of ship or port facility, vandalism and sabotage, hijacking of ship or persons on-board, use of ship as weapon for terrorist activity, etc. are commonly listed examples of marine transport related security threats. A particular type of threat being credible for a particular ship obviously depends on how potential actors perceive the threat type and the ship to match to their objectives and perceived capabilities for successfully executing the planned malicious act. Vulnerabilities (i.e. gaps or defects/weaknesses) identified in the protections of ship systems could be considered as an example of potential incentives for attempting the act and selecting the ship as the target.

The actors for malicious acts may be external to, or come from inside, the organization. Traditionally execution of malicious acts has required physical presence of the actors and intrusion into the target system. The growing usage of networked ICT technology, however, has made it possible to try to access systems virtually through network interfaces and gain unauthorized remote capability to manipulate or exploit the system or its particular elements in some undesired manner.

Cyber security

The continuous increase of connected on-board ICT systems to support ship operations and the use of different types of data networks to make the ships at sea accessible for various types of remote onshore services has initiated common concerns on cyber security of such systems. In other words, serious questions have been raised whether the implementations of such systems can actually effectively resist malicious acts on ships that may become attempted remotely via the ICT infrastructures. This concern and provoked awareness is reflected, for example, in IMO safety committee work topics, special numbers on professional journals, and by the guidelines that Lloyd's Register recently issued for ICT systems' design and assurance on ships.

Concerns on cyber security are further increased in the context of autonomous and tele-operated ships, in which the connectivity of systems is further expanded to allow the ships to run in autonomous mode or be operated remotely. This implies that, in principle, anybody skilful and capable to attain access into the ICT system could take control of the ship and change its operation according to hackers' objectives. This could mean simply some disruptive actions or manoeuvres introduced for annoyance or demonstration, hijacking of the ship and cargo for ransom, but also powered groundings or collisions created on purpose to cause severe destruction. In addition to hacking into the systems, operation of autonomous ships could also be threatened by intentional jamming or spoofing of AIS or GPS signals or the data communications between the ship and the shore control centre.

Protection against cyber threats would call for elimination of vulnerabilities in the ICT infrastructure and implementation of effective measures for intrusion prevention, as well as intrusion detection, damage control and safe recovery in case of the prevention measures failing. Reflecting the fact that potential attackers will get more skilful over time, and will have more advanced techniques available to them, the oversight on cyber security needs to be dynamic and proactive introducing updates in the systems accordingly. Data classification, data encryption, user identification, authentication and authorisation, data protection against unauthorised use, data integrity protection, connectivity protection, and activity logging and auditing are examples of common cyber security methods foreseen to be needed. Although some parts of the protection in cyber security may be automatic there is no doubt that a sufficient amount of resources need to be allocated for this purpose. In addition to the technology implementation the level of cyber security would obviously depend on education and the organizational culture guiding performance of the people involved.

Occupational safety and health

Social security is a topic that has several meanings. Within the framework of AAWA, we may include under its cover some issues related to occupational safety, health and well-being of the seamen on-board ships and ashore. In this area autonomous and tele-operated actions or ships may help in avoiding or at least reducing occupational accidents on-board. It may be possible to include many different security matters, with inter-active feedback mechanisms and impacts among the lists of high-level interest topics of the industry when new technology is implemented on-board.

Within the framework of AAWA some issues already included e.g. in the relevant conventions of ILO[8] may also be seen as indirect proactive measures against cyber threats. A wide, holistic view may bring new aspects and points of view into discussion. Although a deeper analysis of social security is left out of the scope of this study, it must be recognised that many different concepts of social security of the maritime community and society exist, and many of them are often interconnected.

4.4 Cargo management

In conventional ships, the first officer and ship master are in charge of accepting the cargo and its loading into the cargo spaces. Lack of permanent crew on-board the autonomous ships would emphasise the role of port operators in accepting the cargo and assuring that it is correctly loaded and stowed on-board in accordance with shipping regulations and the ship specific cargo manual. Furthermore, in unmanned ships and ships under remote control possible actions to take any cargo related measures at sea are more limited than in conventional ships, if no extra equipment facilitating additional measures, e.g. for additional cargo monitoring, securing or control, are provided.

In case of autonomous ships, assurance of proper initial status of the cargo for the foreseen sea trip would rely mainly on the longshoremen. This could increase the risk of cargo related incidents, as it is believed that crew members and officers sailing on-board do have a deeper personal interest to ensure that cargo loading and the securing work are safely done and the equipment used are fit for the purpose in all conditions. Any actions to cure cargo related problems identified on-board, like: cargo shift, leaks, problems with moisture, fire and flooding are limited to those that can be handled either by automation or tele-operation.

4.5 Managing emergencies

Lack of trained crew members on-board could be expected to increase the risk of failure in coping with emergency situations that can be encountered during voyages. Decreased crew size may create a

[8] International Labour Organization (ILO), see e.g. Maritime Labour Convention, 2006 (MLC, 2006) (with entry into force: 20 Aug 2013), or the earlier Convention C165.

higher risk of failure to handle emergencies on-board when actions are needed. Capability of specific prompt response actions in situ or evacuation of the vessel, if needed, has raised strong doubts on the autonomous operation concept being applicable at all.

How the ship can assist in emergency situations related to other ships is another question with several uncertainties due to the limitation in the currently available technical specification. Emergency situations include a wide area of potential operations that need to be discussed in more detail when detailed solutions are available.

However, although reducing the crew size might result in diminished capability to assist other ships in emergency situations by hands-on help, the automated ships could have alternative positive contributions to emergency management. A study suggests that, thanks to increased sensor data, the automated ships could reproduce information to authorities if needed. Video and sensor data could be transmitted directly to vessel traffic monitoring services, which could be helpful in increasing authorities' situational awareness in emergencies.

5. Managing shipping safety and security in short and long term

Management of ship safety and security in the short term may be seen mainly as a process that requires having specific well-defined systematic procedures applied in the classification and approval processes. Such processes are sufficient for assuring safety and security of such ships. However, there may also appear needs to be able to act in unforeseen situations. When the operation of a new, large and safety-critical system, such as a merchant ship is considered to be allowed for even a limited use, a precautionary principle is suggested to be followed. When the system can pass all the checks and tests understood necessary to confirm its safety and security, a step towards a more complicated system or use in a different environment may be considered.

In the short term the mistakes made by autonomous systems may be still attributed to humans, as the software is planned and produced by humans. However, controls must be in place to ensure that no bad or erroneous information or distorted ideas of the functionalities or environmental conditions are used.

In the longer time perspective, management of safety of autonomous ships could be expected through IMO regulations and conventions being adapted to better encompass also autonomous modes of ship operation and the associated safety risks. The initial risk-based approaches for approval could be expected to develop into standardised prescriptive and goal-based requirements to guide the design and implementation of autonomous features on ships and the onshore control centres. Safety management should be directed to a comprehensive, holistic view extended to aspects and issues related the full life-cycle of the autonomous ship.

5.1 Qualification of new technologies for use

Qualification of new technologies, such as ICT systems to enable autonomous or tele-operated ships, for commercial use can be outlined as a step-wise process. Small steps that gradually build up confidence in the new technology proposed with continuous improvements ensuring that it fulfils the requirements identified for safe operation. Implementation of new technology can be seen as a learning process during its whole lifetime.

Currently internationally agreed conventions, such as SOLAS (i.e. Safety of Life at Sea), specify the minimum standards for the construction, equipment and operation of ships considered to enable safe operation together with such codes and regulations as COLREG[9], ISM[10] and STCW[11] etc. These standards include prescriptive requirements on structural design, specific equipment, size and qualifications of crew, etc., compliance to which needs to be proofed for each individual ship. Deviation from any prescriptive requirement requires the ship owner to demonstrate with sufficient evidence that the proposed deviation is at least as safe as the initial requirement in the considered service. Based on such documented evidence on unaffected or reduced safety risk, the Flag state can then issue an exemption permit for the deviant solution in a particular ship and service.

The safety assurance process for a proposed alternative solution needs to start with a thorough description of the ship operations, both normal and abnormal, on which the proposed solution is foreseen to be involved, followed by identification of hazards and other safety issues considered relevant to these operations. The role, capabilities and limitations of the proposed solution in controlling the hazards and contributing to the risk of accidents then needs to be thoroughly identified and assessed to produce a suitable body of evidence to support the argument of safety equivalence of the alternative solution. The 'standard' solutions compliant with the prescriptive requirements provide the baseline for risk comparison.

Autonomous or tele-operated ships represent a major technological and operational change with a number of uncertainties regarding their safety in operation, and no relevant field data currently available to support their approval for commercial use. Well planned demonstrator studies, carried out initially at specially planned simulator settings, and later on-board actual sea going vessels are seen as the way forward for learning and building gradually the evidence and confidence on safety of

[9] The International Regulations for Preventing Collisions at Sea 1972 (Colregs)
[10] International Safety Management Code
[11] Standards of Training, Certification and Watch-keeping for Seafarers

such ships and the operating concepts. Obviously demonstrator studies on-board actual vessels need to start with limited scope and endeavour, and having a competent crew on-board as a backup and ready for take over the control in case of serious problems. The shore control centre (SCC) work processes constitutes another area of the autonomous ship system in which demonstrator studies are seen necessary.

5.2 Managing the risks during technology transition

Due to the nature of shipping industry, the transition from the current conventional concepts in marine transportation to a stage dominated by autonomous, unmanned ships is expected to take place slowly, and has been claimed to require at least a couple of decades. During this period there would be a mixture of vessels with different levels of autonomy operating at sea. In the worst case, this may lead to unexpected behaviour of some systems, hazards, and, consequently risks.

One important aspect in the technology transition is the management of maintenance and repair of systems, and ensuring only as-planned interactions between e.g. subsequent software generations. The well-performed management with standardised routines of up-to-date documentation is an important part and feature of the systemic approach. The areas of responsibility should always be clear during all phases of the technological transition.

5.3 Obtaining and maintaining operator skills

It is clear that an updated training regime of STCW (Standards of Training, Certification and Watch-keeping for Seafarers) will be needed, before any further steps are made to allow crew reductions. The crew members need to be trained in any case to fulfil all functional tasks and capabilities left for the crew in autonomous ships. It is not quite clear to us how this will affect the crew lists, but at least in the beginning there is an important phase, when the automatic of tele-operated operations need to be observed and supervised on-board.

Similar type of requirements as in STCW may eventually have to be developed for persons operating ships remotely. It is recommended that persons working in the Shore Control Centres (SCCs) are required to have a sufficient amount of experience related to similar ships, i.e. with regard to dimensions, deadweight and power and their relations. These requirements of competence, knowledge and understanding, based on hands-on training in sea service and simulators, should be clearly higher for the supervisors in the SCCs.

Good skills are needed in safety critical and challenging situations. There are several issues to be considered in obtaining and maintaining the operator skills for remote operation tasks. Manual skills weaken when they are not used, that is, it could be problematic if the operator usually only monitors the ships and at times takes control. In remote monitoring challenging situations seldom happen, yet high level of capability would be needed in challenging situations in particular. Working knowledge can only be achieved through repeated use of the system and if the work mainly involves monitoring, this might not be possible. In the maritime context, the vessels are usually all more or less different. The operator would not need to learn the particularities of all of the ships, but at least both theoretical and practical knowledge and understanding of the main cause and effect relations and their variations due to the peculiarities would be advisable.

Overall, well designed simulator training would be needed for practicing challenging safety critical situations. This is not unproblematic, since, at least in principle, the simulator cannot present unimaginable surprising situations. Creating challenging situations demands creativity and understanding of maritime accidents from the developers of training. The operators would need to have sufficient training days at the simulator, where these surprising and challenging situations would take place. Debriefing after the simulator sessions is important and need to be designed as well. In debriefing, the operator should be able to evaluate his or her own performance and hence would learn from successes as well as from failures. One option is to show and discuss video clips of operators' actions during safety critical situations at the simulator.

5.4 User-centred design and validation of the shore control centre operation

In view of safety, it is essential for the design of good remote operation and monitoring systems to do field studies on actual maritime activity on regular ships. The studied conventional ships should perform the same tasks as the new unmanned ships would actualize. Well done field studies allow understanding safety critical aspects of work and means for maintaining safety. Task-analyses based on the field studies allow understanding of what aspects in activity should be left for the automation and alarms and what should be monitored by other means. Field studies can also reveal surprising safety-relevant aspects from workers' activities. Knowledge of these allows taking them into consideration in design.

After designing and implementing the system, validation that it truly works as wanted is essential. In other safety critical domains, such as in nuclear power plant operation, this involves contrasting the findings from testing the system to safety standards and demands.

6. Building risk understanding for the future

As a step towards the era of autonomous maritime traffic, the Finnish AAWA project aims to make its share in building up the awareness and understanding on safety and security risks relevant to the envisioned autonomous concepts, and the measures needed to manage these risks effectively.
Based on initial identification of hazards and risks carried out on the concept of unmanned ship, a number of risk issues have been pointed out that could be problematic in terms of safety or security, but to which we have confidence that effective solutions, risk control options, can be found with properly focused and systematic testing and research. On the other hand, the new concepts of operation and the technologies aimed to facilitate it incorporate issues that we know to entail elements of risk, but the seriousness and the complexity of the risk is currently largely unknown to us. Finally, characteristic to any novel technology in its infancy, we can assume that some risk issues could yet be hidden or vague to us.

The risk knowledge will be built up gradually through comprehensive analyses, simulator studies, pilot demonstrator studies executed on actual sea going vessels with some thoroughly considered restrictions, and finally in commercial use. Consequently, in the following phases of AAWA project, the main emphasis regarding safety and security issues will be placed on:

- systematic risk identification and assessment focusing on both design and operation interactions and processes;
- assurance of cyber-security;
- validation of algorithms for autonomous navigation, including obstacle detection and collision avoidance, and assurance of each corresponding software, and their safe interactions, by analysis and simulations;
- user-centred design and validation of shore control centre operations;

Aside from these efforts to improve knowledge on relevant safety and security risks and their control, comprehensive Safety Case documentation will be compiled in AAWA for the planned field demonstrator case(s) to support approval of the exemptions needed from the national maritime safety authorities for carrying out the demonstrator studies.

7. Recommendations

Based on the work carried out so far in the AAWA Initiative the following recommendations can be made:

- Remote and autonomous ships shall be made at least as safe as existing vessels with sufficient confidence, taking in to account relevant uncertainties, e.g. environmental conditions and disturbances

As the share of uncertainty and risk may grow at least in the beginning, when moving towards higher levels of automated routines, the target level of safety must be set actually higher than the current one. There is some potential to reduce human based errors, but at the same time some new types of hazards and risk may arise and will need to be addressed, e.g. in the area of cyber security.

- Progress only by small and cautious steps

Application of this precautionary principle means a careful and systematic approach in risk assessment, design, deployment and operations. This requires increasing knowledge and understanding by research in the 'uncharted areas' of 'unknown'. Additionally, it is important to listen to all relevant stakeholders, improve dissemination and flow of information, in order to avoid unacceptable risk and to confirm safety.

- Co-operative actions are needed to develop international standards and guidelines for the maritime industry, preferably in co-operation within IMO

International co-operation between the national administrations, classification societies and other relevant bodies with interest in the field to utilize the global maritime knowledge under the wide umbrella of IMO is recommended for the further development.

Co-operation is necessary to be able to create a common ground for a coherent, safe approach when laying out the first sketches of principles to be followed in the procedures to be used guiding and controlling the technical and operational safety of autonomous and tele-operated ships. It will be even more important if and when the further new technological artefacts, like autonomous and tele-operated ships start to interact with the operational environment of the maritime society.

Maritime safety and security is a very wide and deep conceptual topic. It can be divided in many sectors, including e.g. ship safety, cargo safety, maritime traffic safety, environmental safety, occupational safety and security. The recommendations above are presented on a very general level in an early phase of the progress and development of autonomous ships. Therefore, it must be underlined that the above recommendations are not all-encompassing. It is believed that AAWA Initiative acts in changing shipping, but not in isolation from the whole maritime sector and society. The latter have many features and actors giving feedback to and shaping AAWA, too, to some as yet unknown amount. So, the development of the new technology will occur in many interactions, known to be typical for the social construction of all significant technologies. All this needs to be taken into account, when safe and secure technology, depending both on design and operation is developed.

Business

Jouni Saarni, Development Manager, Turku School of Economics, University of Turku

Sini Nordberg-Davies, Doctoral Candidate, Turku School of Economics, University of Turku

Hannu Makkonen, Docent, Senior Research Fellow, Turku School of Economics, University of Turku

From Innovations to Markets – Redefining Shipping

1. Redefining shipping – a transition to autonomous shipping

Autonomous technologies which enhance self-guiding capabilities of technical systems have received a considerable amount of attention in various different industries. The marine sector is now following suit. While the concept of a completely autonomous ship may be controversial, it is nevertheless undeniable that the shipping sector is facing considerable changes as digitalisation gradually sweeps over the technological landscape. The technological change is connected to a social one, as the AAWA slogan "redefining shipping" suggests; autonomous shipping is not merely about technology but also about the respective social change. Figure 1 synthesises the key elements into a perspective on autonomous shipping in the AAWA project.

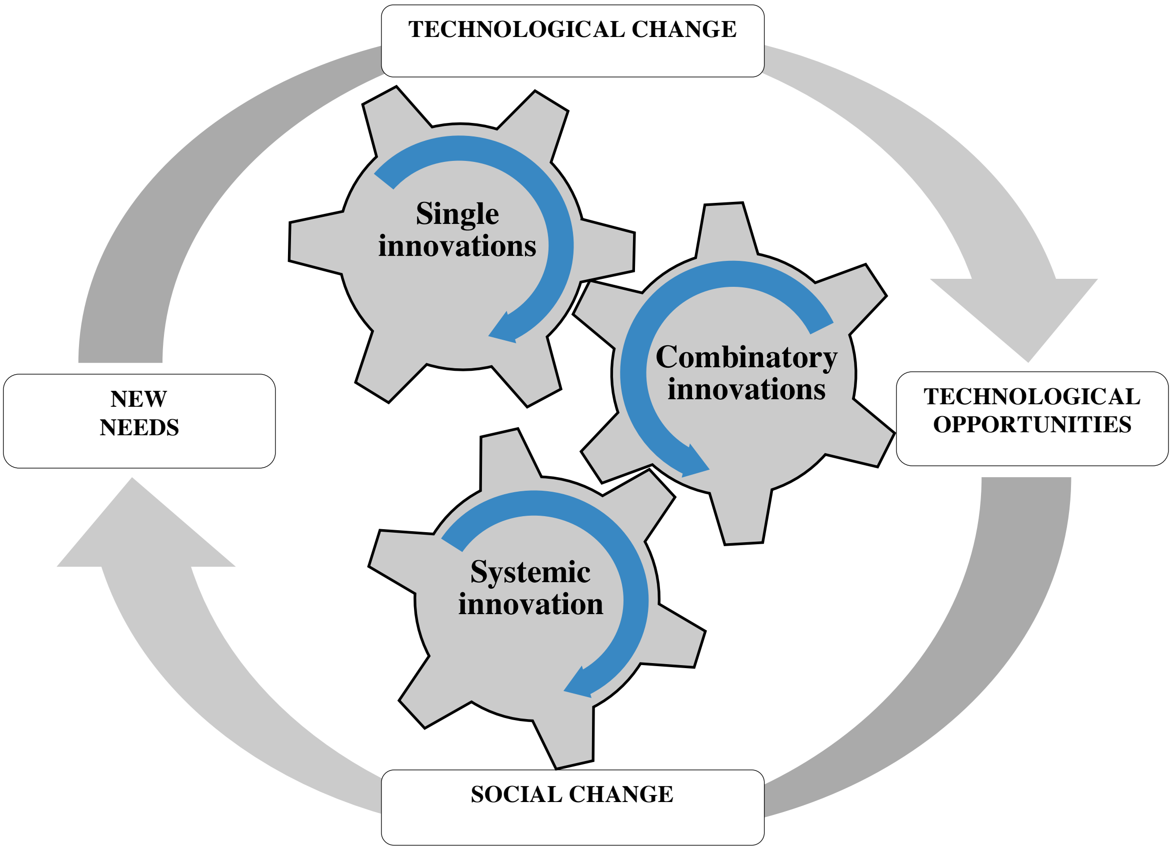

Figure 1. AAWA – Redefining shipping

The central panel of the figure describes the levels of innovation for autonomous shipping: *single innovations, combinatory innovations, systemic innovation*. The single innovations represent the product innovations created from key technologies, for example, cameras, radars, and other types of sensors that comprise a combinatory innovation of a situational awareness system (see Arthur 2009). Other such technical combinations to be developed in AAWA include e.g. navigational systems or communications links. These kinds of building blocks comprise the key technology areas for systemic innovation, i.e. the concept of an autonomous ship. The outskirts of Figure 1 describe *technological and social changes* that comprise a mutually feeding loop: technological development produces *technological opportunities*, whereas social change alters the social landscape generating *new needs*. The mutually reinforcing interplay between the technological and social change produces a socio-technical transition that describes a state in which the new technological opportunities and those related needs are materialised into practice and put into use. For example, containerisation as well as the development from sails to steam engines and further to diesel engines describes such socio-technical transitions in the maritime sector (see Geels 2002).*

Lessons learned from past socio-technical transitions

* The past socio-technical transitions in the maritime sector have some joint similarities. Firstly, the transition usually lasts a long period of time, often decades. Ships have large long-term investments involved and they are constantly a part of transportation functions of world trade. Secondly, the transition typically begins from small special markets. Some combinations of tasks, cargo and routes fit well with the novel technologies that are emerging in the beginning of the transition. Thirdly, it is typical in a transition phase that the old existing regime and new entrants co-exist at the same time and compete. Later, market selection occurs favouring a so-called dominant design from different technological alternatives (see Murmann & Frenken 2006).

When the selected technology diffuses within markets and users it also causes social impacts. More concrete targets are the needed infrastructure and service networks for e.g. maintenance. Also regulations and policies might face changes as well as industry structures. More vaguely traceable are institutional and cultural dimensions on routines, practices and mind-sets. (Geels 2005.)

Taking the history of containerisation as an example, the social factors were of the utmost importance. Containers and container ships were technologically rather straightforward. More importantly, they were process and organizational innovations. The idea of using containers to streamline the loading and unloading was already variously experimented during the 1950s. However, true utilisation of them needed a change in thinking from operating ships to transportation chains. As a consequence, shipping and port operations became more capital-intensive. This provoked social resistance, and contractual negotiations on container sizes and standards took many years. It took over a decade until the late 1960s for the first purpose-built containerships to be completed. After this, containers' diffusion in shipping companies and ports with related investments and practice-building lasted for several decades. (Levinson 2006).

Figure 1 connects the levels of innovation with the technological and social change in two ways:

1. The ongoing technological development (digitalisation, the internet of things, autonomous driving etc.) and respective social change in which these technologies become socially accepted and desired feed the innovation activity in the field of autonomous shipping (the spin of the outer circle accelerates the spin of the innovation gears).
2. The innovation activities for autonomous shipping accelerate the

"All this positive publicity and enthusiasm that you can see around Google car etc. is helping our efforts in the maritime sector."

technological and social change in general (the spin of the gears accelerates the spin of the outer circle), and thus reinforce the cross-industrial socio-technical transition towards autonomous technologies and their application in the society.

The *business models* of the key actors in the shipping sector mediate the connection between the innovation activities and the technological and social change. The innovation activity is dependent on the extent to which the key actors perceive business opportunities regarding autonomous shipping. This is again related to the issue of how other key actors will be mobilised to the topic, and what kind of relationships and networks are to emerge to advance the technological and social change. Thus, autonomous shipping is largely a social issue in which the prevailing norms and routines of the shipping business that promote stagnation are to be overcome. Furthermore, on a societal level digital solutions need to be seen as measures for improving the quality of life instead of threatening it. Based on the findings of the first phase of the AAWA project, autonomous shipping is not a question of whether or not, but rather a question of when.

2. Autonomous shipping – an issue of business relationships and networks

Due to its systemic nature, the emergence of autonomous shipping is first and foremost an issue of managing the relevant relationships and networks (Håkansson & Snehota, 1995; Håkansson, Ford, Gadde, Snehota, & Waluszewski, 2009), and the ecosystems based on these. In terms of technology, the shift towards an era of autonomous shipping requires convergence of the relevant technologies. Similarly, in terms of the market side for autonomous shipping this shift requires that autonomous shipping is perceived to deliver the expected benefits: on the micro level; seafarers experience that their working conditions are improved, on the meso level; marine industry players see cost, efficiency and safety gains, and on the macro level; the society benefits from the redivision of work and lowered emissions. The combinatorial development between technologies and markets within the marine industry occurs in conjunction with similar development in other relevant industries (e.g. automotive and aviation), that altogether comprise a cross-sectoral autonomous technologies ecosystem (as described in Figure 2). Technological innovations and the dawn of the new concept of autonomous shipping motivates the actors to develop new business models and further, new business models with intentional activities to generate commercially viable applications feed the technologies to develop as described in Figure 2.

"Increasingly, all these systems are discussing with each other so much that the discussion is no longer between two systems, but all systems. And this requires a certain level of networking. But on what level? It's not a simplistic situation in fact."

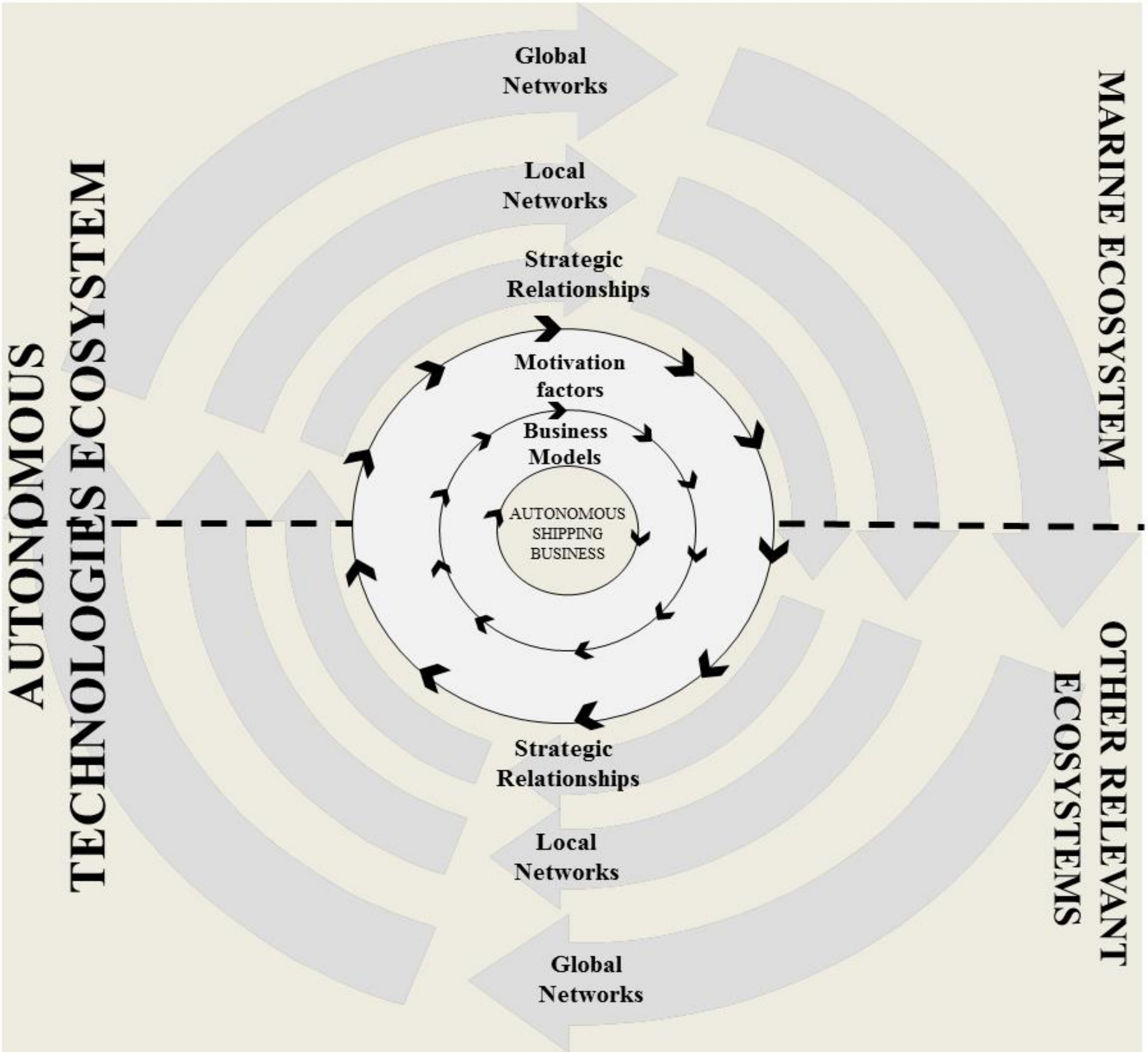

Figure 2: The networks and relationships for autonomous shipping business

Figure 2 describes the autonomous shipping business to emerge as a result of matching evolving needs and evolving technologies within *strategic relationships, local networks for technology platforms*, and *global networks for new markets*. Currently, the development of suitable technologies for autonomous shipping takes place largely in strategic relationships; business actors develop solutions to serve their current business in their key relationships. This can be exemplified by a satellite communications firm working with current suppliers and customers to achieve safer communication links, or a video technology firm working with algorithm specialists to develop the computational power of video cameras.

Secondly, industry-level local networks exist in which actors have come together to build the concept of autonomous shipping intentionally, as exemplified by development networks such as AAWA. These local networks truly begin to question the prevailing, traditional logic of shipping and aim at a new dominant logic by providing a technology platform, on which future development can take place (compare Frenken 2000). While the actors in a local network may have expectations for short-term returns based on single innovations, autonomous shipping truly becomes a driving force for innovation in local networks. This development towards autonomous solutions has progressed further in other relevant industries. For example, the automotive industry has for a long time developed technologies (e.g. cameras, radar, ultrasonic sensors) that form the basis for intentional activities to develop and launch autonomous driving platforms, such as those of Google and Tesla. These currently represent local networks but are transforming towards global networks not only comprising development, but also production and use of commercially viable applications.

It is only when other actors, e.g. customers and other stakeholders in the logistics chain, understand the applicability of autonomous shipping for their needs, the development of autonomous shipping becomes a matter of increased value instead of a feat of engineering. At this point, the local networks, i.e. hot spots of autonomous shipping, gradually gain momentum and scale to generate global networks engaged into the development and operation of autonomous shipping. It is in these global networks that autonomous shipping eventually evolves into the new dominant form, i.e. redefine shipping.

3. Autonomous shipping – a renewed set of roles between the key actors

Autonomous shipping will lead to a new kind of role-set and division of work between the actors in the shipping sector. Some of these roles are played by the traditional players and some by new entrants. For autonomous shipping there will be new functions and respective actors who specialise in technologies enabling these functions, e.g. a remote control centre operator and an autonomous systems integrator. Each actor must consider their position in the market relative to the other players, meaning that actors shape their business models accordingly. Holding a key position in the technology platform for the new dominant logic of autonomous shipping is crucial for competitive advantage (Makkonen, Vuori, Puranen, 2016). As global networks emerge, more and more actors engage both in the technological framework as well as usage in autonomous shipping. This will alter the prevailing structures and processes of the shipping industry in its entirety. In other words, the autonomous shift will not only streamline technology-related operations but more widely facilitate a critical evaluation and reorganisation of the way the shipping business operates.

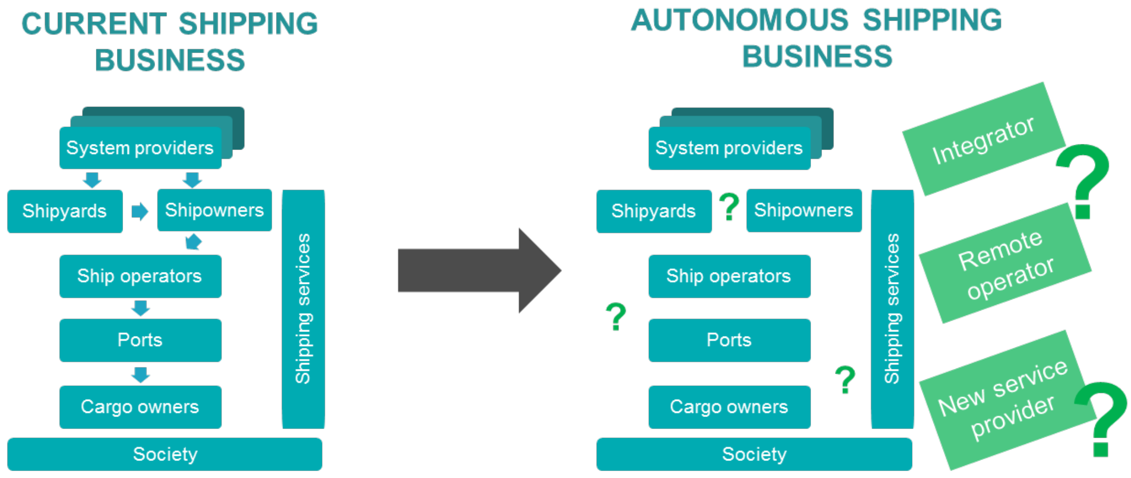

Figure 3 The renewed set of roles for the autonomous shipping business

Figure 3 describes the possible entrance of new actors as well as the change of the roles of the current actors in the shipping business. The increasing intelligence that comes along with autonomous shipping is likely to 1) bring in new actors to the field of autonomous shipping business as well as 2) bring in a different philosophy in terms of maintenance and service functions. In terms of the former, new technologies develop and technological potential materialises in applications originally developed in other areas, which can serve the emergence of autonomous shipping, as demonstrated by e.g. the development of drone aircraft and semiconductors. In terms of the latter, even after the design and production of an autonomous ship, new capabilities can be added due to the digital nature of key systems. In this sense, the once produced solutions and systems are never really complete (Yoo et al. 2012), and thus the network of actors and functions are likely to be in continuous evolution.

4. Transition drivers to autonomous shipping

The anticipated benefits and challenges of autonomous shipping to businesses can be broadly viewed from the perspectives of shipping companies, existing maritime system and service suppliers, and possible new suppliers entering the market.

From the perspective of **shipping companies**, in discussions with the industry both direct cost-reducing benefits and other indirect benefits have been pointed out. The direct benefits are often listed in a

"The industry needs now to start searching for assignments where an autonomous ship pays off exceptionally well."

vessel level as more efficient use of space in ship design, more efficient use of crew and their skills, and more efficient use of fuel. Shipping companies are also likely to benefit and see new revenues from tailoring transportation chains with autonomous applications as well as from increased cargo space on the ship. Indirect benefits are actualised more in a company and network levels of the shipping sector. Autonomous shipping allows improved optimisation of operations and processes. For example, optimising operations based on real-time data enables economies of scale at fleet (or company) level, and reduces the likelihood of human errors contributing both to safety and service quality. The AAWA team sees that these indirect benefits are the key for gaining long-term competitive advantages from autonomous shipping.

Radically rethinking operations with remote and autonomous systems is deemed to be hindered by the current regulatory environment, causing uncertainty in terms of being among the first to engage in autonomous shipping. Modifying regulation for remote and autonomous shipping is a broad task because it is a combination of both national and international rules. Nevertheless, rules reflect the social opinions, and if autonomous shipping is seen to offer benefits, it will gradually challenge the prevailing rules.

From the perspective of **maritime system and service suppliers**, autonomous shipping can bring more possibilities in designing for improved ship efficiency. Suppliers can also benefit from significant new business opportunities particularly regarding data-related services. By engaging in the development of autonomous applications, suppliers will gain new capabilities, which can be leveraged both in finding new business opportunities as well as improving and building upon their existing offerings in the short term. This learning is enhanced by the increasing cross-sectoral cooperation that is taking place around autonomous shipping. Knowledge and skills as well as technologies travel across industry borders, which supports the emergence of autonomous systems not only in the maritime sector but also in e.g. the automotive and aviation sectors. The innovation efforts of maritime system and service suppliers are gradually supported by the related societal acceptance of autonomous systems overall. Furthermore, regulatory bodies in differing flag states are also showing increasing interest in backing the creation of cooperative networks that pursue the development of autonomous shipping.

"Personally, the firm, the community, the industry, the society, everyone benefits from exchanging experiences and thoughts on some level."

However, the current regulatory environment can be an obstacle for developing new business solutions in particular around remote control. While remote control is regarded as an area with high potential for rethinking operations without much competition, the reason for low levels of competition comes down to regulations governing certain practices that could otherwise be handled remotely. Questions are also raised whether the conservative natured maritime industry would be ready to adopt autonomous technologies with the same speed as they become available. Also, autonomous shipping is recognised to have a major impact on the business models of suppliers whose current models are built around the shipping operations of today. Reluctance to change the prevailing business models may hinder the emergence of autonomous shipping. Lastly, uncertainty surrounding liability issues needs to be resolved before commercialisation of autonomous solutions is possible. Thus, leaping into the business of autonomous shipping would require certainty of the insurers' willingness to cooperate.

Autonomous shipping can pave the way for **new suppliers** to enter the industry, in particular from sectors where the necessary hardware and software technologies (e.g. different types of sensors, data analytics etc.) are already in use. For these types of entrants, autonomous shipping has the potential to uncover new global markets in shipping. Increased ship intelligence opens up new service opportunities in particular for suppliers specialising in data and software. At the dawn of a digital era, the industry is likely to see the arrival of a startup scene enriching the industry's software capabilities. Furthermore, due to lower demands for reaction time, a ship can be a less demanding platform for the performance of many systems, in comparison to e.g. cars and airplanes, making shipping a more lucrative sector for development efforts.

Despite the opportunities that autonomous shipping can provide new suppliers, shipping is nevertheless a tough business environment to enter into. For example, certain equipment developed for use on land may face durability issues at sea if not adapted to the sea conditions. It may be difficult to enter the industry as a new player due to the investment required to get all the equipment approved to be able to bring them on a ship, thus offering portfolios for the maritime sector need to be carefully planned. Also, building business relationships in the conservative industry may be a lengthy endeavour. Furthermore, the marine industry could be considered to be competing for knowledgeable suppliers against other industries that are more advanced in their steps towards autonomy, and thus commercialisation of solutions. The maritime industry is at a disadvantage in terms of unit volumes when compared to the automotive sector in particular.

"It's a very conservative industry, so before you have established a name and trust on the customer side, it takes a long time."

5. Transition roadmap

Based on findings made on academic literature on innovations, markets and sociotechnical transitions supported by preliminary interviews, a sketch in Figure 4 was made on how the autonomous transition in the maritime sector might take place. The figure is not meant to be predictive ordering. Rather, it is a tool for understanding the different *triggers* needed for the transition to proceed forward. The basic concept in Figure 4 is that the *social acceptance* for autonomous shipping affects what innovations are adopted and taken into use. Complex systemic change such as autonomous shipping cannot be immediately adopted as a whole but it is rather a path and a chain of interrelated events.

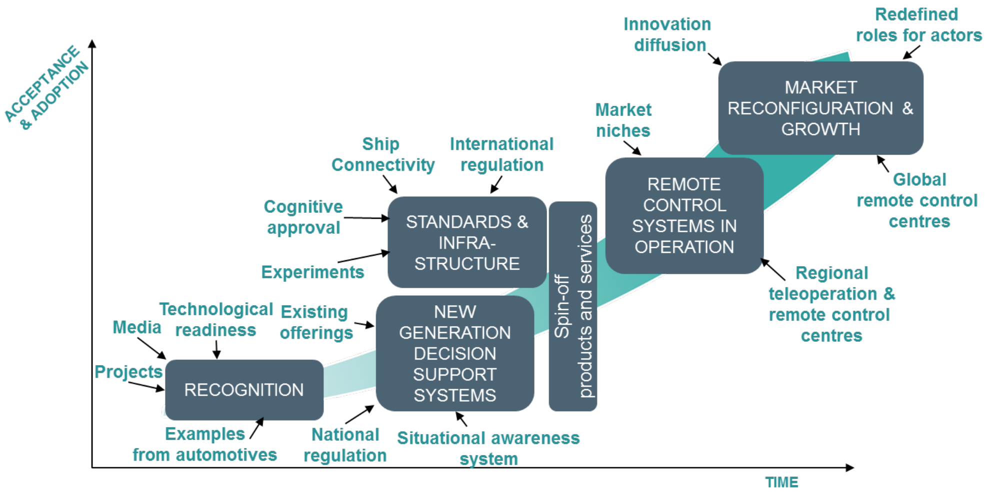

Figure 4. Transition roadmap to autonomous shipping

At the first stage the society needs to recognise that the concept of autonomous shipping is at least in some form possible and imaginable. Society is meant here in a wide sense covering also the relevant industry players but also authorities and the general public. To separate a realisable idea from science fiction the recognition phase involves conditions that signal the different actors that there are realistic underlying possibilities. Knowledge from existing technical performance both in maritime and other sectors shapes the boundaries of what is thought as possible. Existing technologies like dynamic propulsion systems or high-speed satellite communications give a tested ground on where to think up more functionalities. Professionals are naturally more familiar with the technical details but a shared understanding of prevailing technological capabilities nevertheless exists in the society. Recently the automotive sector has been feeding numerous examples from autonomous development. Besides technical aspects like sensors it also brings up more complex themes into discussion. There are more and more stories on regulation or ethics of robotics. Here the media has an important role in spreading the word around and challenging existing thoughts. The awareness and "buzz" is culminated in the form of R&D projects like AAWA. Their task is to explore the nearby hanging opportunities and take steps forward in the sector in question. AAWA itself is one element contributing to recognition of autonomous shipping. Wide interest in autonomous shipping is already showing that recognition has been progressing fast and it is now time to move forward in the figure.

After the recognition some visionary individuals, the early adopters will see the concept also not only as possible but also as desirable. As theories for systemic innovations suggest, the innovations in shipping follow an incremental approach. A ship won't be made directly as fully autonomous but rather in smaller steps. First concrete offerings might for example be new kinds of decision support systems. They will be built over existing offerings for ship navigation and manoeuvring. A precondition for that is a situational awareness system that must be developed with suitable sensor combinations. A decision support system will offer a basic level of autonomous capabilities for enhanced observation and self-guidance in different operational scenarios. Even if it is not necessarily in conflict with the regulation, based on the system's capabilities and performance, changes to national regulation must be evaluated, so that the decision support system could be brought into markets. An important characteristic in autonomous shipping is that partial innovations created have a good chance to spin-off to markets already along the way.

At a third stage more detailed planning occurs and instead of a single ship more attention is given to management of traffic in an autonomous era. In early developments it is typical that many different technological alternatives emerge and compete together. Even though this accelerates technical experimenting, at some point a need rises to standardise procedures. Users tend to want a unified concept for technological artefacts. This also means that people need to cognitively have a shared understanding of what is meant by the autonomous ship concept. It must be fairly similar as to how today's conventional ship is understood to hold a certain homogeneity between different ships. Discussions will start regarding what will be the standards of autonomous shipping in different dimensions. As the technologies become into wider use there must be suitable infrastructure in place to support it. Ship connectivity network based on satellite and shore-based communications are to be gradually enlarged to support the autonomous traffic. Finally standards, infrastructure and the rising need for doing business with the new technology will affect international regulation. As shipping is global, the standards and rules must be internationally agreed upon. Naturally it is a long process, however it is constantly reflected with novel applications brought to be contested by the market and by social acceptance.

When the essential standards, rules and elements of infrastructure have been settled the development becomes a question of expanding. There can be already some special market niches that show the new technologies to produce very good outcomes. These niches start to expand in their own regions and markets. Gradually some regional sea areas will become harnessed to have a full-scale infrastructure for autonomous operations.

In the final stage of the figure the regional and niche-specific processes will start to accumulate into a global scale. Autonomous applications diffuse inside the innovation, reaching a point where it has a significant impact on global shipping and world trade (compare Greve 2009). This will alter the roles and structure based on conventional shipping. Data and services will bring more value to customers. Transportation chains will allow more optimisation and will be more tailored for specific needs of different industries and customers. Management of autonomous fleets might consolidate and global remote control centres for these kinds of ships are built. A shift from product innovations to process innovations occurs to start producing autonomous offerings more efficiently. On a social level, regime is changed. Regulation, routines and practices gradually incorporates the autonomous shipping as taken for granted. Institutions of shipping include the features and infrastructure derived from autonomous technologies.

6. Conclusion

The transition to an era of autonomous shipping is a more complex matter than a mere technological invention. The realisation of an autonomous ship requires a plethora of technologies to be integrated systemically, which means that cooperation is required between various actors who can master the different technological areas. However, engaging in such innovative efforts must realise a business case for the actors involved – both in the short and long term. Thus, benefits must be realised already before autonomous shipping can become the norm. Often this means new or improved offerings in the short term, which can be realised with the new skills that actors learn during the cooperative innovation process. As such, the business around autonomous shipping is built iteratively as a result of the continuous development of sub-components that together comprise the autonomous ship and the technologies needed for its operation (e.g. the remote control centre and communications technologies). Yet the viability of the new business area requires actors whose input makes the operations possible. These include e.g. regulatory bodies, insurers, classification societies, ship managers, ship owners, shipyards, etc. Moreover, viable shipping business also requires certain norms to be broken, e.g. the marine industry needs to overcome its conservative nature if it is to benefit from new solutions, and the society needs to accept digital solutions as improving the quality of life instead of threatening it. In other words, to fully realise the potential of autonomous shipping, the developed technologies must be deemed valuable by the wider marine industry as well as the society as a whole.

Technology	It's doable!	✓
Industrial networks & suppliers	Are getting organized	✓
Economic incentives	Value has been recognized	✓
Regulative environment	A lot of work but solvable!	✓
Societal perspective:		
Cultural-cognitive: Autonomous shipping is recognized	Attention has arisen	✓
Normative: Autonomous shipping is appropriate	Persuasion towards the change is starting!	✓

Table 1: The way forward to autonomous shipping

Table 1 presents the way forward to autonomous shipping. In summary, autonomous shipping is possible from a technological perspective, as the respective industrial networks and suppliers are increasingly becoming organised to make the concept a reality, and the value of autonomous shipping has been recognised for different actors in the maritime industry. Even issues regarding the regulatory environment, the often pointed out barrier to autonomous shipping, appear to be solvable if there is political will. As the elements for autonomous shipping are coming together, attention should be turned to how people perceive autonomous shipping in the society and the industry. Autonomous shipping must become culturally recognised, and it needs to become an appropriate norm in the industry. Such changes in mind-sets do not happen overnight, but there is indication that change is taking place as attention and wider public discussion around autonomous shipping is increasingly on the rise.

To provide the maritime industry with further understanding of the complex phenomenon of autonomous shipping, researchers at Turku School of Economics continue their work in 2016-2017 in close cooperation with industry representatives. Research will include exploring the wider marine stakeholder perspectives via a stakeholder survey, and investigating the new business models of key actors in the autonomous shipping ecosystem through workshops, enriched by insights from other relevant industries such as automotive and aviation.

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Advanced Autonomous Waterborne Applications (AAWA) partners

Company	Input
Rolls-Royce	System Integration and Automation Control
Deltamarin	Ship Design
Inmarsat	Satellite Communications Technology
DNV GL	Classification and Regulatory Guidelines
NAPA	Software House providing solutions for Ship Design and Operation

Universities	Input
Aalto / VTT (Technical Research Centre of Finland)	Safety and Security
Tampere University of Technology / University of Turku	Technology Research
University of Turku	Business Aspects
Åbo Akademi / University of Turku	Legal Aspects

AAWA project coordination

Markus Laurinen
markus.laurinen@rolls-royce.com

www.rolls-royce.com/marine