NAVIGATION AND INTERNATIONAL REGULATIONS FOR PREVENTING COLLISIONS AT SEA (COLREGs) IN AUTONOMOUS SHIPPING

BACHELOR THESIS

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CHIOS
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Gratitude and Appreciation

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ABSTRACT

The shipping industry is an international industry where the shipping companies and the maritime and maritime related organizations are highly impacted by the changes and evolutions that occur in the technological, financial/economic, social, political, environmental and legal fields that surround it. Particularly, the interplay between the maritime sector and the technological sector, throughout the years, has been crucial for the maritime industry’s sustainability and evolution. The need for the shipping companies to keep up with all the latest technological inventions and advances reflects the need to survive, modernize and reach up to the expectations of their commercial partners, as well as the society in general. As a result of that, digitalization is slowly, but steadily, entering the shipping industry with digital applications and innovations, that can be both applied to ships and used by shipping companies, emerging. One of these innovations is the design, the development and the construction of vessels that will be able to safely carry out voyages without any manning onboard. Instead, these vessels will be either fully autonomous or will be autonomous at a certain degree. By employing those vessels, shipping companies will be able to achieve cost reduction mainly due to the minimization of manning, and limit the effect of the human factor during incidents at sea. The navigation aspects and the implementation of the International Regulations for Preventing Collisions at Sea (COLREGS) by autonomous vessels are being analyzed in the bachelor thesis that follows, after describing the concept of autonomous vessels. The methodology used for the preparation of the following Bachelor Thesis consists of information and data collection from external and secondary sources, such as scientific articles and papers, and their critical synthesis in a text with meaningful continuity.

**Keywords:** autonomous vessels, navigation systems, COLREGS, dynamic positioning, unmanned surface ships, port navigation, Shore Control Center, MASS
1. INTRODUCTION

Autonomous vessels were first introduced as a concept back in 1970 in a book called «Ships and Shipping of Tomorrow» written by Rolf Stonchnknecht. In 1980 the minimization of the costs connected to the employment of the crew on the vessels, was the main reason why Japanese people conducted a more thorough research on autonomous vessels. In the following decade the idea of ships sailing without crew on board, but with the use of navigation systems, such as GPS, or artificially intelligent systems was still being explored. Despite the research that was carried out during those years, the high investment and maintenance costs were making the concept of autonomous vessels less attractive for the shipowners. In 2007, in a paper published by Waterborne TP, which is a «cluster of European maritime stakeholders» (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016), automization was considered welcome in the maritime industry, as well as autonomous vessels. (AUTOMATED SHIPS ARE ALMOST HERE – WHAT IS GOING TO BE THEIR IMPACT IN SHIPPING? )

The concept of autonomous vessels is being researched and studied because of the advantages that these vessels appear to have in comparison to manned vessels and the benefits that the shipowners and the maritime industry in general are expecting to gain by their employment.

The main advantages of the employment of autonomous vessels are:

Human factor:

– A main reason why the concept of autonomous vessels is being explored is the need for mitigating the risk of the human errors being the causes of incidents at sea. (NIKITAKOS, 2018) According to the U.S. Coast Guard « human errors are responsible for 96% of the incidents at sea» (NIKITAKOS, 2018).

– The lack of seafarers due to the fact that the profession is not as attractive as it used to be. (NIKITAKOS, 2018)

– Piracy is another reason for the development of autonomous vessels. (NIKITAKOS, 2018)

– Cost reduction that can be achieved by reducing the cost for employing seafarers on vessels and reducing the cost for fuels (NIKITAKOS, 2018). Electricity
is expected to be used for powering the propulsion system, instead of fossil fuels, and therefore the costs for fuels are expected to be lower (A growing commercial case for autonomous shipping, 2019).

– With the use of electricity or other renewable sources of energy (such as solar or wind power) the autonomous vessel’s emissions are expected to be significantly reduced (NIKITAKOS, 2018). Thus, compliance with 2020 sulphur cap (0,5%) imposed by the International Maritime Organization (IMO) for the global fleet will be easier to be accomplished (A growing commercial case for autonomous shipping, 2019).

These advantages and benefits of the autonomous vessels, together with the restrictions that they appear to have, are further analyzed in the sections that follow in relation to the autonomous shipping projects and navigation systems.

2. PROJECTS RELATED TO THE DEVELOPMENT OF UNMANNED VESSELS

2.1. THE «MARITIME UNMANNED NAVIGATION THROUGH INTELLIGENCE IN NETWORKS - MUNIN» PROJECT

MUNIN is the abbreviation for Maritime Unmanned Navigation through Intelligence in Networks and it is a project in the European 7th framework program with a duration of three (3) years. (Burmeister, Bruhn, Rodseth, & Porathe, 2014)

The total budget for this project was 3.8 million euros with European Union funding 2.9 billion euros. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

The project is a concept of the operation of a merchant vessel which has no manning on board, not necessarily for all the parts of a voyage, and, also, includes an assessment of the technical, economic and legal feasibility of such concept. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)
The MUNIN project used a dry bulk carrier that operates in intercontinental tramp routed as its case of investigation, due to a number of advantages that it offers, but mainly due to the fact that this kind of vessels carry out their deep-sea voyages from the port of their departure to their destination without having to frequently make port calls in order to charge or discharge cargo like containerships. This feature of operation that dry bulk carriers have makes them the best choice for the MUNIN project, as it focuses on the operation of an unmanned vessel in a deep-sea voyage and not in restricted or congested waters. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

The main reasons why autonomous and unmanned vessels are considered a contribution to a more sustainable and efficient European maritime industry, according to the MUNIN project, are:

- The expected reduction on operational expenses
- The low environmental impact
- The attraction of seafarers (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

2.1.1. Elements of the project

The aim of the MUNIN project is to develop a vessel that will be autonomously operated with the usage of technologically advanced systems onboard and its operation will be controlled and monitored by a Shore Control Centre located ashore. Components of the autonomous operation of such vessel, according to the concept of the project, are: (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

- An «Advanced Sensor Module». This module collects sensor data from navigational systems, such as AIS and radar, and images from infrared camera combined with daylight in order to perform lookouts on board.
- An «Autonomous Navigation System», which follows a voyage plan and a route that has been predefined, but allows a certain degree of freedom for the voyage plan to be adjust so that it complies with the rules of good shipmanship and
legislation. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

- An «Autonomous Engine and Monitoring Control system», which offers «advanced failure predetection» while retaining an optimal level of efficiency. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

- A «Shore Control Centre (SCC)», which is the center of monitoring and controlling the autonomous vessel during its voyage. The faculty of the SCC consists of (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016):

  A «Shore Control Centre Operator», whose work is to monitor the safe operation of more than one autonomous vessel from a cubicle station and to give commands of high level in order to control the vessel. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

  A «Shore Control Centre Engineer», who is of assistance to the operator when it comes to technical issues and is responsible for preparing the maintenance plan of the vessels «based on a condition-based maintenance system». (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

  A «Shore Control Situation Room Team», that handles the remote control of an unmanned vessel in particular situations «via a shore side replica of the vessel’s bridge». The team, also, uses a «Remote Manoeuvring Support System» with which they acquire situation awareness when having to control the vessel directly despite of their physical distance from the vessel. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

  A graphical presentation of the abovementioned elements is illustrated in Figure 1 and a graphical presentation of the project’s concept is illustrated in Figure 2.
Figure 1. Elements of the MUNIN project. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

Figure 2. Graphical presentation of the MUNIN project’s concept. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

2.1.2. Legal analysis of the project’s concept

The main areas of concern, when it comes to the adaption of a legal framework for the unmanned vessels, are manning and navigation regulations. It is believed that unmanned vessel will bring changes to those regulations, as well as to the standards concerning their construction, design and equipment. It is, also, believed that an array of issues will have to be tackled until the unmanned vessels will be able to sail at sea.
Furthermore, the attribution of the master duties to a person involved in operating such vessel that has relevant knowledge and experience is an important issue when it comes to liabilities. There has to be a clarification to whether the SCC operators and masters will share this legal role or this role will be attributed to a particular entity in the SCC. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

2.1.3. Advantages of unmanned vessels according to the concept of the project

1) The mitigation of the increased crew costs connected to slow steaming was the main aim of the project. A primary reason for implementing slow steaming is the reduction in fuel consumption. For instance, for a «medium sized bulk carrier» (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016) a 30% decrease in speed contributes to an almost 50% less fuel consumption. On the contrary, slow steaming prolongs the duration of a voyage, leading to an increase in seafarers’ wages, as well as making the profession less attractive for the seagoing professionals due to the long periods of time (several months) that they will have to be away from their homes. By employing unmanned vessels the abovementioned drawbacks of slow steaming will extinguish. Moreover, is highly possible that unmanned vessels will use alternative fuels for their operation. The use of such fuels combined with slow steaming is expected to result to a significant decrease on exhaust gas emissions by the vessels. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

2) The superstructures that are used for the accommodation of the crew on ships have a negative impact on the operation efficiency of the vessels. Therefore, by omitting those accommodations operating efficiency will be achieved easier. Furthermore, «advanced automatic energy management systems» combined with advanced routing and navigation can boost operation efficiency even more. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)
3) On unmanned vessels the risk of an accident or a fatality occurring will be eliminated as those vessels do not have any crew on board. Additionally, the automatisation of look-outs, collision avoidance and navigation systems will result to a significant reduction of maritime incidents and casualties. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

2.1.4. Restraints of unmanned vessels according to the concept of the project

1) Regarding the Shore Control Centre: The idea of building unmanned vessels that are completely independent of a SCC exists, but for the present time the onboard systems and technologies that those vessels require are very expensive for the shipowners to invest on. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

2) Regarding the operation of these vessels, the ports of their departure as well as the ports of their arrival will be requested to invest on proportionate infrastructure so that they can accommodate these vessels, making bulk carriers operation less attractive. Also, whenever an autonomous vessel encounters congested waters, in order for it to sail through them safely, direct monitoring is expected to be applied. Moreover, in the future is expected that «operating licenses will depend on agreements between the flags and the coastal states involved», restraining the operations of these vessels. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

3) Design: Unmanned vessels will presumably have a new and very different design than the compatible vessels without accommodation superstructures, and their technical systems will be simplified. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

4) Control and monitoring: The systems onboard will be responsible for monitoring the condition of the cargo, the condition of the machinery and of the
technical components of the vessel, detect any failures and any boardings without authorization, since there will be no crew onboard to do so. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

2.1.5. Deep Sea Navigation System

The Deep Sea Navigation System ensures that the unmanned vessel follows the predefined route and the deviations that are allowed, according to the «present operational envelope» (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016). The vessel may deviate due to «severe weather conditions» or in order to avoid traffic. Other functions of this system include (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016):

– Defining COLREG-related obligations of the vessel towards other vessels and manoeuvring the vessel in accordance with the regulations. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

– «Optimization of trans-oceanic voyage plans, based on meteorological forecasts» and data. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

– Operating the vessel with safety, when in situations of harsh weather conditions, in compliance with the «IMO weather guidance criteria». (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)

The operation of this system is completely autonomous. Nevertheless, the Shore Control Centre operator is able to take control of the vessel remotely and interact with the system. (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016)
2.2. THE AUTONOMOUS CONTAINER VESSEL «YARA BIRKELAND»

«Yara Birkeland» is an autonomous container vessel that is being developed by Yara International SA in cooperation with Kongsberg. Yara International SA is a Norwegian company (Yara at a glance) founded in 1905 that offers Chemical and Environmental Solutions as well as crop nutrition services and products (Yara: What we offer), and has its headquarters in Oslo, Norway (Yara at a glance).

Kongsberg is a company founded in 1814 in Norway (KONGSBERG: Who we are). It is a «global technology group which works for organizations across many sectors, such as: deep-sea, digital, defense, merchant marine, oil and gas, fisheries, aerospace and space industries» (KONGSBERG: About us), and has its headquarters in the town of Kongsberg in Norway (KONGSBERG HEADQUARTERS).

The partnership between Yara International SA and Kongsberg for the development of the autonomous container vessel started in May 2017. Also, in September 2017 a sum of $16.7m was announced by the «Norwegian Ministry of Petroleum and Energy-owned company ENOVA» as funding for building the vessel. (YARA Birkeland Autonomous Container Vessel)

The Yara Birkeland autonomous vessel is named after the founder of Yara International SA, Kristian Birkeland. It is expected to have zero emissions, since it will be the first fully electric autonomous vessel. Furthermore, in 2018 the vessel was expected to begin operations with crew onboard while in 2019 its operations will be remote. Its fully autonomous operation will start in 2020. It will be employed by Yara
International SA for the route «between Brevik, Herøya and Larvik ports» that are located in south Norway. «The Norwegian Coastal Administration’s (NCA) Brevik Vessel Traffic Service (VTS) centre will cover the abovementioned route». (YARA Birkeland Autonomous Container Vessel)

According to the present international maritime regulations and law- states, a vessel must be properly manned in order to carry out international and deep-sea voyages, and unmanned vessels are prohibited to operate on such routes. This justifies why Yara Birkeland will be employed on the abovementioned coastal route only. (Matthews, 2017)

2.2.1. Design and development

![Figure 4. The side profile of the Yara Birkeland autonomous container vessel. (YARA Birkeland Autonomous Container Vessel)](image)

The design of Yara Birkeland was made by Marin Teknikk and its testing will be conducted by SINTEF Ocean. The DNV GL classification society will provide the vessel with the appropriate certificates. (YARA Birkeland Autonomous Container Vessel)

«The measurements of the vessel will be: 79.5m overall length, 14.8m moulded width, 10.8m depth, 5m full draught and somewhere around 3200t deadweight». (YARA Birkeland Autonomous Container Vessel)

The operations of berthing and unberthing the vessel will be assisted by an «automatic mooring system», allowing a more automated process at docks. (YARA Birkeland Autonomous Container Vessel)
### 2.2.2. Navigation and communication systems

The systems that will be used for the navigation of the vessel and will assist to its autonomous operation are: sensors, radar, an AIS system (Automatic Identification System), «a light detection and ranging (LIDAR) device», «an imaging system and an infrared (IR) camera». A «virtual private network (VPN) connection through Inmarsat» and a «maritime broadband radio» will be used as means of communication for the vessel. (YARA Birkeland Autonomous Container Vessel)

### 2.2.3. Cargo handling systems

The capacity of cargo carried by the Yara Birkeland will reach up to 120 teus and a «large open cargo will be used to accommodate them». Moreover, electric cranes and equipment will be used for charging and discharging cargo, while the battery pack of the vessel will be used as ballast whenever the vessel will have to sail without being loaded with cargo. (YARA Birkeland Autonomous Container Vessel)

### 2.2.4. Propulsion and performance

The propulsion system of this vessel will be electric. A battery pack «with a capacity of up to 9MWh» will be its source of power. The propulsion system will consist of «two azimuth propeller pods and two tunnel thrusters» giving a speed that will range between 6knots (operational speed) and 10knots (maximum speed). Moreover, the operation of the vessel and its surroundings will be monitored and controlled by three control centres, ensuring its safe operation. (YARA Birkeland Autonomous Container Vessel)

### 2.3. AUTONOMOUS VESSELS DEVELOPMENT BY ROLLS-ROYCE

Rolls-Royce is a company that operates in the aerospace sector and offers products and services to a wide variety of divisions, including: civil aerospace, defence, nuclear, power systems and R² data labs. (ROLLS - ROYCE: Products & Services) The company was established in 1884 by Henry Royce and in May 1904 he
started working with Charles Rolls (ROLLS - ROYCE: Our history). The headquarters of the company are located in London, England (Rolls - Royce headquarters).

Rolls-Royce has announced the development of autonomous commercial vessels and ferries that will «carry luggage and goods» until 2025 and for this purpose they have a partnership with the Finnish Fin Ferries, (a collaboration that is named SVAN (Rolls-Royce, Finferries present world’s first fully autonomous ferry, 2018)) (Zahra, 2018). Those autonomous vessels will be controlled remotely through «intelligent automation software» (Zahra, 2018). In early December 2018 (Baron, 2019) they successfully completed a test, which consisted of a number of trials, of an autonomous ferry close to the city of Turku in Finland (Zahra, 2018). The 53.8m long ferry that was used in the trial, named Falko, was equipped with «the Rolls-Royce’s Ship Intelligence technology kit», which is designed to control the berthing procedures at the port of destination, as well as to monitor the waters and the surrounding of the vessel. Furthermore, the unmanned ferry, during the trial, carried almost 80 VIP passengers onboard in a number of voyages, which lasted about 400 hours. (Zahra, 2018)

The demonstration was conducted in two stages. The first stage included an «autonomous drive trial» of the vessel, while in the second stage the vessel was remotely controlled by an operator who was located in a distance of 30 miles from the ship, until the vessel arrived to its home port with safety. During the voyage the operation of the vessel was fully autonomous. (Zahra, 2018)

A collision avoidance system is installed on board the vessel to handle dangerous situation, but in case of an emergency, a qualified person can take control of the vessel. (Zahra, 2018)

![Figure 5. The Falko autonomous ferry by Rolls – Royce and Fin Ferries. (Baron, 2019)](image-url)
In this field of innovation, Rolls-Royce has, also, formed a partnership with a Finish university, the Tampere University of Technology, called «Advanced Autonomous Waterborne Applications (AAWA)» (Rolls-Royce, Finferries present world’s first fully autonomous ferry, 2018). The primary aim of this partnership is the development of «advanced autonomous shipping» with which the first ever generation of unmanned vessels will not just exist as a concept but will become a reality. (Rolls-Royce, Finferries present world’s first fully autonomous ferry, 2018)

![Remote controlling an autonomous vessel from a Shore Control Center – concept by Roll – Royce. (Matthews, 2017)](image)

**Figure 6.** Remote controlling an autonomous vessel from a Shore Control Center – concept by Roll – Royce. (Matthews, 2017)

### 2.4. THE UNMANNED VESSEL “REVOLT” DEVELOPED BY DNV GL

DNV GL is a company that operates worldwide, providing risk management and quality assurance services and products to its customers. The company cooperates with companies from a number of different sectors, such us: «the maritime, oil and gas, energy, food and healthcare industries», as well as many more. (ABOUT DNV GL: Our History) It is, also, a member of IACS (International Association of Classification Societies).

After the merge of the companies DNV and GL, the DNV GL Group began its operations in September 12, 2013 (ABOUT DNV GL: Our History). The headquarters of the Group are located outside Oslo in Norway (DNV GL headquarters in Norway).

The company, by utilizing the existing advanced technology, has developed a concept of an unmanned vessel, named «ReVolt», that will be employed in short sea shipping routes. «The ReVolt research project was initiated in August 2013 and launched in 2014». Despite, the present technological progress, the construction of
such vessel is expected to be completed in the future, when the technologies involved have matured. (Tvete)

![Figure 7. The autonomous container vessel ReVolt by DNV GL. (Tvete)](image)

ReVolt’s length will be 60 meters, it will be powered by battery and it will have zero emissions. The operational speed of the vessel is expected to be 6 knots, its capacity in cargo 100 teus containers and its range of operation 100 nautical miles. Furthermore, the vessel will not be equipped with an accommodation superstructure, since it will not have any manning onboard, resulting to lower operational and maintenance costs compared to a similar manned ship. (Tvete)

DNV GL in collaboration with the Norwegian University of Science and Technology (NTNU) run a test, between the years 2015 and 2018, by using a mini ReVolt model. Through this test, collision avoidance and «sensor fusion» in autonomous vessels were examined. (Tvete) Specifically, the vessel would sail across Trondheim Fjord, while two students were monitoring its operation from the shore (Sames).

DNV GL is, also, developing navigation rules for autonomous vessels that will be applied only on short sea routes, until international regulations are being developed by the International Maritime Organization (IMO) (Sames).
3. IMO REGULATIONS AND AUTONOMOUS VESSELS

The International Maritime Organization (IMO), which is the main maritime regulatory body, has started taking initiatives regarding the safety, security and environmental aspects of autonomous vessels. Those vessels are described as «Maritime Autonomous Surface Ships (MASS)». The Maritime Safety Committee (MSC) has endorsed a framework that includes definitions of MASS and levels of autonomy, «a plan of work» and a methodology. (IMO takes first steps to address autonomous ships, 2018)

According to the MSC’s definition of MASS, it is: «a ship which, to a varying degree, can operate independently of human interaction». The degrees of autonomy that a MASS operates with can differ, even during the same voyage. There are 4 degrees of autonomy (IMO takes first steps to address autonomous ships, 2018):

- «Ship with automated processes and decision support»: The vessel has manning onboard that is in control of the systems, functions and decision making, but a small number of operations might be automated. (IMO takes first steps to address autonomous ships, 2018)

- «Remotely controlled ship with seafarers on board»: The vessel has manning onboard, but is operated and controlled from a different location. (IMO takes first steps to address autonomous ships, 2018)

- «Remotely controlled ship without seafarers on board»: The vessel has no manning onboard and is operated and controlled from a different location. (IMO takes first steps to address autonomous ships, 2018)
• «Fully autonomous ship»: The vessel operates, makes decisions and takes actions autonomously, without any crew or operator involved. (IMO takes first steps to address autonomous ships, 2018)

Firstly, there will be an assessment of whether current provisions can or cannot be applicable to vessels with any degree of autonomy and whether they may or may not shut out any MASS operations. (IMO takes first steps to address autonomous ships, 2018)

Moreover, factors such as the human element, technology and operational features will be taken into consideration while analyzing the most suitable way of «addressing MASS operations». (IMO takes first steps to address autonomous ships, 2018)

The IMO’s instruments that will be covered during the conduction of the MSC’s scoping exercise for MASS are: «safety (SOLAS), collision regulations (COLREG), loading and stability (Load Lines), training of seafarers and fishers (STCW, STCW-F), search and rescue (SAR), tonnage measurement (Tonnage Convention), and special trade passenger ship instruments (SPACE STP, STP)». (IMO takes first steps to address autonomous ships, 2018)

Moreover, one of the Strategic Directions for the Organization that were adopted by IMO in 2017 addresses the «integration of advanced and new technologies in the regulatory framework». Although these technologies might have numerous advantages, there are concerns regarding safety, security, environmental impact, international trade, costs and the ways in which they might affect the crews and the personnel ashore. There must be an equilibration of the benefits and the concerns that are raised against these new technologies. (IMO takes first steps to address autonomous ships, 2018)
4. NAVIGATION SYSTEMS AND COLLISION AVOIDANCE IN AUTONOMOUS SHIPPING

4.1. ARTIFICIAL INTELLIGENCE IN MARITIME NAVIGATION – THE NAVAL ARTIFICIAL INTELLIGENCE (NAI) SYSTEM

Navigation systems in vessels have made great progress over the years. Current technological systems that are being used by the bridge team for navigation support purposes include: Automatic Identification System (AIS), Automatic Radar Plotting Aid (ARPA), Electronic Navigation Charts (ENC), and NAVDEC, which is a Navigational Decision Support System (NDSS). The need for improvement and progress of the naval navigational systems will always be existent within the maritime clusters and organization, especially with the rise of autonomous vessels. (Kulbiej & Wolejsza, 2017)

Furthermore, artificial intelligence has become part of our lives and is being incorporated in many technologies that are utilized in a wide spectrum of divisions, like telecommunications, the medical sector and many more. Artificial intelligence could be defined as «a computer-driven machine that can imitate intelligent human behavior» (Kulbiej & Wolejsza, 2017). An artificially intelligent system that could be used in navigation is called «Naval Artificial Intelligence». This system could be employed in the position of the Masters of the vessels by performing some of their duties, such as monitoring the vessel and the systems, ensuring the safety of the vessel and the cargo and completing the tasks and activities connected to the successful conduction of the voyage. The figures below show the duties of a Master in comparison to the services that a Naval Artificial Intelligence (NAI) system will offer, once employed on a vessel. (Kulbiej & Wolejsza, 2017)
The NAI system will be responsible for planning the most efficient and safe route from the port of arrival to the port of destination. This route may be subject to constant changes and adjustments by the «optimization algorithms» of the system, so that the vessel can respond to any unexpected situation or avoid any obstacles in the way. Also, the system will notify the vessel’s shipowner for the route and for any changes or deviations that may occur, and will receive their remarks. These remarks will, also, be used by the system when deciding the route plan. (Kulbiej & Wolejsza, 2017)

Maintenance of the hardware, the main and the auxiliary engines will be performed by the NAI system, ensuring that their performance will not deteriorate throughout the voyage. Another important element is the handling of the cargo during the voyage and especially at the time of charging/discharging. These activities must be carried out with caution by the system. The berthing and unberthing processes that take place prior to loading and unloading cargo may be conducted by the NAI system, or with the assistance of the port worker and the port’s mooring equipment. (Kulbiej & Wolejsza, 2017)
4.1.1. Safety and security of the vessel in the NAI system – International Regulations for Preventing Collisions at Sea (COLREGs)

As abovementioned, the NAI system must ensure that the planned route of the vessel is safe and secure. In case of an emergency situation, the system must navigate the vessel appropriately. In order for that to happen, the NAI driven vessel must comply and implement COLREG rules during its voyages, as well as proceed to assist any object or person in need at sea. If the actions that the system decides to take for any reason or under an unexpected and dangerous circumstance, for example manoeuvre to avoid an object or steer away «in respect to other vessels and boats», inevitably cause loss or damage to the cargo, damage to the environment, fire or leak onboard, the system is ought to minimize the damage by using the appropriate installed equipment. The figure 11 below is a graphical presentation of the equipment and facilities that the «whole item-three» of NAI consists of. (Kulbiej & Wolejsza, 2017)

![Graphical presentation of «whole item-three» of the Naval Artificial Intelligence (NAI). (Kulbiej & Wolejsza, 2017)](image)

4.1.2. The «Behaviour Model» of the NAI system

The NAI system will collect data from a number of devices and systems such as GPS and will display and process them intelligently. Since, the NAI is an intelligent system it will be able to make its own decisions and solve problems, but to be able to do that it must be granted authority over the vessel and be autonomous at a certain degree. There are different ways of solving a problem whenever the system encounters one. Firstly, a solution to the problem will be searched in a bank of
knowledge, depending on whether the same problem has been encountered before and has been stored in the bank. The system, then, will apply the solution to solve the problem. If a solution cannot be found in this bank of knowledge the system may use one of the «preinstalled algorithms modules» to solve the problem. This indicates that the system will operate autonomously and not automatically like the existing systems. In case the problem has remained unsolved, the assistance of ashore personnel can be used and their immediate response is extremely significant. Another feature of the system that indicates its efficiency is the «self-learning module» with which the response to a problem will be automatic, shall the same problem is encountered more than once. (Kulbiej & Wolejsza, 2017)

This problem-shooting algorithm and the behavior tree of the system are graphically presented in the figures 12 and 13 below. (Kulbiej & Wolejsza, 2017)

**Figure 12.** Problem – shooting algorithm of the Naval Artificial Intelligence (NAI) system. (Kulbiej & Wolejsza, 2017)
The activity of «way leading» is an activity in which a number of different parts of equipment and machinery cooperate to ensure that the voyage will be carried out successfully. (Kulbiej & Wolejsza, 2017)

### 4.1.3. Components of the NAI system

The components that the NAI system will consist of are the following:

- An autonomous vessel. This autonomous vessel will have no manning on board, which means that the bridge and the engine room will operate autonomously, and will have a specific «communication protocol». (Kulbiej & Wolejsza, 2017)

  The technology of the engines installed in conventional vessels is, already, autonomous. Therefore, there are not many things that must be reconfigured in order for those engines to be installed in an autonomous vessel. Furthermore, there will be a shore center that will supervise and, occasionally, remote control the autonomous vessel. (Kulbiej & Wolejsza, 2017)

  In the bridge area of the vessel, navigational electronic devices and systems, like AIS and radar, are most likely to be used for the navigation of the vessel. The data collected by these instruments will be, also, sent to the control center ashore, contributing in monitoring the NAI system’s and vessel’s operation. (Kulbiej & Wolejsza, 2017)

- Communication protocol. The autonomous vessels must be equipped with the appropriate communication protocol. The communication between the vessel and the...
shore can be achieved via satellite very fast, since the speed of data transmission has increased and is expected to increase more in the future. (Kulbiej & Wolejsza, 2017)

On the contrary, communication between vessels which is very significant especially when transmitting information regarding a manoeuvre, might not be as efficient and fast as the shore-vessel communication. The systems that are currently being used by vessels for this purpose could be, also, used in autonomous vessels with a few alterations, so as to meet their requirements. To name a few of those systems, Automatic Identification System (AIS) and Digital Selective Calling (DSC) could enable communication between autonomous vessels or between an autonomous and a manned vessel. It is extremely important that the messages are transmitted autonomously. (Kulbiej & Wolejsza, 2017)

Additions to the existing standards of the communication systems could be (Kulbiej & Wolejsza, 2017):

- Through Message 5, data regarding the route to the next port and all of the waypoints (WPs) or five of the waypoints could be sent, by adding more slots in the message. Message 5 includes information related to the voyage and the static of the vessel. (Kulbiej & Wolejsza, 2017)

- Message 14 that is used for transmitting messages related to safety could be used for the broadcasting of navigational and meteorological warnings. Moreover, information regarding «anti-collision manoeuvres» could be transmitted in Message 14 as well. (Kulbiej & Wolejsza, 2017)

It is considered crucial that «anti-collision systems» communicate directly with the AIS system, by sending and receiving messages related to collision avoidance situations. (Kulbiej & Wolejsza, 2017)

4.1.4. Advantages of the autonomous vessels according to the concept of the NAI system

- Elimination of the human element. According to studies, 75% to 96% of the incidents and collisions at sea are caused by erroneous human actions, a fact that has been mentioned again in previous sections. The variation of the percentage is a result of the different times and locations that the incidents took place. Collision avoidance systems and algorithms will operate to avoid any dangerous situations and possible incidents automatically and efficiently, while humans might have to deal with their
anxiety and emotional state that is most likely to have a negative impact on their ability to handle those circumstances with sanity and success. (Kulbiej & Wolejsza, 2017)

- Cost reduction through elimination of the seafarers’ wages. The International Maritime Organization (IMO) and the international Labour Organization (ILO) have estimated that in the year 2020, 40000 officer positions on vessels will be vacant, as there is a lack of officers. The main reason why the number of seagoing personnel declines is that the profession is becoming less and less attractive. Despite the lack of seafarers, the number of vessels is following the opposite direction and is increasing. Assuming that the average number of officers on deck and in the engine department of the vessel is 8, there will not be officers to man around 5000 vessels. The first generation of autonomous vessels could replace those manned vessels. (Kulbiej & Wolejsza, 2017)

- Fuel consumption reduction achieved with algorithms. In the case of a 8000 TEUS containership, the average consumption of Heavy Fuel Oil (HFO) (Kulbiej & Wolejsza, 2017), like IFO 380 which is the heaviest fuel oil consumed by vessels (World Bunker Prices, 2019), is 260MT when it operates at full speed. An algorithm that gives the «optimal anti-collision trajectory» can reduce the time of manoeuvres and subsequently reduce the fuel consumption (Kulbiej & Wolejsza, 2017). If, for example, the time that is needed to complete a manoeuvre of the vessel is reduced by one minute a day, then the fuel consumption can be reduced by around 65 tons of fuel per year (Kulbiej & Wolejsza, 2017). With the average price of IFO 380 being 454 USD per Metric Ton (World Bunker Prices, 2019), the shipping company this could save up to almost 29510 USD per year.

In overall with the employment of autonomous vessels, instead of conventional ones in the international seaborne trade, is expected to reduce the cost of transportation by sea and subsequently, the cost of goods and cargo that are being transported.
4.2. ROBOTIC SAILING BOATS

Aland Sailing Robots is a project carried out by Aland University of Applied Sciences and its main purpose is the development of a fully autonomous sailboat that will be able to cross the Atlantic Ocean. The project will, also, contribute to the existing knowledge and research on eco-friendly technologies and autonomous vessels. Sailing robots are expected to operate without involving any human assistance and perform route planning and manoeuvres whenever needed. (Eriksson & Friebe, 2015)

4.2.1. Sail control

There are publications in the area of «automatic sail control» from 1990, but there still research that has to be conducted in order to answer the numerous remaining questions. (Eriksson & Friebe, 2015)

There are two types of wing sails that can be used in the construction of a sailing robot: rigid wing sails and fabric wing sails. On the one hand, improved «lift-to-drag ratio», reliability and avoidance of sail luffing or flapping are some of the features of the rigid wing sails that make them a better choice compared to fabric sails. On the other hand, problems in enabling reliable reefing and the costs of constructing lightweight, resilient and rotating wings sails must be tackled, in order for the rigid wing sails to become the optimal choice in wing sails. (Eriksson & Friebe, 2015)

Most of the strategies in sail control are based on the angle of the sail relative to the wing. Therefore, the wind and its direction are important factors in determining the appropriate sail control strategy of an autonomous sailing robot. (Eriksson & Friebe, 2015)

4.2.2. Route control and planning

As abovementioned, the wind and its direction are very significant, when it comes to sailing robots. For that reason, the route selected for a sailing robot to sail from one point to the other may not be the shortest, unless the wind direction and
power are the desired. Weather conditions and obstacles are, also, factors that affect the determination of the optimal route for a voyage. (Eriksson & Friebe, 2015)

Long term and short term routing are two different categories of route control. In long term routing, weather forecasts, the ship’s properties and «sea charts» are taken into account for route planning, while in short term routing measurements from local sensors are the main element used in route planning. (Eriksson & Friebe, 2015)

The planning of the route that the robotic sailing boat will follow is manually planned before the beginning of the voyage and during the voyage the route may alter automatically or manually to adjust to the sailing conditions or to unexpected events. Information concerning traffic, depth of waters, weather, energy and other factors are significantly useful in those adjustments. For instance, if the energy for the vessel is generated by solar panels and the boat is sailing in daylight, but has to make a deviation that will result in sailing in cloudy weather for a long period of time, then the stored energy might not suffice for the completion of the voyage. (Eriksson & Friebe, 2015)

Collision avoidance is another important element in route planning. Data collected by navigation devices and systems, such as Automatic Identification System (AIS), radar sensors and infrared cameras can be used in avoiding situations of collision and ensuring a safe voyage. (Eriksson & Friebe, 2015)

4.2.3. The Microtransat Challenge

«Microtransat Challenge is a transatlantic race of fully autonomous sailing boats, no longer than 4 m (LWL)». According to Microtransat, in order for a boat or a ship to be considered a vessel and be compliant with the International Rules for Preventing Collision at Sea (COLREG), it must carry cargo or passengers onboard. For that reason, according to Microtransat, the sailing boats cannot be considered vessels but buoys, and therefore COLREGs are not applicable to them. (Eriksson & Friebe, 2015)
4.2.4. Legal aspect of the concept and International Regulations for Preventing Collisions at sea (COLREGs)

The International Regulations for Preventing Collisions at Sea (COLREGS) definition for the vessels that must be compliant with them is: «The word «vessel» includes every description of water craft, including nondisplacement craft, WIG craft and seaplanes, used or capable of being used as a means of transportation on water» (Eriksson & Friebe, 2015). Therefore, the sailing boats should be considered as vessels, because many of them are «being used as a means of transportation on water». This realization was the result of a heavy criticism that the Microtransat interpretation of COLREGs received. Also, there are great possibilities for a sailing boat to be involved in a collision with another vessel and cause damage to another property or to humans (passengers, crew). Therefore, the implementation of COLREGs by sailing boats becomes even more necessary. (Eriksson & Friebe, 2015)

There are not any provisions for autonomous or semi-autonomous vessels in the COLREGs and other regulations yet. This means that autonomous vessels cannot operate on a large scale, for example conduct deep-sea voyages until their mode of operation and navigation are regulated. Moreover, there are COLREG Rules, for instance “Rule 5 on lookout”, that state the use of human senses, such as hearing, excluding autonomous vessels that has no manning on board. On the contrary, there are COLREG rules that do not state human senses. Instead, they state the use of navigational systems and devices, like radar, to ensure navigation safety in particular circumstances. Those rules could be implemented by autonomous vessels, regulating their navigation processes and allowing them to be commercially employed as means of transport for certain trade routes and minimal operations. (Eriksson & Friebe, 2015)

One strategic decision for an autonomous vessel or a sailing robot to sail safely in accordance with COLREGs is to keep a safe distance from other vessels or objects that it might encounter during the voyage. This strategy may sound simple and easy to apply, but sometimes factors beyond the control of the vessel (or the boat) might make it difficult for it to keep a safety distance from the objects surrounding it. For instance, there are times when the curiosity of the seafarers that are onboard conventional vessels makes them want to approach the autonomous vessel, or the vessel sails through harsh weather and navigation is difficult. In these situations, it is
necessary that dangerous circumstances are being avoided by implementing COLREGs. (Eriksson & Friebe, 2015)

4.2.5. Tracking of sailing boats

Tracking autonomous sailing boats is extremely important, since they operate without crew onboard. Their location must be known at any minute for safety and security purposes. «A satellite based tracking system» is considered more suitable for tracking boats and vessels in ocean routes and passages. «Those systems quite often use the low orbiting Iridium satellite system». (Eriksson & Friebe, 2015)

As mentioned above, Automatic Identification System (AIS) is a system that is used in navigation and has become mandatory «under the provisions of Safety of Life at Sea (SOLAS) Conventions». With AIS vessels and boats can be visible from other vessels, since their stigma is displayed on the radar of other vessels, and vice versa. A new tracking technology that has been developed for the maritime sector is the «satellite AIS tracking system» with which the signals from the AIS system can be detected by a satellite orbited close to earth, providing worldwide coverage of all the vessels that are equipped with AIS. (Eriksson & Friebe, 2015)

Another system that has been developed by the ENSTA Bretagne team in collaboration with Aland Sailing Robots team is called «SWARMON» and is a 3G tracking system. It is an embedded system that allows real time tracking of sailing robots and has been used in marine events like the «World Robotic Sailing Championship». (Eriksson & Friebe, 2015)

4.3. UNMANNED AERIAL SURVEILLANCE FOR COLLISION AVOIDANCE IN AUTONOMOUS SHIPPING

Navigation of vessels in the sea and route planning are mainly based on electronic navigation systems, such as radar, ARPA, AIS, ENC and ECDIS, as well as the remarks and decisions of the Master, to ensure that the vessel will conduct the voyage with safety and security. Despite the worldwide coverage of the sea and waters that these systems provide, there are still small areas or objects in the sea that are unmapped and can cause damage to the vessel or create dangerous circumstances
leading to collisions. For the detection of those unmapped objects and obstacles equipment such as LIDAR sensors and cameras could be installed on vessels, alongside with the rest of the navigational systems. This equipment will enable the scanning of the proximate waters and the surrounding of an autonomous vessel. However, in order for them to accurately and clearly distinguish objects in the vessel’s environment, they must have «line of sight» to those objects. This feature may have a negative effect on their efficiency. «Satellite remote sensing» is another solution to this problem, but the number of disadvantages that it appears to have, including limited accuracy and resolution, deficiency in constantly providing real-time data and partial coverage, makes it a less attractive option. (Johansen & Perez, 2016)

The concept of using «unmanned aerial vehicles (UAV)» that will operate like the abovementioned systems, allowing the scanning of waters for the detection of unmapped objects is being discussed. Specifically, the name of this concept is «Unmanned Aerial Surveillance System (UASS)» and in this concept UAVs will perform «low altitude surveillance» in an area around the vessel’s route, while flying ahead of the vessel. (Johansen & Perez, 2016)

The UAVs can be of assistance to both manned and unmanned vessels, but this concept focuses on the implementation of the UASS by unmanned vessels and boats that operate autonomously or remotely from ashore. The UASS is not to be considered the main sensor system of the vessel, but an auxiliary system that will provide detection and identification of objects within a relatively short distance from the vessel. (Johansen & Perez, 2016)

4.3.1. Expected benefits from the Unmanned Aerial Surveillance Systems (UASS)

The expected benefits from the usage of UAVs as systems of maritime surveillance are (Johansen & Perez, 2016):

- The extension of the «light of sight», enabling the observation of the sea and the detection of any potential hidden object and obstacle from a direct angle. Moreover, there is a possibility that sunken objects that are close to the sea surface, such as swimmers and marine mammals, will be, also, detected by the UAVs. (Johansen & Perez, 2016)
The detection of the motion of the objects on the surface with higher accuracy and resolution. This can contribute to reducing the risk of a potential collision between the autonomous vessel and an object that is on its route or near its route, by tracking the object’s trajectory. (Johansen & Perez, 2016)

The system could assist in the implementation of the «Rules of the Road» or officially known as International Regulations for Preventing Collisions at sea (COLREG) by the autonomous vessel. With the data and information provided by an UAV, combined with the information displayed by the other navigational systems, the vessel’s ability to assess its right of remaining on its route or give way to another vessel in accordance with COLREG will be enhanced. Thus, navigational and operational safety will be ensured. (Johansen & Perez, 2016)

4.3.2. Potential constraints of the Unmanned Aerial Surveillance Systems (UASS)

- The weather conditions may impact negatively the efficiency of the LIDAR and camera equipment of the UAVs. More specifically, rainy or foggy weather and generally harsh conditions can limit the required visibility for the operation of those devices. In the future, the development of advanced robotic systems and the commercialization of radar systems, like SAR, that are now expensive and impractical for UAVs are considered solutions to the aforementioned problem. (Johansen & Perez, 2016)

- Extremely harsh weather, like «strong wind» and ice, is likely to limit the operating efficiency of the UAV. (Johansen & Perez, 2016)

- «Multi-rotors» are not considered of use for the operation of the UAV, since UAV’s speed must exceed the vessels operational speed and precede the vessel, and it must have «long endurance». Special facilities on the vessel could be used for charging or refueling the UAV, but in this case measures have to be taken regarding the landing and the launching of the UAV. (Johansen & Perez, 2016)

- The autonomous operation of the UAV «Beyond-line-of-sight (BLOS)» involves radio communications, «air traffic management and airspace regulations» that have to be addressed. (Johansen & Perez, 2016)
4.3.3. Function of the UAS System

The UASS will be used by autonomous vessels as a navigational system, providing safe route planning and navigation, collision avoidance and compliance with COLREGs. The system is expected to comprise the following features and information (Johansen & Perez, 2016):

- «An electronic map of static hazards». (Johansen & Perez, 2016)
- A predesigned nominal path to the port of arrival ensuring the safety of the vessel against groundings. (Johansen & Perez, 2016)
- Information regarding the vessel’s velocity, position, «heading and yaw rate», based on real-time calculations. (Johansen & Perez, 2016)
- Assessment of the ability to alter the vessel’s route and speed under «steering and propulsion commands», enabled by a «mathematical model of the vessel». This model will be, also, used to predict wind’s power and ocean currents. (Johansen & Perez, 2016)
- Estimations of the forces that the vessel receives from the wind and the ocean currents. (Johansen & Perez, 2016)
- Objects and obstacles detection within «line of sight» provided by instruments such as LIDAR, radar and «infrared thermal imager». (Johansen & Perez, 2016)
- «Telemetry radio link» between the vessel and the UASS with a sensor, enabling the vessel to control and command the system and detect and identify objects or obstacles and their particular characteristics. (Johansen & Perez, 2016)

The figure 14 below illustrates the sub-systems that the UASS consists of and the flow of information between them. (Johansen & Perez, 2016)
Firstly, the «Ship Autopilot» sub-system receives as input from the «Mission Planning and Execution» sub-system information regarding the speed-over-ground and the path that the vessel will sail on as a sequence of waypoints (WPs). The Collision Avoidance System (CAS) is an independent «external system» responsible for ensuring that the path and trajectory of the vessel is free of possible groundings and collisions. It, also, calculates the positions and contemplates the trajectories of objects and obstacles that are near the vessel’s path and trajectory. The command that is received by the autopilot regarding the route «angle offset» is used as a CAS outlet. The CAS, also, outputs to the pilot a list of waypoints (WPs) and a «nominal speed» of the vessel. Moreover, time is extremely important when avoiding dangerous circumstances and collisions, taking into consideration that the dynamics of the vessel are much slower than those of the objects around it. For that reason, both trajectories and time are considered and represented in the CAS, while the autopilot disconnects time and position into steering and propulsion system. The CAS has, also, command over the speed of the vessel and, thus, it can lower, reverse, or even «set to zero» the speed. (Johansen & Perez, 2016)

A vessel simulator is employed by CAS, so as to assist CAS in determining its policy of control by assessing a number of scenarios. The status of the vessel, the approximately calculated trajectories of the objects and obstacles and the control policy which includes the route offset and the «propulsion command» are taken into account when forming each scenario. A «nominal scenario», which does not include route offset and in which the vessel operates at the nominal speed, could be selected.
when the level of hazard that it entails is low. If the level of hazard of this scenario is not as low as desired, then the control policy that is the least dangerous is chosen. During the simulation the impact of the forces of the wind and ocean currents on the vessel should also be taken into consideration. Risk of collision and grounding as well as the implementation of COLREGs are assessed with the use of weights for each of them and the outcome of the assessment is used in the process of minimizing the criterion of hazard. Restrictions and conflicting matters may lead to compromising minimum hazard definition. (Johansen & Perez, 2016)

Finally, operators ashore and radio telemetry can receive messages from CAS in the form of alarms. (Johansen & Perez, 2016)

A number of navigational systems and devices that are installed onboard the vessel, such as AIS, radar, Global Navigation Satellite System (GNSS) and sensors provide data and information regarding the position and velocity not only of the vessel, but also of the obstacles, objects and other ships around the vessel. This information is, then, processed by the «ship Situation Awareness and Sensor Fusion (SASF)» which can, also, give orders to the UAV. The area of interest that the UASS will focus its research on will be determined by SASF after assessing the present situation. The UAV will, then, receive commands by SASF on the list of waypoints that it will surveille. Furthermore, the operation of the UASS is based on a list of waypoints and includes gathering images that will be processed by «machine vision». As an outcome of processing the real-time images, the machine vision tracks, identifies and calculates the location and velocity of any obstacles and objects that might exist near the course of the vessel, and relates them to a database of standard and recently approached by the vessel obstacles and objects. The catalog that includes the objects and obstacles, their features, status and estimations is being updated and transferred to CAS, after SASF has combined and «cross-referenced» the information and data produced by the rest of the systems and devices. (Johansen & Perez, 2016)

A matter of consistency of the objects’ and obstacles’ identification and detection by the sensors of the SASF may arise. A number of factors may affect the operability of the sensors including obstacles out «of the line of sight» as well as obstacles and noisy environments getting in the way of detecting other objects and obstacles. A method with which the speed and location of the objects can be calculated is the «least squares curve fitting» of the information and data that have been collected. (Johansen & Perez, 2016)
UASS’s method and strategy of conducting survey and searching the area of interest around the course of the vessel should take into consideration the following (Johansen & Perez, 2016):

- Verification of inefficient or potential tracings of objects and obstacles by the vessel’s system of sensors. (Johansen & Perez, 2016)
- Retention of up-to-date calculations and observations related to objects and obstacles, by adopting detection and survey operations. (Johansen & Perez, 2016)
- In case of a sudden alteration of route by the vessel that results in the entrance of the vessel in an unsearched area, the UASS must have the ability to plan ahead of such situations reducing uncertainty. (Johansen & Perez, 2016)

4.3.4. Collision Avoidance in the UAS System

Despite the fact that International Regulations for Preventing Collisions at Sea (COLREGS) have not, yet, incorporated provisions and rules that could regulate and be implemented by autonomous vessels or systems like UASS, there are, still, existing rules that are applicable to the UASS concept. Those rules are the following (Johansen & Perez, 2016):

- Rule 6: «Safe Speed». A number of factors are involved in ensuring the existence and retention of a safe speed. Ocean currents, force of the wind, waves, draught in relation to the depth, congested waters, visibility to name a few. (Johansen & Perez, 2016)
- Rule 8: «Actions to avoid collision»: Any action to avoid collision should be taken, depending on the circumstance and the time available. Some of those actions include deviations, reduction of speed or stop, retention of a safe distance from other vessels, boats and objects and performing manoeuvres when there is enough space. (Johansen & Perez, 2016)
- Rule 13 – «Overtaking»: An overtaking vessel should never get in the way of the vessel that it overtakes. (Johansen & Perez, 2016)
- Rule 14 – «Head-on situation»: The «course to starboard» must be changed whenever the courses of two power-driven vessels are almost reciprocal, increasing the possibility of a collision between them occurring. (Johansen & Perez, 2016)
- **Rule 15** – «Crossing situation»: In the case of two «power-driven vessels crossing» in a way that can create a collision situation, one of them is obliged to keep out of the way. The vessel that will have to keep out of the way is the one that has the other vessel «on her own starboard side». (Johansen & Perez, 2016)

- **Rule 16** – «Actions by give-way vessel»: «Take early and substantial action to keep well clear». (Johansen & Perez, 2016)

- **Rule 17** – «Actions by stand-on vessel»: Retain speed and course. If an action is needed, then the vessel «then the ship should try to avoid to alter course to port for a vessel on her own port side». (Johansen & Perez, 2016)

- **Rule 18** – «Responsibilities between vessels»: «A power-driven vessel shall keep out of the way of: a vessel not under command, a vessel restricted in her ability to manoeuvre, a vessel engaged in fishing, and a sailing vessel». (Johansen & Perez, 2016)

Other rules, like «Rule 9 - Narrow channels», «Rule 10 – Traffic separation schemes» and rules concerning lights and sound equipment, such as Rule 22 – «Visibility of lights» and «Rule 33 – Equipment for sound signals» (Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs)) could, also, be applicable (Johansen & Perez, 2016).

### 4.4. NAVIGATION OF AUTONOMOUS VESSELS IN PORTS

So far an extensive analysis has been carried out on navigation related systems and systems compliant to the International Regulations for Preventing Collisions at Sea (COLREGs) that could be employed by autonomous vessels and assist their navigational and collisional avoidance operations in a sea environment. However, nowadays almost the 2/3 of the duration of a voyage is spent in the port area and facilities, where the vessel loads and discharges cargo and passengers. Safe and secure navigation of the autonomous vessel in that area is of great importance, due to the potential hazardous situations that it might encounter. Factors including dangerous weather conditions, traffic and unnecessary manoeuvres increase the risk of a vessel potentially colliding with another vessel, an object or even the pier when it departs or arrives at a port. For the abovementioned reasons, it is considered legitimate that the
appropriate measures are taken to ensure the safety of the autonomous vessel and its surroundings.

An approach to the navigational aspects of the operation of an autonomous vessel while in the port area is based on the division of these aspects into 4 different «control levels». These levels are: «strategic, tactical, critical and super critical». The control levels are fully separated from each other. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

The strategic level is responsible for controlling the processes that take place prior to the unberthing of the vessel. To be able to perform control, selection of data and information regarding the port of destination and the Estimated Time of Arrival (ETA) to that port, objects and parts of the port’s equipment and estimation of the anticipated «traffic density» are needed. The planned route for the vessel is not to be affected by the position and «behavior» of other vessels, in this level of control. The strategic control level ends when the vessel leaves the dock. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

This is when the tactical control level begins. In this level of control, information regarding the behavior and operation of other vessels in the port environment are taking into consideration for the creation of solutions to potential navigation issues. The primary aim of this level is to ensure that the vessel will follow the predesigned course. VHF communications are not needed in this level. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Response to sudden and unexpected behavior and actions of nearby ships is given by the critical control level. In this level, vessel’s velocity and «heading» alterations and adjustments occur, so as to avoid dangerous situations. Communication between an autonomous and a conventional vessel is, also, considered viable. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

In the super critical level, the vessel aside of coping with the unforeseen circumstances mentioned in the critical level, it is likely to deal with objects in the water that it cannot communicate with. These objects include people, items, ships with a non-functioning communication equipment and «oil spills». Circumstances like the aforementioned require very particular solutions. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

The graphical representation of the four control levels is given in the figure below. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
4.4.1. Evaluation of solutions

The solutions were evaluated according to the area of their application, for example «density of traffic», and the priorities of the «investors and operators», as well as their effect on these solutions. Any essential advanced sensor technology and technology based on artificial intelligence (AI) was also considered. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.2. Concept solutions

In order for a «navigation system» to be the desired, it must provide solutions that will serve not only one control level, but all four of them. Such system can be viable, but it is expected to comprise connection and coordination between the different control levels, in the form of inputs and outputs. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
4.4.2.1. **Solutions within the strategic control level**

The predesigned route of the autonomous vessel that connects the starting point with the port of arrival or the final destination, as well as a matching navigational behavior of the vessel are parts of the solutions ideas for this control level. For instance, in liner shipping the cooperation with port authorities and operators in order to plan the route of the vessel and determine the time of its departure and arrival is considered extremely important. Port authorities and operators collect, on a daily basis, a vast amount of data and information regarding traffic, the vessels that approach the port and their positions. This information could be used in optimizing the predefined route and the estimated time of departure and arrival of the vessel. Furthermore, it is not unlikely for the scheduling of the voyage and the preliminary planning of the route to depend on the containers’ time of delivery at the port. In this case, the information needed for determining the time of departure and arrival of the vessel have been collected at an earlier point in time, so as to deal with any restraints imposed by the arrival of the containers easier. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.2.2. **Solutions within the tactical control level**

For the tactical level the data needed are the predefined route of the vessel and the sailing behavior that have been decided in the strategic level, as well as the Estimated Time of Arrival (ETA). The outputs of this level include constant alterations and changes on the autonomous vessel’s route, «sailing profile» and Estimated Time of Arrival (ETA) in order for the vessel to respond to “predictable behaviors” of other vessels that sail nearby. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

**Platoons including conventional vessels**

The autonomous vessels could follow a manned vessel that will sail on the same route as them on a «fixed distance» in order to arrive to its destination. This idea is called «ship platooning». During ship platooning the manned vessel will be responsible for handling communication related to traffic status, while the
autonomous vessels will simulate, in a way, the sailing behavior of the manned vessel. In this way, the number of circumstances and situations that are included in the critical control level decreases. The manned vessel will play an important role in navigating and providing a «safe-to-sail» route for the autonomous vessels that participate in the platoon, but will not take any responsibility for them. Moreover, in order for platooning to happen conventional vessels must sail through the area in which an autonomous vessel is sailing and operating, define and communicate a desirable route «based on waypoints» with it. The desirable routes that the autonomous vessel will receive from the nearby manned vessels will, then, be controlled and monitored by the owner of the autonomous vessel who will operate from a shore control center (SCC). The participation of the port authority in monitoring traffic is, also, recommended. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

The organizational components that are required for the concept of ship platooning are (van den Boogard, Feys, Overbeek, & le Poole, 2016):

a) «An online platform». In this platform masters of manned vessels, as well as «terminal operators», will enter information regarding the vessels and the routes. The Shore Control Center (SCC) will be responsible for monitoring this online platform. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

b) The designing of the routes will be based on waypoints and lanes with limited space for deviations from the masters of the manned vessels (only in case of an emergency or a particular manoeuvre). (van den Boogard, Feys, Overbeek, & le Poole, 2016)

c) Coordination between VHF (Very High Frequency) sectors. Coordination between VHF sectors within the port is expected to maximize the efficiency, when it comes to routes that are longer, and increase predictability of both the manned and the autonomous vessels. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Moreover, during platooning the autonomous vessels will be able to choose the most efficient and suitable combination of manned vessels to follow, taking into consideration the Estimated Time of Arrival (ETA) and the routes of the manned vessels. Specifically, the best combination is considered to be the one that is closest to the initial ETA for the autonomous vessel. The masters of the manned vessels must
approve the platooning with the autonomous vessels, before it takes place. Furthermore, information regarding the positions and speeds of the vessels that participate in a possible combination are, also, needed. For this purpose, the Automatic Identification System (AIS) could be used to provide this information with augmented accuracy and frequency. Route projection that is being provided by the AIS could be, also, utilized with some improvements. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

The Harbour Master Management Information System (HaMIS) could, also be of assistance to the concept of ship platooning by providing data about the characteristics of the manned vessels and any «cargo hazards» to the autonomous vessel, so that the autonomous vessel can define a «safe following distance». These data must be communicated with security and integrity. Other devices that could be used to assist the process of platooning are Laser Imaging, Detection and Ranging (LIDAR) sensors. These sensors enable the unmanned vessel to simulate the sailing behavior of the leading vessel while sailing in a line behind the unmanned vessel and retaining a safe fixed distance from it. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

In the case of an autonomous vessel that is not a part of a platoon, a Shore Control Center could take on the navigation of the autonomous vessel by remotely controlling it. Finally, in order for the masters of the manned vessel to be fully aware of the situation when they participate in a platoon, a module could be installed onboard the unmanned vessels to transfer information regarding the other vessels and the platoon. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Traffic situations

Another concept for the navigation of the autonomous vessel that is being explored involves the «anticipation of traffic» by the autonomous vessel. In this concept the autonomous vessel must follow a route and adapt a sailing behavior and profile that will ensure avoidance of critical situations. For this concept the involvement of the port authority and of a Shore Control Center (SCC) is crucial. The port authority can provide data and information regarding the vessels’ traffic, congestion, position and sailing profile inside the port, while the SCC will control remotely and monitor the unmanned vessel by utilizing those information. Moreover,
in this concept the levels of autonomy differ. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Navigation systems such as AIS, LIDAR and «stereo cameras» can be used when the unmanned vessel operates fully autonomously. By employing those systems, the autonomous vessel can fully autonomously «anticipate traffic» and be aware of the conditions that prevail in its direct and visible environment as well as in blind spots. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Information related to vessels that are expected to join the existent traffic could be provided by the Harbour Master Management Information System (HaMIS). The most efficient and suitable route will be chosen, again, with respect to the Estimated Time of Arrival (ETA). Finally, a «safety perimeter» is recommended to be set around the autonomous and the manned vessels so that all the vessels can sail and pass through other vessels’ route safely. In the case of a breach in the safety perimeter, the critical control level will be activated. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Table 1. «Gradations of autonomy and shore control center role within the concept of anticipating traffic situations» (van den Boogard, Feys, Overbeek, & le Poole, 2016).

<table>
<thead>
<tr>
<th>Degree of autonomy</th>
<th>Role of shore control center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote control</td>
<td>Determines path solution, controls autonomous vessel</td>
</tr>
<tr>
<td>Remote decision, local control</td>
<td>Determines path solution, communicates solution</td>
</tr>
<tr>
<td>Local decision and control, remote approval</td>
<td>Checks autonomous path solution</td>
</tr>
<tr>
<td>Fully autonomous</td>
<td>Monitors autonomous vessel behavior only</td>
</tr>
</tbody>
</table>

Portwide route optimization concept

In this concept time of departure, Estimated Time of Arrival (ETA) and the destination of each cargo vessel are used to define and plan their routes centrally. There will be a «central planning system» which will process data and information from terminals and vessels so that that it can determine the optimal route for each vessel. In this way, it will not be necessary for the vessels to communicate with one another. Again, the HaMIS could be used with an extension so that it includes inland waters and vessels. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
By employing a central planning system, the autonomous vessel, as well as the masters of the conventional vessels, will have to follow the routes and paths defined by the system and discipline to its instructions. Electronic Chart Display and Information System (ECDIS) that is installed onboard the manned vessels to assist in navigation will display the routes and the sailing behavior determined by the central planning system to the masters of the manned vessels. Also, port regulations will be taken into consideration by the central planning system. Despite the fact that the masters of the manned vessels, in this concept, will have to obey and follow the instructions and routes given to them by the central planning system, they are always expected to «apply good seamanship» and use their knowledge, experience and judgment when it comes to unexpected, critical and emergency circumstances. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Finally, due to difficulties regarding the extensions and development of the systems involved in this concept (HaMIS and ECDIS), which are expected to take many years, this concept is less likely to be implemented in the proximate future. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.2.3. Solutions within the critical control level

The information that are used as an input to the critical control level include the «current location, path and speed» of the vessel, but not the Estimated Time of Arrival (ETA). Unexpected and emergency circumstances activate this level of control. These circumstances must be «identified, evaluated and solved». The speed and route of the vessel are changed, as a result of solving the unexpected situation encountered, and then the navigation of the autonomous vessel goes back to the tactical control level. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Identification of unexpected situations

For the identification of the abovementioned unexpected and emergency situation a whitelist is used. The content of this whitelist consist of data and information regarding the environment and surrounding of the autonomous vessel that have been gathered beforehand. Afterwards, this information is compared to the
information collected real–time by the vessel’s sensors. If the comparison leads to the realization that this information is different and does not match, then the critical control level is activated. Another method that could be used to identify these unpredictable situations is by having people supervise and monitor with cameras, as well as using their critical thought process to trigger this level of control. Finally, the third way of identifying these situations includes a safety perimeter around the vessel. Features of the autonomous vessel, such as mooring, will be used to determine the perimeter’s magnitude. In this case, the critical level of controlled will be activated once a nearby vessel violates the safety perimeter. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Handling the critical control level

Critical control level situations can be handled with three different methods. The first method includes remote control. Specifically, a VR (virtual reality) bridge and «transmission of acoustic and motion senses» will enable an operator to act so as to handle those situations. For that purpose, proper communication and interaction between the operator and the autonomous vessel is extremely significant and, therefore proper «machine-human interaction». (van den Boogard, Feys, Overbeek, & le Poole, 2016)

The second method involves the Shore Control Center (SCC). The SCC could pick a number of waypoints in order to solve the critical situation. Following the identification of the situation, a «new path» can be designed as a response to the situation. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

The third way has to do with alterations of the route of the autonomous vessel. During this method of solving a situation in the critical control level, the operator from the SCC uses paths that has requested from the vessel to send them and then decides which one is the best for the vessel to follow. Through the VHF infrastructure the operator informs the rest of the vessels that operate in the same area as the autonomous vessel about the actions that they take. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
4.4.2.4. Solutions within the super critical control level

This level of control is activated once the critical controlled level has failed to handle the situation that has activated it. The information and data used as an input to this level are the same with those of the critical control level. What is different in comparison to the critical control level is that the information needed is not necessarily provided by external sources and that this level requires concepts that are «more specialized» in order to overcome the communication difficulties of this level. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Identification of super critical situations and solutions

Sensors and control systems that are installed on board the unmanned vessel will locate and identify objects that are in the immediate environment of the vessel. A whitelist could be used to classify circumstances and situations that the vessel might come across, such as wreckage, a person in the water or polluted waters (for example from an oil spill). The abovementioned situations are not considered as dangerous. In the case of the vessel encountering hazardous objects and elements a corresponding blacklist can be used to classify those circumstances and contribute in solving the situation. Finally, an operator could supervise the vessel as an alternative but the workload for this task is considered very high and therefore this option is not recommended. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

There are three different concepts that can be used to deal with situations that are included in the super critical level. The one is connected to a fully autonomous operation of the autonomous vessel. In this way the vessel will autonomously respond to a super critical situation. For that purpose artificial intelligence advances are required. Remote control of the vessel is considered the second way of handling those situations. Finally, the third way includes an automatic reaction of the vessel. Specifically, the autonomous vessel will send a warning to the Shore Control Center or to nearby vessels and then the super critical situation will be solved with remote controlling. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
4.4.3. Area of operation

The solutions of each control level are affected by two factors, the one is the operational range and the other is traffic density. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

The operational range determines the «area of operation of the autonomous vessel, the design components of the vessel, such as its capacity, and the organizational requirements for monitoring and controlling the vessel». Moreover, the distance that the vessel will have to sail is, also, influenced by the operating range. Specifically, the distance varies, based on whether the vessel operates locally in the port or it has to cover the entire port. These two possible scenarios represent the two extremes of the operational range. Furthermore, organizational requirements, schedule planning and communications are expected to be affected by any increase of the distance that the vessel will have to travel, when providing shuttle services. Additionally, any increases of the operational range are expected to increase the tactical route and, therefore, increase the need for information and the possibility of the critical and super critical level to be activated. Longer distances are considered more suitable for «liner services», as well as for ship platooning. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Traffic density is «the number of vessels in the area of operations of the autonomous vessel» (van den Boogard, Feys, Overbeek, & le Poole, 2016). When the number of vessels that operate within the same area is big then the space available for manoeuvres is reduced, situation that can lead to triggering the critical control level. For the strategic control level, traffic density has a negative effect on route planning. In order to avoid areas of dense traffic, statistical data can be used in route planning to ensure a more effective route. Regarding the tactical control level, «portwide route optimization» is not affected that much by traffic density since the routes are already planned, making communications through VHF unnecessary and reducing the risk of critical situations occurring. Finally, «sensor and object classification systems» are preferred compared to human surveillance and supervision, since they can process data and information faster and create whitelists and blacklists of hazardous items and objects near the autonomous vessel. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
4.4.4. Parties interested in the concept of an autonomous shuttle

Possible investors for the concept of the autonomous shuttle are: «terminal operators, port authorities, the inland shipping community, shippers and external high-tech companies». (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.4.1. Terminal operators

Terminal operators aim on providing flexibility and saving time and money. The best solutions for terminal operations in each control level are (van den Boogard, Feys, Overbeek, & le Poole, 2016):

Strategic control level: «Cargo based scheduling» that provides efficiency and flexibility. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Tactical control level: «Anticipating traffic situations» is considered more efficient. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Critical and super critical control level: «Autonomous identification» of situations. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.4.2. Port authorities

Priorities for the port authorities are investments in innovations and «high standards of safety and sustainability». The Information Technology (IT) systems that are used by port authorities, like «HaMIS and Portbase in the port of Rotterdam», and the data that they can provide are considered essential for the concept of autonomous vessels. (van den Boogard, Feys, Overbeek, & le Poole, 2016) The best solutions for port authorities in each control level are (van den Boogard, Feys, Overbeek, & le Poole, 2016):

Strategic control level: «Cargo based scheduling» which utilizes the abovementioned systems. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Tactical control level: «Portwide route optimization» that can be used to optimize route planning not only for the autonomous vessel but also for the manned vessels that operate in the port. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
Critical and super critical control level: Remote controlling of the autonomous vessel and «human supervision» are considered the most preferable solution for this level because they can provide higher levels of safety. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.4.3. Inland shipping community

The interference of the autonomous vessel with manned vessels is expected to be small. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Tactical control level: «Ship platooning» is expected to be the best acceptable solution for this level. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Critical and super critical control level: A combination of an «automated object detection system» a whitelist or a blacklist and a safety perimeter is expected to be used. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.4.4. Shippers

For the shippers of containers «safety, reliability» and compliance with the schedule are their priorities. Also, by employing an autonomous vessel they could reduce the costs of the port operations related to the handling of the containers.

Tactical control level: «Anticipating traffic situations» is preferred. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.4.5. External high-tech companies

For those companies an autonomous container shuttle is perceived as a source of income and profits. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Critical and super critical control level: Systems and concepts that correspond to this level of control but are not available, yet, could be developed by these companies since they have the needed expertise and they carry out research on new technologies. «Automated detection and response systems» are some of them. (van den Boogard, Feys, Overbeek, & le Poole, 2016)
4.4.5. Required technological evolutions

The evolutions in technology that have to take place in order for the abovementioned concepts to be realized include the fields of artificial intelligence and sensing. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

Sensing: Sensors are expected to be used for detection and identification of objects and items nearby in the surroundings of the autonomous vessel. The information produced by the sensor system can be processed and interpreted by the people that will be responsible for remotely controlling and monitoring the autonomous vessel. LIDAR range, «camera optics and object identification and classification» are some of the fields that require further development and improvement. Furthermore, «anticipation of traffic situations» is the solution of the tactical control level that suits those developments the most. For the critical control level, the creation of a whitelist of objects and items is more likely to be implemented, given the fact that the developments of the sensor systems are expected to improve accuracy and allow a more detailed description of the objects. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

4.4.6. Artificial intelligence in autonomous shipping

The focus of the developments in this field is machine learning. With the implementation of machine learning the autonomous vessel will be able to learn from «previous experiences» and use this knowledge to handle or avoid situations and circumstances in the future. At the same time it will increase the level of autonomy of the vessel. «Anticipating traffic situations» is the most autonomous solution in the tactical control level and is recommended. The higher level of autonomy that machine learning provides diminishes the need for remotely controlling the vessel in the critical and super critical level. Moreover, VHF communication will become easier for the autonomous vessel by using «speech recognition technology». This technology is, also, expected to be a result of the improvements and developments in artificial intelligence. With VHF communication the autonomous vessel will be able to take part in port traffic, transmit information to and interpret information received from other vessels by utilizing the existent infrastructure. «Anticipating traffic situations»
will be, also, benefited from VHF communication. (van den Boogard, Feys, Overbeek, & le Poole, 2016)

5. DYNAMIC POSITIONING AND AUTONOMOUS VESSELS

5.1. DYNAMIC POSITIONING

The International Maritime Organization (IMO) in 1994 with Maritime Safety Committee circular 645 (MSC/Circ.645) «Guidelines for vessels with dynamic positioning system» «introduced guidelines for dynamic positioning». (Giddings, 2013)

The following points were listed in the opening of the guidance (Giddings, 2013):

1. «These Guidelines for vessels with dynamic positioning systems have been developed to provide an international standard for dynamic positioning systems on all types of new vessel». (Giddings, 2013)

2. «Taking into account that dynamically positioned vessels are moved and operated internationally and recognizing that the design and operating criteria require special consideration, the Guidelines have been developed to facilitate international operation without having to document the dynamic positioning system in detail for every new area of operation». (Giddings, 2013)

3. «The Guidelines are not intended to prohibit the use of any existing vessel because its dynamic positioning system does not comply with these Guidelines. Many existing units have operated successfully and safely for extended periods of time and their operating history should be considered in evaluating their suitability to conduct dynamically positioned operations». (Giddings, 2013)

4. «Compliance with the Guidelines will be documented by a Flag State Verification and Acceptance Document (FSVAD) for the dynamic positioning system. The purpose of a FSVAD is to ensure that the vessel is operated, surveyed and tested according to vessel specific procedures and that the results are properly recorded». (Giddings, 2013)
5. «A coastal State may permit any vessel whose dynamic positioning system is designed to a different standard than that of these Guidelines to engage in operations». (Giddings, 2013)

The first two points revolve around the issue of dynamic positioning as a part of the international operation of vessels. Regarding the point number four, in the recent years some classification societies are carrying out this verification and acceptance procedure after having been granted authority by a flag state. However, even in these cases the flag state remains responsible for the Flag State Verification and Acceptance Document (FSVAD). (Giddings, 2013)

The definition of a dynamic positioning vessel according to the IMO guidance document is: «Dynamically positioned vessel (DP-vessel) means a unit or a vessel which automatically maintains its position (fixed location or predetermined track) exclusively by means of thruster force». (Giddings, 2013)

Systems like Automatic Position Mooring (APM) as well as Thruster Assisted Mooring System (TAMS) have been developed, with which the position of the vessel is maintained by using «thruster force and components from the mooring system». The figure below illustrates the contribution of thruster force to positioning. (Giddings, 2013)

![Figure 16. «Contribution of Thruster Force to Positioning»](Giddings, 2013).
5.2. REDUNDANCY

According to the IMO guidance document (Giddings, 2013):

«Redundancy means the ability of a component or system to maintain or restore its function when a single failure has occurred. Redundancy can be achieved for instance by installation of multiple components, systems or alternative means of performing a function». (Giddings, 2013)

Moreover, according to the document (Giddings, 2013):

«For equipment classes 2 and 3, at least three position reference systems should be installed and simultaneously available to the DP-system during operation» and «for equipment classes 2 and 3, at least three position reference systems should be installed and simultaneously available to the DP-system during operation». (Giddings, 2013)

For instance, two Differential GPS (DGPS) could be installed on the vessel and selected as position reference systems with another position reference system available «but not selected». (Giddings, 2013)

5.3. EQUIPMENT

Over the years there are some new technologies that have been developed and incorporated in the existing dynamic positioning systems. Some of them are: «data communications networks, data loggers attached to the DP and voyage data recorders, the unified bridge where individual units have been replaced by monitors showing the readout from the appropriate instruments and data forwarded and operator station designation where operator stations can be set to be a station for whatever area is felt to be appropriate». (Giddings, 2013)

Information regarding the vessel’s position and the magnitude, as well as the forces affecting its position is provided by «acoustic position reference sensors, combined with wind sensors, motion sensors and gyrocompasses» (DYNAMIC POSITIONING – IMO CLASS 2).
5.4. FLAG STATE VERIFICATION AND ACCEPTANCE DOCUMENT (FSVAD)

The Flag State Verification and Acceptance Document (FSVAD) that is issued by a flag state or another organization that has received authorization by a flag state must have the following characteristics (Giddings, 2013):

- «Should be issued after survey and testing». (Giddings, 2013)
- «Is issued for an unlimited period or one specified by the administration». (Giddings, 2013)
- «Should cease to be valid if significant alterations are made to the DP system or its components». (Giddings, 2013)
- «Should cease to be valid if the vessel is transferred to another flag». (Giddings, 2013)

The Dynamic Positioning (DP) class of the vessel will be determined by the abovementioned criteria. It is not impossible for the criteria that the classification societies set in order to place a vessel in a DP class to differ from the criteria of the IMO document. However, the vessel will be placed in the same class despite the possible differences between the original criteria and the ones that a classification society might set. (Giddings, 2013)

5.5. DYNAMIC POSITIONING (DP) CLASSES

The IMO document identifies three DP classes: 1, 2 and 3. There are operators and owners of vessels that have made suggestions for more classes «like DP Class 2+ that has been suggested from Rolls Royce» and «DP Class 4 that has been suggested for the vessel mv North Sea Giant», but retaining only those three classes is considered as a preferred solution. Some classification societies include another class, Class 0, but it is not used as much as the other three classes. (Giddings, 2013)

According to DNV Classification society the classes are described as follows (Dynamic Positioning Classes):

«Class 0: Manual position control and automatic heading control» (Dynamic Positioning Classes)
«**Class 1:** Automatic and manual position and heading control. No redundancy => Loss of position can occur in the event of a single fault.» (Dynamic Positioning Classes)

«**Class 2:** Automatic and manual position and heading control. Loss of position should not occur from a single fault of an active component or system such as generators, thrusters, switchboards, remote control valves etc. However, loss of position can occur after failure of static components such as cables, pipes, manual valves etc.» (Dynamic Positioning Classes)

«**Class 3:** Automatic and manual position and heading control. Loss of position should not occur from any single failure including a complete burn fire subdivision or flooded watertight compartments. Redundant and separated components.» (Dynamic Positioning Classes)

Table 2. «Equivalent classification society DP class notations» (Dynamic Positioning Classes).

<table>
<thead>
<tr>
<th>IMO Equipment Class</th>
<th>LR</th>
<th>DNV</th>
<th>ABS</th>
<th>GL</th>
<th>BV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No equivalent</td>
<td>DP (CM)</td>
<td>No equivalent</td>
<td>DPS-0</td>
<td>No equivalent</td>
<td>Dynapos SAM</td>
</tr>
<tr>
<td>No equivalent</td>
<td>No equivalent</td>
<td>DYNPOS AUTS</td>
<td>No equivalent</td>
<td>No equivalent</td>
<td>No equivalent</td>
</tr>
<tr>
<td>Class 1</td>
<td>DP (AM)</td>
<td>DYNPOS AUT</td>
<td>DPS-1</td>
<td>DP 1</td>
<td>Dynapos AM/AT</td>
</tr>
<tr>
<td>Class 2</td>
<td>DP (AA)</td>
<td>DYNPOS AUTR</td>
<td>DPS-2</td>
<td>DP 2</td>
<td>Dynapos AM/AT R</td>
</tr>
<tr>
<td>Class 3</td>
<td>DP (AAA)</td>
<td>DYNPOS AUTRO</td>
<td>DPS-3</td>
<td>DP 3</td>
<td>Dynapos AM/AT RS</td>
</tr>
</tbody>
</table>

### 5.6. HUMAN ELEMENT

Dynamic positioning of a vessel includes an operator that has the proper training and experience on how to use the dynamic positioning system. Those operators are called Dynamic Positioning Operators (DPOs). Furthermore, the Standards on Training, Certification and Watchkeeping (STCW) Convention address the issue of training that is required for operating a dynamic positioning system, but they do not sufficiently address the issues of assessment and certification raising concerns to the people involved. Moreover, according to statistics «the two thirds of Dynamic Positioning Operators (DPOs) have less than two years’ experience». (Giddings, 2013)
5.7. DYNAMIC POSITIONING IN AUTONOMOUS VESSELS

For dynamic positioning in autonomous vessel, devices and systems like sensors and GPS systems could be also used. Also, systems that are expected to be developed in order to facilitate navigation of autonomous vessels could be used in dynamic positioning. Moreover, an interesting area of study and exploration is the placement of an autonomous vessel in one of the three DP classes and whether that process should be carried out solely by a flag state or by both the flag states and authorized bodies like classification societies. Since the three DP classes are established for manned vessels the question that rises is whether the autonomous vessels will be able to be placed in those, or whether amendments and alterations or expansion of those classes should be discussed in order to include autonomous vessels. Finally, since the fully autonomous vessels do not require any human involvement in their operation, Dynamic Positioning Operators seem to be unnecessary. However, in the case of a Shore Control Center (SCC) remotely controlling, monitoring and operating the autonomous vessel, a member or a team of the SCC’s personnel could take on the duties of a Dynamic Positioning Operator.
6. CONCLUSIONS

The maritime industry is an international industry and the maritime companies employ their vessels on routes all around the world. A result of this very special characteristic of the maritime industry is that the industry is impacted by changes and developments that occur in the economic, social, environmental, political, legal and technological environment. The progress and development in the field of artificial intelligence that is taking place in the present years and is expected to take place in the future as well, for instance, with the development of autonomous vehicles has, also, affected the maritime industry leading to the exploration and development of the concept of autonomous vessels. Even though the routes of the concept of autonomous vessels are traced back in 1970 (AUTOMATED SHIPS ARE ALMOST HERE – WHAT IS GOING TO BE THEIR IMPACT IN SHIPPING? ), and throughout the decades research was carried out on the feasibility of such concept, the breakthrough occurred in 2007 with the publication of a paper by Waterborne TP that discussed the concept of autonomous shipping.

Many companies related to the maritime industry, such as classification societies and shipping companies are currently carrying out research and projects on autonomous shipping, and especially on the navigational aspect of the autonomous vessels. A project on autonomous vessel is the Maritime Navigation through Intelligence in Networks (MUNIN) project carried out as part of the European 7th framework program (Burmeister, Bruhn, Rodseth, & Pørathe, 2014) and investigates the concept of autonomous vessels and their operation that is controlled and monitored by a Shore Control Center (SCC) (RESEARCH IN MARITIME AUTONOMOUS SYSTEMS - PROJECT RESULTS AND TECHNOLOGY POTENTIALS, 2016). Furthermore, in the field of research, some of the autonomous vessels that have been developed and constructed are: the autonomous vessel Yara Birkenland that is developed by Yara International SA and Kongsberg and is the first electric autonomous container vessel destined to be employed on Short Sea Shipping routes between ports in south Norway (YARA Birkeland Autonomous Container Vessel), the development of autonomous commercial vessels and ferries by Rolls-Royce and its partnership with the Finnish Fin Ferries for that purpose (Rolls-Royce, Finferries present world’s first fully autonomous ferry, 2018) and the unmanned
container vessel ReVolt that is developed by DNV GL and is expected to perform Short Sea Shipping voyages (Tvete).

The interest in autonomous shipping that is expressed by companies and organizations of the maritime industry through research and projects that have been and are carried out is highly connected to the advantages that they appear to have in comparison to the conventional manned vessels. The most significant benefits that the shipping companies are expected to receive from employing autonomous vessels instead of manned vessels are cost reduction (by diminishing the number of seafarers onboard the vessel and using alternative and less expensive fuels like electricity), more effective compliance with the environmental rules and regulations imposed to the maritime industry like the most recent 2020 Sulphur Cap Regulation, (by using alternative fuels to reduce exhaust gas emissions) and minimizing the human erroneous actions that can lead to incidents at sea.

The operation of the manned vessels is regulated by a number of international conventions issued by the International Maritime Organization (IMO), the international regulatory body of the maritime industry, and other Committees and regulatory bodies. Such conventions include: the International Regulations for Preventing Collisions at Sea (COLREGs), the ISM Code, the ISPS Code, MARPOL Convention, Safety of Life at Sea (SOLAS) Convention and Standards on Training, Certification and Watchkeeping (STCW) convention and are mandatory for all the shipping nations and countries that are also members of the IMO. In order for autonomous vessels to be employed, especially on deep-water routes and international voyages, their operation must, also, be regulated by those conventions and incorporated in their provisions. It is, also, possible that new conventions and regulations will be issued as a result of the developments on autonomous shipping. The IMO, acknowledging the importance of regulating the operation the autonomous vessels, has commenced taking initiatives regarding the safety, security and environmental aspects of their operation (IMO takes first steps to address autonomous ships, 2018). The autonomous vessels have been named “Maritime Autonomous Surface Ships (MASS)” by the IMO. Moreover, the Maritime Safety Committee (MSC) of the IMO has endorsed a framework that includes definitions of MASS and levels of autonomy, “a plan of work” and a methodology (IMO takes first steps to address autonomous ships, 2018).
Another very significant element of the operation of the autonomous vessels that is extensively analyzed and described in this bachelor thesis is navigation and the implementation of the International Regulations for Preventing Collisions as Sea (COLREGS) by the autonomous vessels. Navigational systems and methods to assist safe navigation in autonomous shipping as well as implementing COLREGS are issues that are being investigated and studied by stake holders of the maritime community as well as by Universities. Artificial intelligence is expected to play an important role in autonomous vessels’ navigational systems, since those vessels when fully autonomous they operate without the interference of humans. Technologies and systems that are being developed and studied in order to be installed on board unmanned vessels and assist in navigation include:

- “Naval Artificial Intelligence (NAI)” system, which is a system that could be used to replace the Masters of an autonomous vessel by performing some of their duties, such as monitoring the vessel and the systems, ensuring the safety of the vessel and the cargo and completing the tasks and activities connected to the successful conduction of the voyage (Kulbiej & Wolejsza, 2017).

- Unmanned Aerial Vehicles (UAV) that could be used in assisting navigation of autonomous vessels (Johansen & Perez, 2016). These vehicles are designed to be equipped with systems and devises like LIDAR, cameras and sensors in order to scan the area from which the autonomous vessel will sail through, while also implementing COLREGS when needed (Johansen & Perez, 2016).

Dynamic positioning of autonomous vessels is another very interesting area of study in the field of navigation, given that dynamic positioning systems are required on vessels and their operation is regulated by IMO, which has also defined three different classes of dynamic positioning. Moreover, flag states or authorized organizations like classification societies are responsible for issuing the Flag State Verification and Acceptance Document (FSVAD) in which the criteria for placing a vessel in one of the three Dynamic Positioning (DP) classes are included (Giddings, 2013). Dynamic positioning class 3 shows the reliability level that is required by autonomous vessels. In order for autonomous vessels to operate offshore where dynamic positioning is already applied further research must be carried out regarding enhancements of existing systems and devices, possible additions of new classes and
extensions of the existing DP classes, as well as reviewing the role of the Dynamic Positioning Operator (DPO).

Finally, navigation in the port area is considered equally and sometimes even more important than navigation in the open sea, taking into consideration that vessel traffic, the weather and port structures can create a number of different and hazardous circumstances that the autonomous vessel might encounter. Especially during the process of mooring, berthing and unberthing a manned vessel, communication between the master of the vessel and the masters of the tug vessels is very frequent and of great importance for the safety of the vessel and the nearby vessels. For the purpose of ensuring safe navigation and manoeuvring in ports a concept of different control levels of navigation and applicable solutions is being investigated (van den Boogard, Feys, Overbeek, & le Poole, 2016). However, it is recommended that further research should be carried out on the methods and systems that are required in order to enable communication of a fully autonomous vessel with other manned vessels and tugs, like VHF communication, in the port area in order to mitigate the risk of possible incidents and ensure safety.

Conclusively, the concept of autonomous vessels is closer to reality and is being more and more investigated and researched by the maritime community because of the benefits and advantages that the autonomous vessels appear to have in comparison to manned vessels. Further on, technological advances from autonomous vessel research can also enhance safety of manned vessels. Ensuring safety of life, security and protection of the environment is extremely important and therefore international regulation and verification of the safe and proper operation of the autonomous vessels has to take place. The required technological advance in the field of autonomous vessels navigation is expected to be reached in the future due to the time that is needed for many advanced and artificial intelligence related technologies to mature and become commercially available with reasonable acquisition cost. It is also recommended that further research should be carried out regarding navigation and implementation of International Regulations for Preventing Collisions at Sea (COLREGS) by autonomous vessels.
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