MARITIME TECHNICAL JOURNAL

2022 1 (224)

DOI:10.2478/sjpna-2022-0004

THE ASSESSMENT OF UNMANNED VESSEL OPERATION IN HEAVY TRAFFIC AREAS. CASE STUDY OF THE NORTH SEA CROSSING BY UNMANNED SURFACE VESSEL SEA-KIT

Karolina Zwolak*, Rafał Miętkiewicz, Julia Dąbrowska***,**
Neil Tinmouth****

* *Polish Naval Academy, Śmidowicza 69 str., 81-127 Gdynia, k.zwolak@amw.gdynia.pl*
** *Polish Naval Academy, Śmidowicza 69 str., 81-127 Gdynia, r.mietkiewicz@amw.gdynia.pl*
****Polish Navy, 3rd Flotilla of Ships, Rondo Bitwy pod Oliwą 1, 81-127 Gdynia, Poland, juliadabrowska3@gmail.com*
**** *Sea-Kit Int., Blackwater House, Woodrolfe Rd, Tollesbury, Essex, CM9 8SE, United Kingdom, neiltinmouth@gmail.com*

ABSTRACT

The continuous development of autonomous and unmanned technology is accelerating the adoption of unmanned vessels for various maritime operations. Despite the technological developments there is still a lack of clear regulatory and organizational frameworks for testing and exploiting the potential of unmanned surface vessels (USVs) in real-world maritime conditions. Such real-world testing becomes ever more complex when operating in multiple nations territorial waters. In May 2019 USV 'Maxlimer' crossed the North Sea from the United Kingdom to Belgium and back, carrying goods, to demonstrate the ability of unmanned surface vessels to interact with real marine traffic in an uncontrolled environment. The paper presents this mission in light of the current state of marine autonomy projects as well as the regulatory works conducted by various organizations worldwide.

Key words:

Unmanned Surface Vessel, Autonomous Surface Vessel, marine autonomy, USV 'SEA-KIT', collision avoidance

Research article

INTRODUCTION

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are widely used in a variety of industries from toys, to transportation, aerial photography, agriculture, mapping, and military operations. Similar systems are increasingly being adopted within the marine community to widely operate the MASS (Maritime Autonomous Surface Ships), although the popularity of such solutions is at present incomparably smaller than the aerial industry.

It is difficult to claim that the reason for the slow adoption within the maritime sector is due to a technological barrier. In fact, automation of various systems, process, and operations have been widely adopted onboard modern vessels for a long time. As early as the 1960s, computer-controlled dynamic positioning (DP) was operational on various vessels. With the rapid improvements in sensor technologies coupled with the decrease in costs, many maritime tasks have become either augmented or automated, reducing the need for crews on board. However, there are numerous other factors, which have affected the speed of adoption of completely unmanned or autonomous maritime vessels, including legal constraints, insurance companies' policies, the need to deal with unexpected failures, and certainly the common seamanship practices and adherence to the Collision Regulations. All these listed factors evolve constantly. New technical developments and proofs of successful unmanned marine operations are the basis for new considerations on how to manage and overcome these factors.

A successful two-way crossing of the North Sea between UK and Belgium, completed in May 2019, by the UK-registered Unmanned Surface Vessel 'USV Maxlimer' of SEA-KIT type, carrying a box of cargo on board, provided an opportunity to analyse the current state of this type of vessels operational usage in the heavy marine traffic areas.

2. Unmanned Vessel in the reality of modern shipping

The following section presents the various aspects of the current level of vessels autonomy in the scope of modern shipping, management, and regulations. It will allow the assessment of the examined case of unmanned vessel cruise properly in terms of technological advancement and safety of operation.

2.1 Understanding of basic autonomy related terms

At the beginning of all considerations regarding the unmanned or autonomous marine operation, one must be able to define what is and what is not an autonomous vessel. With the lack of international guidelines or internationally adopted regulations, several countries and organisations have begun work in terms of regulation of MASS-related operations and adequate nomenclature. Examples of national guidelines, documents and ideas for unmanned/autonomous vessel classifications are presented below.

IMO, the leading agency of the maritime world, standing behind the most fundamental regulations of modern shipping could not ignore vessel's autonomy technology, as this developing branch of marine industry can potentially revolutionize the way international shipping is run. Since 2017, IMO's Maritime Safety Committee (MSC) has conducted extensive works on the MASS issues, with a correspondence group on MASS being established to prepare the scoping exercises and agree on the proper methodology (IMO 2018).

The MASS classification initially used by IMO introduces four levels of autonomy (IHO 2018):

(1) Ship with automated processes and decision support, which means that only chosen operations are automated. Seafarers are present on board. Their task is to control shipboard systems and functions and operate some of them.

(2) Remotely controlled ship with seafarers on board, where the ship is operated and controlled from a different location (perhaps, on-shore).

(3) Remotely controlled ship without seafarers on board, which refers to an unmanned vessel, controlled and operated from another location.

(4) Fully autonomous ship, where it is the operating system of the ship, is capable of making decisions and determining actions by itself.

Due to the extensive work of Scandinavian autonomous systems producers, it seems appropriate to present the Norwegian Forum for Autonomous Ships approach, which first determines the method of casting the navigation bridge (three levels), and secondly the level of autonomy of performing individual operations (four groups) (NFAS 2017). The six-level autonomy system of navigation systems was proposed by the Lloyds Register classification society (LR 2017).

Due to many years of experience in the use of unmanned platforms in warfare, for comparison, it is worth following the military approach on the subject of system autonomy. The NATO Industrial Advisory Group (NIAG) also identified four levels of autonomy (NIAG 2004):

(1) Remotely Controlled System - where system reactions and its behaviour depend on operator input (non-autonomous).

(2) Automated System – both reactions and behaviour depend on fixed built-in functionality (pre-programmed)

(3) Autonomous non-learning system - the behaviour of the system depends upon fixed built-in functionality or upon a fixed set of rules which dictate system behaviour (goal-directed reaction and behaviour)

(4) Autonomous learning system with the ability to modify rule defining behaviours - Behaviour depends upon a set of rules (also modified) for continuously improving goal-directed reactions and behaviours within an overarching set of inviolate rules/behaviours.

The US Navy Office of Naval Research proposed six levels of autonomy (Williams 2008).

(1) Human Operated - activity in the system is a direct result of human inputs (no autonomy).
(2) Human Assisted - such systems can perform activities in parallel with human input, (augmenting the ability of the human to perform the desired activity).
(3) Human Delegated - the system can perform limited, delegated control activity.
(4) Human Supervised - the system can perform a wide variety of activities given top-level permissions or direction by a human (no capability to self-initiate behaviours except those within the scope of its current tasks).
(5) Mixed Initiative - the system can initiate behaviours based on sensed data (the authority of the system with respect to human operators is regulated).
(6) Fully Autonomous - No human intervention required to perform any of the designed activities (all environmental conditions).

Finally, RAND Corporation's proposal includes the following levels of autonomy of unmanned surface units (RAND 2013):

Level 0: No autonomy (remote-controlled)
Level 1: Rudimentary semi-autonomy (waypoint navigation without collision
avoidance).
Level 2: Semiautonomous (waypoint navigation including collision avoidance).
Level 3: Advanced semi-autonomy (generates the best course to target).
Level 4: Autonomous under most conditions (application-driven).
Level 5: Fully autonomous under all conditions (application-driven).

The examples presented here show different approaches to the theme of autonomy of unmanned maritime platforms resulting from the extremely different purpose of commercial systems versus applications used in security and defence.

In general, all modern vessels, operated according to current regulations, can be considered as first autonomy level ships. Does it mean that the first autonomy level is non-autonomous? It is evident that some marine autonomy solutions are present today and utilized on crewed vessels, which is a clear sign that the direction taken by both IMO and national organizations is relevant or even inevitable.

IMO tends to generalize their highest level of autonomy, compared to previously presented detailed classifications of the ratio of autonomous to human-controlled functions. From a regulatory point of view, this approach appears reasonable. The minimum safety and control requirements must be met at each accepted portion of automation in a particular vessel.

2.2 USV's operation in the frame of international maritime regulations

At present, the operational usage of unmanned ships is relatively limited compared to their manned counterparts as the technology has not been widely adopted outside the marine scientific research communities (as in the case analysed here), and the defence sector which is increasingly utilising USVs for a wide range of marine operations (CMI 2018). However, the exponential development of unmanned technology means that widespread adoption is imminent and regulatory preparedness is an increasingly pressing concern.

One of the main challenges that is slowing the rate of USV adoption is that current regulations were established with the presumption that all vessel are manned with crew on board (Carey 2017).

To further complicate these regulatory issues, an explicit distinction needs be made between unmanned and autonomous ships as there is currently no legal definition for either. Even members of research communities or jurisprudence are not unanimous.

The acceptance of commercial usage of unmanned ships is more likely as those which onboard crew could be replaced by a shore-based operator (SBO) as a form of remote control (AAWA 2016). With a man present albeit via remote control station, it would fulfil a broad range of requirements such as personal liability or communication specifications.

Maritime law is a functional term used for describing a whole range of various sources of law which govern the legal framework related to shipping. Its provisions are accepted on a large scale as representing customary law (AAWA 2016). IMO or UN regulations are regarded as the major ones, but not exclusive. Many other international, bilateral, or national regulations impose multifarious obligations which are to be adjusted to the technological advancement in unmanned ships, e.g. regime of international carriage of goods and bill of lading: Hauge-Visby Rules, Hamburg Rules, and Rotterdam Rules, which is a joint amendment of the first one and the Hamburg Rules (Koziński 2011).

In February 2017, nine states submitted a motion to the Maritime Security Committee (MSC): 'Maritime Autonomous Surface Ship (MASS). Proposal for a regulatory exercise.' Initiators perceived a need to review and amend or create new if necessary, international regulations in order to create the possibility of using MASS on a wide scale. In June 2017, the MSC agreed to include the issue of MASS on its agenda (IMO MSC 2017). This will be in the form of a scoping exercise to determine how the safe, secure, and environmentally safe operation of MASS may be introduced in IMO instruments. The MSC working group is expected to proceed with the aim of completing the regulatory scoping exercise in 2020. The list of instruments to be covered in the MSC's scoping exercise for MASS includes *International Convention for the Safety of Life at Sea* (SOLAS), *Convention on the International Regulations for Preventing Collision at Sea* (COLREG), *International Convention on Load Lines* (Load Lines), *International Convention on Standards of*

Training, Certification and Watchkeeping for Seafarers (STCW), *International Convention on Standards of Training, Certification and Watchkeeping for Fishing Vessel Personnel* (STCW-F), *International Convention on Maritime Search and Rescue* (SAR), *International Convention on Tonnage Measurement of Ships* (Tonnage Convention), *International Convention for Safe Containers* (CSC), *Special Trade Passenger Ships Agreement* (STP) and *Protocol on Space Requirements for Special Trade Passenger Ships* (SPACE STP). The Legal Committee of IMO also included the issue of MASS on its agenda with a target completion year of 2020 (IMO MSC 2018).

It is anticipated that it would take a significant amount time to amend all regulations as the issue is quite complex. The fundamental question to be answered is whether an unmanned ship is a 'ship' or 'vessel' within the meaning of maritime law, through technical requirements, appliance, and fitting, ending with rendering assistance on the sea, liability, insurance or training.

A major part of maritime law is the Law of the Sea (UNCLOS) which is formally accepted worldwide. Its provisions are accepted on a large scale as representing customary law (AAWA 2016). For this reason, it also applies to non-party members. However, there is parallel jurisdiction between the ship and the international regime, depending on which maritime zone is concerned and flag states' regulation. As far as the flag state's jurisdiction is concerned, states enjoy quite a discretion in some issues. For example, states are free to fix conditions for granting nationality to ships or constraints for ships entering their ports or internal waters (UNCLOS 1982). Furthermore, some maritime administrations in flag states determined special areas for MASS to be tested (Rudziński 2019). In other maritime zones, the rights of coastal states are more limited. Even at territorial sea, which is *de jure* and *de facto,* in the territory of the state, foreign ships enjoy the right of 'the innocent passage' which cannot be disturbed by anyone as long as it is not prejudicial to the peace, good order, or security of the coastal state (UNCLOS 1982). The jurisdiction to prescribe national requirements is even more limited in other maritime zones (straits used for international navigation, exclusive economic zone) with the high seas which lie beyond the jurisdiction of any coastal state.

The preceding indicates how complex the issue is. However, the legal challenges mentioned here are not insurmountable as laws can always be amended to keep pace with new technologies. The question is whether there is social acceptance and preparedness in the maritime community and beyond to make changes to accommodate unmanned ships (AAWA 2016).

2.3. Current ASV projects

It is believed that the rapid development of autonomous technologies in the maritime domain, is in two main directions, namely: military and security applications and civilian (sea-transport) purposes.

With the announcement of reducing the hazard for deck operators, especially in high-risk regions (so-called: dirty missions) or time-consuming tasks (e.g.

mine countermeasures, anti-submarine warfare), unmanned platforms and the architectures of cooperated unmanned underwater and air systems will play a crucial role in the future naval operations (Miętkiewicz 2018). Together with the development of artificial intelligence (responsible for high autonomy levels) and swarm tactics in conjunctions with contemporary biomimetic constructions, hybrid platforms (two and three state systems) autonomous technologies creates considerable influence in the mission planning process. With advantages and general positive influence on mission efficiency, autonomous systems also represent prolific hazards. Since the autonomous surface systems, like the Protector or SeaGull, were equipped with lethal weapon systems and the first strike of an autonomous system (Shark 33) against naval unit took place, the autonomous systems are considered as a potential threat for both military and non-military sea householders.

Among the projects dedicated to military applications, there is a tendency to develop larger and larger surface vessels offering increased naval capabilities. Large Unmanned Surface Vehicles (LUSVs) with a length of between 55 and 90 meters together with Medium Unmanned Surface Vehicles (MUSVs), 12 to 55 meters in length, are the US Navy concepts designed to balance the challenges created by Chinese constructions (e.g. D3000 with a length of 30 m as an Anti-Submarine Warfare, Anti Surface Warfare and combat support dedicated unit) (CRS 2019).

Other examples of this general worldwide tendency to increase the size and scope of ongoing missions are Swedish constructions (Very Large USV Saab with a displacement of 300 tons) or British proposals (Rolls-Royce 60-meter unit designed for drones deployment during Intelligence, Reconnaissance, Surveillance, Mine Counter Measures and fleet screening). The analysis of the available constructions of autonomous units makes it possible to conclude that modern unmanned surface systems operating at sea can implement a wide range of missions both independently and in cooperation with manned units.

The basic assumptions underlying the development of autonomous commercial shipping is to reduce labour costs, increase operational efficiency, increase space at the expense of crew rooms (estimated by about 2%), as well as eliminate the human factor as a source of error. According to Allianz, between 75% and 96% of maritime accidents are caused by human error (Allianz 2018).

The development of autonomous technologies dedicated to commercial shipping raises many questions about man's role in the process and the issues related to the ecological aspects of this type of solutions (the impact of autonomous ships on the environment) (Koikas, Papoutsidakis, and Nikitakos 2019). Other critical aspects for determining the development and adoption of autonomous shipping, mainly in the coastal zone, include such elements as the special importance of the crew in cabotage shipping due to frequent port operations (loading and unloading of goods) or the need to develop automated systems responsible for port operations. Other factors are the increase in traffic in coastal areas, and necessary technical inspections as a critical parameter due to the high failure frequency of the main onboard mechanisms. The issue of exhaust emissions requirements in the coastal zone is also significant.

Threats to the cybernetic domain is an important element affecting the future security environment of using autonomous technology in the seas. (Rodseth and Burmeister 2015). The most well-known projects of autonomous systems (ships) in commercial shipping are:

- MUNIN. The goal of the European project Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) was to develop the concept and assess the technical, economic, and legal feasibility of an unmanned commercial vessel (MUNIN 2016).
- Advanced Autonomous Waterborne Applications (AAWA) project and the Rolls-Royce concept (project leader) of two scenarios. In the first case, the unit carries out independent navigation, and a repair crew may be on board. In the second case, the ship is fully autonomous or controlled from the shore control centre (SCC). The concept of an autonomous ship is based on the concept of dynamic autonomy enabling the operation of the individual at various levels of autonomy (Jokioinen 2016),
- ReVolt project, 60-meter container feeder project for short-sea shipping. According to the constructors' assumptions, the electric-powered unit is expected to generate 34 million USD in savings over 30 years of operation compared to a conventional engine-powered unit. (Hartkopf-Mikkelsen 2016),
- The Chinese concept of a small unmanned ship (500 tons displacement) Cloudborne, equipped with an automatic scheduling system that cuts staff both on-board and ashore to reduce costs and improve efficiency (Oceanalpha 2020),
- Hronn project dedicated to servicing the energy sector and fisheries (2016). Other applications contain survey, remotely operated vehicle (ROV) and unmanned underwater vehicle (UUV) operations, touch-down monitoring and transportation of light intermodal cargo to offshore installations (Ship Technology 2020),
- RAmora 2400 project (Robert Allan Ltd.), a versatile multitask tug and Svitzer Hermod (Svitzer and Rolls-Royce), a 28 m remote-controlled tug designed preliminary for bow tug operations and ship-handling, transit and locks operations, firefighting as well as rescue and salvage, Marine environment protection and monitoring missions (Hertog 2018).
- the concept includes vessels for special tasks (fire ship, rescue ship) proposed by QinetiQ (QinetiQ, 2016),
- a research unit Mayflower Autonomous Ship. During her first transatlantic crossing, Mayflower will carry research kits containing meteorology, oceanography, climatology, biology, marine pollution and conservation, and autonomous navigation sensors (Williams 2019).
- Yara Bikeland, first zero-emission, autonomous container ship project with electric propulsion (100-150 TEUs) to operate with a range of 12 NM from the Norwegian coast and provide a permanent connection between three

dedicated ports. The ship is believed to move from manned operation to fully autonomous operation by 2022 (Kongsberg 2020).
- To counteract the challenges of marine pollution, the British company Bluebird Marine Systems created the SeaVax unit. Its purpose is to clean the sea and rivers surface from pollution (plastic) (Bluebird, 2020).

Based on a literature query and research aimed at creating a database of autonomous units, which includes over 170 units from around the world, the following areas of application of autonomous systems in the maritime domain have been identified:
- Commercial shipping (see above),
- Naval operations applications (a wide range of missions and tasks) - Seagull, Piranha, Inspector, Sea Hunter.
- Maritime security (mainly surveillance of port areas, combating terrorism and piracy) - Protector, L30B, M75A.
- Marine scientific research (sea currents, climate, including in the Arctic regions) - Wave-Glider, C-Worker, SAILBUOY.
- Academic constructions (researching unmanned craft issues)- Inception Class Mark II USV, SCOUT.
- Oceanography - Q-Boat, Heron, M40A.
- Monitoring and protection of the marine environment - C-Enduro, TC40.
- Ecology - C-Enduro, Reef Rover, Saildrone.
- Sea and shore search and rescue missions - EMILY, TODAK.
- Fishery and tug operations support,
- Sport and recreation.

SEA-KIT is a new design of unmanned surface vessel, dedicated to hydrographic and ocean mapping surveying and cooperation with Autonomous Underwater Vehicle (AUV). USV ‘Maxlimer’, the prototype boat of this type is described in detail in the following sections of this paper.

3. Unmanned vessel in real heavy traffic conditions – a case study of the North Sea crossing by Unmanned Surface Vessel SEA-KIT

The results of the series of rigorous tests on unmanned vessels, conducted under various weather conditions but with controlled traffic have highlighted the exciting potential of unmanned surface vessel technology. However, additional testing in a heavy traffic environment, including crossing situation is required to prove the usability in the existing conditions.

The area chosen for proving the technology capabilities included the North from the Thames Estuary, the North Sea part at the entrance towards the English Channel and the approach to the Oostende harbour provided. These areas provided the opportunity to expose the Unmanned Vessel technology to the most demanding navigational conditions in the scale of European waters, including . crossing the Strait of Dover; the busiest international seaway in the world. According to (MarineInsight 2019), around 400 commercial ships operate within Strait of Dover daily, including heavy traffic of cargo-carrying ships and numerous ferryboats carrying up to 2,400 passengers daily, which connect the UK, French, and Belgian harbours (MarineInsight 2014).

3.1. Vessel characteristics

SEA-KIT's USV 'Maxlimer' (Figure 1) is a new class of unmanned surface vessel, capable of the launch and retrieval of various payloads.

USV Maxlimer was designed and built as part of the GEBCO-Nippon Foundation Alumni Team's entry into the Shell Ocean Discovery XPRIZE competition. The Shell Ocean Discovery XPRIZE competition was an global competition which challenged teams to develop a unmanned or autonomous system that would be capable of mapping the ocean floor at the depths exceeding 4000 m. As part of the GEBCO-NF alumni Teams entry into the XPRIZE competition, USV Maxlimer was designed and developed to transport, launch, and recover a Hugin AUV, whilst also providing positioning data during deep water high-resolution bathymetric survey (Zwolak et al. 2017; Proctor et al. 2018; Zarayskaya et al. 2019). The Team was announced as the winner of the competition after the successful demonstration of common, synchronized USV and AUV operation in Kalamata, Greece.

Figure 1. USV Maxlimer at the Mediterranean Sea, during the preparation to the final survey of the Shell Ocean Discovery XPRIZE competition (photo XPRIZE).

USV Maxlimer has a length of 11.75 m and a beam of 2.2 m. For transportation the mast and under-keel gondola can be removed and placed in the payload area reducing the height from 8.5 m to 2 m. This allows SEA-KIT to be transported in a single standard 40-feet shipping container, which significantly reduces the transportation costs and allows rapid mobilization to anywhere in the world.

SEA-KIT was originally designed to be operated in conjunction with an AUV such as a Kongsberg Hugin. During transport to and from site the AUV is stored within the payload area for. Upon arrival at the site, SEA-KIT's open transom design allows the AUV to be remotely deployed and retrieved via the specially designed launch and recovery system. The hull design ensures the optimal utilisation of space while still providing good stability, which allows SEA-KIT to be used as a standalone survey vessel, with a multibeam echosounder installed on the gondola under the hull. SEA-KIT's modular USV design means the USV can also be adapted to transport, deploy and retrieve various types of AUVs and ROVs with minimal modification required.

Two 10 kW / 1200 rpm electric directional thrust motors on SEA-KIT ensures the operational speed of 6 knots and a maximum speed of 8 knots, which is suitable for a survey vessel. Bow thrusters assure high manoeuvrability. The vessel is equipped with three independent types of power supplies: two 18kW 48V DC generators, 56 AGM VRLA Marine batteries and four dry cell AGM VRLA Marine Dual-Purpose Batteries.

Control of the vessel is done remotely from a control centre which can be located anywhere in the world. Primary communication to and from the vessel is via VSAT connection with additional backup systems; UHF, iridium, 4G and marine broadband radio providing redundancy. The VSAT connection is also used in transmitting the situational awareness sensor data from which the vessel captain ashore can base their operational decisions. The control of the vessel is detailed in section 3.2 below.

3.2. Vessel Control method

The primary method for controlling SEA-KIT's USV as well as accessing its situational awareness systems is via satellite communication technology, VSAT. VSAT utilizes Very Small Aperture Terminal which ensures practically unrestricted operational range in terms of communication to the onboard controller systems from the shore control station. This allows an operator in the control station to access the navigation equipment and situation awareness data, similarly as the watch officer on the vessel's bridge. Radar display with AIS input, data from GPS and heading, course over ground and magnetic course measurement devices are sent continuously in real-time from the vessel to the shore control station, as well as meteorological and depth measurements. Similarly, the VHF communication device can be accessed by the shore operator. The direct visual observation is replaced by the closed-circuit television cameras, providing the 360 degrees observation around the vessel, supported by thermal imaging. The shore operator workstation is presented in Figure 2.

To increases the vessel reliability and the safety of operations SEA-KIT's USV has multiple control and communication options to provide alternatives for keeping the vessel under surveillance and control in case the primary control method deemed unreliable or is not the most suitable given the nature of the operations.

The most basic control method is to use the joystick-shape helm and throttles on board the vessel by the crew on board. The vessel is then operated as a conventional manned vessel. Life-saving equipment is installed onboard to ensure the safety of manned operation. This option requires no communication with the shore, except what is demanded by usual marine operations. Although what is the base of the unmanned vessel concept, is the ability to control the ship from a remote location; hence, other options are utilized majorly during the vessel exploitation.

Remote control handset allows for manoeuvring from within up to 200 m. It uses UHF connection to send the steering and thruster commands to the vessel. The other control methods are based on the K-MATE Autonomy Controller, with various available ways of communication between the vessel and the shore station. K-MATE via MBR is based on the use of Kongsberg Maritime Broadband Radio unit, which ensures the connection with the vessel's onboard controller within the line of sight, due to the restrictions of ultra-high frequency signal propagation. The next option is to access K-MATE via 4G network, which operates everywhere within the 4G coverage provided to the vessel by the land-based mobile network masts.

In case of operations that are out of range of these alternatives the backup satellite connection is performed by Iridium satellite network as a redundancy.

Figure 2. Shore Mission Control Station providing access to K-MATE Autonomy Controller and Situational Awareness System (photo: K. Zwolak).

3.3. Mission overview

SEA-KIT's USV "Maxlimer" started her voyage in Tollesbury, England, on May 6, 2019, heading along her pre-determined route towards Ostend, Belgium. The total duration of the transit was 22 hours. After a 15-hour stopover in Ostend, the vessel started the journey back to Tollesbury and finished 21 hours later, just before midnight on the 9th May of 2019. Three weeks prior to the unmanned voyage the route was determined after the completion of a reconnaissance mission. The predetermined route took into consideration traffic separation schemes, shoals, windfarms anchorages, and other prohibited areas, as well as other local regulations. The tidal and weather conditions were also taken into account. A vessel track during both parts of the transit, based on the GPS data recorded during the operation, is presented in Figure 3.

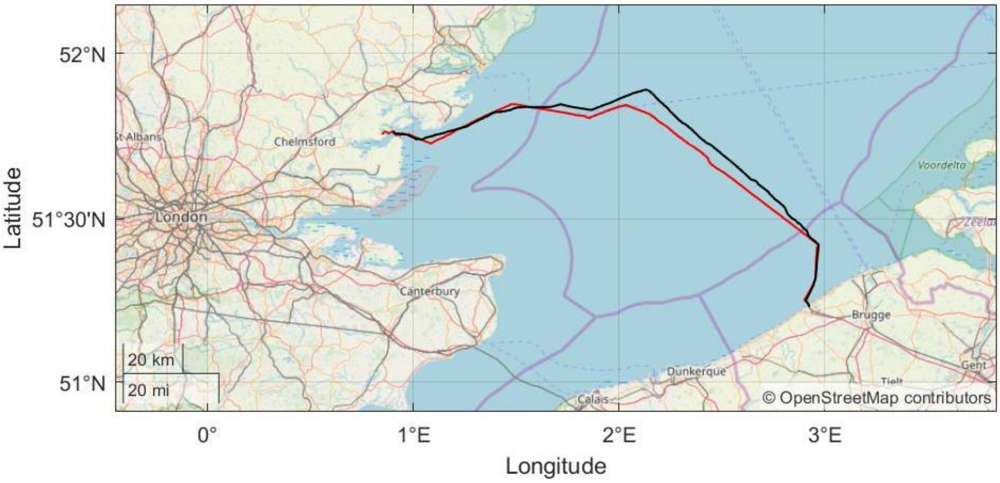


Figure 3. The track of USV 'Maxlimer' during both parts of the North Sea transit. Red colour indicates the route from Tollesbury, England, to Ostend, Belgium. The return route is presented in black.

3.4. Data acquisition during the passage

The truly unmanned North Sea transit passage has been an excellent occasion to provide unprecedented data for extended analysis of the interactions between manned and unmanned vessels in the real navigation conditions. During the acquisition of the transit data, all the signals on the vessel, carrying the navigational information were recorded to a stand-in Voyage Data Recorder system set up to fulfil the role. By recording the data flow in the NMEA2000 network, the following information was captured to be able to retrace the passage: UTC time, GPS fix data, autopilot sentences, depths of water and depth below transducer, true and magnetic heading, deviation and variation, heading steering command, speed and angle of wind - true and relative, rate of turn, distance travelled through water, track made, and ground speed. The traffic situation can be analysed from the record of all AIS signals transmitted and received by the vessel's device. In addition, all the CCTV images and radar display were recorded throughout the operation, providing a complete overview of USV Maxlimer's performance and interactions with other vessels at sea.

The data from AIS, automatic tracking and data exchange system which helps mariners in the decision-making process for safe navigation, was found to be particularly valuable to assess the navigational situation during the passage in terms of collision avoidance - one of the most important aspects of unmanned ships operations. During both legs of the transit a total of 588 AIS stations participated in the information exchange resulting in 485,325 AIS messages being sent between these AIS stations and USV Maxlimer.

All the AIS data was recorded in the text file, containing the lines of AIVDO/AIVDM messages. AIVDO indicator contains data sent by own vessel, while AIVDM packets are received from other ships. Each of the messages is composed in the standard form of text and number character, separated by commas and started with the exclamation mark and the identification signs. The information may be split into several lines of messages when it exceeds the maximum number of 82-characters. Each line contains the count of fragments, the fragment number, the message ID to properly assemble the multi-sentence messages, the code of radio channel, the payload and the checksum. The payload is coded by 6-bit ASCII code, according to (ITU 2014). Matlab script has been written to decode and visualise AIS data recorded during the passage.

Since the AIS data is used here for the assessment of the vessel's behaviour, the reliability of these data should be examined. Felski and Jaskólski (2012) investigated this issue, based on the 24 hours data recording in the Gulf of Gdańsk in 2006. They reported 2.5% of incomplete positioning data in receiver messages with 6.5% of all the ships broadcasting those incomplete data. In the later analysis (Felski, Jaskólski, and Banyś 2015), the authors examined the AIS dataset from December 2010 to January 2011 and developed their concept of defining the integrity and completeness of AIS information. The mean completeness of geographic position information, defined as a cumulative distribution for the completeness exponential, is reported on the level of 0.9986 and can be understood here as the portion of time the AIS delivers the proper data. In our case, 99.9 per cent of received messages contained complete positioning information. Three hundred forty cases of improper position information (means that Latitude value exceeded +/- 90 degrees or Longitude value exceeded +/-180 degrees) have been observed in the 326, 420 received messages. Improper messages came from 8 unique AIS stations. This simplified reliability-related observation fits with the recently published results of researches based on the AIS system. All the recorded positioning data are presented in Figure 4, which also provides the outline of the navigation patterns in the area of the passage and the boundaries of the range of data recorded from the vessel crossing the presented area. The red line indicates the SEA-KIT track, while all the black dots represent the positions of other ships and stations, received by means of AIS.

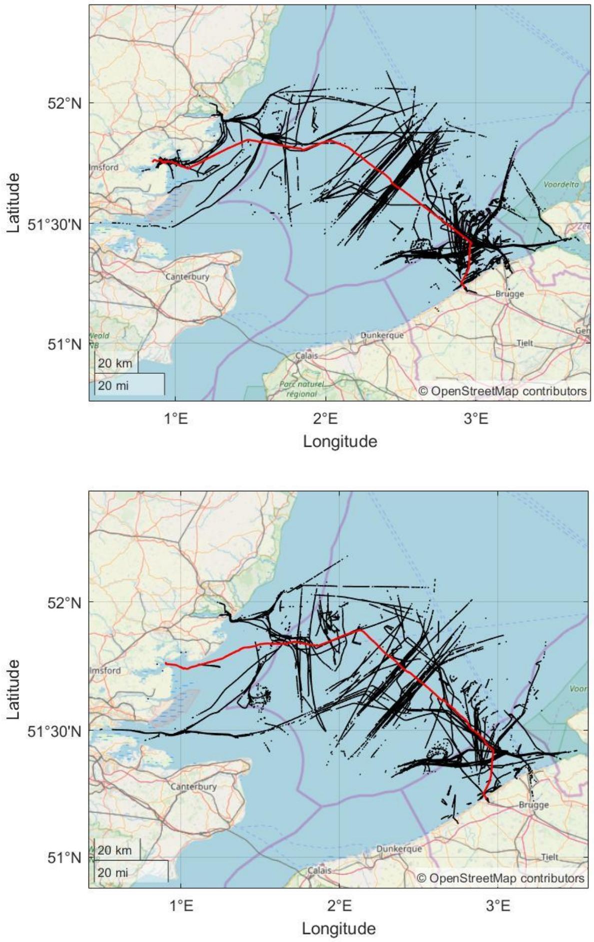


Figure 4 Positioning data of SEA-KIT (red) and other vessels during the passage (black), based on the transmitted and received data from the AIS system.

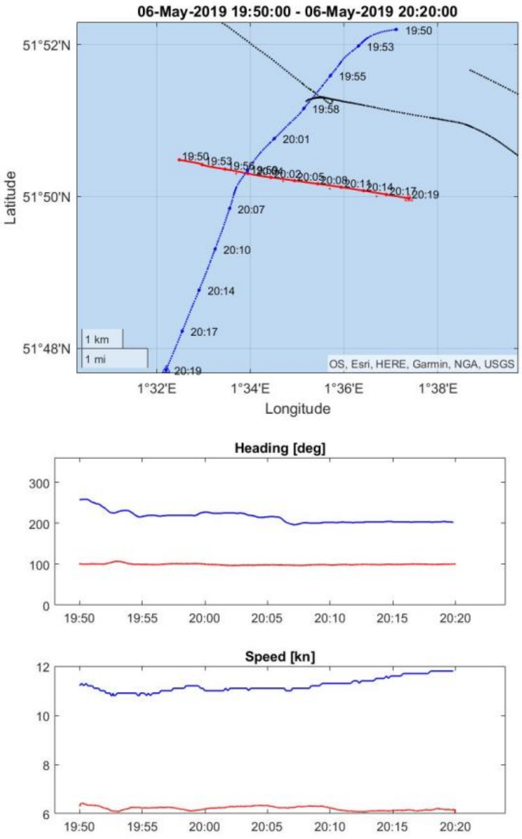
4. Unmanned vessel performance assessment in terms of shipping regulations and good seamanship practices

The difference between unmanned and autonomous vessels is clear when we analyse the way collision avoidance decisions are taken. The only collision regulations in force are those stated by the Convention on the International Regulations for Preventing Collisions at Sea from 1972, amended in 2013. Those regulations drive the seaman's decisions, and none of the actions at sea can be conducted neglecting those rules. In terms of unmanned vessels, one must reflect on some of them. Rule 3 - 'General Definitions' says that 'Vessels shall be deemed to be in sight of one another only when one can be observed visually from the other.' (COLREGS 2013). This definition is particularly important, as it decides which Section of the Collision Regulations is in force (Section II - Conduct of vessels in sight of one another or Section III - conduct of vessels in restricted visibility). 'Visually' can mean by the naked eye, use of binoculars, or use of a field glass. Can it mean using a camera and sending an image onshore? According to judicature, it cannot mean 'observing radar echo' (Rymarz 2004). At some point, those definitions probably must start considering LiDAR detection or automated image processing. Similarly Rule 5 - 'Look-out' states that 'every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision.' If we accept using image, sound or electromagnetic sensors in the role of sight and hearing, we can assure the compliance with this rule.

Numerous works are conducted to automate the collision avoidance process, and some report promising results based on the tests in a controlled environment. Although there is no evidence of any fully automated collision avoidance system proved in real navigation conditions on the market and in the available literature, but unmanned vessels have already been utilized in such environments. The following question arises: is it possible to execute proper COLREG's-compliant manoeuvring, without a crew onboard? The unmanned crossing of the North Sea between the UK and Belgium has been a unique occasion. In fact, it was impossible to achieve it without a solution for collision avoidance in the world busiest shipping route. But the correctness of the behaviour of the unmanned vessel and the manned vessel in the crossing situation with the unmanned platform can be evaluated in hindsight.

The passage described here took only 43 hours total, but due to the extensive traffic, several situations occurred, when a particular action has been required from at least one vessel to avoid a collision. The examples of collision avoidance manoeuvres are presented below in the form of plots, presenting the positions of all the vessels in the vicinity of the manoeuvre location on the given points of time. On all the plots, SEA-KIT's track is given in red, and the other vessel participating in the crossing situation is marked in blue. Black dots indicate the tracks of other vessels. Times are given only for stand-on and give-way vessels. Additionally, headings and speeds of both these vessels are presented on the auxiliary plots to indicate the exact data about the vessel's behaviour.

Figure 5 presents the conduct of 101 m long hopper dredger, who after altering the course to port at 19:53, realized that without any action, a close-quarters situation might develop. In 5 minutes, it altered the course to starboard to give way to the SEA-KIT on her own starboard, in compliance with Rule 15 - keeping the safe Closest Point of Approach distance.



a) b)

Figure 5. a. The collision avoidance manoeuvre plot. Give-way vessel's track in blue and the SEA-KIT's track in red. b. Heading and speed values of both vessels: blue - give-way vessel, red - SEA-KIT, here stand-on.

Figure 6 presents the example of a safely conducted overtaking of SEA-KIT by a faster 399 m long container ship. According to Rule 13 - 'Overtaking': '…any vessel overtaking any other shall keep out of the way of the vessel being overtaken.' The container ship slightly adjusted her course to maintain the safe distance to the smaller and slower unmanned vessel and overtook her from her port side.

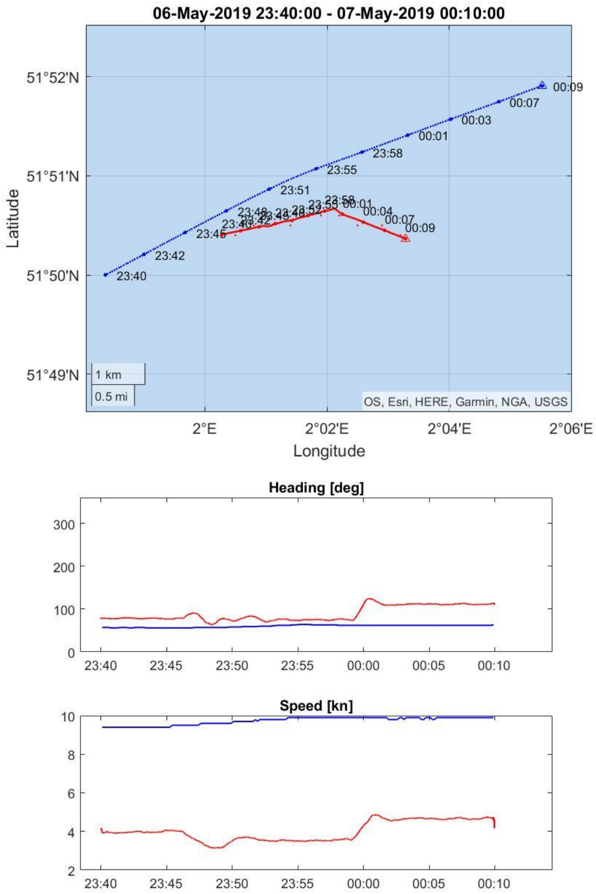


Figure 6 a. The example of safe overtaking. Overtaking vessel's track in blue and the SEA-KIT's track in red. b. Heading and speed values of both vessels: blue - overtaking vessel, red - SEA-KIT, here stand-on.

140 m long container ship gives way to SEA-KIT by altering the course to starboard from 230 to 250 degrees on the next example of a crossing situation, presented in Figure 7.

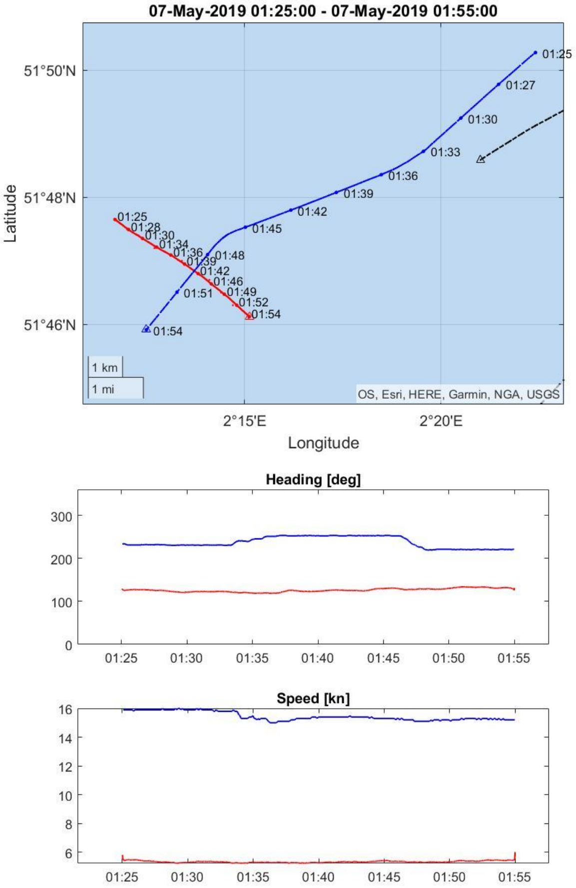


Figure 7. a. The collision avoidance manoeuvre plot. Give-way vessel's track in blue and the SEA-KIT's track in red. b. Heading and speed values of both vessels: blue - give-way vessel, red - SEA-KIT, here stand-on.

SEA-KIT conducted the passage as the underway using the engine's vessel, so it was not a rule that she was a stand-on vessel. The example of her, properly giving way to the 288 m long bulk carrier is presented in Figure 8.

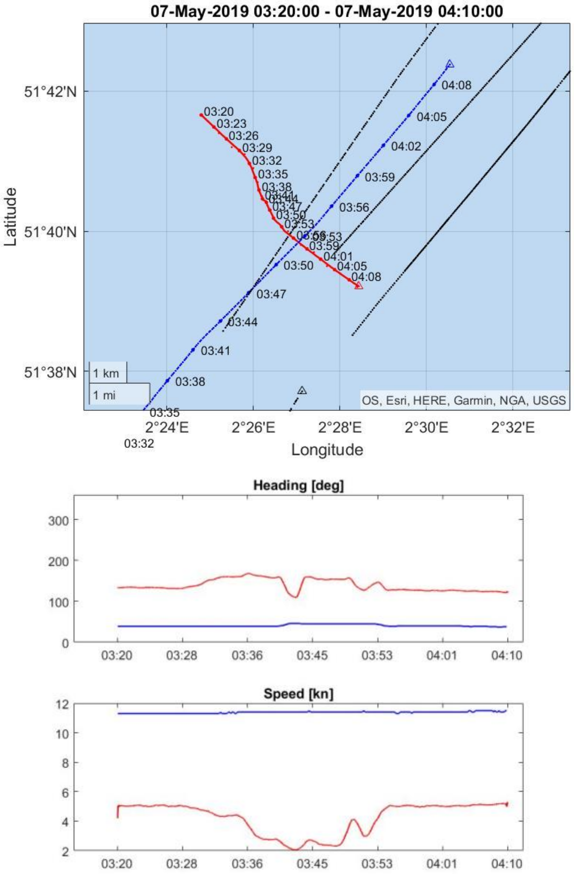


Figure 8. a. The collision avoidance manoeuvre plot. Stand-on vessel's track in blue and the SEA-KIT's track in red. b. Heading and speed values of both vessels: blue - stand-on vessel, red - SEA-KIT, here give-way.

The last example of a crossing situation comes from the return passage (Figure 9). 99 m long container ship gives way to SEA-KIT by changing her course from 44 degrees to 62. Course change caused a slight speed reduction.

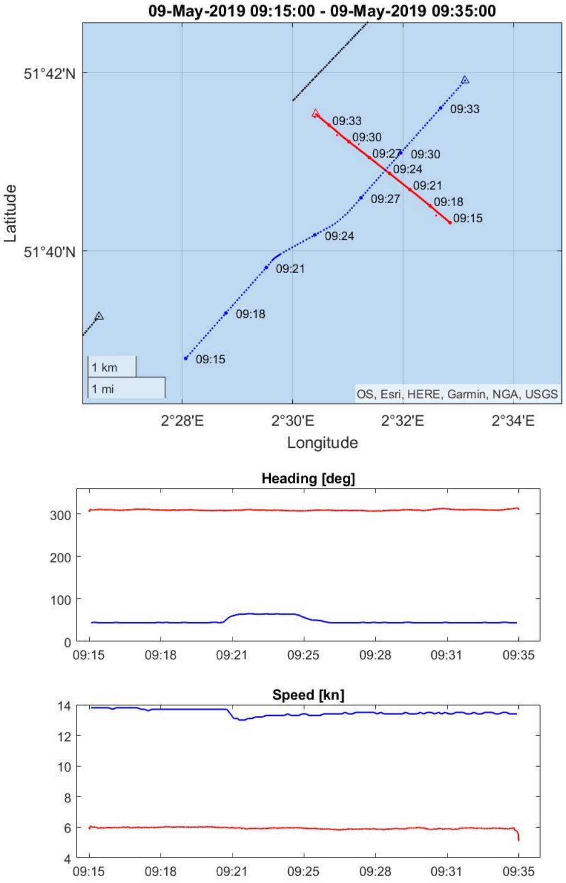


Figure 9 a. The collision avoidance manoeuvre plot. Give-way vessel's track in blue and the SEA-KIT's track in red. b. Heading and speed values of both vessels: blue - give-way vessel, red - SEA-KIT, here stand-on.

The manoeuvres presented here may look trivial, and like a textbook example if they were arranged in a controlled test area. However, it must be emphasized that they represent real, unarranged navigational situations in the busiest shipping channel in the world, and therefore, prove the capabilities unmanned vessel in an operational environment. At the same time, it must be noticed that it was not an autonomous passage. The manoeuvres are the results of two watch officers' decisions - but one of them was onshore, and his decisions were made based only on the data from the Situational Awareness system.

Collision avoidance manoeuvres are presented here using AIS data to generate manoeuvring plots, although it does not mean that AIS is the only source of information to plan the manoeuvre. In the case of conventional vessels, it should always be the fusion of information from direct observation, radar data and AIS.

For an unmanned vessel, the direct observation must be replaced by other sources of information, possible to be obtained remotely. The role of radar became dominant, complemented by the CCTV image. This configuration is the principal configuration in the cases of pleasure crafts or similar vessels, without AIS onboard.

5. Conclusions

The presence of unmanned vessels at seas is not a futuristic vision. This is already a reality. The increasing number of unmanned and autonomous vessels related projects leads to the necessity of organizational and regulatory frames to use those vessels operationally for various purposes in diverse areas of worldwide seas.

The appropriate works in the fields of maritime regulations and management are conducted by private, government and international organizations. The increasing amount of related publications and meetings, as well as the structural approach of the International Maritime Organization, helps in the coordination of those works. At the same time, the rapid development of autonomy technology means that the regulations will struggle adapt at sufficient pace, thus slowing the adoption of the technology until the regulations eventually catch up. Any trials, which are as close to the real marine conditions as possible, are extremely valuable in terms of gaining the experience and further proving the technology and building trust for a more widespread adoption. The North Sea passage of unmanned surface vessel USV ‘Maxlimer’ proved the capability of the coexistence of manned and unmanned ships at sea and can be used as an example in future works, leading to the legal and management framework for unmanned vessels operations.

References

Allianz, 2018. Safety and Shipping Review, An annual review of trends and developments in shipping losses and safety. https://www.agcs.allianz.com/content/dam/onemarketing/agcs/agcs/reports/AGCS-Safety-Shipping-Review-2018.pdf.

Advanced Autonomous Waterborne Applications Initiative (AAWA), 2016. Remote and Autonomous Ship – The Next Steps. https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/ marine/ship-intel/aawa-whitepaper-210616.pdf. (07.01.2020).

Bluebird, 2020. www.bluebird-electric.net/oceanography/Ocean_Plastic_International_Rescue/SeaVax_Ocean_Clean_Up_Robot_Drone_Ship_Sea_Vacuum.htm. (13.02.2020).

Carey, L., 2017. All hands-off deck? The Legal Barriers to Autonomous Ships. NUS Centre for Maritime Law Working Paper 17/06. https://law.nus.edu.sg/cml/pdfs/wps/CML-WPS-1706.pdf. (05.02.2020).

Congressional Research Service (CRS), 2019. Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress, https://fas.org/sgp/crs/weapons/R45757.pdf. (01.02.2020).

Comité Maritime International (CMI), 2018. International Working Group Position Paper On Unmanned Ships And The International Regulatory Framework. https://comitemaritime.org/work/mass/. (04.02.2020).

(COLREGs) Convention on the International Regulations for Preventing Collisions at Sea. 1972.

Felski, A. and Jaskólski, K., 2012. Information unfitness as a factor constraining Automatic Identification System (AIS) application to anti-collision manoeuvring, Polish Maritime Research, 3(75) 2012 Vol 19.

Felski, A., Jaskolski, K. and Banyś, P., 2015. Comprehensive Assessment of Automatic Identification System (AIS) Data Application to Anti-collision Manoeuvring. Journal of Navigation. 68. 10.1017/S0373463314000897.

Hartkopf-Mikkelsen, J., 2014. DNV GL: Unmanned container vessels could become reality in five years. https://shippingwatch.com/suppliers/article9024890.ece. (05.02.2020).

Hertog, V., 2018. RAmora - New Possibilities for Ship Handling. British Tugowners Association Conference, 18 April 2018. https://www.ukchamberofshipping.com/documents/1030/Vince_denHertog_RAL_BTA_2018_v2.pdf. (03.02.2020).

International Maritime Organization (IMO), 2018. IMO takes first steps to address autonomous ships. http://www.imo.org/en/MediaCentre/PressBriengs/Pages/08-MSC-99-MASS-scoping.aspx. (22.01.2020).

International Maritime Organization Legal Committee (IMO LEG), 2018. IMO Legal Committee 105th session, 23-25 April 2018, http://www.imo.org/en/MediaCentre/MeetingSummaries/Legal/Pages/LEG-105th-session.aspx. (22.01.2020).

International Maritime Organization Maritime Safety Committee (IMO MSC), 2017. Maritime Safety Committee 98th session, 7-16 June 2017, http://www.imo.org/en/MediaCentre/MeetingSummaries/MSC/Pages/MSC-98th-session.

International Telecommunication Union (ITU), 2014. Recommendation ITU-R M.1371-5, 'Technical characteristics for an automatic identification system using time division multiple access in the VHF maritime mobile frequency band', https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.1371-5-201402-I!!PDF-E.pdf

Jokioinen, E., 2016. Advanced Autonomous Waterborne Applications (AAWA) Initiative. MESA's "The Connected Ship and Shipping", Brussels 29.6.2016. https://www.waterborne.eu/media/18556/Advanced-Autonomous-Waterborne-Applications-AAWA-Initiative.pdf

Koikas, G., Papoutsidakis, M., Nikitakos, N., 2019. New Technology Trends in the Design of Autonomous Ships, International Journal of Computer Applications. Volume 178, No. 25. https://www.ijcaonline.org/archives/volume178/number25/koikas-2019-ijca-919043.pdf

Kongsberg. 2020. Autonomous Ship Project, key facts about Yara Birkeland. The World's First Zero-Emission, Autonomous Container Feeder. https://www.kongsberg.com/maritime/support/themes/autonomous-ship-project-key-facts-about-yara-birkeland/. (05.02.2020).

Koziński, M., 2011. Wybrane problemy nowej regulacji przewozu ładunku w polskim prawie morskim, (in Polish), Prawo Morskie, No XXVII, p. 26.

Loyd's Register (LR), 2017. LR Code for Unmanned Marine Systems, London.

MarineInsight, 2014. Dover Strait crossings: channel navigation information service (CNIS). https://www.gov.uk/government/publications/dover-strait-crossings-channel-navigation-information-service/dover-strait-crossings-channel-navigation-information-service-cnis. (03.01.2020).

MarineInsight, 2019. The Strait Of Dover- The Busiest Shipping Route In The World. https://www.marineinsight.com/marine-navigation/the-strait-of-dover-the-busiest-shipping-route-in-the-world/. (03.01.2020).

Miętkiewicz, R., 2018. Unmanned surface vehicles in maritime critical infrastructure protection applications - LNG Terminal in Świnoujście, Scientific Journal of Polish Naval Academy, 2018 (LIX) 2 (213). www.amw.gdynia.pl/images/AMW/Menu-zakladki/Nauka/Zeszyty_naukowe/Numery_archiwalne/2018/2018_2/Miętkiewicz.pdf

MUNIN, 2016. Research in maritime autonomous systems: Project results and technology potentials, https://www.cml.fraunhofer.de/content/dam/cml/de/documents/Sonstiges/MUNIN%20-%20final%20brochure.pdf (07.02.2020).

NATO Industrial Advisory Group (NIAG), 2004. Pre-Feasibility Study on UAV Autonomous Operations, NATO Industrial Advisory Group Special Group 75. (04.01.2020).

Norwegian Forum for Autonomous Ships (NFAS), 20017. Definitions for Autonomous Merchant Ships, Norway, http://nfas.autonomous-ship.org/resources/autonom-defs.pdf. (05.02.2020).

Oceanalpha, 2020. Autonomous Cargo Ship. https://www.oceanalpha.com/product-item/cloudborne/ (04.02.2020).

Proctor, A.; Zarayskaya, Y.; Bazhenowa, E.; Sumiyoshi, M.; Wigley, R. A.; Roperez, J.; Zwolak, K.; Sattiabaruth, S.; Sade, H.; Tinmouth, N., 2018. Unlocking the Power of Combined Autonomous Operations with Underwater and Surface Vehicles: Success with a Deep-Water Survey AUV and USV Mothership. In OCEANS, Kobe.

QinetiQ, 2016. Propeling maritime technology. HIS Fairplay. www.slideshare.net/ChristianAzolan/qinetiq2016. (13.02.2020)

RAND, 2013. U.S. Navy Employment U.S. Navy Employment Options for Unmanned Surface Vehicles (USVs). https://www.rand.org/content/dam/rand/pubs/research_reports/RR300 /RR384/RAND_RR384.pdf (10.02.2020).

Rodseth, Ø.J., Burmeister, H.C., 2012. Developments toward the unmanned ship, http://www.unmanned-ship.org/munin/wp-content/uploads/2012/08/R%C3%B8dseth-Burmeister-2012-Developments-toward-the-unmanned-ship.pdf (05.02.2020).

Rudziński, D., 2019. Morski autonomiczny statek nawodny - MASS https://www.gospodarkamorska.pl/Porty,Transport/morski-autonomiczny-statek-nawodny-%E2%80%91-mass.html. (01.02.2020).

Rymarz, W., 2004. Międzynarodowe prawo drogi morskiej w zarysie. Trademar. Gdynia (in Polish).

Ship Technology, 2017. Hronn Autonomous Offshore Support Vessel. https://www.ship-technology.com/projects/hronn-autonomous-offshore-support-vessel/

United Nations Convention on the Law of the Sea (UNCLOS), 1983. Dec. 10, 1982, 1833 U.N.T.S. 397.

Williams, A., 2019. The Mayflower Autonomous Ship. https://www.plymouth.ac.uk/news/a-mayflower-for-a-new-generation. (23.02.2020).

Williams, R., 2008. Autonomous systems overview. BAE Systems. http://www.aircraftbuilders.com/files/2716/File/BAE_%20Systems_Text_Version.pdf. (18.02.2020).

Zarayskaya, Y.; Wallace, C., Wigley, R. A.; Zwolak, K.; Bazhenova, E.; Bohan, A.; Elsaied, M.; Roperez, J.; Sumiyoshi, M.; Sattiabaruth, S.; Dorshow, W.; Ketter, T.; Sade, H.; Proctor, A.; Rhyzow, I.; Tinmouth, N.; Simpson, B.; Kristoffersen, S.M., 2019. GEBCO-NF Alumni Team Technology Solution for Shell Ocean Discovery XPRIZE Final Round. In OCEANS, Marseille.

Zwolak, K.; Simpson, B.; Anderson, R.; Bazhenowa, E.; Falconer, R.; Kearns, T.; Minami, H.; Roperez, J.; Rosedee, A.; Sade, H.; Tinmouth, N.; Wigley, R.A.; Zarayskaya, Y., 2017. An unmanned seafloor mapping system: The concept of an AUV integrated with the newly designed USV SEA-KIT. In OCEANS, Aberdeen.

Acknowledgements

The North Sae passage presented here has been organized and conducted by Sea-Kit International. Authors would like to thank Sea-Kit International authorities for the participation in this undertaking. Data collection on board has been partially funded by the Polish Naval Academy from the statutory funds on the research activities.

Declarations of interest

None. Neil Tinmouth is an employee of Sea-Kit International, which ensured the good communication with the SEA-KIT operators, but it had no influence on any analysis presented here.

Author contributions

Conceptualization: K.Z.; Data curation K.Z.; Formal analysis: K.Z., J.D., R.M.; Investigation, K.Z., J.D., R.M.; Methodology: K.Z.; Resources: N.T.; Software: K.Z.; Supervision: K.Z.; Visualization: K.Z.; Roles/Writing - original draft: K.Z., J.D., R.M.; Writing - review & editing: N.T.