Proceedings of the ASME 2018 37th International
Conference on Ocean, Offshore and Arctic Engineering
OMAE2018
June 17-22, 2018, Madrid, Spain

OMAE2018-77672

AUTONOMOUS SHIP NAVIGATION UNDER DEEP LEARNING AND THE CHALLENGES IN COLREGS

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ABSTRACT
A general framework to support the navigation side of autonomous ships is discussed in this study. That consists of various maritime technologies to achieve the required level of ocean autonomy. Decision-making processes in autonomous vessels will play an important role under such ocean autonomy, therefore the same technologies should consist of adequate system intelligence. Each onboard application in autonomous vessels may require localized decision-making modules, therefore that will introduce a distributed intelligence type strategy. Hence, future ships will be agent-based systems with distributed intelligence throughout vessels. The main core of this agent should consist of deep learning type technology that has presented promising results in other transportation systems, i.e. self-driving cars. Deep learning can capture helmsman behavior, therefore that type system intelligence can be used to navigate autonomous vessels. Furthermore, an additional decision support layer should also be developed to facilitate deep learning type technology including situation awareness and collision avoidance. Ship collision avoidance is regulated by the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) under open sea areas. Hence, a general overview of the COLREGs and its implementation challenges, i.e. regulatory failures and violations, under autonomous ships are also discussed with the possible solutions as the main contribution of this study. Furthermore, additional considerations, i.e. performance standards with the applicable limits of liability, terms, expectations and conditions, towards evaluating ship behavior as an agent-based system on collision avoidance situations are also illustrated in this study.

INTRODUCTION

Ocean Autonomy
Autonomy can be expressed as a situation, where one can have freedom from external controls or influences. However, the same should have adequate intelligence to make appropriate decisions in relation to possible internal and external variations. The same concept has been adopted towards mechanical and electrical systems by introducing machine intelligence-based decision-making facilities to operate themselves. Such self-operating systems, i.e. autonomous systems, should consist of advanced decisions making facilities, therefore various technologies to support the same should also be developed by the respective industries. Recent technological advancements in autonomous systems, i.e. self-driving cars, robots, etc. [1], can be such examples consisting of adequate decision-making facilities. Furthermore, these autonomous systems are also supported by internal and external IoT (i.e. internet of things), big data and communication infrastructure to overcome the respective challenges. However, the success of decision-making features in these autonomous systems is yet to be evaluated, comprehensively by the respective authorities [2].

Autonomous systems will be an important role in the future transportation systems, even though there are many challenges [3]. Since self-driving vehicles have already been introduced on public roads, similar systems will also be introduced by air and maritime transport systems. This study focusses on the navigation side of maritime transport systems with autonomous and remote-controlled facilities, i.e. Autonomous and remote-controlled ships. That will also be a part of ocean autonomy as a transportation system. However, ocean autonomy into the offshore sector yet to be developed.

Modern vessels are facilitated with onboard and onshore IoT to support various digitalization applications in the shipping industry. Industrial digitalization converts conventional paper-based information handling approaches into data driven applications. A comprehensive overview of vessels and ship systems can be captured under industrial digitalization and that information should use towards decision-making facilities of future ships. Hence, industrial digitalization should support ocean autonomy under the maritime transportation, where human inference can be minimal by transforming big data collected by IoT into intelligent decisions [4].

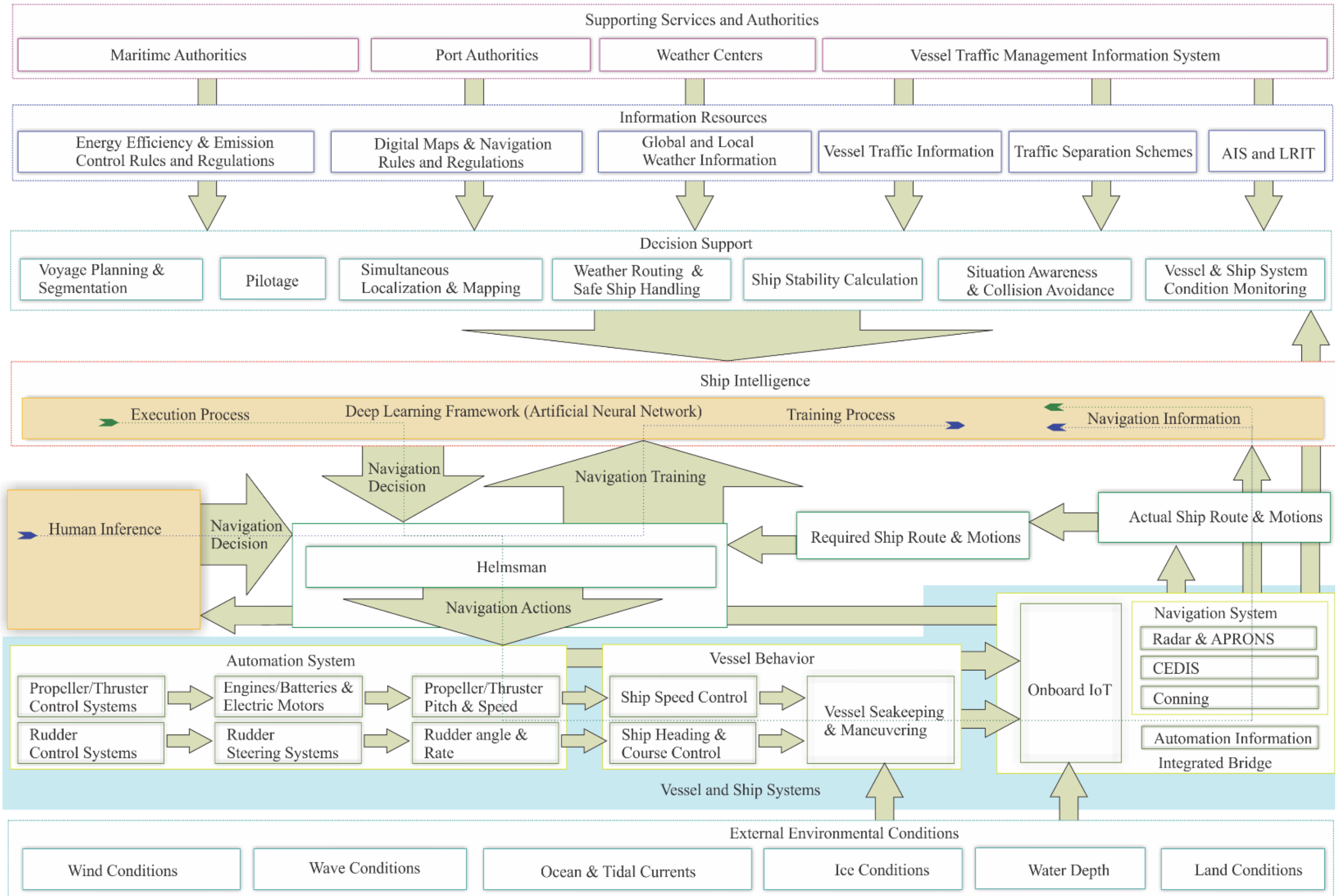

Fig 1: A general framework for autonomous ship navigation

There are several millstones that should be achieved by the shipping industry to make autonomous ship navigation a reality. "Remote Controlled Ship" can be an important milestone in this route [5] and this same state, i.e. remote controlled navigation facilities, can always be a part of autonomous ship navigation. In general, each voyage can have both autonomous and remote controlled navigation sector that should be segmented by considering the operational requirements of future vessels. The required maritime infrastructure to support both remote controlled and autonomous ship operations should be developed and that can also be another important milestone in the same route [6]. The success in ship intelligence, i.e. artificial intelligence to navigate and operate vessels and ship systems, will make the most important milestone in this journey. Appropriate decision support facilities to support ship intelligence should also be developed and that will be another important milestone. Finally, adequate tools and techniques to evaluate vessel behavior under ship intelligence with decision support facilities should also be developed, where the acceptable risk and limits of liability, terms, expectations and conditions under autonomous ship navigation should be defined.

Agent Based Systems

This study proposes the autonomous ship as an agent based system. It is believed that this approach can also satisfy the respective milestones, appropriately. An agent can be defined as a system located in a specific environment, therefore it interacts with the environment by intelligent decisions and actions to satisfy its design objectives. However, other similar and/or different agents can also be located within the same environment, where these agents should interact. Therefore, various cooperative and non-cooperative interactions among these agents are expected in this same environment. However, each agent may have its own design objectives, therefore adequate intelligent to fully or partially satisfy the same should be facilitated. If individual design objectives cannot be achieved (i.e. unsatisfactory) in this environment, adequate compromising strategies to satisfy appropriate group objectives should be considered. Such situations can be categorized as a cooperative multi-agent learning approach with machine learning approaches (i.e. reinforcement learning) [7]. Therefore, adequate system intelligence in each agent should be facilitated to handle rather complex interactions among agents in the environment.

It is expected that autonomous ships will be agent based systems, therefore various cooperative and non-cooperative interactions among vessels in open sea areas and traffic lanes are expected. In general, such intelligent agent should have the following basic properties [7]:

- **Autonomy:** Each agent should operate by its own actions and/or internal states without the direct inference of humans or others.
- **Social-ability:** Each agent should interact with other agents (i.e. including humans) by appropriate agent-communication language.
- **Reactivity:** Each agent should not only interact with the environment but also respond to a timely fashion for the respective environmental changes and challenges.
- **Pro-activeness:** Each agent should not only interact with the environment but also take appropriate initiatives to exhibit goal-oriented behavior to satisfy its design objectives.

One should note that these properties should also be a part of future autonomous vessels. Therefore, the interactions among vessels and ocean environmental conditions can be facilitated by agent based systems. However,, vessels and ship systems should have adequate ship intelligence and decision support facilities to support these agent functionalities and that can overcome the respective challenges in autonomous ship navigation.

AUTONOMOUS VESSELS AND SHIP SYSTEMS

Future Vessels and Onboard Systems

It is expected that the shapes and types of future vessels will be changed due to remote-controlled and autonomous operational conditions. Remote-controlled vessels that will open the path towards autonomous vessels will create the next generation maritime transport systems. Human presence will be limited in such vessels, where ship systems that supports humans onboard, i.e. accommodation systems, air-conditioning, etc., can be eliminated. Hence, the cost of installing human support systems can be reduced, considerably and their maintenance can be eliminated. Since remote-controlled and autonomous vessels may not require to have adequate comfort for humans, the shapes of such vessels can be designed in a way that reduce the respective ship resistance, further.

However, additional vessel stability issues may rise under such ship designs and that should also be addressed. Though on the other hand, new ship systems, i.e. modern decision support facilities, to support remote-controlled and autonomous operations should be installed in these vessels. Furthermore, the respective maintenance processes for these new systems should be initiated. The overall reliability of these vessels and ship systems should considerably be higher to cope with harsh environmental conditions, therefore adequate condition monitoring and condition based maintenance approaches onboard as well as onshore should be available. Future vessels will be facilitated with various onboard and onshore IoT to monitor health conditions of individual systems in real-time, i.e. possibly at component levels. Such network connectivity will create big data sets and the respective system health conditions, i.e. system information, can be extracted from the same data sets. Hence, the respective system and component failures can often be identified at an early stage due to their health information. A considerable amount of recent research and development activities are focused on conditions monitoring (CM) and condition based maintenance (CBM) applications in the shipping industry. There are onshore condition monitoring centers, i.e. intelligent asset management centers, are introduced to support future vessels by various industrial players [9].

System Intelligence

The navigation side of Autonomous vessels to achieve the required level of ocean autonomy is discussed in this section. It is expected that autonomous vessels will be trained by humans, i.e. to navigate like an experienced helmsman. Similar training case studies have successfully been implemented by other transport systems, i.e. autonomous car, drones [10], therefore the same approaches can be adopted by the maritime transport systems. Furthermore, adequate system intelligence should be developed within these vessels to absorb such knowledge from the navigators during their training processes. Such intelligence can be transferred from one vessel to another and that same can further be improved during future ship operations. System intelligence in autonomous vessels may consist of a complex systems of system supported by additional decision supporting facilities. A general framework to support the navigation side of autonomous ships with the required technologies (i.e. navigation and automation systems) is presented in Figure 1.

Initially, ship navigators will train these vessels to achieve the respective system intelligence levels, i.e. to operate both navigation and automation systems. The training process can be done by onboard human presence and onshore remote-controlled centers by introducing various navigation decisions (i.e. human inference). That will be converted into navigation actions. The navigation actions that required to achieve the required ship route vs actual ship route can be considered as the first level inputs to the training process (i.e. navigation training) of ship intelligence (see Figure 1). Such navigation actions will be implemented on the ship automation system, i.e. propeller/thruster and rudder control systems, of the vessel to achieve the required ship behavior i.e. ship speed, heading and course.

One should note that these propeller/thruster and rudder control system configurations can vary from one vessel to another. Therefore, the navigator actions on propeller (i.e. propeller pitch and speed) and rudder (i.e. rudder angle) control systems can vary from one vessel to another. Furthermore, vessel seakeeping and maneuvering behavior can be influenced by vessel structures, ship systems and external environmental conditions other than navigator’s actions. Both vessel behavior and external environmental conditions should be monitored by onboard and onshore IoT to provide required navigation information. Each voyage consists of a required (i.e. expected) ship route, therefore appropriate navigation actions should be taken by the helmsman to achieve the same with respect to the actual ship route.

Ship navigation systems consist of various IoT including ECDIS (Electronic chart display and information system), Radar and APRA (Automatic radar plotting aid), Conning and additional systems and sensors. A combination of such systems is classified as an integrated bridge system (IBS) [11]. IBSs can collect and visualize the most important vessel navigation and automation information including vessel seakeeping and maneuvering behavior in the actual ship route (i.e. vessel position, speed, course, heading and draft). This information is collected as big data sets that should further be analyzed to extract the respective seakeeping and maneuvering behavior of the vessel. The accumulation of seakeeping and maneuvering behavior and external environmental conditions (i.e. navigation information) collected by IoT along with the navigator's actions are considered as the second level inputs to the training process of ship intelligence. These two inputs, i.e. navigation actions and information, complete the typical training cycle, i.e. Training Process in Figure 1, of an autonomous vessel. However, there are additional system layers that should support system intelligence to succeed autonomous ship navigation. These system layers are further illustrated in Figure 1 as: Decision support, information sources and supporting services and authorities.

Deep Learning in Shipping

A considerable section of ship intelligence will consist of a deep learning based framework, i.e. artificial neural network. The same framework will create the respective agent behavior within autonomous vessels. Similar frameworks have been implemented by other transport systems, i.e. autonomous navigation systems of drive-less cars, and that have achieved promising results in terms of navigating with the required safety levels [12]. In general, deep leaning based frameworks transform a self-driving vessel problem into a data classification problem. e.g. convolutional neural networks (CNN, or ConvNet) are a class of deep learning framework [13] that can solve complex image classification problems and that have also been used for self-driving vehicles. The same classification approach can provide an elegant mechanism to capture helmsman behavior, i.e. agent behavior in ship navigation. Initially, such deep learning frameworks should be the observers to manual or remote controlled vessels that are operated by human navigators. That step is previously categorized as a training process (see Figure 1) and the main objective of this phase is to train the respective neural networks to capture ship behavior with respect to navigator's actions. Therefore, adequate features of vessel seakeeping and maneuvering behavior can be accommodated into these neural networks.

When such neural networks are adequately trained, that technology can be used to navigate the first level autonomous vessels. In addition, the same deep learning based frameworks can be distributed (i.e. shared knowledge) among several vessels and that can also be further trained during their operations. These networks are often trained by image based information and navigator actions rather than system parameters. A similar approach can also be adopted towards the training phase of autonomous vessels. These networks can transfer from one vessel to another as mentioned before, however additional training periods may require to capture highly accurate ship behavior in some situations. If these vessels are standardized during their ship design phase, then additional training requirements can be eliminated. After a successful navigation training period, ship intelligence can navigate such vessel as an experienced helmsman, i.e. execution process in Figure 1.

Several technological challenges in controlling such vessels, specially under rough weather conditions, should also be expected. Conventional vessels are often categorized as under-actuated systems, i.e. rudder and propeller control systems may not able to control vessels completely during some sea going situations. This ship controllability issue, i.e. under-actuation, can complicate the training process of autonomous ships. One should note that drones or under water vehicles navigate in a single environmental media (i.e. land, air or water). Ships are navigating between two environmental media (i.e. air and water) and the interactions between both media influence on vessel seakeeping and maneuvering behavior. That can further complicate the training process of ship intelligence in under-actuated vessels. The inertia in heavy vessels makes ship controllability an extremely difficult challenge especially under rough weather conditions.

The rudder and propeller control systems, i.e. only available control units for vessel actuation, may fail to control vessels under rough sea going conditions. When ships are navigating under moderate or high speeds (i.e. over 3-4 knots), the capabilities of thrusters are negligible. The control solutions developed for autonomous surface vehicles (ASVs) and autonomous underwater vehicles (AUVs) are not acceptable for large vessels due to the same reasons that are mentioned previously. Similarly, the control solutions developed for autonomous land vehicles, i.e. driver-less car, are not acceptable due to the same reasons, i.e. land vehicles are light weight transportation units compared to ships and have a better controllability over the rods. Hence, the controllability of under actuated vessels under various navigation conditions should be investigated in the near future. It is also expected that deep learning frameworks supported by the decision support layer (see Figure 1) may overcome some challenges in ship controllability.

Decision Support Facilities

The decision support layer with various onboard and onshore IoT supports ship intelligence. Each ship route may divide into several voyage segments during voyage planning, i.e. possible autonomous and remote-controlled navigation segments. Some voyage segments of ship navigation may execute as remote-controlled routes due to the respective safety and security reasons. Global and local digital maps including navigation and emission control rules and regulations should support the same voyage planning phase. Furthermore, additional decision support facilities such as weather routing and pilotage can also be a part of voyage planning. Even though global maps are already included under ECDISs, local maps (i.e. harbor areas and confined waters) with the respective navigation rules and regulations can be supplied by local maritime and port authorities during the ship operation phase. Such local information improves the safety of autonomous ship navigation, therefore the pilotage type activities, i.e. humans with local knowledge employed onboard ships to guide vessels, can be eliminated. In addition, the respective maritime authorities can further enforce energy efficiency and emission control rules and regulations [14] on these vessels by distributing the respective information. The energy efficiency and emission control rules and regulations are enforced, extensively on the designated emission control areas (ECAs). Hence, local digital maps can provide of those information, accurately to enforce the respective energy efficiency and emission control rules and regulations in future vessels.

Local digital maps can be integrated with global maps to support autonomous ship navigation under SLAM (Simultaneous localization and mapping) type applications [15]. The SLAM type applications support intelligent agents, i.e. autonomous vessels, to locate themselves within global and local maps by considering the information collected from onboard and onshore IoT. The agents can also learn about the environment in some situations by executing possible actions. Therefore, additional sensors, i.e. Lidar and Laser, should also be available in autonomous vessels to support SLAM type applications. Additional information resources such as VTI (vessel traffic information), TSS (Traffic separation Schemes), AIS (Automatic identification system) and LRIT (Long-Range Identification and Tracking) can also support the same SLAM type applications in future vessels. Some information sources are provided by vessel traffic management and information systems (i.e. VTMIS).

Weather routing and safe ship handling should also support ship intelligence under the decision support layer to improve the safety and efficiency of ship navigation (see Figure 1). The required global and local weather information can be obtained from weather centers by autonomous vessels. Weather routing facilitates autonomous vessels by providing the recommended ship routes prior to and during each voyage under various navigational constraints and global weather forecast [14]. Safe ship handling facilitates autonomous vessels by providing recommended ship position, orientation and speed conditions on the recommended route under similar navigational constrains and local weather conditions [16]. In general, safe ship handling applications have often been used for unexpected rough weather conditions in ship routes. Therefore, both weather routing and safe ship handling should support future vessels under global and local weather forecast and that can also be an important part of the voyage planning phase. Furthermore, weather routing and safe ship handling can support each other during the operation phase to achieve the required energy efficient and safe ship navigational levels of autonomous vessels.

Conventional vessels consist of stability calculation systems to estimate the respective ship loading conditions. Since cargo loading and unloading activities at ports, vessels stability should be calculated at the begging of each voyage. It is expected that autonomous vessels should have similar decision support facilities with additional IoT to verify the respective loading calculations, accurately. Since future cargo loading and unloading conditions in posts will also be automated, that information can be shared with these decisions supporting layer.

Situation awareness and collision avoidance among stationary and moving objects will play an important role in autonomous ship navigation. The stationary objects, i.e. land masks, shipwrecks, etc., are marked in global and local digital maps and unexpected ones should be detected by onboard IoT. The avoidance of both objects may relate to a path planning type problem, especially under harbor or confined water navigation. Situation awareness and collision avoidance facilities should consist of adequate intelligence to detect and identify stationary and moving objects. Such stationary and moving object detection and classification has been done under deep learning frameworks with successful results [17], therefore similar approach can be adopted towards autonomous ship navigation. A general overview in situation awareness and collision avoidance of autonomous vessels in relation to the respective rules and regulations is discussed in the following sections.

Situation Awareness and Collision Avoidance

Future vessels should be facilitated with appropriate collision avoidance technologies. However, the behaviors of such technologies should also be evaluated to guarantee the respective safety levels of ship navigation [18, 19]. This section illustrates the respective challenges in evaluating situation awareness and collision avoidance technologies in autonomous vessels. In general, such evaluation procedure for autonomous vessels should consist of the following basic units:

- Legal frameworks and their regulatory failures
- Autonomous and target vessels and their behavior
- Testable systems to evaluate ship behavior

Legal Frameworks and Their Regulatory Failures

All sea going vessels should follow the law of the sea. The International Maritime Organization (IMO) in 1972 by the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) has introduced a legal framework to regulate ship encounter situations [20]. The respective studies of ship collisions indicate that 75%–96% of maritime collisions and causalities caused by some types of human errors and 56% of major maritime collisions involved one or more violations of the COLREGs rules and regulations [21]. Future ships should also be regulated by the same rules and regulations during their vessel encounter situations and that behavior should be evaluated by testable systems under acceptable performance standards. Three distinct ship encounter situations that involve the risk of collisions can be considered: overtaking, head-on, and crossing. In general, the decision space of ship encounter situations with two vessels can be categorized into the following stages in open sea:

- When none of the vessels are at a collision risk range, both vessels have the option to take appropriate actions to avoid a collision situation.
- When both vessels are at a collision risk range, the "give-way" vessel should take appropriate actions to achieve safe passing distance in accordance with the COLREGs rules and regulations, and the "stand on" vessel should maintain course and speed conditions.
- When both vessels are at a critical collision risk range, and the "give way" vessel does not take appropriate actions to achieve a safe passing distance in accordance with the COLREGs rules and regulations, then the "stand on" vessel has the option to take appropriate actions to avoid the collision.
- However, local navigation rules and regulations, traffic lanes, offshore operations and special types of vessels (i.e. fishing vessels) can override some of the same decision space especially under overtaking and head-on situations.

The COLREGs may have some regulatory failure situations under the same decision space and that may lead towards collision situations [22]. Such situations have been reported in the previous studies [23], while applying the COLREGs rules and regulations into if-then-else type computer codes under Fuzzy Logic. Those situations are further illustrated in this section to illustrate COLREGs regulatory failure situations.

Figure 2 represents a situation, where the target vessel is in a head-on situation from the port, slightly with the own vessel. That can create a regulatory failure situation within the COLREGs rules and regulations, i.e. the directions these vessels should pass each other. The respective vessel positions, $O(k)$ & $P_i(k)$, course-speed vectors, $V_o(k)$ & $V_i(k)$ and relative navigational trajectory of the target vessel are also presented in the figure. Figure 3 represents a situation, where the target vessel relative navigational trajectory varies from head-on to crossing situations with the own vessel. Therefore, such situations can also create a regulatory failure situation within the COLREGs rules and regulations, i.e. which rules in head-on or crossing situations should apply. Similarly, the respective vessel positions, i.e. $O(k)$ & $P_i(k)$, course-speed vectors, i.e. $V_o(k)$ & $V_i(k)$ and relative navigational trajectory of the target vessel are also presented in the same figure. Figure 4 represents a situation, where multiple target vessels are approaching the own vessel from different directions. Therefore, such situations can also create a regulatory failure situation within the COLREGs rules and regulations, i.e. which vessel avoidance should have the priority.

One should note that these are selected regulatory failure situations of the COLREGs rules and regulations that are observed by previous studies. Therefore, additional regulatory

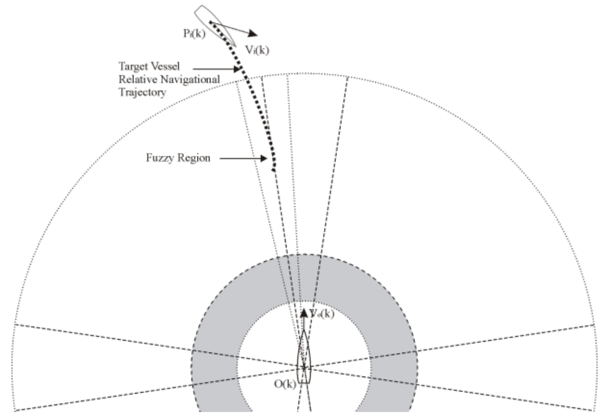

Fig 2: Ship encounter situation 1

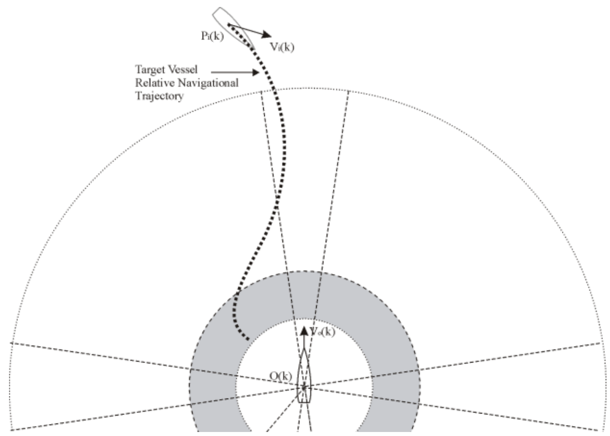

Fig 3: Ship encounter situation 2

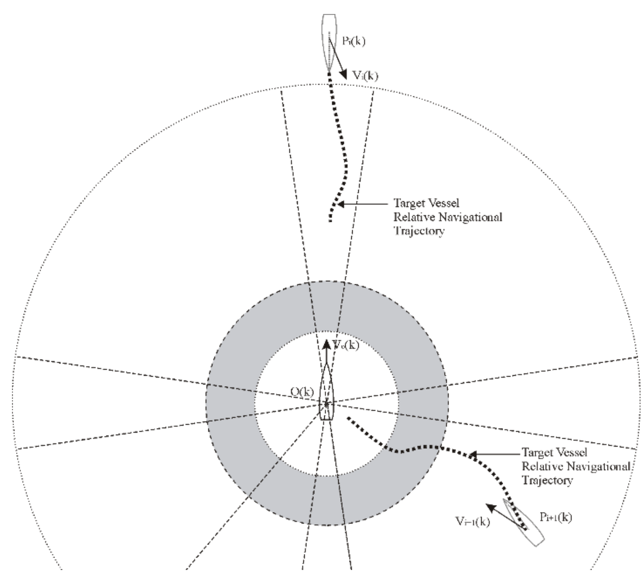

Fig 4: Ship encounter situation 3

failure situations are yet to be discovered in the future, when these rules and regulations are implemented under the decision support layer (see Figure 1). Adequate measures to overcome such regulatory failure situations within the COLREGs legal framework should be considered and that will eventually improve the required safety levels of autonomous ship navigation.

Autonomous and Target Vessel Behavior

Vessels may not honor rules and regulations in some navigation situations and that may create high collision risk situations. One should note that such ship encounters are clear regulatory violations within the COLREGs legal framework and cannot be categorized as regulatory failure situations. That may result in ship collisions and close encounter situations in open sea and the COLREGs legal framework may not provide clear guidance to overcome for such situations. In general, ship navigators use their experiences to avoid such situations and that may also lead to "crash stopping" type maneuvers of the "stand on" vessel due to a lack of distance for speed reduction. One should note that the "stand on" vessel represents the ship that has the priority for navigating in an encounter situation.

The characteristics of the "stand on" vessel with respect to its "stopping distance" and "turning circle" should be considered for developing appropriate collision avoidance strategies for future vessels in such situations. Since the expert knowledge has been used for such ship encounter situations, it is expected that the same knowledge can be absorbed by the deep learning framework of ship intelligence. These high collision risk situations can be intentional or unintentional, however the respective situation awareness and collision avoidance facilities under ship intelligence should take appropriate actions to find appropriate navigational solutions. On the other hand, adequate tools and techniques to predict the intensions of vessels should also be considered to support ship intelligence.

High Collision Risk Ship Encounters

The responses (i.e. vessel behavior) of autonomous vessels, i.e. ship intelligence, in such high collision risk encounters should also be evaluated and the acceptability of their navigational actions should be investigated. That can be done by proper testable systems supported by appropriate performance standards to evaluate ship intelligence. These performance standards are likely to be defined by the respective maritime authorities or classification societies and evaluates the behavior for autonomous vessels. However, the evaluation process of autonomous vessels under critical collision situations should be carefully formulated, since collision avoidance approaches also depend on vessel maneuverability characteristics. The maneuverability characteristics may be captured by ship intelligence under deep learning type frameworks. Therefore, ship intelligence may provide initial performance standards to evaluate the first generation autonomous vessels.

Various ship navigation situations with high collision risks should be recreated to evaluate vessel behavior, i.e. ship intelligence, under the testable platforms. The results, i.e. vessel behavior under ship collision or near collision situations, should be communicated towards system developers in autonomous vessels to improve their ship intelligence and decision support facilities. Furthermore, testable systems should suggest the required autonomous ship behavior, i.e. to reduce the collision risk, with the appropriate reasoning about compliance requirements of the legal frameworks, i.e. the COLREGs and local navigational rules and regulations. Any unusual vessel behavior or collision avoidance failures, i.e. regulatory failure situations, may lead to introduce additional modifications into the legal frameworks. One should note that collision worthiness and survivability can also be important features for transport systems. However, autonomous vessels may focus on collision avoidance features for ship encounter situations rather than collision worthiness and collision survivability, extensively.

Testable System for Vessel Behavior

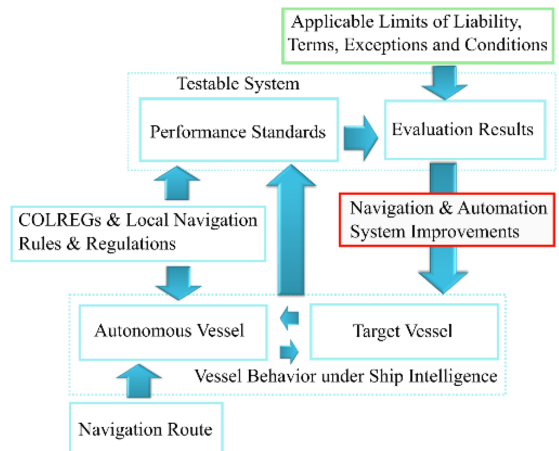

Fig 5: Testable system for evaluating autonomous vessel behavior

A testable system with required components to evaluate collision avoidance behavior of autonomous vessels is presented in Figure 5. That is influenced by two or more legal frameworks i.e. COLREGs and other local navigation rules and regulations. This system evaluates autonomous ship behavior, i.e. as an agent based system, under various encounter situations with target vessels. Therefore, several navigational ship routes with varying weather conditions should be introduced in the same to create realistic ship navigation conditions. Autonomous vessel behavior can further be detailed into navigation and automation system levels by monitoring the respective systems. Therefore, vessel and ship system behavior should be evaluated by the testable system with pre-defined performance standards. That provides the specific performance expectations that should be satisfied by autonomous vessels for various ship encounter situations.

Appropriate course and/or speed changes, at any cost, must be taken by the vessels to avoid collision situations, as highlighted in the COLREGs. Hence, that unique feature can introduce the minimum expectation level for the performance standards of the testable systems. However, the ultimate expectation of the performance standards may relate to selected policy options and/or legal frameworks. Furthermore, that will also be influenced by the applicable limits of liability, terms, expectations and conditions that are introduced by the insurance industry. However, existing performance standards [24, 25] for ship navigation can also be adopted by the same testable systems.

The initial performance standards for situation awareness and collision avoidance should be developed in relation to a two vessel encounter situation and that can be expanded towards multiple vessel encounter situations. Hence, the performance standards should illustrate the following navigation features to evaluate vessel encounter situations:

- Autonomous and target vessel domains
- The collision risk between the vessels
- The distance and time to a possible collision/close encounter situation
- Autonomous and target vessels course-speed vectors
- The bearing vector between two vessels
- Autonomous vessel decisions and the time to execute the same decisions into actions
- Autonomous and target vessel predicted and actual behavior.
- The satisfactory level (i.e. under the performance standards) of the decisions and actions that have taken by the vessels.

If the autonomous vessel fails to satisfy the expected performance standards, then the recommendations on navigation and automation system improvements should be forwarded to the respective manufacture. Therefore, adequate modifications not only in a system level but also a ship intelligence and decision support level should be considered (see Figure 5). It is also recommended to implement the following testing levels in the proposed platform to evaluate situation awareness and collision avoidance behavior in autonomous vessels under ship encounter situations:

- Testing level 1: Both autonomous and target vessels are simulated by software programs.
- Testing level 2: Target vessels are simulated by a software program and the autonomous ship is represented by a full-scale/model-scale vessel. The autonomous vessel is navigating in approved waters.
- Testing level 3: Both autonomous and target vessels are represented by full-scale/model-scale vessels. That are navigating in open sea.

It is expected that testable systems will initially evaluate autonomous vessels under the first testing level. Both autonomous and target vessels can be considered as agent based systems in this situation, where appropriate mathematical models to simulate realistic ship behavior are required. In addition, several weather conditions can also be introduced in this situation to observe the variations in vessel behavior. The respective sea trial data that are collected from ocean going vessels can be used to develop such mathematical models for these vessels [26]. Such mathematical model of ship maneuvering should consist of: ship course-speed vector, heading vector and turning rates. That can also be estimated from time-series data sets, i.e. AIS data, and such data sets can also influence on the respective performance standards.

The lessons learned from the first testing level should consider for the second testing level and that represents realistic ocean-going conditions. The implementation of the third testing level can be a challenge due to the difficulties in creating vessel collision situations in open sea, intentionally (i.e. due to maneuverability difficulties in vessels). Therefore, the first and second testing levels can be considered as possible situations that can be implemented in the testable system. Such two vessel encounter situations can be accumulated towards multi-vessel encounter situations, as mentioned previously.

These evaluation procedures of ship behavior in the testable systems should consider realistic ocean-going conditions. That include all possible navigation scenarios including various ship encounter situations, varying environmental conditions, and random ship system & sensor failures. However, the main objective in this testable system is to evaluate vessel behavior of autonomous and target ships rather than the reliability of hardware and software systems. Even though system hardware and software failures can eventually influence on ship intelligence and decision support layers of future vessels, a considerable amount to tools and techniques to regulate such failures have been developed by the respective industries. In general, both hardware and software developments are often guided by system development (i.e. the V model) [27] and agile software development approaches [28] by various manufactures. Therefore, future ship systems will have higher reliability levels due to the maturity of the respective technologies. Hence, adequate research focuses should be aimed towards ship intelligence and decision support facilities of autonomous vessels, rather than individual system and component failures.

CONCLUSIONS

A general framework to support the navigation side of autonomous vessels is discussed in this paper and that consists of various technologies to achieve the required level of ocean autonomy. Since decision-making processes in autonomous vessels will play an important role under ocean autonomy, the same technologies should consist of adequate system intelligence. Each onboard application in autonomous ships may require a localized decision-making process, where a distributed intelligence type strategy should be considered. Hence, the ship should be an agent-based system with distributed intelligence throughout the vessel. The main core of such agent consists of deep learning type frameworks, i.e. ship intelligence, to simulate the helmsman actions in ship navigation. Furthermore, an additional decision supporting layer should also available to facilitate situation awareness and collision avoidance among vessels. Hence, a considerable amount of research and development work will be required to achieve required ship intelligence within deep learning frameworks and machine learning applications for decision support of autonomous vessels.

The required technologies to implement and evaluate ship intelligence in transport systems are still in a preliminary stage. Therefore, a considerable amount of such knowledge yet to be created. The same knowledge should be shared among research communities to develop safer maritime transportation systems. Autonomous system developers will play a crucial role in developing and sharing the knowledge on ship intelligence and decision support facilities and that may push machine learning into a more regulated industry. However, the human interactions and their outcome under artificial intelligence yet to be investigated by the research community.

Collision avoidance among autonomous and target vessels is focused in this study. The same ship intelligence with decision support facilities in collision avoidance should also be evaluated under various ship encounter situations. That can be done by testable systems of situation awareness and collision avoidance and the outcome should be compared with the applicable limits of liability, terms, expectations and conditions in ship navigation. That will be resulted in appropriate performance standards to evaluate vessel behavior as an agent based system in various ship encounter situations. It is also noted that the respective navigation rules and regulations may have regulatory failure and violation situations under ship intelligence and decision support facilities, therefore adequate measures to overcome such challenges should be considered.

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