Situation Awareness of Autonomous Ship Navigation in a Mixed Environment Under Advanced Ship Predictor

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SITUATION AWARENESS OF AUTONOMOUS SHIP NAVIGATION IN A MIXED ENVIRONMENT UNDER ADVANCED SHIP PREDICTOR

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ABSTRACT
Autonomous ship navigation in a mixed environment, where remote-controlled, autonomous and manned vessels are interacting, is considered. Since these vessels can have various encounter situations, adequate knowledge on such situations should be acquired to take appropriate navigation actions. That has often been categorized as situation awareness in a mixed environment, where appropriate tools and techniques to extract the respective knowledge on ship encounter situations should be developed. The collision risk assessment procedure has an important role in the same knowledge and that can eventually be used towards the respective collision avoidance actions. Hence, possible ship collision and near-miss situations can be avoided by both humans as well as systems due to their actions. Ship collision avoidance actions are regulated by the International Regulations for Preventing Collisions at Sea 1972 (COLREGs) in open sea areas and additional local navigation rules and regulations can also enforce especially in confined waters and maritime traffic lanes. It is expected that the COLREGs and other navigation rules and regulations will be interpreted by both humans as well as systems in future vessels and those interpretations will be executed as collision avoidance actions by the respective vessels in a mixed environment. Adequate understanding on situation awareness should be achieved to overcome possible regulatory failure due to human and system decisions in these situations. Hence, this study focuses on identifying such challenges in future ship encounters with possible solutions to improve situation awareness in a mixed environment as the main contribution.

INTRODUCTION

Ship Navigation Safety
The accuracy of the collision risk assessment is an important factor in evaluating situation awareness in ship encounter situations [1]. Since collision avoidance actions of ship navigators completely depend on the risk of possible collisions or near-miss situations (i.e. within a considerable confidence interval), that can play an important role in their decision-making processes. However, the decision-making processes of ocean-going vessels can further be complicated in the future due to encounter situations of remote-controlled, autonomous and manned ships. These have often been categorized as ship encounters in a mixed environment. Appropriate tools and techniques to extract the respective knowledge on ship encounter situations in a mixed environment should be developed, such that possible ship collision and near-miss situations can be avoided. This approach should consist of adequate measures to evaluate situation awareness including the collision risk in vessel encounters to improve the respective navigation safety. Hence, this study investigates such challenges in future ship encounters along with the tools and techniques that can improve situation awareness in a mixed environment as the main contribution.

COLREGs & Collision Risk
Ship encounters that relate to possible near-miss and collision situations are regulated by the International Regulations for Preventing Collisions at Sea 1972 (COLREGs) [2] in open sea areas. Furthermore, additional local navigation rules and regulations can be enforced in ship navigation, especially in confined waters and maritime traffic lanes. The COLREGs classify the respective vessels in a close encounter situation, i.e. as stand-on and give-way vessels, where the stand-on vessel should hold its course and speed, with the highest priority for navigation and the give-way vessel (i.e. with the less priority for navigation) required to keep out of the way of the stand-on vessel. One should note that in any ship encounter situation, if there is no collision risk, then the vessels should continue their course and speed conditions, irrespective of the crossing

direction accordance with the COLREGs. That can be further illustrated as: if there are no collision risk, then there will not be any give-way or stand-on vessels in ship encounter situations; therefore none of the vessels should change their course and speed conditions and/or the respective navigation trajectories. This is also an important concept to consider, since the change of course and speed conditions in one vessel can cause a possible collision or near-miss situation and such actions can confuse other vessels that are following the COLREGs rules and regulations. On the other hand, if the collision risk can be detected relatively far away from a ship encounter situation, then both vessels can take appropriate actions, irrespective of the COLREGs rules and regulations. That can be done by a slight change of vessel course and/or speed to reduce the respective collision risk and that eliminates the possibility of any close ship encounter situations. Even though this is an important and simple research concept to consider, i.e. the early detection and elimination of close ship encounter situations with a slight change of course or speed, it has been ignored by a majority of collision avoidance algorithms and studies.

One should note that it is extremely difficult to create a vessel collision situation in realistic ocean-going conditions, i.e. due to the same reason of a slight change of course or speed actions can completely eliminate the respective collision or near-miss situation. Such course and speed changes can occur not only due to navigator’s actions, but also to external environmental conditions, i.e. wind and wave conditions. In general, ship encounter situations can be quantified by the respective collision risk. To quantify a ship encounter situation as a possible collision or near-miss situation, the respective collision risk level should hold continuously. In general, increasing or decreasing collision risk conditions can eliminate possible collision or near-miss situations. Therefore, this situation can also be an extreme or optimal situation, i.e. to hold a continuous collision risk level, due to the same reason of a slight change of course or speed actions can eliminate the respective collision risk, completely. Vessels can often be influenced by various environmental factors i.e. wind and wave, etc., therefore constant collision risk levels may not be possible to occur as mentioned before. The collisions and near-misses in ship navigation can be infrequent situations due to the same reasons and a slight change of course and speed changes can be used to avoid such situations.

Comprehensive course and speed control actions, i.e. such as path planning type approaches, may therefore not be required to avoid collision or near-miss situations. On the other hand, such approaches may also violate the COLREGs. That can be taken as an important concept to consider for the respective collision avoidance approaches in ship encounter situations. If the vessels have taken appropriate collision avoidance actions when they are in a possible collision or near-miss situation, that can mitigate the respective collision risk. Since the collision risk has been eliminated from the ship encounter situation, then the vessels should keep their course and speed unchanged to eliminate any possible future collision or near-miss situations.

On the other hand, any course and speed changes can lead towards another collision or near-miss situation and that can also be a violation of the COLREGs. Furthermore, if the vessels are in a close encounter situation without the collision risk or eliminated collision risk, then both vessels should continue their course and speed conditions in accordance with the COLREGs. Any course and speed change actions can be violations of the COLREGs resulting in a possible collision and near-miss situation. Therefore, the navigator actions in a close ship encounter situation without an adequate collision risk assessment procedure can result in possible collisions or near-miss situations. However, this simple concept, i.e. an appropriate collision risk assessment procedure to support collision avoidance actions, has also been ignored by many research studies, where rather complex algorithms based on sophisticated optimality conditions are proposed. It is a possibility that such optimization algorithms can often violate the COLREGs. On the other hand, those approaches can be neither realistic nor computationally effective enough to be implemented on-board vessels.

When onboard systems are making a considerable amount of navigation decisions in future vessels, i.e. autonomous vessels, those algorithms can further complicate ship encounters in a mixture environment. On the other hand, non-collision risk situations can be transformed into possible collision or near-miss situations due to the same reasons. As a possible solution, the collision risk among vessels should be monitored continuously for both long-range and close ship encounters as a part of situation awareness in future ships. Therefore, this study considers developing tools and techniques, a so called solution framework, to detect and monitor the respective collision risk among vessels in long-range (i.e. global scale) and close (i.e. local scale) ship encounters. Furthermore, the applicability and evaluation procedures of such a solution framework in future ship navigation in a mixed environment are also further discussed.

Ship Under-Actuation

It is well known that ocean-going ships are under-actuated systems, because these vessels may not have the full controllability of their motions. Ship under-actuation can further complicate close encounter situations due to unexpected motions, especially under rough weather conditions. Hence, a navigator should always be on the bridge to evaluate/re-evaluate the collision risk with respect to ship behavior, i.e. resulted due his course and speed control actions. Ship under-actuation can also complicate the navigator`s decision-making process in such situations, where adequate understating of situation awareness may not be able to achieve. While systems are making navigation decisions in future vessels, situation awareness should be a part of their system intelligence to overcome the same challenges. The voyage in a future ship, i.e. an

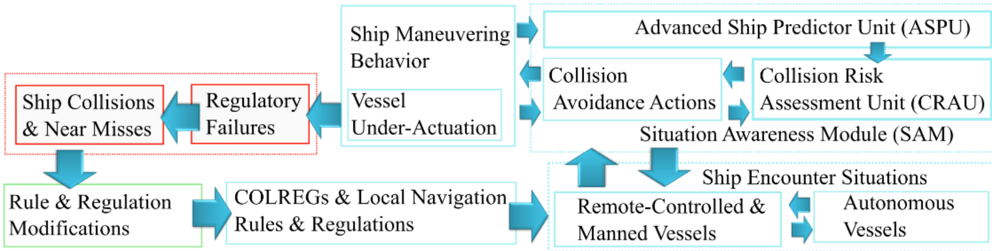

Fig. 1. Ship encounter situation under the solution framework.

autonomous ship, may consist of both manned (i.e. remote controlled) and unmanned voyage legs. When onboard systems (i.e. unmanned voyage legs) are making navigation decisions in autonomous vessels, ship under-actuation can further complicate not only those system decisions but also their interactions (i.e. the outcomes) with the decisions made by manned vessels (i.e. human decisions). Since ship under-actuation that can result unexpected and undesirable vessel motions in such encounter situations, adequate measures to understand and quantify the situation awareness should be considered.

Since future vessels will have both autonomous and remote-controlled capabilities, ship under-actuation should also be further investigated under not only from the system perspective but also from the regulatory perspective. One should note that the complete controllability of ocean-going ships is something impossible to achieve, therefore adequate tools and techniques to predict such unexpected and undesirable motions, i.e. due to ship under-actuation, can help future vessels to prepare for such situations. The same will further improve the safety in ship navigation as a part of situation awareness. It is also believed that the proposed solution framework, i.e. to detect and monitor the respective collision risk among vessels in local and global scales, can provide an elegant solution to ship under-actuation by predicting such unexpected and undesirable ship motions. Hence, both humans and systems can take appropriate navigation decisions to cope with such motions, where the safety levels of the respective ship encounter situations can be further improved.

Research Challenges

Even though these issues can be crucial to improve situation awareness in ship encounters, they have been overlooked by the research community, as mentioned before. Hence, this study incorporates such issues into situation awareness (i.e. including the collision risk assessment process) of ship encounters in a mixed environment under the proposed solution framework. In addition, how to integrate the complexities in ship behavior, i.e. ship seakeeping and maneuvering, into the collision risk assessment procedures have also been considered under the proposed advanced ship predictor. The outcome of the proposed framework can improve ship collision avoidance actions that can be taken by humans as well as systems during vessel encounter situations. Furthermore, the same outcome can also be used to identify possible regulatory failures in ship navigation, where appropriate regulatory modifications under the same framework can be proposed. This can improve the COLREGs and other local navigation rules and regulations, when applied towards manned, remote-controlled and autonomous vessels. Furthermore, the same solution framework can contribute to knowledge creation and competence development in the research area of the safety and risk assessment in mixed environmental operations, where manned, remote-controlled, and autonomous vessel encounters can occur.

THE SOLUTION FRAMEWORK

Advanced Ship Predictor

The proposed solution framework to address the respective research challenges is presented in Figure 1 with the special focus on close ship encounter situations in a mixed environment. This framework is developed under the research project of UiT Autonomous Ship Program. That starts with analyzing the COLREGs and local navigation rules and regulations and understanding their contributions to avoid ship collisions. Ship encounter situations in open sea areas and high traffic shipping lanes can be a part of such a framework in relation to the regulatory analysis of the COLREGs and local navigational rules and regulations. The outcome of such a regulatory analysis can be used towards the proposed situation awareness module (SAM). The two main components of the SAM considered (see Figure 2): the collision risk assessment unit (CRAU) and advanced ship predictor unit (ASPU).

Advanced Ship Predictor

The ASPU is proposed as a solution to ship under-actuation, where the positions and orientations ahead of time in multiple vessels can be estimated. These vessel position and orientation estimations can be done by collecting onboard sensors in a local scale and AIS data in a global and then fusing this information by considering appropriate ship maneuvering models [3] with estimation algorithms [4]. Since future vessels will be facilitated by various sensors, this approach can be seen as a method of harvesting ship seakeeping and maneuvering information from the respective data sets and that will also be a part of situation awareness in ship navigation. One should note that that unexpected vessel behavior due to ship under-actuation can be captured by the ASPU by predicting possible future vessel positions and orientations with adequate confidence intervals. When future vessel positions and orientations can be predicted for a ship encounter situation, the same information can be used to predict possible ship collision and near-miss situations under the CRAU. Therefore, the outcome of the ASPU can facilitate the CRAU to enhance its risk estimation capabilities under the proposed solution framework.

The CRAU consists of detecting a collision or near-miss situation for a two vessel encounter and these two vessel encounter situations can be extrapolated towards a multi-vessel encounter situation. In general, one vessel's relative navigation trajectory with respective to another vessel can be considered to determine the respective collision risk. That can also be identified as the predicted relative trajectory of one vessel with the respective other vessel. The violation of the ship domain of one vessel with respect to another vessel's relative navigation trajectory can be categorized as a possible collision or near-miss situation. That violation can be quantified to estimate the respective collision risk in the ship encounter situation. Such an approach has been implemented by the previous studies and that concept has been adopted towards this solution framework. Furthermore, the collision risk between two vessels should be evaluated with respect to not only the time but also the distance until a possible collision or near-miss situation [5]. The combination of the time and distance until possible collision or near-miss situation can further improve the existing collision risk assessment procedures.

The respective collision avoidance actions in remote-controlled, autonomous, and manned vessels can be supported by the outcome of the CRAU, where adequate information on future ship behaviour should be communicated (i.e. by the ASPU). One should note that the information coming from the CRAU should be shared among the vessels in the respective encounter situation, i.e. by integrated bridge systems. Therefore, the same information should be obtained by the following three navigation groups to improve situation awareness: on-board humans in manned vessels, shore-based humans in remote-controlled vessels and on-board systems in autonomous vessels. Each group can have their own perspectives on the ship encounter situation, even though they are receiving the same information. However, the decision/action differences among remote-controlled, autonomous, and manned vessels for each collision situation in a mixed environment are yet to be investigated in the future. The combination of the ASPU and CRAU, with the respective collision avoidance actions, completes the SAM. This can be a standard framework to overcome the respective challenges in situation awareness of close ship encounter situations in a mixed environment consisting an appropriate collision risk assessment procedure, i.e. based on advanced ship predictor, under the COLREGs and local navigation rules and regulations.

Experimental Evaluations

This framework, i.e. the SAM, should be evaluated with various ship encounter situations of remote-controlled, autonomous and manned vessels [6] under both bridge simulator conditions and realistic ocean-going conditions. However, adequate research infrastructure, including bridge simulators, ocean going vessels and human resources are required to evaluate such a solution framework. Modern bridge simulators are facilitated with adequate features to simulate and study various ship encounter situations and that can be an appropriate and less expensive platform to achieve the expected outcomes. It is expected that future ship navigation will also be done by shore-based control centers, therefore the usage of bridge simulators can create an initial step towards such an approach. That can also satisfy future training requirements, where the required shore-based navigators, i.e. in remote-control centers, for autonomous ships should be trained. Furthermore, various ship types and environmental conditions can be introduced in this environment and the vessels can be controlled by both remote-controlled and on-board modes under the supervision of experienced ship navigators.

An example of such an experiment is described in this section (see Figure 2 for the SAM in a bridge simulator). Bridge simulators may have the facilities to create multi-vessel encounter situations with several simulated vessels. E.g. Vessel A, B, C and D, etc.. Each vessel can have its own navigation and control unit/station. Ship navigators should be placed in these in these navigation and control units to create remote-controlled and manned vessel navigation situations. The behaviour of an autonomous ship in the same vessel encounter situation can be created by a system that consists of the Parallel Decision-making Module (PDMM) and Sequential Action Formulation Module (SAFM). The PDMM module creates appropriate collision avoidance decisions, i.e. course and speed changes, by considering the collision risk estimated from the CRAU and the COLREGs and local navigation rules and regulations. The SAFM arranges those collision avoidance decisions into appropriate actions in a sequential format that can be implemented in ship rudder and propeller control systems with respect to an appropriate timeline. These modules that have been developed and experimented in simulations and limited model scale vessel experiments [7] should complement to each other as a decision–action execution model to facilitate intelligent collision avoidance features into autonomous vessels, while respecting the COLREGs and local navigation rules and regulations.

One should note that various computational intelligence approaches have also been used to transform the COLREGs and local navigation rules and regulations into system readable formats. The proposed modules are one approach that have been implemented before, therefore the same can be implemented as a decision–action execution model for autonomous ship navigation. Furthermore, additional computational intelligence approaches to improve such a decision–action execution model should be investigated. These approaches should support ‘if-then-else’ type conditions, since the COLREGs and local navigation rules and regulations are often following a similar logic. The decision–action execution model (i.e. PDMM and SAFM) should be connected to the bridge simulator during these experiment evaluations to imitate a digital helmsman in autonomous ship navigation.

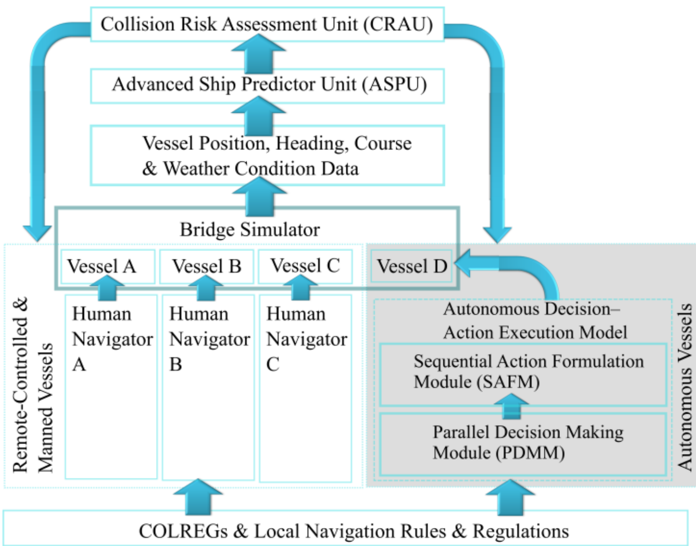

Fig. 2. The proposed situation awareness module (SAM) in a bridge simulator.

It is expected that the outcome of bridge simulator experiments can consist of various ship collision and near-miss situations, where possible regulatory failures can occur. The regulatory failures that can be observed under the experimental results should be further be investigated and the outcome can be used to introduce required regulatory modification into the COLREGs and other local navigation rules and regulations. Furthermore, the same outcome can also be used to improve the SAM by considering the respective lessons learned during these experiments.

Ship Encounter Situations

The evaluation of the same framework under vessel encounters in realistic ocean-going conditions can be an extremely difficult task due to the complexities in ship navigation. Such complexities of a two-vessel encounter situation are discussed in this section and that may give one an overview of the respective issues that should be investigated in the future. A two-vessel close encounter situation is presented in Figure 3 with the positions of P_a $(x_a(t), y_a(t))$ and P_b $(x_b(t), y_b(t))$ for vessel A and B, respectively. The course-speed vectors of both vessels denoted by $V_a(t)$ and $V_b(t)$ and the heading vectors, i.e. surge velocity vectors, are denoted by $u_a(t)$ and $u_b(t)$. An imaginary position P_{ab} is also denoted in the same figure to represent a possible collision or near-miss situation. As discussed before, ocean-going vessels are considered as under-actuated systems with respect to their ship seakeeping and manoeuvring behaviour. Therefore, such vessels may not have complete controllability in the sway direction, i.e. denoted by $v_a(t)$ and $v_b(t)$, with propeller-rudder control systems (i.e. resulting in ship under-actuation behaviour). The ship course-speed and heading vectors can have two separate directions due to the same reason and that can complicate the controllability of these vessels due to undesirable and unexpected vessel motions.

The external forces, i.e. hydrodynamic and wind forces and moments, influence on the sway direction of vessels, can complicate seakeeping and manoeuvring behaviour [8]. Even though rudder and thruster systems are installed in these vessels to overcome such under-actuation behaviour, i.e. by providing enough force against the sway direction, those systems may not produce adequate thrust to control vessels when ship speeds are over 3-4 knots. In general, a majority of ship navigation situations are beyond this speed range. These sway velocity component effects are neglected by a majority of research studies, i.e. by assuming fully actuated vessels. Therefore, that may not represent realistic ship navigation situations. Furthermore, the solution provided by such studies may not be applicable for ship navigation situations with vessel under-actuation. Hence, ship encounter situations can have such complex navigational challenges with compared to other transport systems and that have not been addressed by the research community [9], adequately.

The same under-actuation behaviour can complicate the encounter situations, especially with remote-controlled, autonomous and manned vessels. Since ship on-board systems in the future will make a considerable amount of navigation decisions, i.e. based on machine learning and artificial intelligence, ship under-actuated behaviour can introduce additional challenges. Furthermore, the interactions between system and human decisions in the same environment can further complicate ship encounter situations. On the other hand, the human and machine perceptions on the same collision avoidance rules and regulations can vary, therefore the collision avoidance actions can be different. However, that difference can also increase the risk of ship collisions considerably and result in ship collisions and near-misses including possible regulatory failures. Such challenges in ship encounter situations in a mixed environment have not been studied in realistic ocean-going conditions previously. Therefore, this study proposes to investigate such fundamental requirements and develop a realistic collision risk assessment procedure in vessel navigation, e.g. including ship under-actuation behaviour, as a part of situation awareness.

ADVANCED SHIP PREDICTOR

Ship Prediction

Predicting ship behaviour [10], accurately ahead of time in a close ship encounter situation, can support the decision maker, i.e. human or system, to take appropriate collision avoidance

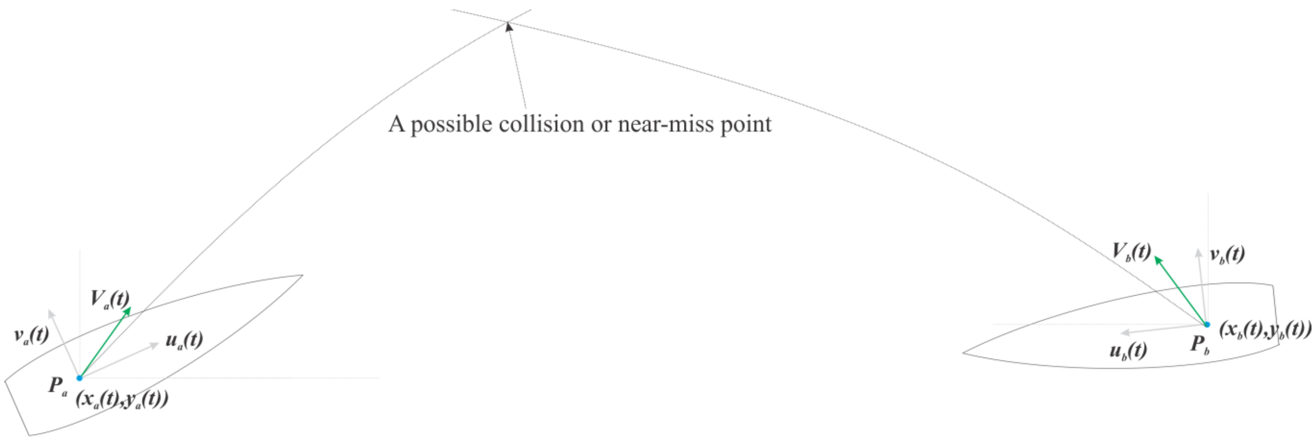

Fig. 3. Ship encounter situation.

actions, and can also be a solution to ship under-actuation behaviour. Therefore, unexpected ship motions due to vessel under-actuation can be observed as the collision risk and adequate actions by both humans and systems can be taken to prevent possible collision and near-miss situations. The collision risk assessment procedure [11] should be facilitated by an advanced ship predictor methodology, i.e. the ASPU, that estimates the future positions and orientations of the vessels in the respective encounter situations. Therefore, the ASPU can be an integrated part of the collision risk assessment procedure to support situation awareness.

The on-board sensors in ships can collect the information on vessel translational and rotational motions. Furthermore, AIS (i.e. Automatic identification system) data [12] of ocean-going vessels can be used to collect the information on ship navigation behaviour. Therefore, this study proposes an advanced ship predictor methodology, i.e. the ASPU, that uses on-board sensor and AIS data to extract the required information and predict future ship behaviour. Such ship behaviour prediction can be done in two scales: local scale and global scale. These two scales in predicting ship behaviour are further elaborated in the following sections.

Local Scale

Various kinematic, dynamic or combined models (both kinematics and dynamics) have been considered for ship manoeuvring. However, the dynamic models in ship manoeuvring can introduce additional challenges, while they are implementing under state and parameter estimation algorithms. This is due to the respective nonlinear hydrodynamic forces and moments that can be a part of such dynamic models and that those forces and moments cannot be measured by on-board sensors. Various unobservable states and parameters can be a part of such dynamic models in ship manoeuvring. Therefore, the estimation algorithms may not able to capture the respective system model due a large number of unobservable states and parameters. On the other hand, the accuracy and the system-model uncertainties of such models are yet to be discovered. The eventual outcome is the divergence in the parameter estimation process and the errors in the estimated vessel states and parameters. Therefore, the prediction accuracy of ship manoeuvres can be degraded.

A kinematic model-based ship manoeuvring prediction algorithm is considered in this section. The modelling difficulties in ship manoeuvring, i.e. complex vessel dynamic conditions, can be avoided by this method. Similarly, unobservable vessel states and parameters, i.e. forces and moments, can also be avoided by this method and that can be the main advantage in this approach. The hydrodynamic forces and moments can be observed as vessel accelerations as an important part of a kinematic model in ship manoeuvring. One should also note that the vessel accelerations can be measured accurately and that can improve the state and parameter estimation process.

The ship on-board sensor data with a kinematic vessel manoeuvring model and pivot point motion information has been used to estimate the future vessel position and orientation (i.e. heading) within a shorter time period. This approach has been investigated in [10], where its capabilities are presented in a simulated environment. This consists of a simplified mathematical framework that is presented in Figure 4. The current vessel position is presented by P_g $(x_g(t), y_g(t))$ with the course speed vector of $V_g(t)$ and the heading angle of $\psi_g(t)$. In addition, the future vessel position is presented by P_f $(x_f(t), y_f(t))$ with the course speed vector of $V_f(t)$ and the heading angle of $\psi_f(t)$. One should note that the pivot points of the current and future vessel pivot positions are denoted by P_{gp} and P_{fg}, respectively. It has been shown that the current vessel position and orientation (i.e. heading), measured by on-board sensor measurements with an appropriate mathematical algorithm, can be used to estimate the future vessel position and orientation [10]. The algorithm is briefly discussed in this section and consists of two sections.

The first part of this algorithm consists of estimating the current vessel states and parameters by considering a kinematic vessel manoeuvring model. This state and parameter estimation process is supported by an extended Kalman filter

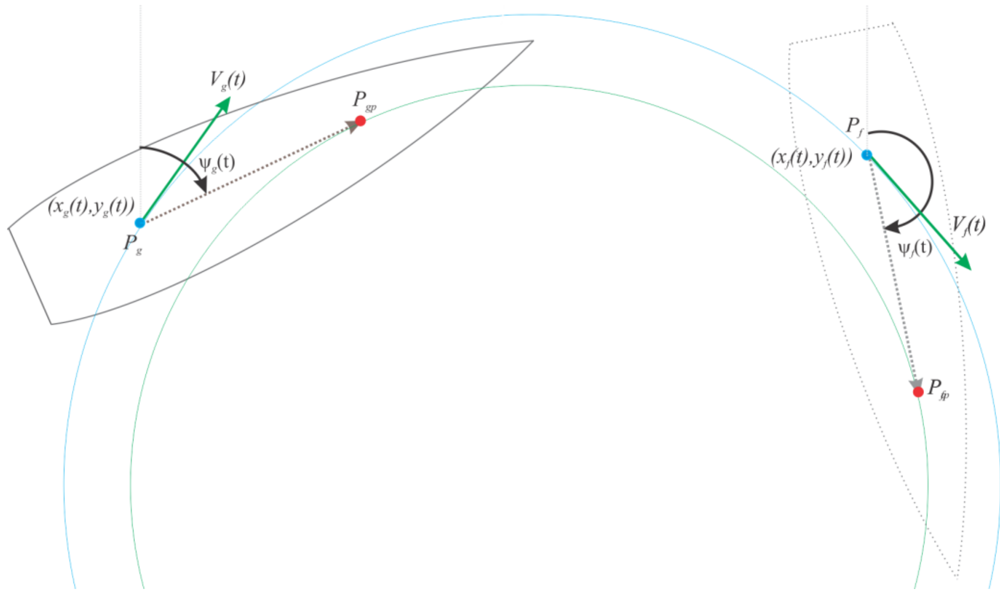

Fig. 4. Ship predictor in local scale.

(EKF) with the sensor measurements of vessel position, heading, yaw rate and acceleration values. The second part of this algorithm consists of estimating the future vessel states and parameters by considering the current vessel states and parameters. This state and parameter estimation process is supported by a navigation vector dot and cross product approach that consists of the pivot point information. Therefore, the outcome of this algorithm is the future vessel position and orientation (i.e. heading) within a short time interval. It is expected that the respective weather and environmental conditions can be observed as a part of ship motions under the on-board sensors, i.e. wind and wave conditions.

While vessels are making circular type manoeuvres, that can be associated with constant state and parameter values, i.e. Rate of Turn (ROT), etc. as presented in Figure 4. However, the prefect circle type manoeuvres cannot be possible in some situations, due to external environmental conditions that can influence on vessel states and parameters. Therefore, the circular type ship manoeuvres can be resulted in parabolic shapes due to external forces and moments. One should note such external forces and moments are resulted due to weather and environmental conditions and that can be slow varying processes. Hence, the constant ROT values can be changed due to external forces and moments in ship manoeuvring. Such variations should be captured by the estimation algorithms to predict vessel behaviour. This is where the EKF algorithm with the proposed kinematic mathematical model for vessel manoeuvres can play an important role by capturing such slight variations in vessel states and parameters. That can improve the predictability of ship manoeuvring, i.e. future vessel positions and orientations. Since weather and environmental conditions can be captured by the kinematic ship manoeuvring model and estimation algorithm, this can be considered as another advantage in this method. The respective computational results for ship predictor in local scale is presented in Figure 5. That consists of the current and future vessel positions and orientations, predicted vessel pivot point trajectory and predicted vessel trajectory. The respective data set is simulated to verify the capabilities of the proposed approach as a part of the advanced ship predictor in a local scale.

Global Scale

Ship behaviour can also be predicted on a global scale. This entails predicting the future vessel position and orientation (i.e. heading) within a longer time period. Based on the predicted vessel behaviour, the ships in the respective encounter situation can make necessary collision avoidance actions far in advance. Simple speed or course alterations will likely be sufficient at this point to avoid a close-encounter situation from occurring at all, significantly reducing the risk associated with ship operations. That can be the main advantage of having a ship predictor in a global scale.

In general, such global behaviour predictions are however difficult to conduct, as the future intentions of the vessels are unknown in a majority of the encounter situations. Historical AIS data however provide insight into ship behaviour for specific regions. By exploiting these data sets in an intelligent manner, one can estimate the future behaviour of a selected vessel based on its own trajectory and past trajectories of other vessels in the same region on a global scale. [11] presents a thorough survey of methods to exploit AIS data for ship navigation under such situations. The majority of the work utilizing AIS data has focused on general traffic trends, anomaly detection and long-term predictions [12-14]. Such information can be very useful for general situation awareness, but limited with respect to collision avoidance [15, 16]. Hence,

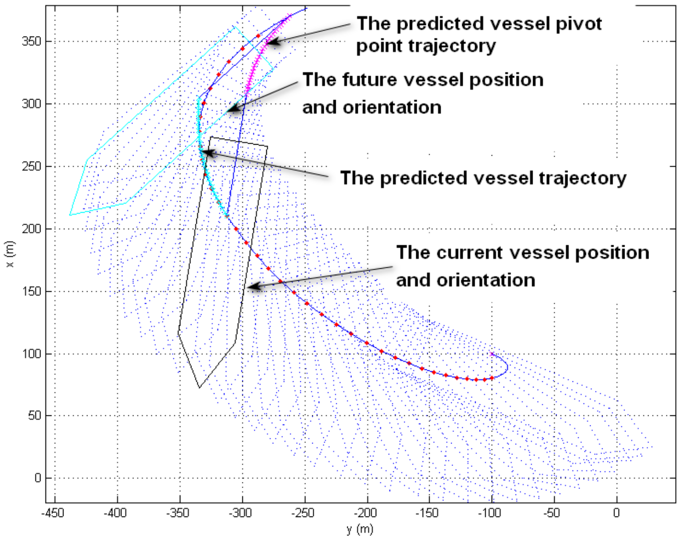

Fig. 5. The current and predicted vessel positions and orientations with the ship predictor in a local scale

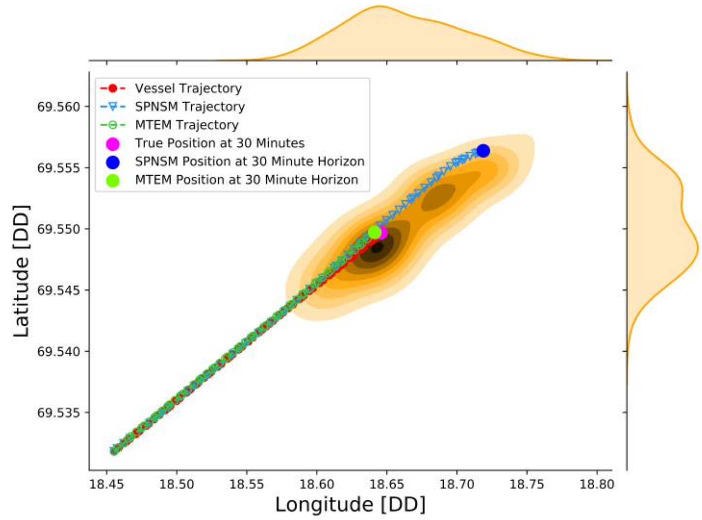

Fig. 6. The current and predicted vessel positions with the ship predictor in a global scale

short-term vessel trajectory prediction techniques than can be useful in terms of collision avoidance in such situations.

[17] builds upon the single point neighbour search method (SPNSM) in [15] and introduces an improved multiple trajectory extraction method (MTEM). In this method, respective trajectories are extracted from a circular initial cluster centered around the position of a selected vessel. The trajectories with speed and heading values outside of a selected threshold in the initial trajectory cluster are discarded in this approach. This results in the extraction of trajectories with a high degree of similarity to that of the selected vessel. The clustering based iterative prediction technique [15] is then run on the extracted trajectories for a given prediction horizon as the next step. The resultant predicted vessel trajectory can provide a higher degree of situation awareness of the ship encounter situation in a global scale, as it can now have an indication of the future intentions of the respective vessels. The multiple extracted trajectories can also give an indication of the spread of data for a given prediction horizon, where the respective positions after a period of time corresponding the desired prediction horizon can be described by a probability density distribution. That represents the probability that the selected vessel can be located after the selected period of time. An example of predicting vessel positions using the MTEM is visualized in Figure 6. A 30 minute trajectory prediction using the SPNSM is compared with the MTEM indicating improved performance for the MTEM in this figure. The orange contours represent a kernel density estimate of the extracted trajectory data after 30 minutes using Gaussian kernels.

Implementation Steps

As described previously, the advanced ship predictor can be used to estimate the future vessel position with a short (i.e. in a local scale) and long (i.e. in a global scale) time horizons. Therefore, this can be a good supporting tool to estimate the respective collision risk under various ship encounter situations. This includes remote-controlled, autonomous, and manned ship encounters, where human and system decision-making situations can be encountered. The COLREGs and local navigation rules and regulatory failures due to ship under-actuation and human-system decision-making are expected as the outcome of such situations. This should further be investigated under both bridge simulator and realistic ocean-going conditions of vessel encounters to support situation awareness. The required modifications into the COLREGs and local navigation rules and regulations [18] due to the respective regulatory failures should also be investigated and that can further enhance the required safety levels of future vessels.

The proposed advanced ship predictor, i.e. the ASPU, is a part of the solution framework that has proposed to overcome the respective challenges in situation awareness of ship encounter situations of remote-controlled, autonomous, and manned vessels, i.e. by introducing an appropriate collision risk assessment procedure based on the advanced ship predictor. Therefore, that should also be a part of the collision risk assessment procedure. The ASPU can be evaluated under bridge simulator conditions with various ship encounters [19], initially and then onboard vessels under realistic ocean-going conditions. Development and demonstration of the advanced ship predictor to support situation awareness in ship navigation and overcome the respective collision avoidance challenges in a mixed environment can be the main contribution of this study. That also introducs an appropriate collision risk assessment methodology, while respecting the COLREGs and local navigation rules and regulations and investigating additionally required rule and regulation modifications.

System Perspective

The collision risk assessment methodology can also play an important role in this proposed solution framework. The collision risk assessment methods proposed by the research community [20-24] should be further investigated and appropriate techniques should be extracted towards the proposed CRAU (see Figure 1 and 2). However, that should accommodate both time and distance-based risk assessment techniques to further improve the existing procedures, as mentioned before. The CRAU with such methods can further enhance the ASPU, i.e. the advanced ship predictor. It is expected that vessel behaviour not only due to ship under-actuation but also to navigator's actions can also be reflected on the ASPU, i.e. supported by both on-board sensor and AIS data. The CRAU can initially be developed for a two-vessel encounter situation and then that can be extrapolated for a multi-vessel encounter situation. Furthermore, that should initially be evaluated under computer simulations, then that can be deployed towards bridge simulators in a later stage and finally in realistic ocean-going conditions [25].

The SAM should be developed as a software module. The facilities of the SAM can be further enhanced by introducing adequate decision supporting features. The SAM can be used as a decision supporting tool for remote-controlled and manned vessels. It is expected that an advanced version of the SAM should be developed with the PDMM and SAFM and implemented as a system decision–action execution model for autonomous vessels. Furthermore, the COLREGs and other local navigation rules and regulations can also be incorporated into these modules to enhance its facilities towards decision-making in autonomous ship navigation, as mentioned before. Therefore, two versions of the SAM should be considered. The first version should support manned and remote-controlled vessels as a decision support unit and the second version (advanced version) should support autonomous vessels as a decision-making unit.

The SAM can be developed in bridge simulators to evaluate its performance under remote-controlled, autonomous, and manned ship encounter situations, as described previously (see Figure 2). One version of the SAM is implemented as a decision support system for remote-controlled and manned vessels and another version (advanced version) is implemented as a decision-making system for an autonomous vessel. A considerable amount of complex ship encounters can be created in this environment to evaluate the performance of the SAM. It is also expected that the outcome of bridge simulator experiments can consist of various collision and near-miss situations, where possible regulatory failures can occur. Hence, the respective regulatory failure situations and lessons learned with possible reasons should be documented during these experiments to further enhance the SAM.

The SAM can also be developed in integrated bridge systems in ocean going vessels to evaluate its performance in a mixed environment as described previously. Similarly, both versions of the SAM can be implemented as a decision support system for remote-controlled and manned vessels and as a decision-making system for autonomous vessels, respectively. A considerable amount of complex ship encounters can occur in this environment, while evaluating the performance of the SAM. It is also expected that the outcome of realistic ocean-going vessel experiments can consist of various near-miss situations (i.e. collision should be avoided at any cost), where possible regulatory failures can occur. Hence, the respective regulatory failure situations and lessons learned with possible reasons should be documented during these experiments to further enhance the SAM.

The respective regulatory failures observed in these experimental conditions should further be studied. The outcome can be used to improve the SAM and the improved SAM can be used in experimental environments with additional experiments to re-evaluate the outcome. Especially, the decision–action execution model (i.e. PDMM and SAFM) that has been adopted for autonomous ship navigation can also be re-evaluated, and appropriate modifications should be introduced during these experiments. On the other hand, the same outcomes, i.e. regulatory failures, can be considered to re-evaluate the COLREGs and other local navigation rules and regulations in both human and system perspectives. The required regulatory modifications can also be investigated under the guidance of the respective authorities.

CONCLUSIONS

This study considers a solution framework to support situation awareness in a mixed environment, where remote-controlled, autonomous and manned vessels are interacting. This consists of an advanced ship predictor as a part of the collision risk assessment methodology to identify unexpected vessel behavior due to ship under-actuation, i.e. influenced by navigators' actions and environmental conditions. The advanced ship predictor consists of both local and global capabilities to estimate vessel positions and orientations. Hence, situation awareness in ship navigation with decision support (i.e. in manned vessels) and decision making (i.e. in autonomous vessels) facilities [26, 27] can be improved. However, this should be evaluated under both bridge simulator and realistic ocean-going conditions, where its capabilities in avoiding collision and near-miss situations in remote-controlled, autonomous and manned ship encounters can be experimented with. The knowledge that can be created under such experiments can enhance the situation awareness in a mixed environment. The identification of the regulatory failures in such ship encounter situations is also an important part of the same knowledge, where possible modifications on the COLREGs and local navigation rule and regulations can be proposed. Finally, the documentation of the knowledge that can be used to improve situation awareness with decision support and decision making features, i.e. including the modified

COLREGs and local navigation rule and regulations, in future ship encounters in a mixed environment is the ultimate objective of this study.

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REFERENCES

[1] L.P. Perera, "Autonomous Ship Navigation under Deep Learning and the challenges in COLREGs," In Proceedings of the 37th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2018), Madrid, Spain, June, 2018 (OMAE2018-77672).

[2] IMO, "Convention on the International Regulations for Preventing Collisions at Sea (COLREGs)," 1972.

[3] L.P. Perera, P. Oliveira and C. Guedes Soares, "System Identification of Vessel Steering with Unstructured Uncertainties by Persistent Excitation Maneuvers," IEEE Journal of Oceanic Engineering, vol. 41, no. 3, 2016, pp. 515-528.

[4] Kalman, R. E. (1960). "A New Approach to Linear Filtering and Prediction Problems". Journal of Basic Engineering. 82: 35.

[5] W. Xiaoyang, W. Yang, and Y. Xinping. Processes in Research Methods for Modeling Accidents, China Safety Science Journal, Vol. 26 No. 3, pp. 46-52.

[6] L.P. Perera, J.P. Carvalho and C. Guedes Soares, "Intelligent ocean navigation & Fuzzy-Bayesian decision-action formulation," IEEE Journal of Oceanic Engineering, vol 37, no 2, 2012, pp 204-219.

[7] L.P. Perera, V. Ferrari, F.P. Santos, M.A. Hinostroza, and C. Guedes Soares, "Experimental Evaluations on Ship Autonomous Navigation & Collision Avoidance by Intelligent Guidance," IEEE Journal of Oceanic Engineering, vol. 40, no. 2, 2015, pp 374-387.

[8] T. A. Johansen, T. Perez and A. Cristofaro, "Ship Collision Avoidance and COLREGS Compliance Using Simulation-Based Control Behavior Selection with Predictive Hazard Assessment," in IEEE Transactions on Intelligent Transportation Systems, vol. 17, no. 12, pp. 3407-3422, Dec. 2016.

[9] L.P. Perera, J.P. Carvalho and C. Guedes Soares, "Solutions to the Failures and Limitations of Mamdani Fuzzy Inference in Ship Navigation," IEEE Transactions on Vehicular Technology, vol. 63, no. 4, 2014, pp 1539-1554.

[10] L.P. Perera, "Navigation Vector based Ship Manoeuvring Prediction," Journal of Ocean Engineering, vol. 138, 2017, pp. 151-160.

[11] E. Tu, G. Zhang, L. Rachmawati, E. Rajabally, and G.-B. Huang, "Exploiting AIS Data for Intelligent Maritime Navigation: A Comprehensive Survey From Data to Methodology," IEEE Trans. Intell. Transp. Syst., pp. 1–24, 2017.

[12] K. Gunnar Aarsæther and T. Moan, "Estimating Navigation Patterns from AIS," J. Navig., vol. 62, no. 4, p. 587, Oct. 2009.

[13] G. Pallotta, M. Vespe, and K. Bryan, "Vessel Pattern Knowledge Discovery from AIS Data: A Framework for Anomaly Detection and Route Prediction," Entropy, vol. 15, no. 12, pp. 2218–2245, Jun. 2013.

[14] F. Mazzarella, V. F. Arguedas, and M. Vespe, "Knowledge-based vessel position prediction using historical AIS data," in 2015 Sensor Data Fusion: Trends, Solutions, Applications (SDF), 2015, pp. 1–6.

[15] S. Hexeberg, A. L. Flaten, B.-O. H. Eriksen, and E. F. Brekke, "AIS-based vessel trajectory prediction," in 2017 20th International Conference on Information Fusion (Fusion), 2017, pp. 1–8.

[16] B. R. Dalsnes, S. Hexeberg, A. L. Flaten, B.-O. H. Eriksen, and E. F. Brekke, "The Neighbor Course Distribution Method with Gaussian Mixture Models for AIS-Based Vessel Trajectory Prediction," in 2018 21st International Conference on Information Fusion (FUSION), 2018, pp. 580–587.

[17] B. Murray and L.P. Perera, "A Data-Driven Approach to Vessel Trajectory Prediction for Safe Autonomous Ship Operations," In Proceedings of the 13th International Conference on Digital Information Management (ICDIM 2018), Berlin, Germany, September, 2018.

[18] L.P. Perera, and C. Guedes Soares, "Collision Risk Detection and Quantification in Ship Navigation with Integrated Bridge Systems," Journal of Ocean Engineering, vol. 109, 2015, pp. 344-354.

[19] P. Silveira, A. Teixeira, & C. Soares, (2013). Use of AIS Data to Characterise Marine Traffic Patterns and Ship Collision Risk off the Coast of Portugal. Journal of Navigation, 66(6), 879-898.

[20] Y.J. Xie, Q. Meng, Analysis of AIS-based Ship Traffic in the Singapore Strait, Proceedings of the Inaugural World Transport Convention, Beijing, China, June 4-6, 2017.

[21] T. A. Johansen, T. Perez and A. Cristofaro, "Ship Collision Avoidance and COLREGS Compliance Using Simulation-Based Control Behavior Selection With Predictive Hazard Assessment," in IEEE Transactions on Intelligent Transportation Systems, vol. 17, no. 12, pp. 3407-3422, Dec. 2016.

[22] W. Xiaoyang, W. Yang, E. Zio, Y. Xinping. What Kind of Resilience Is Needed for Water Transport-A Lesson Learned from Eastern Star. Safety Science. (Revised)

[23] R. Szlapczynski and J. Szlapczynska, "Review of ship safety domains: Models and applications, "" Ocean Engineering, vol. 145, 2017, pp. 277-289.

[24] R. Szlapczynski and P. Krata, "Determining and visualizing safe motion parameters of a ship navigating in severe weather conditions, " Ocean Engineering, vol. 158, 2018, pp. 263-274.

[25] L.P. Perera, and C. Guedes Soares, "Collision Risk Detection and Quantification in Ship Navigation with Integrated Bridge Systems," Journal of Ocean Engineering, vol. 109, 2015, pp. 344-354.

[26] L.P. Perera and B. Mo "Ship Performance and Navigation Data Compression and Communication under Autoencoder System Architecture," Journal of Ocean Engineering and Science, 2018 (DIO: 10.1016/j.joes.2018.04.002).

[27] L.P. Perera and B. Mo, "Machine Intelligence based Data Handling Framework for Ship Energy Efficiency," IEEE Transactions on Vehicular Technology, vol. 66, no. 10, 2017, pp. 8659-8666.