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Manoeuvring areas to adapt ACAS for the maritime domain

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Abstract

Rapidly increasing numbers of ships and ship sizes pose an ever-growing challenge to the maritime industry. Although statistics indicate improved levels of safety in the industry which carries 90% of the world's trade, the risk of navigational accidents, among other issues, remains a prime concern and priority (EMSA, 2010; 2014). In order to address these concerns, the authors turned to another high-risk industry for inspiration. Specifically, they turned to the aviation industry, which has often been used as a source of comparisons and ideas by researchers in the maritime domain.

Keeping up with the trend, the authors of this paper turn to a tried-and-tested system used widely in modern aviation: the Airborne Collision Avoidance System (ACAS). The prime idea behind ACAS is to construct two virtual 3D zones around an aircraft. These zones are dynamic, and depend on the manoeuvring characteristics of a given aircraft. If the system detects an "intruder" (another aircraft) in either of the two well-defined virtual zones, it provides warnings and/or instructions to pilots of both aircraft to take certain precautionary or emergency measures.

In the current paper, the authors explore whether or not such a system is feasible for use in the maritime domain and, if so, how. The paper provides a detailed analysis of the potential benefits and drawbacks of using an ACAS-like system onboard vessels. It also discusses possible means of implementation and integration with current equipment, and explores how the introduction of e-navigation may impact the proposed solution.

Introduction

Ship navigation consists of a number of essential tasks that must be carried out continuously when sailing from a port of departure to a port of destination. As per International Maritime Organization's (IMO) performance standards for Integrated Navigation Systems (INS) (IMO, 2007), the most essential tasks are as follows:

- Route planning;
- Route monitoring;
- Collision Avoidance;
- Navigation Control Data;
- Status and Data display;
- Alert management.

For each of the aforementioned tasks, standard operating procedures require, among other measures, that dedicated workstations, equipment and displays be used to ensure that the Officer on Watch (OOW), responsible for ship navigation at all times, has a comprehensive situational awareness of the prevailing circumstances regarding the status of his own ship status, the environment, and the traffic situation. Operational risks should be managed so that safety-critical situations and accidents can be avoided.

Safe navigation is an ever-growing challenge, particularly due to the rapidly increasing numbers of ships and ship sizes, as well as a rapidly evolving maritime industry. Although statistics indicate improved levels of safety in the industry, which carries 90% of the world's trade, the risk of navigational accidents remains a prime concern and priority (EMSA, 2010; 2014). In order to address these concerns, the authors of this paper turned to other high-risk industries for inspiration. In particular, they turned to the aviation industry, which has often been used as a source of comparisons and ideas by researchers in the maritime domain (Baldauf et. al., 2011).

Keeping up with the trend of ongoing technological developments, particularly in light of potential such developments as autonomous unmanned ships, the authors of this paper turned to a tried-and-tested system widely used in modern aviation – the Airborne Collision Avoidance System (ACAS). Internal studies carried out by various aviation companies suggest that the introduction of ACAS has reduced the risk of mid-air collisions significantly. According to EUROCONTROL, the latest version of ACAS, ACAS II, has reduced the risk of mid-air collisions by a factor of about 4, or approximately 50% alone (EUROCONTROL, 2014).

In the current paper, the authors explore whether a system similar to ACAS can be adapted for use in the maritime domain and, if so, how. The paper introduces the basic concept of ACAS, and discusses how the principle can be applied onboard ships. The authors present and discuss some promising, albeit preliminary, results from an on-going study of the calculation of probabilities risks of a collision under concrete situations, with the aim of supporting onboard decision making.

Collision avoidance in air traffic

In civil aviation, the support available for collision avoidance differs from the current approaches available in the maritime domain. In particular, in air traffic there are clearly defined, commonly accepted and homogenously used minimal time and space standards separating aircraft at all times. The separation criteria represent quantified risk values to ensure safety and efficiency in the air transport sector. It is generally recognised that this contributes to the high safety level in civil aviation, and has prevented conflicts and collisions.

The functioning of ACAS is based on information provided by a secondary surveillance radar and transponder signals. The prime idea behind ACAS is to construct two virtual 3D zones around an aircraft. These zones, which together form a "protected volume" of airspace around an aircraft, are dynamic, and are referred to as the "Caution Area" and the "Warning Area", respectively.

If the ACAS system detects an 'intruder 'aircraft in either of these two well-defined virtual zones, it provides warnings and/or instructions to pilots of both aircraft to take certain precautionary or emergency measures. If an intruder is detected in the "Caution Area", the ACAS system provides a Traffic Advisory (TA) to indicate a potential threat. If, on the other hand, the system detects an intruder inside the "Warning Area", it provides a Resolution Advisory (RA). It is not necessary for a RA to be announced by a preceding TA.

There are generally two types of RA's. A corrective RA requires the pilot to perform certain manoeuvres and to deviate from the current flight path, whereas a preventive RA, gives a recommendation to the pilot to maintain the current flight path, and *not* to perform certain manoeuvres. RA's generally try to provide a vertical separation of between 300 to 700 ft., whenever the threat of a collision is detected.

Should an RA alert occur, the pilot has to follow clear instructions to climb or to descend, generated by the TCAS and given as a voice alarm. This alert cannot be switched off and the alarm thresholds cannot be changed by the pilot.

The "Caution Area" and the "Warning Area" are dynamic in the sense that their dimensions can vary depending on the altitude, speed and heading of the aircraft involved in an encounter.

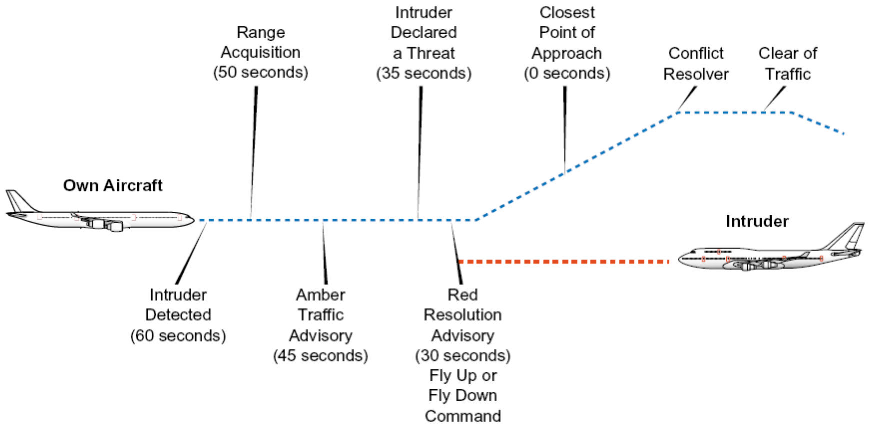

Figure 1. Principle dimensions of ACAS (adapted from EUROCONTROL, 2014)

The vertical limits above and below are between 850 and 1200 ft. for a TA (Caution Area), and between 600 and 800 ft. for an RA (Warning Area) alert. As a general rule, the "dimension" of the "Caution Area" varies from 20 to 48 seconds, whereas the "Warning Area" has a smaller "dimension" of between 15 to 20 seconds – both in the direction of the flight path of the aircraft. This is shown in Figure 1.

In some cases, the time limits for the warning areas are not sufficient or feasible. If this occurs, ACAS relies on Distance Modification (DMOD) defined dimension values of between 0.3 nm and 1.30 nm for TA regions, and 0.2 nm and 1.10 nm for RA regions.

ACAS, to summarise, acts as a "last line of defence system," providing two types of alerts – a "Traffic Advisory" (TA), and a more urgent "Resolution Advisory" (RA). The TA assists the pilot in his visual detection of conflicts, while the RA gives inviolable, clear advice to the pilot on how to manoeuvre to avoid a collision with an intruder. Figure 2 demonstrates the horizontal and vertical alert regions of the ACAS system.

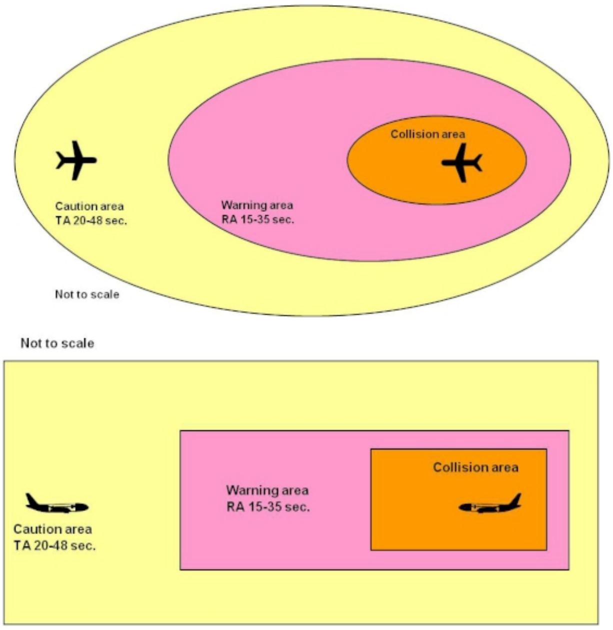

Figure 2. Time/Range regions for ACAS alerts (adapted from EUROCONTROL, 2014)

Enhancing maritime collision avoidance by applying an ACAS-like concept

COLREG – the backbone of collision avoidance in maritime traffic

The maritime equivalent to ACAS, which provides a framework for avoiding collisions on the high seas, is laid down in IMO's 1972 Convention on the International Regulations for Preventing Collisions at Sea (COLREG) (Cockcroft & Lameijer, 2012). However, although COLREG contains a specific rule on "Risk of Collision" (Rule 7), only generic guidance is given as to how such a risk may be determined. Besides a constant compass bearing, no clear parameters or criteria mentioned that should be used to determine the risk of a collision. Numerous comments, scientific studies, and academic articles discuss this situation, suggesting amendments and clarifications for a more harmonised, concrete and detailed procedure on how to determine the collision risk, and when and how to take corrective action.

Contrary to air traffic, the rules and regulations, as well as all mandatory technical systems for collision avoidance in shipping, do not provide any clearly defined safety limits, ranges, or times when a navigator has to take action to avoid a collision. Technical systems to support decision making, especially Radar Automatic Radar Plotting Aid (ARPA) integrated with Automatic Identification System (AIS), provide options to alert the officer of the watch if a dangerous situation in terms of an expected encounter with a passing distance less than a configured limit value is likely to occur in within a time set by the OOW. Although Modern INS usually provide further alerts, most can be completely switched off – a fundamental from ACAS in air traffic.

In maritime traffic the situation is characterised by the use of fuzzy definitions. A vessel shall take action to pass at a safe distance, but no values are given to define such a safe distance. Action shall be taken "in ample time", but no concrete time period is mentioned. Furthermore, no rules or regulations clearly define any separation zone around a ship which is to be kept free of any other vessel (intruder).

However, the COLREGs were found to be good enough as written, and they withstood all attempts of to develop them further. Consequently, in the light of the introduction of so many new technologies into shipping since 1977, when the COLREG was first implemented, one must give credit to this legal framework, which is still functioning even with the application of enhanced and sophisticated tools, such as computer- and simulation-based decision support systems.

Enhancing and applying the concept of "potential area of water" for dynamic risk assessment

A number of concepts and methods have been proposed as options for harmonising and improving maritime collision avoidance in ways similar to those employed in aviation in the past (Benedict et.

al., 1994). One of these methods entailed the concept of the potential area of water (PAW). Göhler (Göhler, 1983), among others, introduced a so-called "expectation area" defined as the area covering all potential positions that a ship could theoretically reach in a certain time period by using the control options of the manoeuvring handles. Inoue (Inoue, 1990) developed a similar approach, and proposed using the PAW as an index for risk assessment in ship handling.

As shown in Figure 3, one take into account the complete range of all manoeuvres on both sides, while the other concepts were looking into probability-related aspects, and were focusing only on one side (the starboard). However, the principle concept is obviously the same, and takes into account all combinations of manoeuvring options of an actual ship. Beside a number of qualitative approaches, there are a number of additional studies dealing with the quantification of the risk of collision using terms similar to the PAW, expectation area, manoeuvring area, and so on.

One of the challenges of the approach is the provision of suitable methods for the provision of the dimensions and expansion of the area by predicting the manoeuvring characteristics of a ship in terms of its hydrodynamic behaviour when responding to a rudder, engine or other manoeuvring controls. This means, on the one hand, that calculations of satisfactory accuracy are required to meet a minimum level of reliability. On the other hand, it means that, especially for real-time-support, the availability of reliable measurement data is a compelling need.

Assuming the aforementioned prerequisites are fulfilled, the authors suggest quantifying the risk of collision by estimating the level of overlap of both ships' manoeuvring areas for a given time period as an expression of the probability of a potentially hazardous contact between the two ships (see Figure 4, top).

$$P_{\text{Collision}} = \frac{N_{\text{Steering options leading to passage without contact}}}{N_{\text{All available steering options}}}$$

The underlying idea for this method is that the overlap of the manoeuvring areas can be taken as a simplified expression of the remaining options of taking those actions that can prevent damaging contact with the other vessel. Montewka and Krata (Montewka & Krata, 2014) describe a similar approach.

The simplification is based on the fact that the overlap does not exactly describe all the options for steering sequences of the involved vessels that would lead to a collision. The exact determination would require the determination of the positions

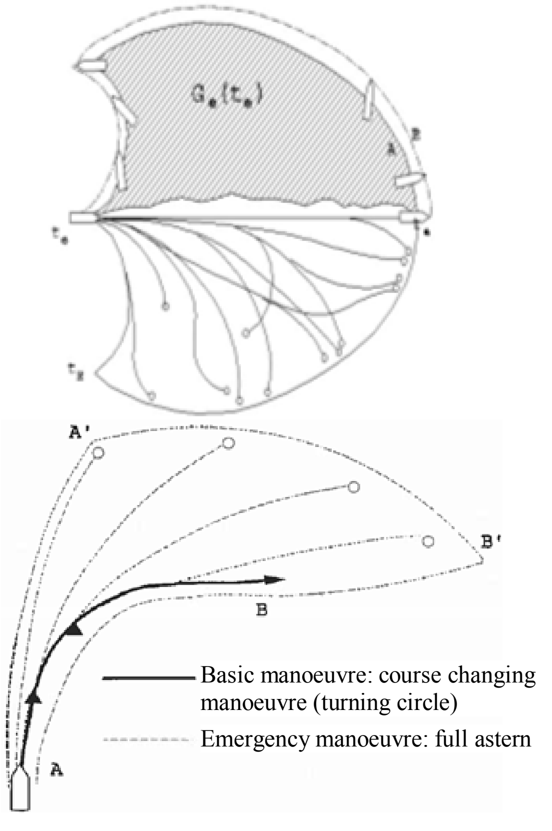

Figure 3. Principle sketches of "expectation area" (Göhler, 1983) – top – and "potential area of water" (Inoue, 1990) – bottom

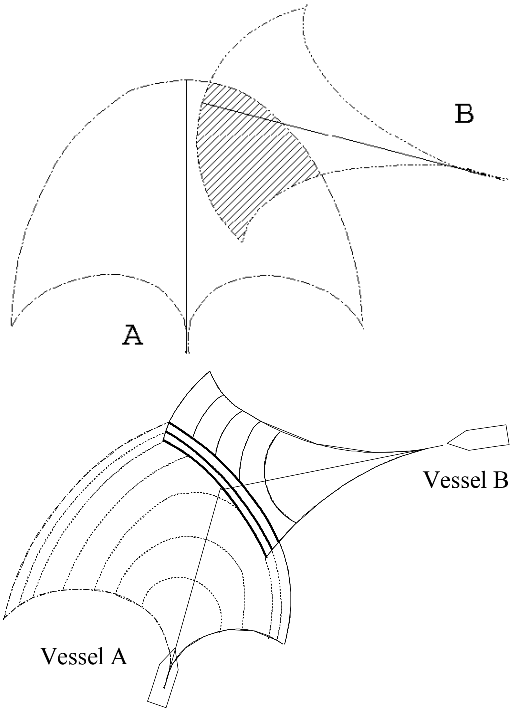

Figure 4. Top: Principle sketches of "expectation area" (Göhler, 1983); and bottom: "Potential area of water" (Inoue, 1990)

both the vessels would reach as a result of any steering sequence at the same time – lines of the same time or isochrones (Figure 4, bottom). However, the overlap can be taken as a good estimation for quantifying the risk of collision during the course of any encounter situation.

Until today such probabilistic approaches to quantifying the risk of collision by taking into account the dynamics of any encounter situation onboard could be considered only in a very generic, simplified and indirect manner. Decision making usually entailed applying deterministic risk models that providing limiting values for taking action to reduce a specified risk.

On the other hand, although theoretical underpinnings have been investigated and studied extensively, the application of such a method is still challenging because, for example, such prerequisites as the provision of suitably quick and exact predictions of manoeuvring areas adapted to concrete situation parameters were not yet available. Nowadays, with the aid of powerful enhanced information and communication technologies, a new situation seems to allow application of enhanced methods for risk assessment.

Prediction of manoeuvring areas

To predict the path or even the manoeuvring area covering all available steering options can be realised by a number of methods.

A rough estimation could be attained by applying the IMO resolution on "Standards for Ship Manoeuvrability" (MSC.137 (76), 2002). The standard aims at defining minimum performance standards for manoeuvring. This standard requires, for example, that the turning ability that the advance shall not exceed 4.5 ship lengths and the tactical diameter of the turning circle shall not exceed 5 ship lengths. Regarding the stopping ability, it is required that a full astern stopping track shall not exceed 15 ship lengths, with exemptions for ships with large displacement and impracticability of the criterion (shall not exceed 20 ship lengths).

It is obvious that this rough estimation as a rule of thumb might only be supportive for a preliminary assessment of collision risk. The actual ship status and the prevailing environmental conditions may significantly affect turning and stopping abilities.

Enhanced estimation of the manoeuvring areas can be performed using sophisticated calculation methods and simulation facilities using equations describing the manoeuvring behaviour of a ship. There are two basic approaches: one makes use of response models and the other employs hydrodynamic force models.

With the rapid development of computer technology, the increased power and performance of computers and their growing memory capacity, it is now possible to implement sophisticated models and develop and apply more and more comprehensive and advanced models for the prediction of ships' manoeuvres. For the first experimental studies, the authors applied the NOMOTO model and for application in an online support tool a 3DoF-model of hydrodynamic forces (see Figure 5, bottom).

Nomoto began his study on the application of the frequency response approach to steering ships, and then attempted to express the manoeuvrability of ships as a whole in terms of two indices. First one "K" indicates the turning ability and the second one "T" indicates the course stability or quick responsibility.

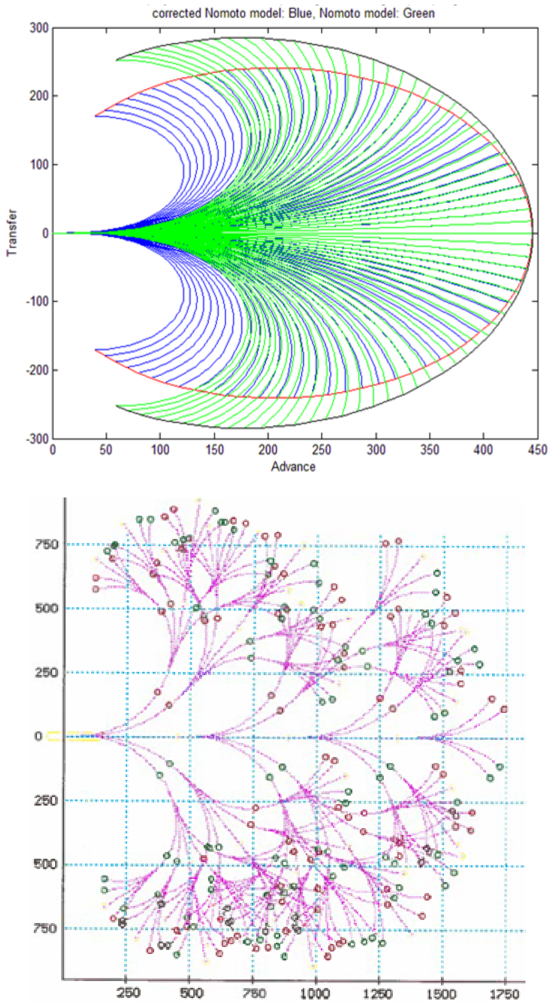

Figure 5. Samples of manoeuvring areas. Top: prediction of manoeuvring area using NOMOTO model and corrected NOMOTO model. Bottom: discrete manoeuvre graph (t = 4 min)

The NOMOTO equation is the simplest mathematical model for ship manoeuvrability. It is used to calculate ship trajectories for each angle between 0 and 35 degree for the same speed, time and hydrodynamic indices, the results shows that the model is feasible for the concept of manoeuvring area. However, due to the absence of drift angles, there is no speed drop in this model. That is why a correction is added to take this into account (see Figure 5 top).

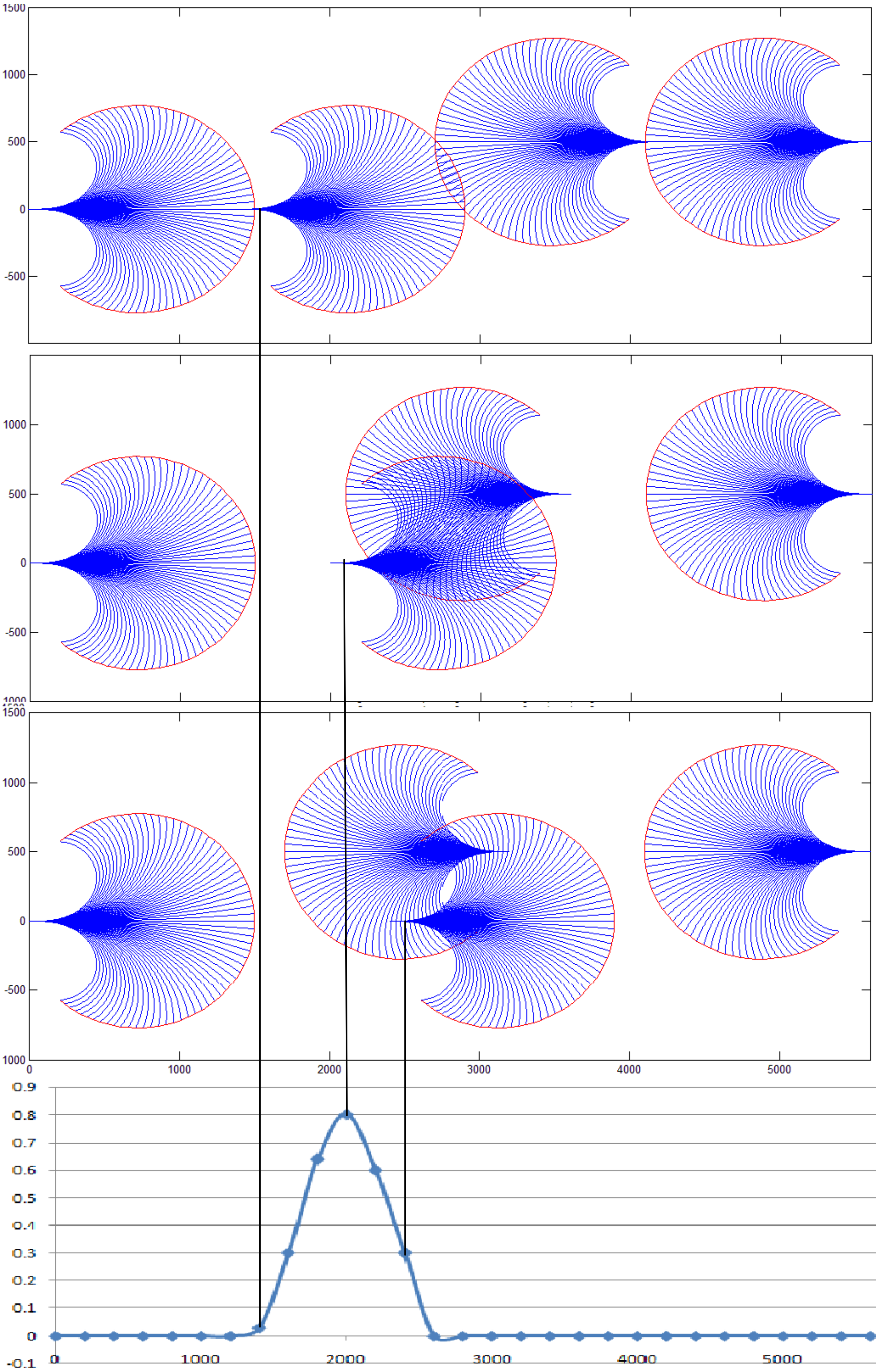

Figure 6. Risk graph for a head-on encounter situation of two cargo ships on opposite courses – risk probability calculated using manoeuvring areas

Preparation of and conducting case studies

Determination of probability and quantification of risk of collision using manoeuvring areas

For the purposes of a simulation study into the operational risk management, an existing NOMOTO model for a cargo ship has been implemented, and algorithms for the calculation of manoeuvring areas for initial speed has been coded using MATLAB. For modelling a cargo ship, the following data has been used: MMSI: 306,366,000; Length: 137 m; Breadth: 20.54 m; Ships draught: 6.8 m (from Nakano & Hasegawa, 2012). The indices for the model were given to $K = 0.85$ and $T = 1.78$, and the manoeuvring area can defined by the time required for the ship to turns 180 degrees or more depending on the risk model assumptions. For the tests in this example the time was taken to be to 3 minutes.

A matrix of situations has been developed taking into account the classification and systematics given in the “Rules of the Road” of the COLREGs (Cockcroft & Lameijer, 2012). First trials of an extensive experimental simulation study have been performed varying the speed and the passing distances of the ships.

The main aims of the pilot tests were to test the software modules and to generate first results for the development of the probability during encounter situations as a basis for continuous assessment of the risk of collision. The results form the basis of further systematic simulation-based scenario studies detailing a comparison of the outcome and validation of the risk graphs with deterministic models for situation assessment. Furthermore, it is intended to collect data for harmonisation as well as for validation of risk assessment, when applying the concept of predicted situation-dependent manoeuvring areas for enhanced algorithms for collision avoidance similar to ACAS. For this purpose, the harmonised and proven thresholds must be derived, and correlated and matched with probability values that will be investigated.

The first results are risk curves for encounter situations visualising increasing and decreasing probability and risk, respectively. A sample is given in the following figure for the encounter of two cargo ships both at a speed of 10 m/s (approx. 19.5 kts), and an initial passing distance of 500 m. The simulation scenario contains no manoeuvre – neither rudder nor engine – of the ships.

Figure 6 shows three snapshots of the encounter situation of both ships heading from east to west and vice versa. The first three sketches represent the overlap of the manoeuvring areas at the initial rising of the overlapping, at the position of the maximum overlap, and when the overlap is already decreasing. The risk curve on the bottom (risk = f (range and time respectively)) depicts the corresponding continuous rising of the risk / probability for the ship proceeding on an easterly course.

Moreover, the graph in Figure 7 shows the development of the decreasing risk/probability for the same encounter scenario with a passing distance greater than in the first considered scenario.

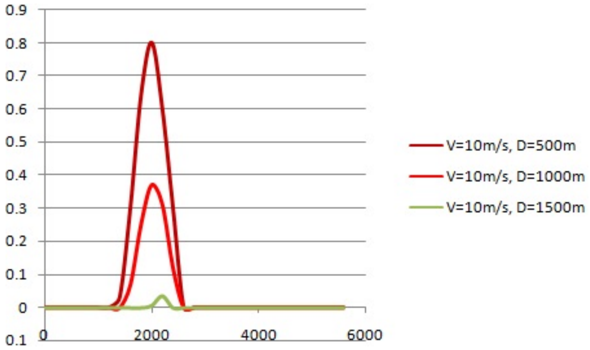

Figure 7. Risk/Probability graphs for encounter situation at three different passing distances

In this example, it can be seen that, for ships with the modelled manoeuvring characteristics, a doubling of the passing distance reduces the maximum probability about half. The variation of the passing distances in this scenario just leads to a quicker rise of the risk to its maximum. Accordingly, a variation of the speed will widen the peak of the risk / probability of collision. Also, there is a shift in the position where risk / probability is at a maximum. This is due to the shape and extension of the manoeuvring area. Further simulation runs using other models for the prediction of the manoeuvring area can study related effects.

Visualisation of situation adapted manoeuvring envelopes to assess risk of collision

A similar development for risk assessment using dynamic, situation-dependent prediction of manoeuvring limits taking into account the manoeuvring characteristics of ships and prevailing environmental conditions has been performed and tested in the frame of the MUNIN project (Krüger, Benedict & Baldauf, 2014). This European project on research and technological development studied the technical feasibility and prerequisites for safe and efficient unmanned autonomous shipping in the future.

One part of this project investigates manoeuvring support using innovative fast time simulation (FTS) technology to predict and visualise a ship’s path taking into account the response of the ship’s movement on actual control settings. Fast time simulation is specifically developed for online support in almost real-time. Real-time simulation calculates per one-second computing time also one-second of simulation time, and is used for ship-handling simulations in education and training. A time simulation calculates future positions and statuses of the ship by means of complex models for up to 24 minutes in advance, and may use steering sequences of the controls (rudder, thrusters, and engine) as input values for path predictions.

The two aspects of manoeuvring support addressed in the MUNIN project are manoeuvring the unmanned ship in "remote control" mode, as for example, when approaching the dedicated anchor position, or navigating in coastal areas and narrow waters as well as in open seas to assess collision risk and to take action from the shore control centres.

For the latter purpose a fast time simulation module based on a hydrodynamic force model can provide visualisation of the manoeuvring limits of the unmanned ship adapted to the prevailing circumstances as indicated by sensors installed on that ship.

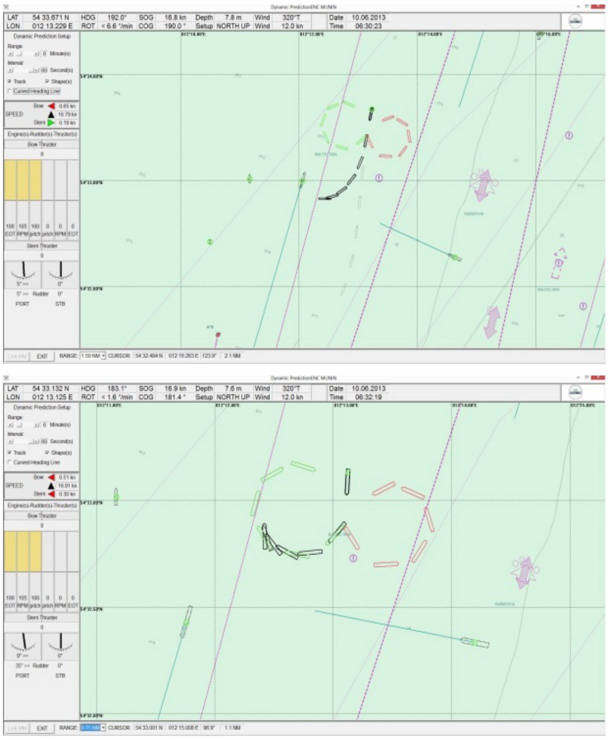

Figure 8. Display of the actual manoeuvring limits during an encounter situation on crossing courses with risk of collision (top). Bottom: according to COLREG Rule 17 – Manoeuvre of the stand-on vessel – a Hard to starboard manoeuvre combined with speed reduction are taken, the predicted path (black ship shapes) indicates the starboard turn that will avoid the collision

The steering limits are displayed in real-time as a so called manoeuvring envelop in one of the screens in the shore control centre. In this sample, the envelop shows the adapted turning circles for both hard to port and hard to starboard manoeuvres, as well as for an emergency stop. The display of these limits is to support situational assessment. For the situation depicted in the Figure 8, the operator ashore can easily assess when a collision can no longer be avoided by emergency stopping or when the option for a course change as an evasive manoeuvre won't contribute to collision avoidance any longer.

From the studies performed so far it seems to be quite obvious that FTS has a great potential to calculate even situation-adapted manoeuvring areas, and provide an even more comprehensive and more realistic shape of the manoeuvring areas and provide a solid basis for ACAS-like applications for maritime collision avoidance.

Summary and conclusions

Investigations are ongoing to explore whether or not a system similar to ACAS can be adapted for use in the maritime domain. A concept for potential transfer of principles and procedures for collision avoidance from aviation to shipping has been developed using predictions of manoeuvring areas. For the prediction of the dynamic areas, two different approaches for modeling have been used and first basic studies have been performed. As a core element, the integration of simulation technologies has been researched in regards to estimating the manoeuvring areas of a ship adapted to concrete situations and ship status parameters.

In order to take into account dynamic aspects in maritime collision avoidance, an enhanced method for the assessment of the risk of collision is developed and applied for purposes of testing its system responses and outcomes and principle feasibility and practicability. The basic idea of the concept for risk assessment is to quantify the risk of collision by using the ratio of overlapping areas as an estimated expression. Using this kind of risk quantification allows for a comprehensive and objective assessment of the risk of collision as the main influencing factors with their dynamics are taken into account.

The results of the case studies showed delivered promising results. The integration of simulation technologies obviously allows for online situation assessment on the objective basis of remaining options to take action to avoid a potential collision.

The authors are of the opinion the method and the applied technologies clearly demonstrate the potential to allow the development and introduction of an ACAS-like collision avoidance system into shipping generating at least a similar effect of risk reduction as in air traffic.

Acknowledgments

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