Unmanned ship simulation with real-time dynamic risk index

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***Abstract*— Currently there is a growing interest in unmanned shipping. In case of unmanned 'autonomous' shipping, the navigation is automated by on-board decision-making systems. Important motives for unmanned ships include the shortage of skilled mariners, the facilitation of slow steaming strategies, efficiency improvements in confined shipping areas and increased safety.**

The aim of the present research is to simulate an unmanned ship through an Automatic Identification System (AIS) based traffic situation. In order to do this, MARIN will use the existing simulation technology Dolphin, and implement a new tool to read AIS data, simulate this large amount of ships and develop an auto-captain. The real-time dynamic risk index developed by MARIN will be integrated in Dolphin, to monitor nautical safety of all ships with focus on the unmanned ship. The simulated unmanned ship will navigate according to the International Regulations for Preventing Collisions at Sea (COLREGS). In more complex situations the auto-captain may use a dedicated decision support tool to find a more efficient solution to pass safely. This approach will be analysed using the real time dynamic risk index, which will be updated based on latest insights.

This paper will discuss the latest development and plans in the unmanned ship simulation project.

I. Introduction

The project described in this paper, is part of a cooperation between the Maritime Research Institute Netherlands (MARIN), the National Aerospace Laboratory (NLR) and the Netherlands Organisation for Applied Scientific Research (TNO), funded by the Dutch government to stimulate cooperation and knowledge sharing between these three research institutes. The overall subject is autonomous transport, which has a different meaning for the different institutes: autonomous vessels (MARIN), autonomous airplanes (NLR) and autonomous cars and trucks (TNO). The definition of 'autonomous' is can be subdivided into different levels. Throughout the paper the Levels of Automation (LoA), introduced by Sheridan (see Table 1) are used to describe the different interpretations of 'autonomous'.

In the next section the simulation of an autonomous ship will be introduced, followed by a general section about conflict handling. Conflict handling consists of both conflict detection and conflict resolution, which are discussed in, respectively, section IV and V. In IV examples are given of conflict resolution models. Furthermore, conflict detection is discussed using AIS based ship domains and the predicted distance at the closest point of approach (CPA). Section V discusses ideas about conflict resolution models and more specifically the application of the International Regulations for Preventing Collisions at Sea (COLREGS) for autonomous vessels. In section VI, the real time dynamic risk index is described, and improvements to this model are discussed. Finally the subjects MARIN currently works on are summarized, which will ultimately result in a dynamic safety assessment model.

II. Simulation of an autonomous ship

Dolphin is MARIN's ship handling and manoeuvring simulator system capable of simulating the behaviour of virtually any type of ship in a wide range of operational situations, such as an FPSO tandem, side by side offloading, ocean towing and pushing a barge on a river. The simulation technology can be used to train operators in various environmental situations and at the same time it may play a valuable role in verifying concepts and conducting feasibility studies. Within the scope of this project, the first step is to upgrade and adjust Dolphin to handle a large amount of ships based on a realistic traffic scenario, given by AIS messages. In case of a one day scenario on the whole North Sea, this results in a large amount of ships to simulate. However, in the first place the focus will be on specific encounter scenarios of only several ships. Second, an auto-captain will be introduced, in order to simulate an autonomous ship, sailing through an existing traffic scenario.

Table 1. Eight Levels of Automation.

LoA	Function performed by the Automation
1	The computer offers no assistance; the human must do it all
2	The computer suggests alternative ways to do the task
3	The computer selects one way to do the task
4	Executes that suggestion if the human approves
5	Allows the human a restricted time to veto before automatic execution
6	Executes the suggestion automatically, then necessarily informs the human
7	Executes the suggestion automatically, then informs human only if asked
8	Selects the method, executes the task, and ignores the human

Making a ship "autonomous" requires adding automated decision making that replaces the human staff, the so-called auto-captain. This project narrows that down to the part of operating a ship that deals with route planning and handling traffic situations. Close-in operations, e.g. mooring a ship or ship-tug interaction, are excluded for this project.

Another limitation of this project is that it only deals with observed ship traffic as seen through AIS messages (which may be inaccurate) or radar observation. It ignores other types of interaction, like radio communication, sound signals or “lights and shapes” shown by other vessels.

In order to simulate an autonomous ship in an existing traffic situation, there is a need to develop software modules for integration in the Dolphin simulator for:

- Planning and following a long distance route. If circumstances change, the route may have to be modified. So it includes observing constraints like shipping routes, obstacles and other limiting factors. Planning is a continuous activity.
- Monitoring the shipping traffic in its environment for potential conflicts.
- Conflict handling, which is a localized phase where the autonomous ship and other traffic influence each other and the autonomous ship may have to take action. The autonomous ship acts in accordance with the COLREGS rules, in case of conflicts.

Interaction starts with observing the other traffic. For this project the properties of that other traffic are limited to what is available in the AIS stream. Relevant properties are:

- Position, SOG, COG: these tell where the ship is and where it is going in the foreseeable future. Rate-of-turn is hardly ever present in the AIS data and cannot be used.
- Dimensions, draught: this gives information about manoeuvrability and restrictions, e.g. limited to deep water channel.
- Type of ship: this gives general information about the ship, e.g. expected behaviour; pilot vessels may exhibit extreme course and speed changes, whereas regular ships are unlikely to do so. Dredging and fishing ships behave differently from transiting ships. Sometimes the type explicitly encodes relevant state information (“Engaged in dredging”, “Moored”).

The “destination” information is not used. It does give information about the ship’s plan, but in a large number of cases has found to be missing, incorrect, not very informative or ambiguous.

Firstly, the focus will be on conflict handling. The planning activity is a next step, which will not be discussed in this paper.

III. Conflict Handling

Very recently Hyundai has been working on a commercial anti-collision system for maritime application (*Hyundai (2014)*). This system does not only prevent collisions by automatically detecting potential obstacles, but it also searches for the optimal sailing route. Unfortunately details about this anti-collision system, or at which LoA level it is operating, are not yet publicly available.

In the aerospace industry a lot of research has been done regarding Conflict Detection and Resolution systems (*Kuchar (2000)*). Kuchar categorizes and discusses over 60 recent Conflict Detection and Resolution modelling methods. Some important elements are

- State Propagation: the method by which the current states are projected into the future. “Conflict detection and resolution can only be as reliable as the ability of the model to predict the future”
- Conflict Detection: a threshold has to be defined to be able to issue a conflict alert
- Conflict Resolution: different methods can be used to generate a solution to a conflict [prescribed (i.e. are manoeuvres fixed during system design based on a set of predefined procedures)/ optimized (i.e. combining a kinematic model with a set of cost metrics)/ force field (i.e. to treat each aircraft as a charged particle and use modified electrostatic equations to generate resolution manoeuvres) / manual and none]
- Resolution Manoeuvres: e.g. turning, vertical manoeuvres, speed changes.
- Multiple Conflicts: situations with more than one aircraft

In the following sections Conflict Detection and Conflict Resolution will be discussed in more detail.

IV. Conflict Detection

The EU project MUNIN (Maritime Unmanned Navigation through Intelligence in Networks) investigates the feasibility of unmanned, autonomous merchant vessels (*Rødseth (2012)).* In the short term they believe in making manned shipping safer and less stressful, by implementing better navigation support and obstacle detection, which can reduce accidents and contribute to improving the sustainability of shipping.

According to *Theunissen (2014)* a fully autonomous system with a Level of Automation 8 (see Table 1) is technically feasible. However, legislative and reliability issues will require a human operator at the decision making level and limit the LoA to 5. Therefore, Theunissen focuses on the human-machine interface that needs to provide the operator with the information needed to timely make informed decisions. Theunissen analysed data presentation concepts originating both from the nautical domain as well as from the aeronautical domain and present a solution which is closely related to the Conflict Detection and Resolution methods.

Figure 1. Example of the visualisation of conflict areas taken from Theunissen (2014).

The basis of the data presentation concepts was developed, in the Seventies of the previous century for the Integration Collision Avoidance and Navigation System (INCAS) by *Chase et al. (1971)* and the High Speed Ship Collision Avoidance and Navigation System (HICANS) by *Puckett et al. (1983)*. These systems were designed to improve the safety and efficiency of ship operators. It determines the Predicted Area of Danger (PAD) as an elliptic area around the predicted point of collision depending on the course of ownship.

By comparing the presentation of conflict areas in the aeronautical domain with the PAD used in the nautical domain, *Theunissen et al. (2014)* argues that the PAD only gives an indication of the area where a collision is predicted to occur. In this paper they created a visualisation of conflict areas showing the area that has to be avoided in order to remain “well clear”.

“Well clear” is subjectively estimated by the captain, but in this paper it is objectively defined using spatial and temporal separation criteria. This way they have a decision support tool, which visualizes which areas should be avoided in order to stay “well clear”. This tool also indicates for which course changes “well clear” will be lost within a certain threshold time. Furthermore, the predicted loss of “well clear” zones change in shape when the speed of ownship changes. This also shows that COLREGS based solutions are not always the optimal solution, since, in some cases you need to change course through the closest point of approach (CPA) which can cause more complex and dangerous situations.

In the study of *Weibel et al. (2011*) a “well clear” threshold for unmanned aircraft systems is derived as a function of risk using a relation between collision risk and the relative state. The relative state between aircrafts is investigated by the relative range and bearing, and time to Closest Point of Approach. A certain threshold is chosen as acceptable risk, defining the boundary of the well clear zone. The collision risk was determined using a statistical encounter model of air traffic considering aircraft trajectories generated using Monte Carlo simulations.

Another way to determine the criteria that define “well clear” is to study all ship tracks during encounters. MARIN developed a method to distinguish between normal and exceptional encounters (*Iperen, W.H. van (2012)*) for the Dutch Ministry of Infrastructure and Environment (I&M). The main goal was to monitor the safety level of the various crossing areas of the busy traffic at the North Sea by identifying exceptional encounters. Criteria to classify encounters were derived by analysing a year of AIS for the Dutch Part of the North Sea, and studying the ship domains, the closest point of approach (CPA) and the time to closest point of approach (TCPA).

For safe and comfortable navigation, ships prefer to maintain a certain minimal distance to other ships. The resulting free zone around the ship is called the ship domain. The absolute ship domain can be observed from tracks of encounters by applying a coordinate transformation that puts each ship in the origin, after which all tracks of encountering ships can be superimposed. This transformation uses the absolute distance and relative bearing between the ships. Fig. 2 (top) shows all tracks of encounters (mainly overtaking and crossing encounters) in absolute ship coordinates that occurred during one month at a busy junction in the traffic separation scheme in the North Sea. The plot clearly suggests the ship domain where few ship tracks are observed, and an increased density of tracks around it. The centre of the domain contains tracks of two towing combinations, that is, pairs of ships that intentionally sail closer to each other than during normal encounters.

The size of the ship domain (either absolute in miles, or relative in ship lengths) can be measured by determining the distribution of tracks per sector and taking for example the 0.5% percentile. Fig 2 (bottom) shows the 0.5%, 1% and 5% percentiles of the absolute ship coordinates in the top figure. The percentiles show a shape that is to be expected for a ship domain. It can be seen that for example for the 0° sector, only 5% of the tracks are within 1 mile of the ship.

Per type of encounter (Overtaking, Head-on, Crossing: give-way ship passes at stern or bow) different criteria are derived to classify whether encounters are exceptional or not (*Iperen, W.H. van (2012)*).

These domains can also help to define a risk based “well clear” zone as proposed by *Weibel et al. (2011*). In this context it might be of interest to consider the time concept as well, in the ship domain definition.

Another critical area that may be used to visualize conflict areas, is provided by *Montewka et al. 2014*. They discuss another collision avoidance system. They study the critical distance between two encountering ships such that there is enough time to perform evasive action. Hereby they also take into account the ship dynamics. They define this critical area as the Minimum Distance To Collision (MDTC) and their goal is to increase the situational awareness with this collision avoidance system. The MDTC was based on COLREGS defined scenarios in simulation runs for specific ship types and specific encounters.

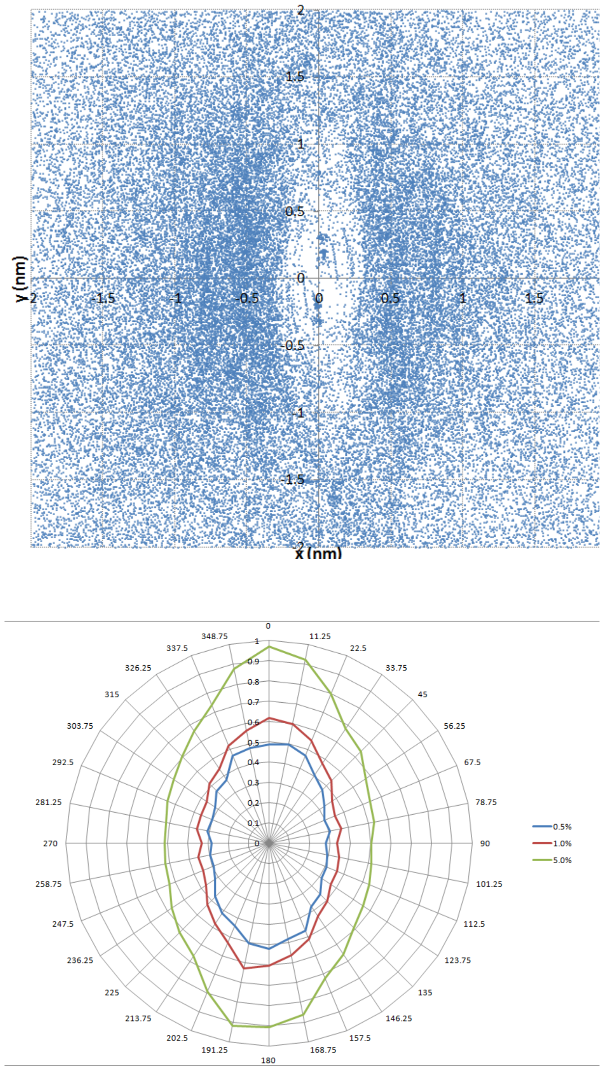

Figure 2. Ship Domain based on AIS data of overtaking manoeuvres.

V. Conflict Resolution

Within the MUNIN project a ship controller has been implemented, complying with the COLREGS, see *Burmeister et al. (2015)*. This paper discusses how COLREGS can be interpreted within the context of the autonomous ship. Furthermore, they suggest to consider an amendment to the COLREGS, to improve the data quality and reliability of AIS, to make it equivalent to the rules for displaying lights and shapes. This will be crucial when AIS is used as input for the automated collision avoidance systems.

Since the interpretation of the COLREGS with regard to the autonomous vessels raises questions, *Allen (2012)* also proposes a revision of the COLREGS. This to answer the questions about unmanned vessels, but moreover to adapt the COLREGS to the increasingly automated vessels.

Autonomous or increasingly automated decision making can be seen as an opportunity to improve safety at sea. Within the MUNIN project, they emphasize that an unmanned system needs to be at least as safe as a manned ship system, see *Burmeister et al. (2014)* and *Porathe (2014)*.

The auto-captain of the simulataed unmanned ship is based on the COLREGS. However, the current COLREGS are not sufficient for an auto-captain to handle very complex situations. Hence, an additional conflict resolution model is required.

The temporally and spatially defined conflict zones described by *Theunissen et al. (2014)* are intended to detect conflicts, and to increase the situational awareness of the operator. In order to add a decision making tool to the auto-captain of the autonomous ship, the conflict zones can be used. By adding risk contours this will lead to more flexible solutions. These risk contours can be defined by for example the risk based "well clear" zone as proposed by *Weibel et al. (2011*), the AIS-based ship domains as determined by *Iperen, W.H. van (2012),* and/or the areas defined by the time needed to perform a collision evasive action as introduced by *Montewka et al. (2014)*. Each of these zones was described in section IV.

Different resolution systems can be implemented in the auto-captain of the autonomous ship in the simulation tool Dolphin. Furthermore, the decision support tools make use of risk based conflict zones described in previous sections. These can be tested against the encounter formulation used in the real time dynamic risk index described in the following section.

VI. Safety: Real time dynamic Risk Index

The risk index was first developed in the EU-project EMBARC (*Van der Tak et al. (2005)*) and was further developed in the EU-project MarNIS *(Koldenhof et al. (2008/2009/2010), Glansdorp et al. (2009))*. The risk index is a risk value for each individual ship, which can be determined based on the characteristics of the ship, its environment and surroundings and can be expressed in risk costs per hour (euro/hour).

The risk index is a combination of the frequency of an unwanted event (accident) and the consequences of the event for an individual ship. The probability of an accident of a specific type (i.e. collision, foundering, hull failure, machinery failure, fire/explosions, ramming contact and drifting contact) is based on casualty statistics, and tuned by multiplication factors for flag state, age of the ship, wind, visibility and the navigation status. The consequences are divided into three main areas: consequences for life, consequences for the environment and structural consequences.

In the first place the risk index was designed as a tool to provide the Maritime Operation Service operator with information about the risk of different ships in their area. A threshold value is defined, to assign vessels a high alert status.

The probability of a collision is also included in the risk index. This encounter model was discussed in the previous workshop of IWNTM (*Koldenhof et al. (2014)*). In this paper an improvement of the encounter model was proposed. Fig. 3 represents a risk weight function depending on the distance at the closest point of approach (DCPA) and the time to the closest point of approach (TCPA). The white lines shows the relation between the DCPA and TCPA of different encounter situations.

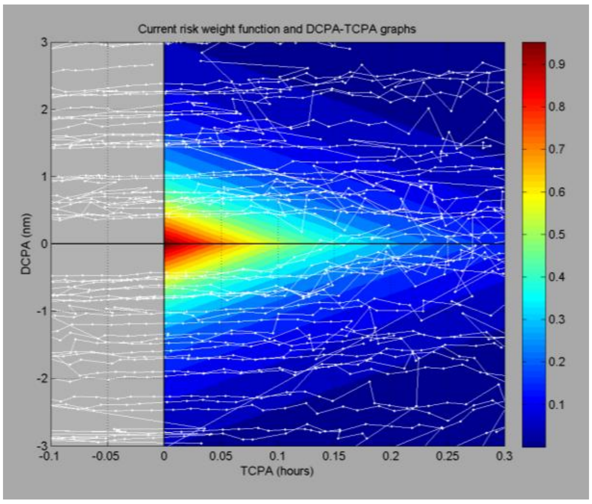

Figure 3. Graphical display of the original encounter formulation.

In order to follow a ship in time, the figure needs to be read from the right to the left. The colouring in the background shows the risk weight, where blue represents a low risk and red a high risk. Variations of the encounter model in the risk index are currently being investigated and a more realistic model will be implemented. This model can be based on the findings in the study of the conflict zones described in the previous sections.

Furthermore, this real time risk index will be coupled to the simulation tool Dolphin. Interesting AIS scenarios representing e.g. close encounters, can be studied using the risk index. These scenarios will be compared to situations where one of the ships is replaced by the autonomous ship with the auto-captain.

VII. Research Outlook

Traditionally, the safety levels of the shipping traffic and the impact of new developments and measures, can be assessed with risk models, such as the SAMSON model (*Van der Tak & De Jong, (1996)*) that was developed at MARIN. In the SAMSON model, risk is a combination of accident probability and consequences. For the risk of collisions, the probability is modelled by estimating the number of encounters between ships with a static traffic model, and multiplying this by the probability of a collision given an encounter.

The traffic model is used to predict routes and shipping intensities in future situations, but it cannot be used to monitor the safety levels of the actual traffic.

A risk index as described in the previous section was developed to apply the risk model from SAMSON to the actual real-time traffic information that is provided by AIS data, which is now implemented in the Dolphin simulator.

The ultimate goal is a dynamic safety assessment model, where the input is not only the exact registered AIS data, but can also be simulated with auto-captains, to be able to simulate future scenarios, see Fig. 4. In this case the auto-captain is not necessarily an auto-captain of an autonomous ship, but for example some Monte Carlo decisions can be implemented to model a 'human captain'. This will result in a 'complete safety assessment model' that can assess current situations (using AIS) and future situations (using simulated AIS) as well.

The current research topics described in this paper can be summarized as follows:

- Simulate recorded AIS-data in the Dolphin simulation tool. A first working version the new modules of the Dolphin simulation tool is planned to be ready by September 2015.
- Implement a COLREG based auto-captain (planned to be ready by September 2015).
- Implement the risk index into the Dolphin simulation tool.
- Analyse close encounter situations with the conflict detection tool of Theunissen and with the risk index, for both the recorded AIS-situation as well as for the situation where the captain of one of the ships is replaced by the auto-captain.
- Study the possibilities of adding risk contour lines to the conflict zones of Theunissen's conflict resolution visualisation model by using ship domains and perhaps something like the Minimum Distance To Collision (MDTC) areas discussed by Montweka.
- Study the possibilities of a resolution model for the auto-captain, based on the conflict zones with risk contours as mentioned above.
- Improve the encounter model in the risk index.

These research steps are an important part of the autonomous transport project, and will contribute greatly to the ultimate dynamic safety assessment model.

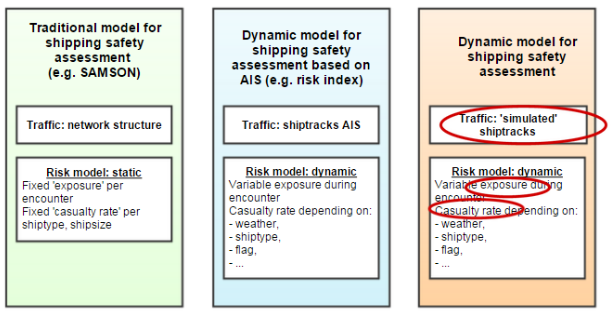

Figure 4. Overview of risk assessment models

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