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Improving maritime traffic safety by applying routes exchange and automatic relevant radar data exchange

Mazen Salous[1]✉, Heiko Müller[1], André Bolles[1], Axel Hahn[2]

[1] OFFIS – Institute for Information Technology
2 Escherweg, 26121 Oldenburg, Germany, e-mail: <first name>.<last name>@offis.de
[2] Carl von Ossietzky Universität Oldenburg
114–118 Ammerländer Heerstraße, 26129 Oldenburg, Germany, e-mail: hahn@uni-oldenburg.de
✉ corresponding author

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Abstract

The e-navigation strategy of the International Maritime Organization (IMO) aims to improve the safety of maritime traffic by increasing cooperation between several maritime stakeholders. The COSINUS (Bolles et al., 2014) project contributes to such a strategy by enabling an automated data exchange (observations, routes and maneuver plans) between ship-side and shore-side navigational systems, developing useful sensor fusion applications upon the new information available from data exchange and introducing new Human Machine Interfaces (HMIs) to support the users of navigation systems.

The project shows potential for improvement in maritime traffic safety by ensuring continuous awareness to all participants involved through sensor fusion applications, i.e. by providing all participants (mobile and stationary navigation systems) with a complete view at all times. These applications include detection of critical situations like radar shadowing areas, early and accurate prediction of potential collisions or closest point of approach (CPA) based on the exchanged routes, and improving the accuracy of radars by ensuring high quality data for obstructed or far away routes. The new HMI concepts introduced within the COSINUS project aim at highlighting critical maritime traffic situations. Thus, the users of such navigation systems supported with COSINUS facilities can easily detect such critical situations and react efficiently to avoid collisions, possible crowded areas and inefficient routes.

Introduction

In November 2005, a Swedish passenger ship called FINNSAILOR and the Maltese bulk carrier GENERAL GROT-ROWECKI (Swedish Maritime Safety Inspectorate, 2006) collided in the Kadertinne in the Baltic Sea. According to the accident report, it happened primarily because the crews of each ship involved in the accident were unaware of the intentions of the others. While the most northern vessel FINNSAILOR intended to leave the traffic separation scheme to the East, the southern vessel intended to go north. Since the intention of the FINNSAILOR was not clear to the other vessel, a collision of vessels occurred. Having access to all relevant information for decision making, the routes in this case, may have helped to avoid this accident.

The importance of safe waterways is increasing worldwide, but particularly in Germany, in accordance with the increasing amounts of German goods transfers which are handled by sea, e.g. 276 million tons of goods were handled in 2010 (Winter, 2011). E-navigation is a strategy defined by the International Maritime Organization (IMO, 2006) and others which aims to improve maritime traffic safety. It recommends the integration, improved communication and cooperation between the actors involved in dangerous situations as central objectives in maritime traffic management. The National Master Plan Maritime Technologies (NMMT) (BMWI, 2014) and the research program "Maritime next-generation technologies (2011–2015)" (EC Europa, 2011) have been incorporated for the achievement of such objectives. The IMO has called for cooperative communication management between ship-side and shore-side systems in order to prevent accidents and increase safety. The objective of research and development must be an increased degree of safety in maritime traffic. This can be supported by the exchange of useful information between ship-side and shore-side systems.

The COSINUS (Bolles et al., 2014) project examines the integration of information in navigation systems on ship- and shore-sides. The main contribution is to produce a comprehensive situational awareness on board a vessel, as well as in land-based vessel traffic services (VTS) centers.

It will enable the exchange of track information and route information between all involved parties and provide value-added information, such as routes-in-conflict detection and the discovery of blind areas in radar coverage. Earlier and more accurate detection of critical situations is available and better decisions can be made.

The COSINUS project aims at ensuring shared situational awareness. Therefore it needs universal data processing and exchange and the introduction of new Human Machine Interface (HMI) concepts for visualization.

According to data processing and exchange, a data stream management system is used to enable data exchange and sensor fusion between navigation systems. Odysseus (Appelrath et al., 2012) is a flexible, feature-rich and extensible framework to design stream management systems. It has many general operators for selection, filtering and joining data streams. Moreover, it can be easily extended to create new operators. Odysseus supports users with Programming Query Language (PQL) to write queries for processing data streams. Each query consists of consecutive and parallel operators to read the incoming data streams, process them accordingly and publish the results.

According to HMI concepts, new user-friendly graphical interfaces are needed to highlight the new features added within the COSINUS project. Thus, the users of navigation systems can easily detect newly added information and react efficiently, e.g. detect a route conflict and react efficiently by modifying the planned route.

After this general introduction, this paper is structured as follows: in the next section we point out to the level of research and implementation, which was done by related works in maritime data exchange and HMIs. We then present a scenario of data exchange in terms of tracks and routes exchange which were implemented to show the importance of the availability of the new data exchanged in preventing potential accidents. After that, we list some of the important applications defined for both targets and routes exchange, each of them will be explained and supported with a suitable HMI for visualization.

Related work

We refer in this section to the related projects that contribute to e-navigation strategy. Some projects like Baltic Sea Safety (BaSSy) (BaSSy, 2007) and EfficenSea (http://www.efficiensea.org) focused on analyzing AIS information and radar images and contributed to risk identification algorithms for VTS systems regardless data exchange or integration between INS and VTS systems.

However, there are projects that have been contributing to data exchange and integration between maritime navigation systems, e.g. ACCSEAS (http://www.accseas.eu) and Monalisa (http://monalisaproject.eu) (I and II).

ACCSEAS focuses on the development of prototypical e-navigation services and the development of a testbed in the North Sea region to demonstrate prototype services. One of the prototypes demonstrates the functionality of route exchange between vessels and VTS systems, and between vessels themselves.

The Monalisa project (I + II) also focuses on data exchange in terms of route exchange from ship to shore and ship to ship. The COSINUS data exchange model (Appelrath, 2012) is a distributed model that depends on all distributed participants' data, while the Monalisa project's model is a centralized model that organizes route planning among different participants in a specific area at sea.

IMO's strategy for the development and implementation of e-navigation

The International Maritime Organization published a strategy plan for the development and implementation of e-navigation (IMO, 2009). The strategy recommends guidelines for both data exchange and HMIs. According to data exchange, the strategy asks for data validity, plausibility and integrity. It also refers to the need to consider the requirements for redundancy, particularly in relation to position-fixing systems.

According to HMIs, the strategy lists some requirements from a visualization perspective. It emphasizes the need for reducing "single person errors" and enhancing team operations by implementing well-designed HMIs.

Data management in e-navigation

According to the recommendations of the e-navigation systems mentioned in the working papers of the IMO and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) (IMO, 2006), Filipowski & Wawruch (2010) proposed their concept of a "One Window" data exchange system for exchanging information between different navigation systems based on one common contact point on shore (e.g. harbor master, ships' monitoring or traffic control center). Their solution for data management between e-navigation systems is a centralized approach, where the user of such centralized software has access to five tabs, each of them representing a specific type of data, such as an ECDIS tab and a Radar Display tab. In contrast to their centralized solution, we introduced, in Bolles et al., (2014), our decentralized architectural design for exchanging data and ensuring the situation awareness of all parties involved (ship masters and VTS operators) by enriching the corresponding mobile and coastal context models continuously (Salous, 2015).

Adding information to existing HMIs in different navigational systems

Route exchange between vessels has been investigated before. Porathe et al. report on a study on the visualization of route information in a busy shipping lane between Denmark and Sweden (Porathe, Lützhöft & Praetorius, 2012). They conclude that route exchange can be helpful to mitigate ambiguity in route negotiations but have observed display cluttering, as well as time constraints, when exchanging information. Keeping Lützhöft's and Nyce's work (Lützhöft & Nyce, 2008) in mind, adding information on routes and targets has to be done with care. The goal should always be to refrain from adding more clutter to the displays that seafarers use on the ships and also for the VTS operators on shore.

Targets and Routes Exchange in the COSINUS Project

The mobile and stationary navigation systems work typically with different data formats, where the ECDIS (Electronic Chart and Display Information System) on ship-side works with National Marine Electronics Association (NMEA) (http://www.nmea.de/nmea0183datensaetze.html) format for representing targets and JSON format for representing the planned routes, the VTS system on shore-side works with IVEF (http://openivef.org) format (Inter VTS Exchange Format). However, the semantics of such different data formats can be the same, e.g. NMEA and IVEF messages represent the same target (ship position) at the same time, or JSON and IVEF messages represent the planned route of the same ship.

We implemented a protocol handler in Odysseus (Appelrath, 2012) for each data format to parse and decode the incoming radar and Automatic Identification System (AIS) messages. Then, we prepared continuous queries (which run continuously as Data Stream Management System (DSMS) queries) in Odysseus to exchange data (targets and routes) between the ship-side and shore-side navigation systems (between ECDIS and VTS). That is, we prepared a distributed data stream management system that consists of Odysseus instances installed and integrated with the corresponding navigation systems on shore- and ship-sides. The queries mentioned run continuously on the installed Odysseus instances in both shore- and ship-sides to enable the routes and targets exchange.

In the following sections we discuss the above mentioned FINNSAILOR scenario and how COSINUS can contribute to avoiding such traffic situations in future.

Targets and Routes Exchange Scenario

In this section we present the scenario we applied in the COSINUS project for exchanging targets and routes (Figure 1).

Targets Exchange

We simulate the real collision using the maritime traffic simulation system MTS (Dibbern & Hahn, 2014) which continuously generates NMEA messages representing the positions of the four ships involved in the collision (Swedish Maritime Safety Inspectorate, 2006). The ECDIS, which is used and considered to be set on the own-ship, receives all the targets (own and foreign ships) from MTS and displays them on its monitor. In parallel, the right Odysseus instance, which is connected between the MTS, right VHF modem and VTS, receives the same targets (own and foreign ships) from MTS, converts the messages into IVEF format, the format used by VTS, and forwards the resulting IVEF targets' messages to VTS, which in turn displays them on its monitor. The useful applications which can be applied based on such target exchanges are explained in detail in the section *Routes Exchange Application in Data Management: Early and Accurate Calculation of CPA and TCPA*.

Routes Exchange

The left Odysseus instance, which is connected between the left VHF modem and ECDIS, asks the own- ship (ECDIS) for its route and forwards it via

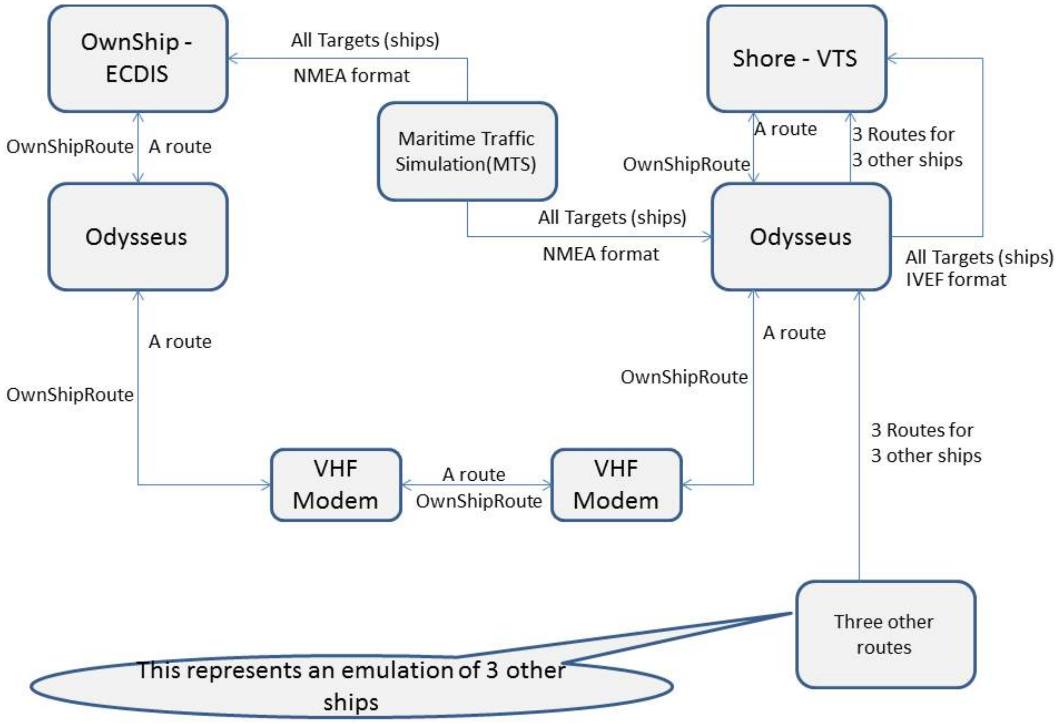


Figure 1. Targets and Routes Exchange Scenario

the VHF modems (the left one is considered to be set on the own-ship and the right one is considered to be set on shore with the VTS) and the coastal Odysseus (right Odysseus) into the VTS. The role of Odysseus instances in this data exchange offers the ability to communicate via different standards, that the Own-ship-Odysseus (the left one) asks the web-service of ECDIS for the own-ship route, receives it via HTTP, and serializes it via RS232 to the VHF modem. On the other side, the coastal Odysseus (the right one) receives the own-ship route from the right VHF modem via RS232 standard, and sends it via TCP to VTS. The discussion of possible useful applications based on routes exchange is detailed in the next sections.

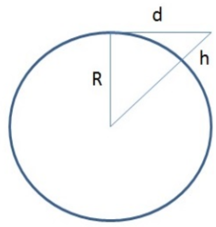
Sensor Fusion Applications based on Track Exchange

As we have seen in the previous section, Odysseus instances constitute a distributed system offering the ability to exchange the detected targets. Given the replicas of targets from many available data sources (ship's radars and VTS), our distributed DSMS can highlight critical situations such as the missed targets in radar ranges, the missed targets in radar shadowing areas and low quality data. Data exchange makes sense then in such important cases. The contribution of our distributed DSMS is the automated relevant data exchange, i.e. to find relevant data such as missed targets and exchange them accordingly.

Calculation of Radar Range, Detection and Exchanging of Missed Targets

The distributed DSMS in COSINUS (Salous et al., 2015) defines the areas covered by radars, and represents them continuously in its context models in order to monitor such areas as areas of interest. Regardless of the different capabilities of different radars, we discuss radar ranges based on the line of sight concept in order to ensure the quality of service to different radars in their line of sight ranges.

Radio Horizon: the radio horizon is defined, based on the line-of-sight concept, as the locus of points at which direct rays from the radar antenna are tangential to the surface of the earth.



R is the radius of the Earth, **h** is the height of the radar antenna, **d** is the line of sight distance

Figure 2. Radar horizon

Based on the Pythagorean Theorem:

$$d^2 = (R + h)^2 - R^2$$

Given the height of the radar antenna h in meters, and the earth radius R as 6371 km, we can get the distance of radar horizon in kilometers ignoring the atmospheric conditions and ignoring the small h in the $2Rh$ phrase (Busi, 1967):

$$d = 3.57 \cdot \sqrt{h}$$

Under normal weather conditions, the horizon increases by about 15% (Dibbern & Hahn, 2014):

$$d = 4.12 \cdot \sqrt{h}$$

The distributed DSMS in COSINUS aims to enable the best range for radars under any atmospheric condition, i.e. in the case of bad weather conditions, the actual radar range may be less than the mentioned range in equations, but the distributed DSMS will detect the missed targets, get them from another data source (VTS or a closer ship which can detect them) and send them to the relevant ship.

Calculation of Radar Shadowing areas (Blind Sectors), Detecting and Exchanging of Missed Targets

The main step in the data exchange process is defining the relevant data to be exchanged and the areas of interest in which the data exchange process makes sense. In this section we point to a situation in which data exchange makes important sense – the radar shadowing phenomena.

Radar Shadowing Phenomena: *The inability of radar waves to continue spreading through an obstacle (very big vessel, mountain, etc.) in their path will cause a blind area behind this obstacle, where the targets in such an area cannot be detected by the radar because the radar waves will not arrive at and reflect on them.*

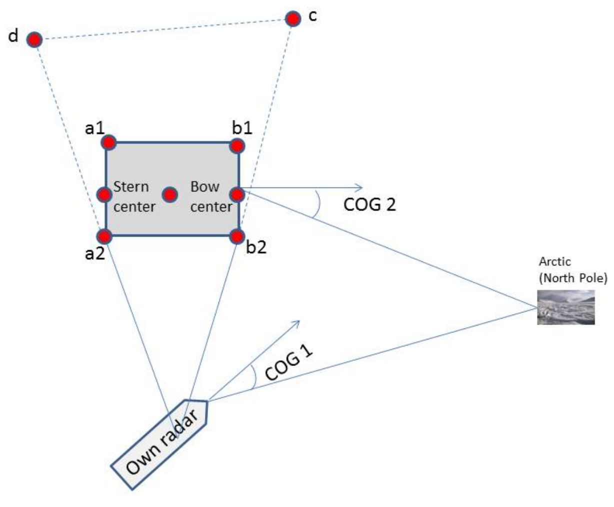


Figure 3. Radar Shadowing

The shadowing area represents an area of interest for data exchange, and the observations of targets (e.g. ships) which are located in this area are considered relevant data to be sent to the obstructed ship which has lost such targets.

The DSMS instances (Odysseus instances) together constitute an overall distributed system, i.e. there are mobile Odysseus instances distributed on ships as supporting systems to ECDISs and another instance is installed on shore as a supporting system to VTS.

This distributed DSMS aims at calculating the shadowing area polygon (a, b, c, d) by calculating the coordinates of its vertices in the earth ellipsoid WGS84 (GPS positioning ellipsoid). Then, it can detect the targets located in this polygon, annotate them as potential missed targets and inform the obstructed ship about such missed targets.

Shadowing Area Calculation Analysis:

The distributed DSMS in the COSINUS project can continuously gather the required data for calculating the shadowing areas which may happen suddenly to a coastal or ship radar because of obstacles (big ships, mountains, etc.). These data are gathered from any available data source, such as AIS transceiver or radar. The following list describes such data with potential data sources (AIS or radar messages):

- **r** the position of the own-ship. This data comes either from the own AIS transceiver messages (AIVDO (AIS VHF Datalink Own-vessel Message)) or from a TLL (Target Latitude Longitude) radar message published by a participant radar in the COSINUS system which can detect the own-ship.
- **m** the position of the obstacle (the big ship). Just like the own-ship position, this data comes either from the AIS transceiver of the obstacle ship (AIVDM (AIS VHF Datalink Message)) or from TLL radar message.
- **COG1** (Course Over Ground) of the own-ship. This data comes either from the own AIS transceiver message (AIVDO message) or from radar TTM message (Tracked target Message) published by a participant radar in the COSINUS system which can detect the own-ship.
- **COG2** (Course Over Ground) of the big ship. Similar to COG1, this data comes either from the AIS transceiver of the obstacle ship as AIVDO message, or from radar TTM message.
- **rm** the distance between the own-ship and the obstacle. This data is either calculated by Odysseus, given the positions of own and obstacle ship, or comes from a radar TTM message published by the own radar or obstacle radar.
- **[rc]** and **[rd]** radar horizon distance, calculated based on the line of sight concept described in the subsection *Related Novel HMI: Display Routes Interesting Information*.

Thaddeus Vincenty's algorithms:

In this section we discuss briefly how the DSMS in COSINUS, which supports VTS and ECDIS, uses the Thaddeus Vincenty's algorithms (Vincenty, 1975) in order to calculate estimated positions and bearings based on the available information.

For calculating an estimated destination position for a ship, Vincenty's algorithms need the current position and course of the ship and the distance to be passed. Thus, Vincenty's algorithms can calculate the latitude and longitude of the destination position with regards to the earth ellipsoid WGS84 (GPS positioning ellipsoid).

Similarly, given the start and end positions in the earth ellipsoid WGS84 (GPS positioning ellipsoid), Vincenty's algorithm can calculate the current course (bearing) for moving from the start position to the end position in a straight line.

Radar shadowing calculation steps:

Based on Thaddeus Vincenty's algorithms to solve the direct and inverse geodesics problems (Vincenty, 1975), COSINUS's distributed DSMS can calculate the coordinates (latitude and longitude) of the vertices (a, b, c, d) by the following steps:

I. When the own-ship radar ***r*** detects the big ship ***m***, an NMEA message Target Latitude Longitude (TLL) and Tracked Target Message (TTM) message will be created by its supporting systems, the former message represents the target (big ship) position, while the latter one contains information of the target (big ship) relative to the own-ship (small ship) such as: distance between them, bearing to own-ship, CPA and TCPA. Both mentioned messages in addition to the AIS messages published by the AIS transceivers of the other ships will be received by Odysseus installed on the own-ship. Here arises the role of sensor fusion in order to identify the AIS message which matches the radar messages (TLL and TTM) by identifying ships based on their dynamics: position, (Speed Over Ground) SOG and COG.

II. After sensor data fusion between TLL, TTM and AIS messages, the own-ship Odysseus can calculate the coordinates of the shadowing area polygon vertices: (a, b, c, d) by applying the following steps:

a. Given the big ship position from the TLL radar message, the big ship length either from the AIS:VDM (AIS VHF Datalink Message) published by its AIS transceiver or from the IVEF message published by the VTS, and the COG from the TTM radar message (it can be given by the AIS message as well, but the radar measurements are more accurate), the own-ship Odysseus can apply the Thaddeus Vincenty's algorithm (Vincenty, 1975) which uses the starting position (big ship position), the distance (1/2 big ship length) and the bearing to north pole (COG2) as inputs and calculates the end position (latitude and longitude of bow center point).

b. Similarly, Odysseus applies the Thaddeus Vincenty's algorithm by passing starting position ***m***, distance (1/2 big ship length) and bearing as an opposite angle of COG of the big ship, then it finds the stern center point.

c. Odysseus uses the Thaddeus Vincenty's algorithm again starting from bow center point and bearing COG2+90 and COG2-90 with distance equals the half of obstacle width to get **b1** and **b2**, and similarly from the stern center point to get **a1** and **a2**.

d. The next step is to choose the correct obstacle edges as shadowing area begin vertices by choosing those edges create the maximum angle with the obstructed radar (own-ship radar). In Figure 3 the beginning shadowing area vertices are a2 and b2.

e. Odysseus applies spatial calculation to calculate the bearing from own-ship to both beginning shadowing area vertices.

f. Finally, Odysseus applies the Thaddeus Vincenty's algorithm starting from the own-ship radar and using the radar horizon as distance and bearing to both beginning vertices in order to calculate the ending vertices of shadowing area **c** and **d.**

Related Novel HMI: Missed Targets in Radar Range

Radar shadowing information is of interest to both seafarers and VTS operators. Maintaining a proper lookout is one of the key tasks seafarers have to perform on a vessel. Being able to highlight certain areas that cannot be covered by the radar may enable the ships' crews to pay special attention to these areas while the shadowing lasts. For the VTS operator it is equally important to have an overview of the vessels in the VTS area that may not have the full situational picture from their own sensors. These vessels will then be provided with target information obtained from other sources. Figure 4 gives an exemplary snapshot of a situation in which one vessel is shadowing the radar of another vessel and thus hiding three targets from the radar's view.

We see the potential benefit in providing VTS operators with a visualization of the radar range of

Figure 4. Shadowed area for a selected vessel with three hidden targets

either one vessel in the area or the ranges of all vessels. In the case of one vessel, the VTS operator may see other targets which the crew on this vessel's bridge are able to detect with their own radar, thus facilitating radio exchange. The overview of the radar ranges of all COSINUS-enabled vessels can give the VTS operator an idea as to whether there might be any blind spots from radar shadowing that would require special care and attention.

Routes Exchange Application in Data Management: Early and Accurate Calculation of CPA and TCPA

The Closest Point of Approach (CPA) and Time for Closest Point of Approach (TCPA) are important for navigation systems, so that early and accurate calculation of the point at which the distance between two ships will reach its minimum value can be calculated in order to evaluate the risk of a collision.

Typically, the existing navigation systems on ships (ARPA: automatic radar plotting aid) predicate the values of CPA and TCPA, but they depend on linear prediction based on the given (or calculated) SOG and COG of both ships. Then, ARPA encapsulates the values of CPA and TCPA in TTM NMEA message. However, such a linear prediction without considering the planned routes can lead to inaccurate values of CPA and TCPA when the speed vectors of the ships go temporarily in different directions (see Figure 5).

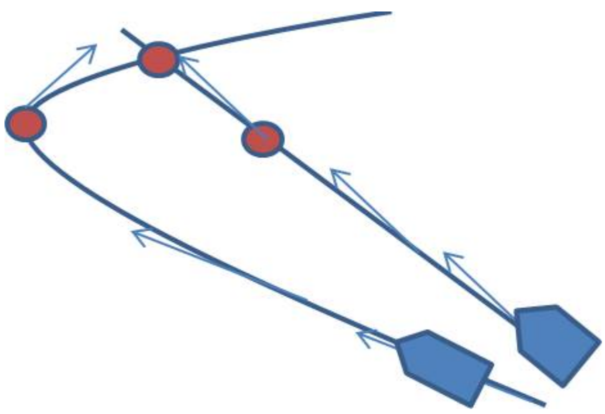


Figure 5. CPA and TCPA Based on Routes

On the other hand, our distributed DSMS takes the planned routes into account after exchanging them with all participants. This means that the actual closest point of approach will be earlier and correctly calculated. If the linear prediction of CPA is done by traditional ARPA, this will lead to negative values (no closest point) while the left ship is moving left in the curve, and then, when it turns right and the speed vectors become in the same direction, the ARPA will be able to predict the next CPA, but it may be too late to avoid a collision in this case. Whereas, our distributed DSMS can calculate accurate CPA and TCPA based on the available routes, where the routes offer the geometry shapes and the SOG and COG in each planned way-point. Moreover, the distributed DSMS can monitor the actual movements of the ships compared with the planned route in order to re-adjust the calculated CPA and TCPA if some sensible differences are detected.

Related Novel HMI: Display Routes Interesting Information

EDCIS systems on ships visualize the movement of all tracked vessels with a speed vector (see Figure 6). These speed vectors are calculated at any moment from the ship's current SOG and COG. No consideration is given as to whether the ship might be turning. This form of display gives a momentary overview but requires the seafarers to do a lot of

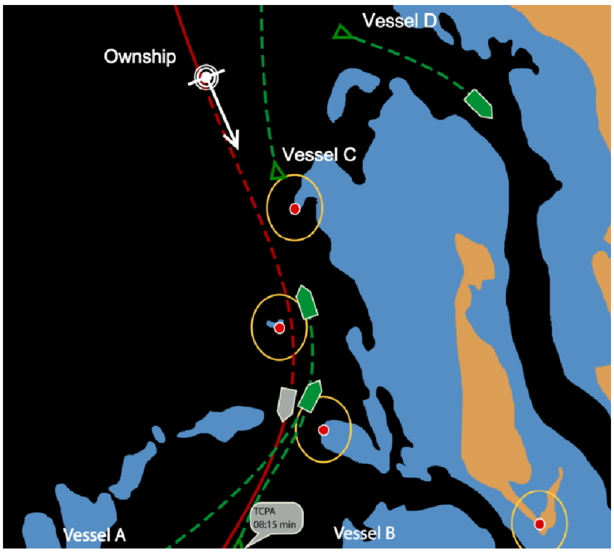


Figure 6. Prediction of ship positions in the future, if following the intended routes

mental calculations and estimations in the process of judging if another vessel might interact with their own-ship in a potentially dangerous manner.

The goal of using the exchanged routes for the prediction of target positions is to reduce some of the ambiguity of today's systems as well as to reduce the mental workload of the seafarer, freeing him for maintaining a better lookout and being able to make the right decisions in a hazardous situation. Figure 6 shows one of our designs which outlines the prediction of future target positions, if they adhere to their intended routes. Any deviation from these routes beyond the permitted limits will result in an alarm.

Evaluation

As we mentioned, the collision that occurred between the Swedish passenger ship called FINN-SAILOR and the Maltese bulk carrier GENERAL GROT-ROWECKI (Swedish Maritime Safety Inspectorate, 2006) in November 2005 in the Baltic Sea was simulated within the COSINUS project. The scenario was to exchange the planned routes of the ships involved in the collision. Providing such planned routes to the ships can avoid such an accident because the crews of each ship involved will know the intentions of other ships and they can react accordingly. Moreover, an automated data exchange also promises to give some suggestions for modifying the planned routes to avoid possible collisions.

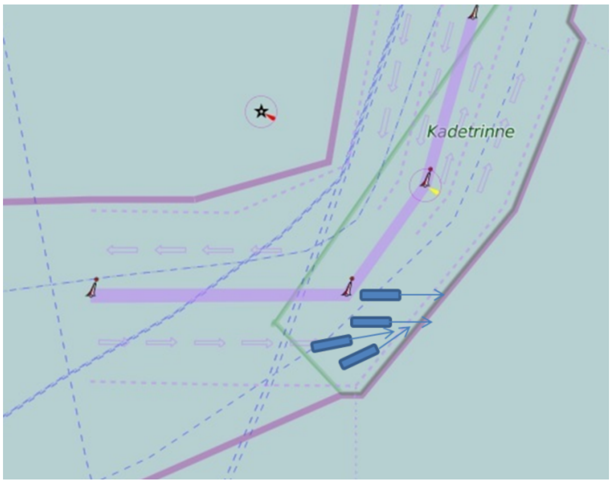


Figure 7. Without routes exchange, the collision occurred

However, our test shows an opportunity to avoid such a collision by sharing the planned routes between the vessels. Thus, the crews of each ship involved in the accident would be aware of the intentions of the others, and could react efficiently by modifying the planned routes to avoid such an accident.

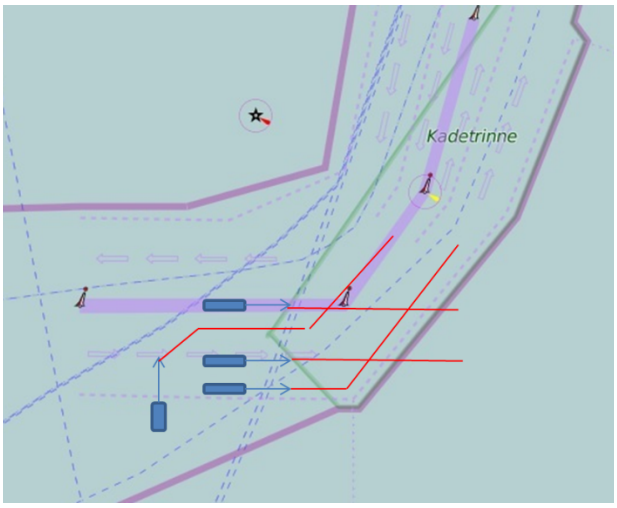


Figure 8. Given the routes of other ships, the collision can be avoided

For radar shadowing, two simulated scenarios were tested for obstacles such as big moving ships or building structures. The results show that some ships can be hidden for specific radar but the distributed DSMS detects this interesting blind area and provides the obstructed radar with this important missed information.

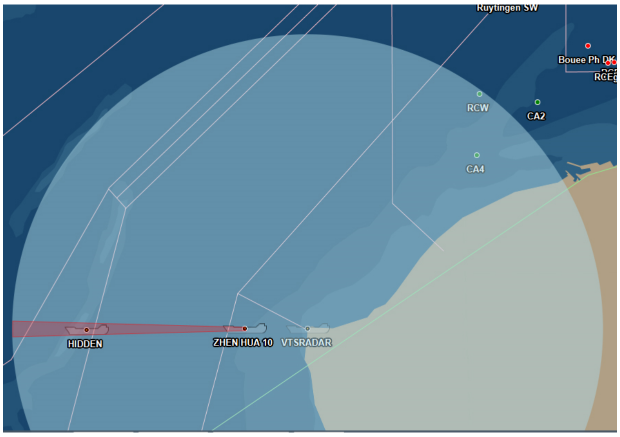


Figure 9. Radar shadowing is detected and information about hidden ships is exchanged

Conclusions

The COSINUS project contributes to e-navigation strategy to improve the maritime traffic safety by enabling automated data exchange between different running navigational systems on ship- and shore-sides. This data exchange is done by a distributed DSMS which consists of many instances of Odysseus, each of them is considered to be installed and integrated with the navigation system to be supported by such a DSMS instance. That is, an instance of Odysseus will be installed as a supporting system for the VTS on shore and other instances for ECDIS on ships. This distributed

DSMS enables sensor fusion to gather the required information from different sensors (radar and AIS transceivers), and based on the new available information from data exchange, the distributed DSMS offers many useful applications such as detection of potential missed targets in radar shadowing areas, calculating and monitoring the radar ranges to detect any missed target, ensuring high quality observations for radars and early and accurate prediction of potentially critical situations. Each of the applications is supported with a novel HMI in order to highlight such a critical situation to the users of the navigation systems. The work presented in this paper has been done in the project COSINUS which is funded by the Federal Ministry of Economics and Energy under the support code 03SX367D.

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