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Navigation decision support for sea-going ships in port approach areas

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Abstract

Port approaches are high-traffic areas with limited manoeuvring space. Navigation in such areas requires the analysis of large amounts of information, which can impede decision processes. One solution may be the development of decision support systems dedicated to these areas. This paper presents an attempt to build a navigation decision support system operable in the approach area leading to the port of Świnoujście (Poland), with ship domain implemented as a safety criterion. Assumptions for a decision support system to be used by sea-going vessels in port approach areas are formulated and discussed. Specific features of these areas, such as traffic density, bathymetry, available manoeuvring space and legal limitations are taken into account. The source and scope of information available to the ship have been analysed. The scope of decision support has been defined. A ship domain has been proposed as a safety criterion. Approach areas leading to the port of Świnoujście have been investigated on the basis of real Automatic Identification System (AIS) data. Vessel movement processes in the chosen area were analysed. Ship domains in various parts of the area were determined. The first results concerning criteria for navigational safety assessment are presented. The conducted studies showed significant differences in the size of domains. A case study was performed on a decision support system operable in the approach area leading to Świnoujście.

Introduction

The ongoing development of modern information technologies (IT) opens up new possibilities for information management and navigators' decision support in the process of ship conduct. In the long run, technological progress creates opportunities for the implementation of autonomous vessels. The navigator's decision support module can be a significant piece of equipment on the navigating bridge and will be a major subsystem on an autonomous ship. Research in this field has been carried out for a number of years and the first navigation decision support systems have now been installed on seagoing vessels. They have been devised to work effectively in the open sea. Navigational decision support in restricted areas, however, including port approaches, fairways and port waters, should take into account the specifics of these areas; factors such as increased vessel traffic, constraints on the selection of the route, varied hydro-meteorological conditions and associated phenomena. Consequently, compared to open-sea decision support, the scope and method have to be modified as the criteria for situation assessment and route selection will be different.

The main purpose of the paper is to present and discuss assumptions for a decision support system for application by sea-going vessels in port approach areas. The proposed solutions are based on state-of-the-art analysis of existing systems, available technologies and systems developed, as well as experiences of navigational decision support systems for seagoing ships. First, navigational safety criteria for ships in port approach areas are presented and discussed. The authors propose the ship domain as the safety criterion and present preliminary results.

The expression "ship domain" was introduced in the 1970s and refers to safety zones in terms of collision avoidance. Many definitions of ship domain have been proposed in the literature. For instance, Fuji and Tanaka define the ship domain as the area around the ship which should be kept clear of other objects (Fuji & Tanaka, 1971). The ship domain and methods for its determination are described and analysed in seventh section.

Related works are discussed in second section. Systems for improving situational awareness and decision support systems are examined. In view of growing interest in autonomous ships, automatic ship steering along a pre-set trajectory is also mentioned. The port approach area and its specific character are described and discussed in third section. The scope and quality of decision support systems depend on information available to the system: navigation information sources and the information they provide are presented in fourth section. Attention is drawn to information acquired in the manual mode. An example of the approach area of the Polish port Świnoujście is taken into consideration in fifth section. The general assumptions for the decision support system in a port approach area are formulated in sixth section. These result from the area's features and availability of information, as well as premises and limitations of navigation decision support systems. Safety criteria, especially the ship domain, are key issues for the generation of a navigation situation solution, discussed in seventh section. A case study is reported in eight section, which examines available AIS data covering the approach area of Świnoujście. Ship domain is proposed as a safety criterion in that analysis. Section ninth discusses the determination method and established ship domains for different types of ships, as well as sub-areas. An attempt to build a decision support system operable in the approach area leading to Świnoujście, with ship domain implemented as a safety criterion is presented in tenth section, followed by conclusions formulated in eleventh section.

Literature overview

As navigational accidents continue to happen, the issue of prevention of collisions at sea remains a constant concern. Actions taken go in different directions. One approach is improving situational awareness through advances in navigational and communication equipment on ships and in land-based centres (Thombre et al., 2016, Thombre et al., 2017). This is related to increased quantity of information available on the bridge. In order to relieve the navigator, data are subjected to integration and fusion, while data selection and display are tailored to suit the situation and the navigator's needs. Example systems are Electronic Chart Display and Information System ECDIS (Xiaoxia & Chaohua, 2002), pilot navigation systems (Gucma et al., 2008; SEAiq Pilot, 2017; seaPro Pilot, 2017), and docking systems (Gucma & Gucma 2010, Trelleborg, 2017). These systems principally have functions of warning and alarming based on predefined rules and criteria. However, they do not automatically generate solutions to existing collision situations.

In another approach, attempts are being made to automate the process of collision avoidance: making a decision on required manoeuvres and manoeuvre performance. A lot of attention is paid to methods of determining a ship's safe trajectory in collision situations to work out and support a decision). These methods are designed for encounters of two or more ships in open and restricted waters. Various methods are proposed for safe trajectory determination, including both static and dynamic optimization methods: they employ classical, heuristic and artificial intelligence (AI) using evolutionary algorithms, fuzzy logic, ant algorithms or neural networks (Tsou & Hsueh, 2010; Szłapczyński, 2011; Śmierzchalski et al., 2013; Lazarowska, 2015). Using them in practice requires several steps, including:

- adopting criteria for navigational situation assessment and criteria for track choice;
- implementation of proposed methods in the form of applications available on board or at land-based centres.

The research also includes processes of automatic ship steering along a preset trajectory (Bertram, 2000; Fossen, 2011). This is particularly important in view of growing interest in autonomous ships (Blanke, Henriques & Bang, 2017; IMO MSC, 2017).

Methods and algorithms for determining the safe trajectory of ship movement find applications in navigational decision support systems (Pietrzykowski, Wołejsza & Borkowski, 2017). These systems, in addition to information functions, which are typical of such systems, generate suggested manoeuvres and ship trajectories in collision situations, together with a justification of the proposed manoeuvre.

The first navigational decision support systems to be used on sea-going ships, launched on the shipping market, are NAVDEC and TOTEM PLUS Decision Support Tool (Pietrzykowski, Wołejsza & Borkowski, 2017; Totem Plus, 2014). Presently, these systems are designed to support navigational decisions in open areas and do not account for the specifics of navigating in approach channels and port waters. Pilot navigation and docking systems mainly perform information functions, where manoeuvres of other vessels are not taken into consideration. In addition, the scope of docking system operation is limited to manoeuvres within port basins.

The complexity of navigational situations in port approach areas, due to heavy traffic, different types and sizes of ships, and a great variety of tasks performed by vessels moving in a restricted manoeuvring area, reduces the applicability of the decision support systems discussed above.

The scope of such systems may be extended by dedicated navigational decision support systems. A major challenge in tackling problems associated with restricted areas is to determine the scope of decision support and the criteria for situation assessment, which is needed for the identification of collision situations and their subsequent solution.

Port approach areas

Port approach areas are waters adjacent to fairways, anchorages and conventional boundaries of port waters. Currently, port waters are frequently covered by vessel traffic services systems, defined by lines marking the obligation to report on VHF radio. Vessels within such an area, upon reporting, identification and providing the required information, are obliged to keep continuous radio watch on a recommended VHF channel (ALRS, 2015). At the same time, if a ship needs additional navigational information and legal advice, it can count on professional information from the system operator. It is particularly important where assistance is needed to identify small vessels not equipped with the automatic identification system (AIS). The intervention of a system operator may prove to be particularly helpful in establishing communication with small ships' crews, often using only their native language. Another benefit is the access to current information on hydrometeorological conditions (e.g., seasonal water level, current direction and speed) and the availability of the most recent navigational warnings.

In port approach areas, as in most restricted waters and narrow passages, the parameters commonly used, such as the closest point of approach (CPA), time to CPA (TCPA), bow crossing range (BCR), bow crossing time (TBCR), or automatic acquisition ring, prove to be insufficient. Their use in the approach area is usually very difficult and requires much experience in their interpretation and practical application. This is clearly visible in the case of ARPA's automatic acquisition ring, which is often replaced in approach and other restricted waters by sectors with different radii covering selected ranges of relative bearings (safety zones).

Port approach areas are characterized by:

- rapidly decreasing depths;
- dense passenger ferry traffic, including high-speed craft;
- intense traffic of small, non-convention vessels;
- presence of vessels and boats engaged in fishing;
- seasonal traffic of pleasure craft;
- traffic of offshore vessels, often signalling the status of a 'hampered vessel';
- high waves, occurrence of tides and currents;
- vast water areas completely or temporarily closed for navigation, or marked as special areas where non-standard principles are in force;
- intensive offshore engineering work and operations, sometimes not published in advance in navigational publications;
- vessels arriving at or departing from the port from/in various directions, in contrast to the open sea, where ships generally proceed along established routes;
- frequent multiple encounter situations.

Sources of navigational information

Navigational information is provided by standard shipboard devices and systems. The equipment includes a log, gyrocompass, radar and echo-sounder. The navigator's decisions are supported by such systems as ARPA (Automatic Radar Plotting Aids), AIS – (Automatic Identification System), ECDIS (Electronic Chart Display and Information System), GNSS (Global Navigational Satellite System), e.g. GPS (Global Positioning System).

The basic information functions of the ARPA system include the determination and presentation of movement and approach parameters of ships tracked manually or automatically (course, speed, bearing, distance, closest point of approach) and signalling dangerous situations based on preset values of CPA and TCPA).

AIS is a system providing automated data exchange between two ships, or a ship and a coast station for identification and collision avoidance. AIS information functions include the repeated automatic transmission of the ship's static and dynamic data. The static data comprise the ship's IMO number, call sign and name, parameters and type. The dynamic data include position and movement − course and speed − parameters of vessels. Other transmitted data include voyage-related information: draft, dangerous cargo, port of destination, estimated time of arrival, and short safety messages, updated if necessary.

ECDIS is a navigation information system, displaying information from its system electronic navigational chart (SENC), including soundings and ship's position from sensors and systems connected: gyro, log, radar, ARPA, echo-sounder, AIS, GNSS, and others. The system determines ship movement and approach parameters, and generates alarms and warning messages concerning the present navigational situation.

GNSS systems, such as GPS, provide positional information and parameters of own ship movement, used in AIS and ECDIS systems. Approach areas and port waters may be covered by systems offering greater positional accuracy, e.g. Differential Global Positioning System (DGPS). Safety information available on board also comes from satellite systems, NAVTEX and GMDSS.

Vessel Traffic Service systems are an important source of information in port approach areas. VTS operators provide information for general vessel traffic or, on request, send it directly to a specific ship. Depending on the VTS centre's range of services, it may provide navigational assistance to an individual ship. Exchanges with VTS operators take place in the manual mode, via voice communication using VHF radio. It should be expected that this information will eventually be sent electronically in the automatic mode.

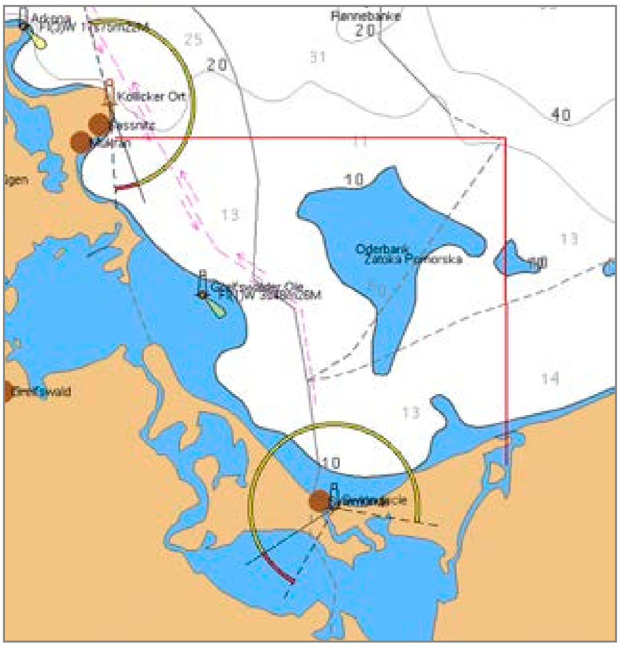

Figure 1. The reporting lines and VTS Świnoujście coverage area (Transas ECDIS NS 4000)

The approach area of the Świnoujście and Szczecin seaports

The approach area of the seaports Szczecin and Świnoujście chosen for this analysis is shown in Figure 1. The area of mandatory reporting for vessels over 20 m in length is bounded by the lines:

a) from the North by parallel φ = 54° 30' N;
b) from the East meridian λ = 014° 45' E;
c) Polish coastline;
d) the sea border line between Poland and Germany, with monitoring of adjacent sea waters of Germany.

Assumptions for the navigator's decision support system in approach areas

Preliminary assumptions that are assumed functionalities for a decision support system to be operated in port approach waters have been formulated on the basis of the analysis of existing navigational systems and the characteristics of these areas. It has been assumed that the system will combine the properties of previously examined pilot systems and navigational decision support systems operated in the open sea. The basic functionalities are as follows:

1) automatic acquisition and distribution of navigational information;
2) determination of the ship's position in an area with specific accuracy;
3) navigational situation display readable to the navigator;
4) analysis of the navigational situation;
5) signalling dangerous situations and displaying the present level of navigational safety on the basis of the criteria used by expert navigators;
6) manoeuvre planning by the navigator;
7) automatic verification of the planned manoeuvre on the basis of established criteria for navigation safety;
8) automatic generation of manoeuvre/s and ship's trajectory in collision situations on the basis of established criteria for navigation safety;
9) justification of the automatically planned manoeuvres;
10) interaction with the navigator.

Generating a ship's trajectory in collision situations will be an important functionality of the system, taking into account the safety and economic criteria, such as lengthened track or increased fuel consumption.

The justification function interprets the navigational situation based on the regulations in force and justifies the manoeuvres proposed and generated by the system.

In the user-friendly navigational situation display, similarly to pilot navigation systems, information is limited, but includes the assessment of the situation.

A preliminary analysis of the assumptions for a navigational decision support system in approach areas refers to the waters of Świnoujście and Szczecin seaports.

Safety criteria

The two criteria (safety and economy) used for analysis and assessment of a navigational situation and determining the ship's trajectory are vital for functionalities 4, 5, 7, 8 and 9. In addition, the specific character of a given area, including restrictions of the manoeuvring area and increased vessel traffic, must be taken into account.

The principal safety criterion used in navigational practice, more precisely in radar and anti-collision equipment, is the closest point of approach, or CPA. The limited dimensions of a navigable area often force the navigator to set varied minimum CPA, depending on relative bearings: for this reason, it is difficult to apply the CPA criterion in confined waters.

These limitations, however, are overcome by using the ship's domain.

Domains proposed by various authors can be divided into two- and three-dimensional ones (2D and 3D). The former describe an area around the ship. Typical shapes of two-dimensional domains include a circle, rectangle, ellipsis, polygon and more complex planar shapes (Goodwin, 1975; Coldwell, 1983; Hansen et al., 2013).

This area is bounded by a line herein referred to as the ship domain boundary GD_S. If we assume a certain level of discretization of relative bearings (e.g., $D\angle K = 5°$), GD_S is described by a curve passing through n points p_{Di} ($i = 1, 2,..., n$), situated on the relative bearings $\angle K_i$ at distances d_{DKi} from the ship's centre (e.g. centre of the waterplane) (Pietrzykowski, 2008):

$$GD_S = \{p_{D1}, p_{D2}, ..., p_{Dn}\} \quad (1)$$

The size of ship domain D_S at each relative bearing sector is then described as follows:

$$D_S(\angle K_i) = d_{DKi} \qquad i = 1, 2,..., n \quad (2)$$

The determination of ship domain requires its boundary to be identified. Three groups of methods for ship domain determination are proposed: statistical, analytical and methods using AI tools. Analytical methods allow the ship domain to be described with a number of more or less complex equations or equation systems, which determine, for example, the length and breadth of the domain (Śmierzchalski & Weintrit, 1999; Dinh & Im, 2016). AI methods allow the acquisition and representation of navigators' knowledge for domain identification using, inter alia, artificial neural networks and fuzzy inference systems (Zhu, Xu & Lin, 2001; Pietrzykowski, 2008). Statistical methods (Goodwin, 1975; Coldwell, 1983), consist of recording trajectories of ships' movements and calculation of ships' track density. The ship domain boundary is determined on the basis of ship track density around the ship. For this purpose, real data e.g., from AIS or ARPA, can be used (Hansen et al., 2013), as well as data registered in simulation experiments (Pietrzykowski, Wielgosz & Siemianowicz, 2012).

The domain shape and size depend on several factors, including ship parameters, the area, hydro-meteorological conditions and vessel traffic intensity. Navigational dangers and special areas should also be taken into consideration.

Traffic processes in the approach area of Świnoujście and Szczecin seaports

The present analysis of vessel traffic makes use of AIS data recorded within the month of April 2017.

Figure 2 illustrates traces of vessels in the approach area to Świnoujście, recorded in April 2017.

The analysis comprised all vessels over 20 m in length proceeding in the area covered by the requirement to report to VTS Świnoujście. The total number of recorded vessels was 3,907. Their average length was 54.5 m.

The traffic is mainly composed of small coastal and Baltic Sea trading vessels.

Figure 3 illustrates the traffic of vessels moving in or out of the VTS Świnoujście area, registered on the VTS reporting lines. The ship number graphs indicate main directions of traffic flow to the port of Świnoujście.

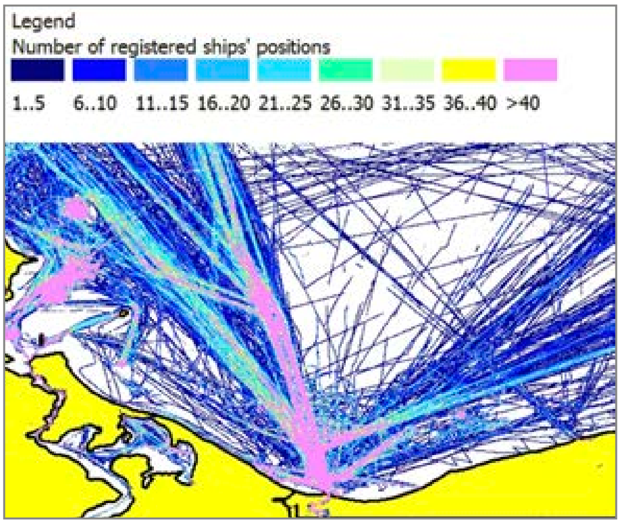

Figure 2. Vessel traffic in the Świnoujście approach area in April 2017

Table 1. The number of recorded vessels by specified type and length

Type	Number of vessels	Length [m]	Number of vessels
Passenger	382	<100	3201
Bulk carrier	842	<=150	291
Tanker	124	<=200	372
Other	2559	>200	43
Total	3907	Total	3907

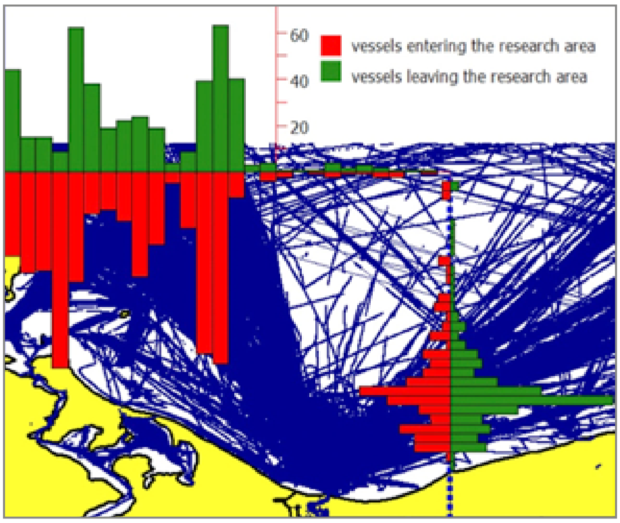

Figure 3. Ships crossing the reporting lines in the VTS Świnoujście area a) crossing northern reporting line, b) crossing eastern reporting line (ingoing ships in the area – green, outgoing ships – pink)

The total number of recorded vessels was 603, with an average length of 62.8 m. Some of them repeatedly entered the area under consideration. These included passenger ships, pleasure craft and fishing boats equipped with class A AIS receivers. A large group consisted of passenger ships, including passenger-car ferries trading on regular lines (Table 2: compare with Table 1).

Table 2. The number of recorded vessels of different MMSI numbers by type and length

Type	Number of vessels	Length [m]	Number of vessels
Passenger	19	<100	479
Bulk carrier	247	<=150	78
Tanker	26	<=200	35
Other	311	>200	11
Total	603	Total	603

On average, each ship entered the examined area 6.5 times, while the most frequent passenger ships crossed it 20 times, ships of other types eight times.

The ship domain as a criterion of navigational safety

The ship domain has been adopted as the basic criterion of navigational safety. The 2D domain was assumed to be an ellipse. In the case of the 3D domain, it can be considered a solid with an elliptical base of the same size, and a height depending on the draught and adopted underkeel clearance.

Parameters of the ellipse representing a 2D domain are determined on the basis of real AIS data on ship movement in the area based on the method described in (Pietrzykowski & Magaj, 2016). It is determined in the following steps:

1. The transformation of the data on ship movements in the area from the true motion display to relative motion display, with the coordinate system origin fixed to the ship (ship's AIS antenna position).
2. Determination of vessel track density.
3. Determination of the ship domain using the adopted method – identification of the domain parameters for the examined areas, taking account of the type and size of the recorded vessels.
4. Approximation of the domain to an ellipse.

In the preliminary stage of the research, domains were determined for passenger ships arriving at Świnoujście from NNW for the research area (2) and for its distinguished part (2A) (Figure 5). The area below the roadstead was excluded (port entry/exit area 3). The excluded area is characterised by increased coastal traffic. Vessels entering the port are observed to reduce speed.

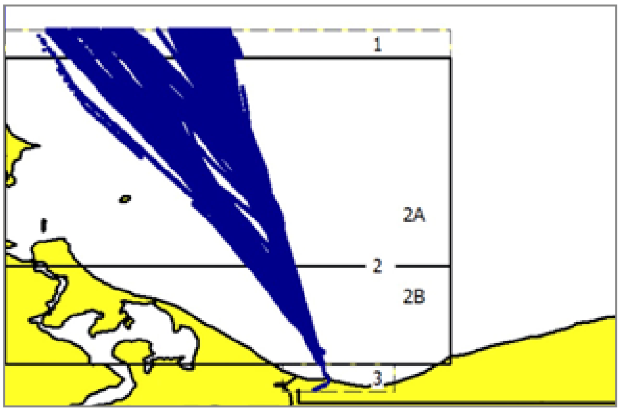

Figure 4. Selected ships' tracks in researched parts of the Świnoujście approach area (1 – traffic flow identification area, 2 –research area, 3 – port entry/exit area)

Figure 5 shows the ship domain determined for the research area, and Table 4 lists domain parameters for both cases.

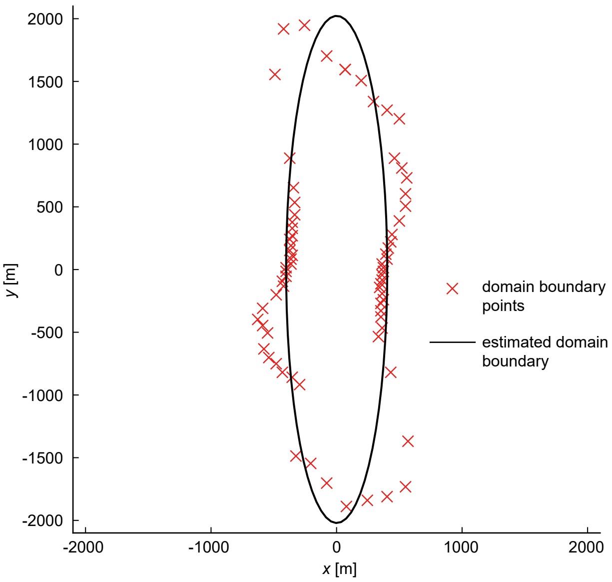

Figure 5. Passenger ship domain in Świnoujście approach area (2A)

Table 4. The domain parameters of passenger ships entering the port of Świnoujście from NNW: *a* – semi-minor axis; *b* – semi-major axis

Area	*a* [m]	*b* [m]
Research area 2	285.6	1694.8
Area fragment 2A	807.2	4045.4

There were clear differences in the size of both domains. It should be expected that the domain size in the excluded area 2B (Figure 4) will be much smaller than domains described in Table 4. This necessitates modification of domain size in various parts of the approach area, which should be examined in further research. At the same time, small values of *c* and *d* parameters were observed, both describing the displacement of the domain centre (ellipse) relative to the ship. The confirmation of the above can facilitate the situation assessment and the ship's safe trajectory determination.

The observed differences of estimated ship domains and a large number of factors influencing their parameters leads to the use of AI methods for this purpose, including artificial neural networks. Such attempts have already been performed. The same concerns ship route determination with the use of genetic algorithms, fuzzy inference methods, ant colony algorithms, or multi-stage fuzzy control. Knowledge engineering methods and tools will be used for this purpose, i.e., machine learning.

The navigation decision support system in approach areas

We have examined the feasibility of building a decision support system operable in the approach area leading to Świnoujście that would meet the assumptions set forth in sixth section.

Sources of navigational information available on board enable automatic acquisition of navigational information necessary in the process of safe ship conduct (assumption 1). It is expected that research in this field will bring additional information, e.g., planned manoeuvres or intentions in ship encounter situations. Such solutions are currently being developed and may significantly contribute to raising the situational awareness of the ship's watchkeeping navigator.

The development of satellite information and communication technologies, measuring instruments and resources results in reliable and accurate data for the parameters of own ship movement and of other ships, including their positions (assumption 2).

It seems justified to apply initially 2D domain and, ultimately, 3D domain, as the criterion for navigational situation assessment (assumptions 4 and 5). An example implementation is shown in Figure 6 based on real AIS data. The ship domain boundary shown on the ENC identifies the area that is supposed to be clear of other objects: it seems that this way of presenting the safety criterion meets assumption 3. The task remains to develop methods and modes of displaying other navigational data/information important in the decision-making process.

The domain display facilitates manoeuvre planning by the navigator, and verification of this manoeuvre using computer simulation (assumptions 6, 7) At the same time it justifies the need for designation and the manner of solving a collision situation (assumption 9).

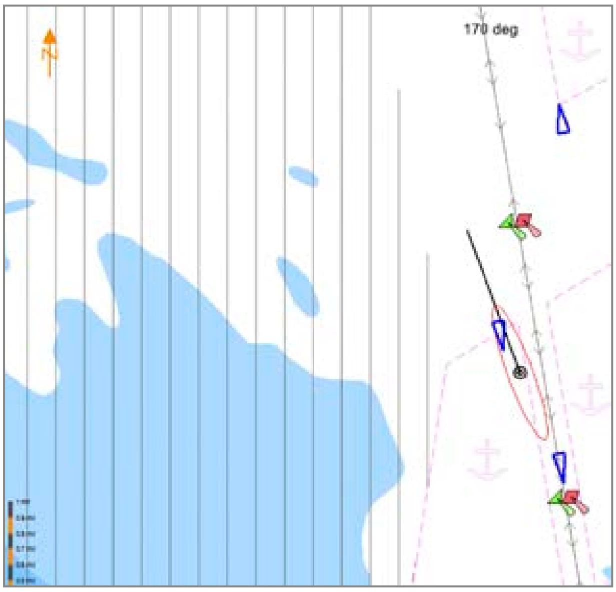

Figure 6. The ship domain in assessing a navigational situation in the Świnoujście approach area

The use of the ship domain criterion and other criteria established by the navigator, such as economy (cost-saving), permits determination of a safe trajectory (assumption 8). A number of methods and tools can be used in this context, dynamic optimization methods in particular. It is also worth considering suboptimal methods, including those based on AI, such as genetic algorithms and methods of control in the fuzzy environment. It should be pointed out that these methods are known, and so are examples of their implementation for collision avoidance functions. The biggest challenge seems to be to define criteria for situation assessment and route choice in collision situations. Preliminary studies confirm the complexity of this issue and the need for further research. This refers to a number of factors; in particular, ship and water area parameters. An issue that remains to be settled is the scope and method of system-navigator interface (assumption 10). Solutions currently used in this type of system for open sea areas may prove useful.

Conclusions

Navigator's decision support in port approach areas remains an important issue, because dense vessel traffic and confined waters always create threats to personnel, ship, cargo and the environment. This type of system has to meet several assumptions. The case study herein described refers to the approach area of Świnoujście seaport. Available IT technologies enable the construction of such a system. The presented research results indicate significant changes of situation assessment criteria, in this case ship domain, on such areas. It is necessary to conduct further research, focusing on the identification of the ship domain as a criterion of navigational safety, taking into account vessel parameters, specifics of the area and current traffic conditions. One possible solution will be the use of artificial neural networks for these purposes. In addition, other AI methods and tools, such as fuzzy inference systems and genetic and evolutionary algorithms, will be tested for safe trajectory determination, especially in multi encounter situations.

Experience achieved in developing navigation decision support systems for seagoing ships will be very valuable in the development of a similar system for port approach areas. The construction of navigational decision support systems for use in port approach areas takes on special significance in the light of increasing interest in unmanned and autonomous ships.

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