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INFERENCE PROCESSES IN THE AUTOMATIC COMMUNICATION SYSTEM FOR AUTONOMOUS VESSELS

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Abstract:

The era of autonomous ships has already begun in maritime transport. The 30-year forecast for the development of marine technologies predicts many autonomous vessels at sea. This will necessitate radical implementation of new intelligent maritime navigation systems. One of the intelligent systems that has to be implemented is a collision avoidance system. The inference process is a key element of autonomous manoeuvres. These authors propose an inference process that enables exchange of information, intentions and expectations between autonomous vessels and gives them an opportunity to negotiate a safe manoeuvre satisfying all the parties concerned. The model of inference in the communication process has been presented. Methods and algorithms for information exchange and negotiation have been developed. These models were implemented and tested under various conditions. The results of case studies indicate that it is possible to effectively communicate and negotiate used the developed method. To demonstrate the effectiveness of the presented approach over 30 random simulations have been carried out. After successful laboratory tests, over 100 scenarios were executed in quasi-real conditions and fully operational conditions. Tests were carried out in the center of the Foundation for the Safety of Navigation and Environmental Protection on Lake Silm in Iława, Poland. In the framework of project AVAL (Autonomous Vessel with an Air Look) POIR.04.01.04-00-0025-16, 82 random scenarios involving four vessels were performed and 60 random scenarios with two vessels. In 2020 tests were carried out in real conditions on the ferries Wolin and m/f Gryf. The communication and negotiation system presented in the article has been designed and developed specially for maritime navigation purposes. The authors believe that the presented solution can be one of various solutions implemented in autonomous shipping in the near future.

Keywords: *automation of communication processes, collision avoidance, autonomous ship, inference processes*

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1. Introduction

While autonomous ships become part of the global maritime fleet, BIMCO prepares a Contract Template for Autonomous Shipping Deals (BIMCO,2020). In a 30-year forecast for the development of marine technologies, many autonomous vessels are expected to trade at sea (Hult et al., 2019). This will necessitate radical implementation of new intelligent maritime navigation systems. The roadmap of such implementation was published in October 2020 (RD Roadmap,2020). Work aimed to build autonomous ships has been undertaken in many countries and for various reasons. The most important goals are to enhance the safety and efficiency of sea shipping. In the region of the Baltic Sea increased vessel traffic as well as a growing number of collision situations and accidents have been observed (Szubrycht, 2020). Another reason is the projected shortage of qualified navigators. The present shortfall of seafarers is notable. Estimated at 16,500 (2.1%), it is expected to rise by 2025 to 147,500 skilled workers (BIMCO,2016). Young people are not interested in working at sea. For example, the number of candidates to the Maritime University of Szczecin was decreasingfor several years in a row, today reaching 50% of the level three years ago.

The number of projects commenced proves that autonomous shipping will be advancing. Although all projects mentioned below are focused on autonomous ships, each of them has its specific purpose. Project MUNIN (MUNIN,2016) was one of the first concepts, while projects Milli-Ampere (Milli-Ampre,2016), Ballstad (Ballstad,2018) and ASTAT (ASTAT-link) focused on short-sea shipping, i.e. ferry shipping in particular. Hull to Hull (Kongsberg,2018) is dedicated to close proximity navigation, while Autoship (Brekke et al., 2019) focuses on target detection. Yara Birkeland (Yara Birkeland,2020) and Ocean2020 (Ocean2020-link) are dedicated to designing and building full-size ships. AVAL (AVAL-link) is one of the first projects to use drone technology for the detection of targets at sea, while Hydrodron (Hydrodron,2020) developed by the Polish company Marine Technology, is used for autonomous hydrographic measurements in port areas, on roadsteads, anchorages, lagoons, bays, lakes, rivers and other narrow areas. A leading research centre, at the Faculty of Ocean Engineering and Ship Technology of the Gdańsk University of Technology, carries out projects related to underwater works (Faculty page-link).

Despite differences between projects and their different goals, there are few factors which are common for each of them. One of the biggest challenges that designers of autonomous vessels face is to develop collision avoidance and communication systems.

2. Literature review

Technically, the modern ship equipped with autopilot and other navigational equipment can sail through the ocean from point A to point B. However, the ship will face a few challenges including heavy weather and various objects. Both have to be avoided. In general terms, ,weather optimization software can also be regarded as collision avoidance systems, as the main goal is to avoid heavy weather and its consequences. The main difference with anti-collision systems for ships is the time span, which in case of weather is much longer.

Currently, the most popular anti-collision system is ARPA (Automatic Radar Plotting Aids). The user can manually acquire targets for tracking. It is also possible to set up automatic acquisition zones. Finally, the user receives reports on tracking objects, including CPA (closest point of approach) and TCPA (time to closest point of approach). Based on visual observation (where possible), the mentioned report and the Collision Regulations (COLREGs) (Rymarz, 2015), the ship's proper behavior can be determined: take action or keep your course and speed) (Lenart, 2015; Ozturk and Cicek, 2019).

Facilities such as Decision Support Systems, e.g. NAVDEC (Navdec-link), are capable of assessing a collision situation and advise a proper action to pass all targets at the presumed safe distance and, at the same, to satisfy COLREGs requirements (Pietrzykowski et al., 2016). Such systems may lay the groundwork for autonomous systems in the future.

Autonomous systems for ships currently draw interest of many researchers (Stateczny and Burdziakowski, 2019; Kulbiej, 2018). One of the reasons is that the International Maritime Organization(IMO) has defined four levels of ship autonomy starting from decision support (Ożoga and Montewka, 2018; Gil et al., 2020) to full autonomy. It is assumed that sooner or later autonomous ships will sail through seas and oceans. To execute such an ambitious goal it is required to determine and plan the vessel's route, which takes into consideration other vessels and objects. Among many proposals of solving this challenge there are approaches, which are based on the existing equipment i.e. ECDIS (Electronic Chart Display and Information System) (Tsou, 2016) or involving artificial intelligence (Zhao and Roh, 2019). Some solutions strictly follow the COLREGs (Naeem et al., 2016) while others look for route optimization (Kang et al., 2018; Koszelew et.al, 2020). Autonomous vehicles and decision support systems are a significant component in shipping as well as other modes of transport. The developed systems work on data from various sources, also taking into account the features of human behavior in order to construct appropriate mechanisms for an autonomous vehicle (Wang et al, 2020).

Despite the provided solution or methodology used for planning a ship's route, it is required to maintain continuous and effective communication to provide up-to-date navigation data necessary to assess the situation and work out solutions.

In business the most common solutions for automatic communication use intelligent agents for submitting and collecting offers (Lin and Kraus, 2012). Agent communication processes make use of, e.g., Knowledge Query and Manipulation Language (KQML) (Finin et al., 1992) and the standards of The Foundation for Intelligent Physical Agents, referred to as FIPA Standards.

The FIPA Agent Communication specifications (FIPA-link) cover messages, message exchange interaction protocols, communication acts based on speech act theory, and content-language representation. FIPA was established to develop software standards, including those for agent-based systems.

Messages sent in accordance with FIPA standards are combined by identifiers into conversations. Consequently, each agent can plan its communication and action strategy and draw conclusions using historical records of conversations. There are many information exchange protocols. In a simple case, the process queries another process and waits for a response before proceeding. In a more developed case, the process allows an indefinite number of responses arriving at irregular intervals in the future. In this case, the client does not know when each message (reply) will arrive and can be busy performing a different task. Such protocols include Request Interaction Protocol, Query Interaction Protocol and Propose Interaction Protocol.

Another interesting language is KQML (Knowledge Query and Manipulation Language) (Finin et al., 1992;). KQML is associated with a protocol. The language is made up of three layers: content, message and communication. Different languages can be used in the content layer as long as both parties to the communication process use the same one. It is therefore not limited by KQML and,for example, the internal language of KIF can be used.

Systems developed for business using the above solutions are characterized by a narrow scope of performed tasks and low flexibility, which makes it difficult or impossible to use them outside the dedicated applications. Compared to those solutions, the communication (Amro et al, 2021) and application processes in sea shipping are not limited to a simple exchange of offers, and on many occasions require a settlement and a solution in a short time. In addition, the above mentioned solutions are commercial outcome. Hence, there are no publications containing a description of the mechanisms and methods used in them

In order to automate communication processes, it is necessary to analyze verbal communication . A characteristic feature of verbal communication processes at sea is the fact that the sender and recipient are not able to use certain communication tools, such as facial expressions, body language, and the tone of voice are limited by hardware capabilities. The communication process between people carries the risk of making mistakes related to, for instance, incorrect perception and interpretation of information (Pritchard, 2010). For this reason, the principles of communication at sea have been developed. One principle holds that messages sent should contain a single piece of information. In case of misunderstandings, navigators are required to use the Standard Maritime Communication Phrases (SMCPs) (IMO, 2000), adopted at the 22nd Assembly of the International Maritime Organization in 2001. Prior to the SMCPs, the Standard Marine Navigational Vocabulary was in use, also developed by the IMO. English as a common language was accepted for navigation purposes, but language difficulties remained. SMCPs were developed as a more comprehensive standardized language, covering all major safety-related verbal messages.

SMCPs contain utterances that have been selected to cover the most important safety and security related areas of verbal ship-to-shore and ship-to-ship communication. The purpose of developing SMCP was to solve the problem of language barriers at sea and to avoid misunderstandings that could lead to accidents.

Voice communication by VHF radio in shipping is carried out in English, adopted as applicable in particular in the case of distress, urgency and safety-related situations . The grammar in such communication is simplified, and the most commonly used structures are question-answer, request-response, and warning / instruction-consent (Pritchard, 2010). The use of the imperative for instructions or orders is typical, that is, the basic form of the verb without specifying the person, number, type, time and mode. The vocabulary used at the beginning and end of the sentence is strictly defined. The beginning contains the sender's name, and the ending usually has the word "Over". The message proper depends on the context.

Communication in shipping is carried out in two ways: broadcasting and exchange. Broadcasting consists in transmitting information, inquiries or warnings, received by all vessels in the specified surroundings of the sender's ship. In the event that, after broadcasting information, specific participants want to continue the dialogue in the form of exchange, they switch to another communication channel. Exchange communication takes place between two participants (one to one).

The transformation of communication from that conducted between people to a fully automatic exchange between systems installed on ships and onshore systems is an ongoing complex process. It includes the automation of communication implemented in three ways: “man to man" - implemented through a computer system, "man to computer system" - in both directions, which may be called semiautomatic communication, and "computer system to computer system" - implemented fully automatically.

There are many studies of the interaction between humans and robots demonstrating the importance of developing an appropriate communication language and protocols for the proper functioning of communication processes (Klingspor et al., 1999). In many cases, it is not limited to language-based interaction (Bonarini, 2020). Additionally, the scope of implemented communication and the development of an application-specific architecture are vital (Tamashiro et al., 2014). However, these studies do not deal with ship-to-ship communication.

Guidelines for communication between ships and land centers and for communication between ships, indicating areas, scope and degree of automation, can be derived from recommendations and regulations on maritime communications contained in the SOLAS Convention (International Convention for the Safety of Life at Sea), standards for GMDSS (Global Maritime and Safety System) and AIS (Automatic Identification System) navigation systems, Admiralty Lists of Radio Signals, SMCP - Standard Maritime Communication Phrases, as well as good marine practices. The automation of communication processes also requires the automation of inference processes conducted so far by people.

It is expected that the automation of communication processes will comprise, among other, selective acquisition of information, including intentions, as well as their automatic interpretation. In the event of divergence of goals, also the implementation of negotiation processes will be included. This requires taking into account the characteristics of the communication process at sea and the specificity of navigational issues in order to be able to manage automated communication processes.

With the development of autonomous ships, the inclusion of communications is increasingly important. These issues call for elaboration and solutions. Currently, the authors have not found publications that would discuss this issue. Most of the solutions in this regard concern the use of existing means of communication, e.g. AIS. However, an interesting solution is based on human-like communication. Communication between robots is based on speech recognition, etc. We believe that autonomous ship communication should be based on inference processes. Such works have not been not presented so far.

The collision avoidance process is complex, hampered by the lack of crew on board. Information could be exchanged externally, e.g. via a base station. In contrast, direct exchange will be faster and easier. Existing systems based on information exchange, not on inference, are currently used. These authors propose a system based on inference.

The process of drawing conclusions based on evidence and reasoning is usually called inference. The inference process in navigating at sea consists of several stages. Bearing in mind that the main objective is safe ship conductwhile maintaining the safety of crew and cargo from the port of departure to the port of destination, we may specify more detailed aspects include mooring manoeuvres, pilotage services, sea passage,anchoring and mooring manoeuvres. The authors focus on the seagoing stage as most probably it will be the first stage executed in the autonomous mode. The collection of evidence (data) in case of an autonomous system is based on data received from the existing systems like AIS and radar/ARPA. These sources can be supported by cameras and lidars (AVAL-link; Hydrodron,2020). The inference process is based on algorithms. These will implement the Collision Regulations and good seamanship practice.

The first inference process, called pre-inference, serves to identify the phase of an encounter situation. The phase is identified from an analysis of the situation in the nearby area, carried out in real time at defined time intervals. The analysis is done on the basis of main parameters, including the distance between vessels, CPA and TCPA ; Wójcik and Banaś, 2016).

3. Situation assessment

The assessment of the situation is very important for the manoeuvre to be performed. Systems on both ships use assessment to communicate, agree and possibly negotiate a collision avoidance manoeuvre. In order to prepare an effective manoeuvre, the current situation should be assessed comprehensively, preferably in the way the human does.

When considering a situation in an open water area, different phases of the ship's encounter can be distinguished. For the purposes of this study, based on, inter alia, Rule 17 of the COLREGs (Rymarz, 2015) six phases are defined:

Phase 1: outside observation area,
Phase 2: observation area,
Phase 3: uncertainty area,
Phase 4: action area,
Phase 5: last moment manoeuvre (LMM) area (Borkowski et al, 2021),
Phase 6: loss minimization area.

In Phase 1, the ships are observing each other, but the distance is too great for action. For the purposes of the communication system, it has been assumed that the distances are greater than 8 Nm. A similar proposal is presented in (Rymarz, 2015), where distance range from 6-8 Nm is considered as the beginning of Phase 2. Since the publication of (Rymarz, 2015), the average speed of ships has increased, the upper limit of8 Nm has been proposed, primarily for safety reasons. This distance can be modified by users.

When the distance between own ship and a target is less than 8 Nm (phase 2), the basic parameters are exchanged together with the manoeuvrability parameters of the ships. This phase covers the area defined by the distance range adopted by the authors, from 3 Nm to 8 Nm. The navigational situation is identified in accordance with the COLREGs and, if necessary, collision collision manoeuvres are elaborated to maintain a safe distance. There is also an exchange of information and intentions of ships in order to maintain safety, including informing about planned manoeuvres and possibly agreeing on joint actions.

Phase 3 begins when the distance between vessels is less than 3 Nm (Rymarz, 2015). This is an area where ships can still perform actions established in the previous phase. If actions are not performed as agreed or communication has not been established successfully, the communication is re-attempted and the expectations of the ships' manoeuvres are expressed.

In Phase 4, the distance is set to less than 2 Nm (Rymarz, 2015), and if there were no effective actions in the previous phases, it is still possible to prevent a collision through joint actions. Entering this area may be related to the non-compliance of the target ship with the activities determined in communication. Even though the classification of the navigation situation shows that the target is a give-way vessel, it is necessary to perform own manoeuvres to avoid collision. Simultaneously with the execution of the manoeuvres, requirements related to the movement of the target ship are sent, for example, to keep the course and speed.

In the event of failure to resolve a collision situation, it is necessary to determine the so-called strong (hard-to-port, hard-to starboard, full ahead, full astern) manoeuvres. The point LMM1 on own ship's trajectory is the position in which we need to start a strong anti-collision manoeuvre to successfully avoid a collision with the target only through own ship manoeuvre. In this case, the distance is not specified as it depends on own ship manoeuvrability.

After passing this point, ships enter Phase 5, in which only the synchronized manoeuvre of the two ships will enable them to avoid a collision. As in Phase 4, the distance depends on ships manoeuvrability. The implementation of such actions is possible until reaching the point LMM2 . There is no negotiation in phase 5 due to time constraints. Communication in this phase is limited to sending requests for manoeuvres of the target and manoeuvres to be performed by own ship. After passing LMM2, the ships enter Phase 6.

In the last defined phase i.e. Phase 6, it is obvious that there will be a collision. Actions that can be taken by the navigators are only related to the minimization of collision losses. Communication therefore consists in suggested manoeuvres of own and target ships.

In the proposed method, the Phases were combined with the inference processes (Wójcik and Banaś, 2016), which had not been proposed before. The division into phases was used in communication.

4. Communication processes in maritime navigation

Conversations in shipping usually consist of three to five message exchange cycles. Message markers are often used, such as question, answer, instruction, request, warning. They allow parties to mark, at the beginning of the message, the intentions associated with the message being sent. In real-time communication, various types of additional polite utterances, unnecessary for the correctness of the communication process, such as "Thank you very much for your cooperation, Bye, Bye", "Good watch to you, Sir, and pleasant journey on the way to ... " However, the necessary markers for message intentions are often omitted (IMO, 2000).

The basic goal of the automation of communication processes is the development of a fully automatic system conducting system-system communication. For the purposes of communication between different systems and creating a user interface, it is also necessary to develop communication and navigation ontologies. They are needed for natural language processing, as discussed in more detail in (Pietrzykowski et al., 2016).

The fully automatic system, the subject of this article, may operate in two ways: as a support for the navigator present on the ship, and as a system operating under supervision. In the navigator support version, the system generates a message and proposes actions, acting as a virtual navigator, working on the basis of available data, presenting the solution via the user interface to the navigator present on the ship and awaiting their acceptance. The navigator controlling the ship accepts or disables actions and messages proposed by the system. Acceptance involves sending generated messages to the target ship and carrying out determined actions, e.g. manoeuvres. In the absence of acceptance, further manoeuvres are performed and messages sent by the navigator present on the ship. The system is still working, offering the navigator determined solutions in subsequent phases of the encounter and informing the navigator about possible threats.

The system operating under supervision automatically generates a message and proposes actions, presenting them through the user interface to the navigator present on the ship and, without waiting for its approval, sends the generated messages and transmits the calculated manoeuvres for implementation. The communication can therefore be fully automatic between the systems or with one-sided or two-sided participation of the navigator, as shown in Fig. 1.

The inference process carried out by the virtual navigator covers the entire navigational situation from the moment the target ship is identified, through the exchange of basic information and agreement of manoeuvres and actions, to the passing of the ships. In accordance with the COLREGs (Rymarz, 2015), three basic encounter situations of ships in good visibility were considered. These are overtaking (Rule 13), head-on (Rule 14) and crossing situation (Rule 15).

The models and inference mechanisms work for open water situations with good hydrometeorological conditions and good visibility, with the option of extending the knowledge base being developed to include other conditions and other water areas. Inclusion of other sea areas would require the implementation of local regulations and, accordingly, rules for inference when switching to such region.

The examined communication is conducted between two ships without additional participants in this process. If it is necessary to communicate with or to be called by another participant for communication, the conversation is conducted separately using the priorities given to the ships. The manoeuvring and classification of the navigational situation takes into account all participants..

The communication processes implemented by the system cover selective acquisition of information, including intentions, as well as their automatic interpretation, and in the event of divergent goals, the implementation of negotiation processes. Inference is made using appropriate mechanisms based on facts and rules contained in the knowledge base (Wójcik et al., 2016, Pietrzykowski et al., 2022)).

The following criteria for the division into individual phases have been adopted (Table 1). The basic criterion for the division is the distance between ships. It includes the LMM1 and LMM2 last minute manoeuvre areas.

In order for the communication to be conducted in an unambiguous manner, rules were developed and stored in the knowledge base for assigning the generated message to the appropriate type and category. The combination of the different types and categories of messages with their meanings and respective phases of the meeting is presented in a tabular form (Table 2).

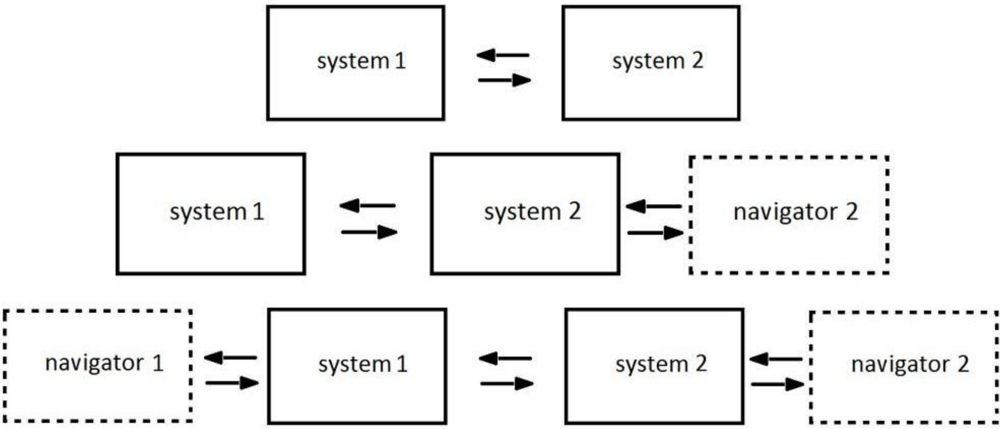

Fig.1. Automatic communication between systems at sea

Table 1. Description of the encounter phases

Phase	Distance - d (Nm)	Description	Communication
1	d>8	Observation	No
2	3<d<8	Identification of the navigational situation. Definition of manoeuvres and trajectory Definition of intentions.	Exchange of the basic information set together with the manoeuvrability of the ship. Possibility to start negotiations.
3	2<d<3	Control of the implementation of actions agreed in phase 2.	Starting communication if it was not carried out effectively in phase 2. Starting communication if actions are not implemented in accordance with Phase 2.
4	LMM1<d<2	Actions compliant with the arrangements. Take individual action with a strong manoeuvre to avoid a collision at the end of Phase 4.	Exchanging intentions and sending requirements for the actions of the target vessel.
5	LMM2<d<LMM1	Take joint action to avoid collisions.	Communicating information on own actions and requesting specific actions from a target ship.
6	0<d< LMM2	A collision is inevitable. Taking action is to minimize losses.	Communicating information on own actions and requesting specific actions from a target ship.

Table.2 Types and categories of messages

Type	Category	Phase	Meaning
question	information	1, 2	**Question about selected parameters of the movement of a target ship.** Content: speed, course, and information about the ship's sea speed or manoeuvring speed.
question	intention	3	**Question regarding intentions.** Content: manoeuvring intentions of the other ship, planned trajectory as well as desired safety criteria, e.g. limit CPA value.
question	permission	2, 3	**Question about permission to perform a specific activity** Content: planned manoeuvre or trajectory, proposed passing at a distance smaller than that defined by the other vessel as the required safe distance.
tell	information	2, 3	**Information concerning selected vessel motion parameters.** Content: ship movement parameters, manoeuvring parameters, reason for refusing to perform specific actions.
tell	intention	2, 3, 4, 5, 6	**Informational regarding intentions.** Contents: planned manoeuvres, trajectory
tell	permission	2, 3, 4	**Message approving or disapproving of a specific planned action.** Content: acceptance or refusal of the ship to perform the specified action.
tell	expectation	2, 3	**Message specifying the expectation of certain actions by the other ship.** Content: actions established at earlier stages of communication, requirements for the other ship, e.g. keeping a certain distance of passing.
tell	request	4	**Message requesting the other ship to perform certain actions.** Content: manoeuvres.
tell	demand	5, 6	**Message demanding that the other ship perform certain actions.** Content: manoeuvres.
tell	warning	5, 6	**Message with an alert attached to another message.** Contents: type / reason for the alert.

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question	permission	2, 3	**Question about permission to perform a specific activity** Content: planned manoeuvre or trajectory, proposed passing at a distance smaller than that defined by the other vessel as the required safe distance.

The description of the implementation of negotiation processes is presented below:
Let us assume that:

- F is a set of facts,
- $R_i = \{r_{i1}, r_{i2}, r_{i3}, \dots, r_{ij}, \dots r_{in}\}$ a set of rules for i-phase,
- U is a set of rules whose premises are facts (activated rules), $U \subset R_i$,
- W is a set of rules used during inference processes, $W \subset R_i$,
- $S = \{s_1, s_2\}$, a set of inference strategies, where s_1 is a strategy consisting in checking rules according to their order established during the construction of the knowledge base, s_2 is a strategy for blocking already activated rules.

Inference appropriate in the i −th phase of the meeting is carried out in six successive steps, which include determining the set of rules to be activated, applying the rule selection strategy, activating the rule, adding conclusions to the fact set, applying the inference strategy for the rule used in the loop until the set of rules to be activated is empty:

Step 1: Determine the set U. If $U = \emptyset$ then go to step 6.
Step 2: Use the $s_1 \in S$ inference strategy to select the rule $r_{ij} \in U$.
Step 3: Activate the r_{ij} rule and add new facts from the conclusion rule to the fact set F.
Step 4: Add the rule r_{ij} to the set of used rules $r_{ij} \in W$.

Step 5: Apply the $s_2 \in S$ inference strategy. If $R_i \setminus W \neq \emptyset$, then go to stage 1.
Step 6: The end.

Facts which, after inference, are added to the set of facts F, are retained in memory for subsequent cycles of message exchange. The system status (meeting phase) varies according to the distance. Facts from previous states are stored in the system memory until the ship is removed from the list of ships with which communication is conducted. After the conversation is over, the memory is cleared. This is due to a change in the context of the next conversation between the same pair of ships, changes in traffic parameters, classification of the navigational situation, meeting phases, etc.

5. Results

The simulation experiment was carried out using an ECDIS simulator at the Maritime University of Szczecin. The ECDIS simulator consists of eight independent NaviTrainer 4000 stations (vessels) from Transas, cooperating with eight ECDIS NaviSailor 3000i stations. It allows implementing various scenarios of ship encounters in selected water areas, and offers several models of ships that have full course and speed maneuvering capabilities. The operator can employ all the systems fitted on the modern navigation bridge, including the AIS (automatic identification system) used in the implementation of the scenarios.

In order to verify automatic communication processes, following hardware and software were used:

1) ECDIS simulator,
2) recorder of data from the AIS, developed and made at the Maritime University of Szczecin;
3) computer workstations carrying out communication processes on both units and recording automatic communication.

Simulations were carried out in the following configuration:

- two stations are manned by operators; each operator canmanoeuvre changing course and/or speed;
- operators receive the results calculated by the system, messages that have been sent and manoeuvres to be performed manually,
- at the beginning of an exercise, the recording starts to store data from the AIS systems of two ships: 'own' and 'target', named as Alfa and Beta, as well as the registration of automatic communication.

The data recorded by the AIS recorder were processed and analyzed in the Matlab.

The purpose of verification was to check the effectiveness of communication carried out automatically, therefore the following features were additionally adopted:

- open water,
- good visibility conditions,
- good weather conditions (no wind, current, no waves),
- communication is carried out between two ships: 'own' and 'target' (Alfa and Beta),
- automatic communication system is available on both ships participating in the tests.

Three variants of navigational situations have been considered: head-on, overtaking and crossing. For each of the variants, several different scenarios have been created, with predefined location, courses and speeds of the ships (depending e.g. on ship type) and various actions of navigators steering the ships.

The recorded communication for the specific vessel contains data on messages sent and received, each in the form of two lines.

The first line contains the following data: year, month, day (e.g. 12/08/2019); hour, minute, second (UTC) (e.g. 120819); information whether the message was sent or received.

The second line contains the following data: communication tag ($ COMM); MMSI (Maritime Mobile Service Identity) of the message sender (e.g. 261181000); message type (e.g. tell); the category of the message (e.g. information); the content of the message (e.g. parameters_set).

The first two messages (Fig 3, 4) aim to exchange the basic parameters i.e. planned route, CPA limit, TCPA limit, manoeuvring/full sea speed. The next two inform of their manoeuvring intentions. In this specific situation (head-on), both ships have to take action. Alpha offers course alteration of 8 degrees to starboard, while Beta 12 degrees to starboard. In the following lines Alfa received a message from Beta with a lack of consent to such a maneuver, because it is insufficient for Beta. Beta has a CPALimit of 1.5 Nm.

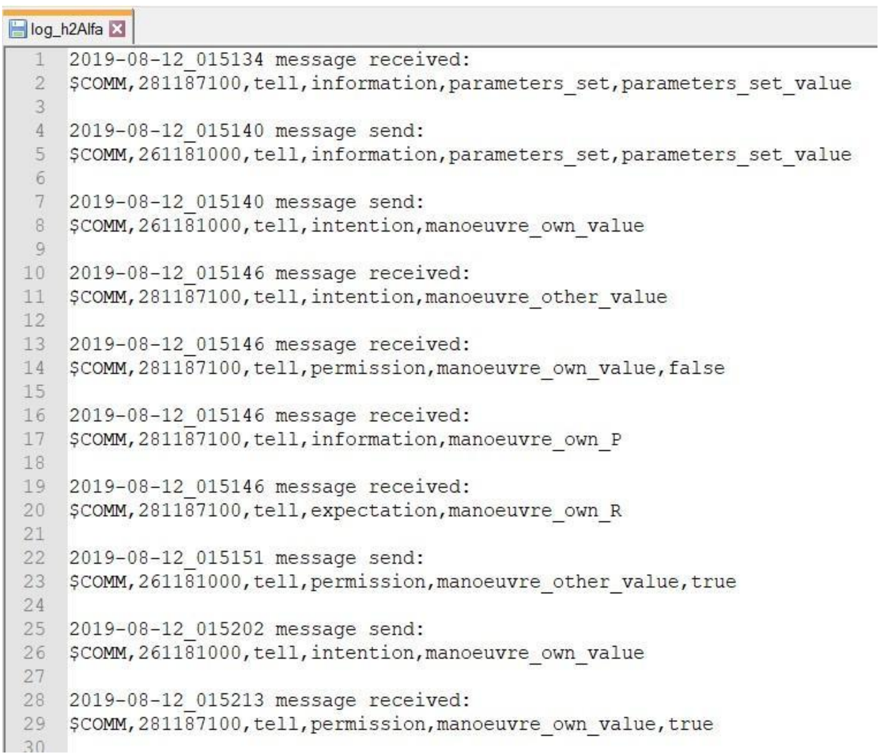
Line 13 contains a message expressing disagreement to Alfa intentions, the following message informs that the reason is the required CPA, the next informs

that CPA 1.5 Nm is required. Based on that information, Alfa transmits new manoeuvring intentions, namely course alteration 12 degrees to starboard. Such manoeuvres are accepted by the Beta ship's system.
After executing the manoeuvres, CPA increased to 1.5 Nm and was maintained until TCPA was less than zero (Fig. 5). Then both vessels altered course to port to return to original trajectories.

The first two messages (Fig 6, 7) aim to exchange the basic parameters. In the following line, Beta, which is the give-way vessel, transmitted her intention i.e. ‘I am going to alter course 17 degrees to starboard. Finally, Alfa accepted that intention.
After executing the intended manoeuvre, CPA increased to 1 Nm. Beta commenced a return manoeuvre, when Alfa safely passed ahead of the other ship (Fig. 8).

Scenario 1

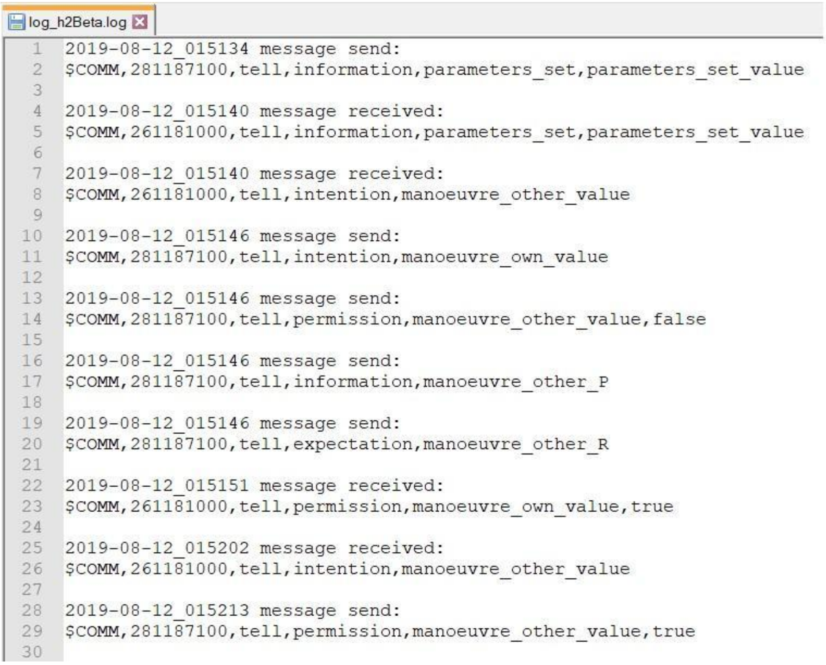
Fig. 2. Initial situation in the scenario 1



log_h2Alfa

```
2019-08-12_015134 message received:
$COMM,281187100,tell,information,parameters_set,parameters_set_value

2019-08-12_015140 message send:
$COMM,261181000,tell,information,parameters_set,parameters_set_value

2019-08-12_015140 message send:
$COMM,261181000,tell,intention,manoeuvre_own_value

2019-08-12_015146 message received:
$COMM,281187100,tell,intention,manoeuvre_other_value

2019-08-12_015146 message received:
$COMM,281187100,tell,permission,manoeuvre_own_value,false

2019-08-12_015146 message received:
$COMM,281187100,tell,information,manoeuvre_own_P

2019-08-12_015146 message received:
$COMM,281187100,tell,expectation,manoeuvre_own_R

2019-08-12_015151 message send:
$COMM,261181000,tell,permission,manoeuvre_other_value,true

2019-08-12_015202 message send:
$COMM,261181000,tell,intention,manoeuvre_own_value

2019-08-12_015213 message received:
$COMM,281187100,tell,permission,manoeuvre_own_value,true
```

Fig. 3. Message log from the ship Alfa (MMSI 261181000)



```
log_h2Beta.log
2019-08-12_015134 message send:
$COMM,281187100,tell,information,parameters_set,parameters_set_value

2019-08-12_015140 message received:
$COMM,261181000,tell,information,parameters_set,parameters_set_value

2019-08-12_015140 message received:
$COMM,261181000,tell,intention,manoeuvre_other_value

2019-08-12_015146 message send:
$COMM,281187100,tell,intention,manoeuvre_own_value

2019-08-12_015146 message send:
$COMM,281187100,tell,permission,manoeuvre_other_value,false

2019-08-12_015146 message send:
$COMM,281187100,tell,information,manoeuvre_other_P

2019-08-12_015146 message send:
$COMM,281187100,tell,expectation,manoeuvre_other_R

2019-08-12_015151 message received:
$COMM,261181000,tell,permission,manoeuvre_own_value,true

2019-08-12_015202 message received:
$COMM,261181000,tell,intention,manoeuvre_other_value

2019-08-12_015213 message send:
$COMM,281187100,tell,permission,manoeuvre_other_value,true
```

Fig. 4. Message log from the ship Beta (MMSI 281187100)

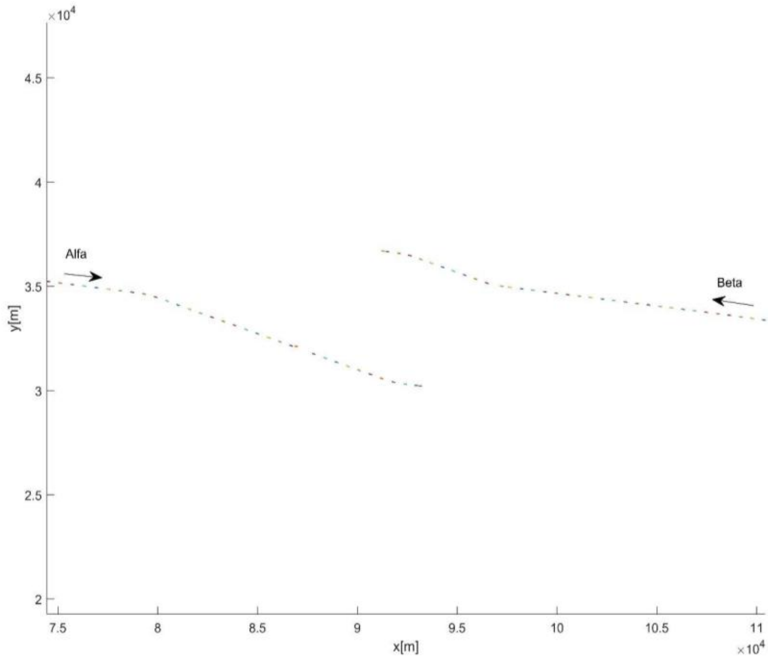


Fig. 5. Alfa and Beta trajectories

Scenario 2

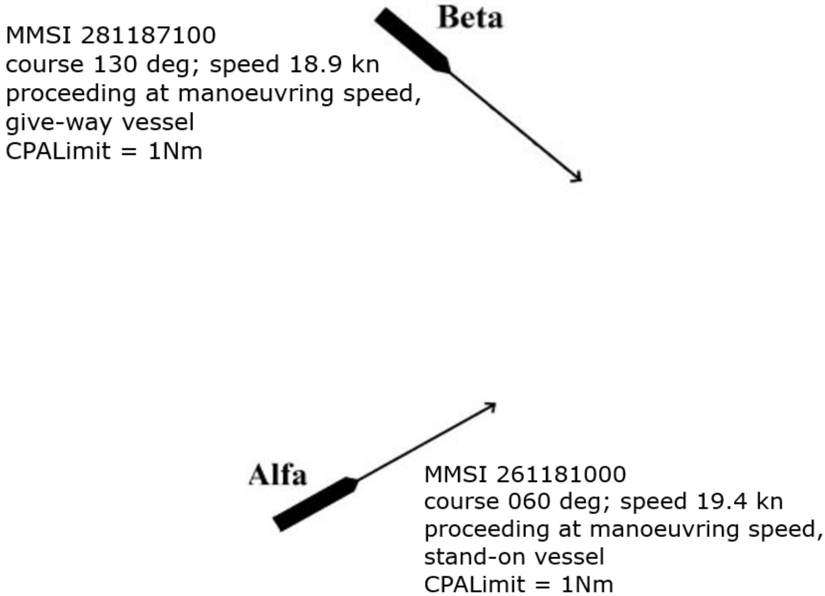


Fig. 6. Initial situation in the scenario 2

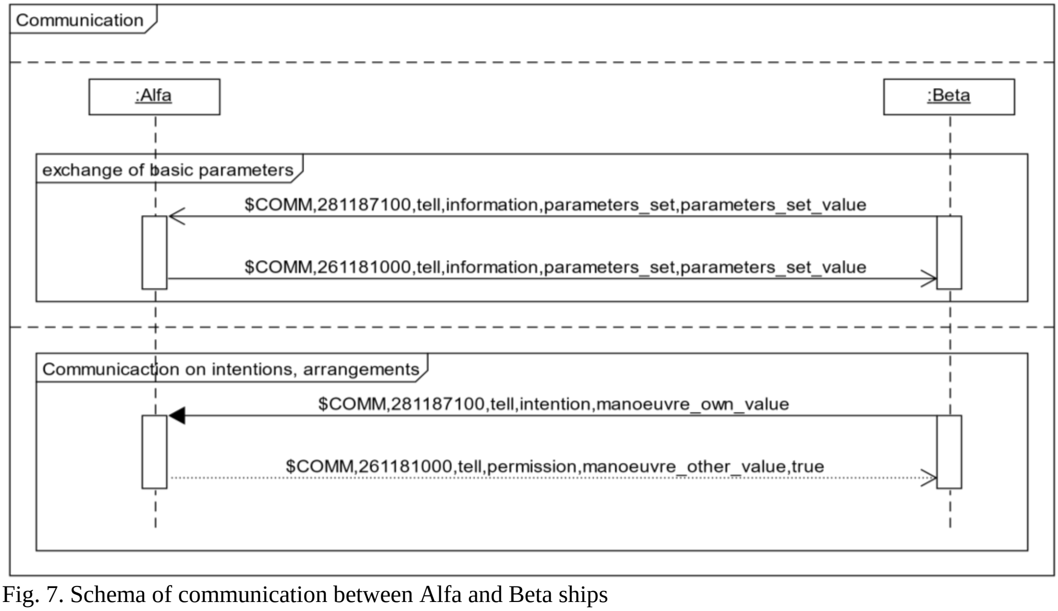


Fig. 7. Schema of communication between Alfa and Beta ships

Scenario 3 (based on a real situation)
The collision between the car carrier Baltic Ace and the container ship Corvus J took place in December 2012 in the North Sea (Bahamas Maritime Autority Report). Despite an early detection of collision risk , neither of the ships took appropriate steps to avoid a collision. The navigators carried out communication to agree on manoeuvres, which was not effective. They misinterpreted each other's manoeuvreing intentions and their final actions did not comply with the COLREGs. Finally, this led to a collision in which the Baltic Ace sank with casualties and huge material damage. Parameters for this scenario are as follows:

- crossing situation between ships Baltic Ace (261181000) and Corvus J (281187100),
- Baltic Ace parameters: course 035 deg; speed 18.9 kn; proceeding at manoeuvring speed, stand-on vessel,
- Corvus J parameters: course 129 deg; speed 13.1 kn; proceeding at manoeuvring speed, give-way vessel,
- The CPALimit distance given by the operators for both vessels is 1 Nm.

The first two messages (Fig 9, 10) aim to exchange the basic parameters. In the following line, Corvus J, the give-way vessel, transmitted her intention i.e. "I am going to alter course 35 degrees to starboard".

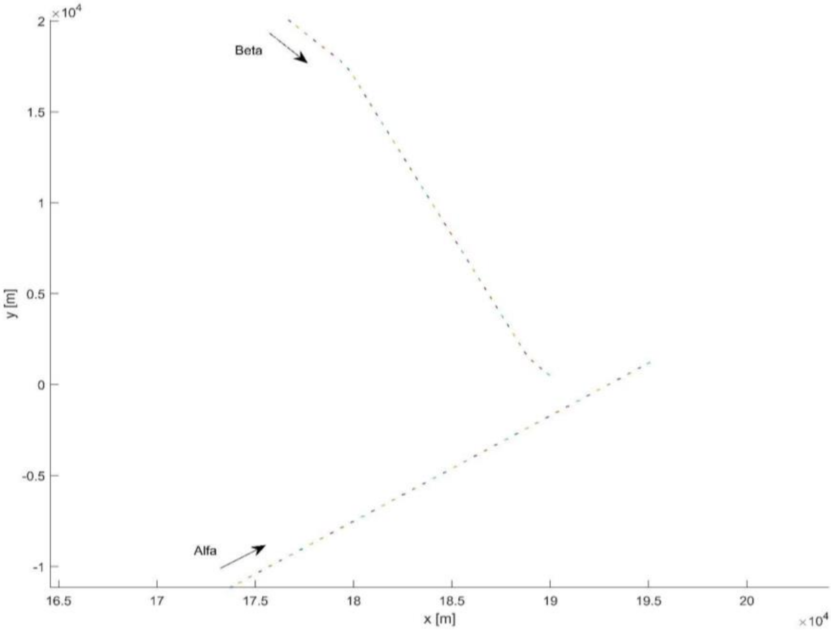
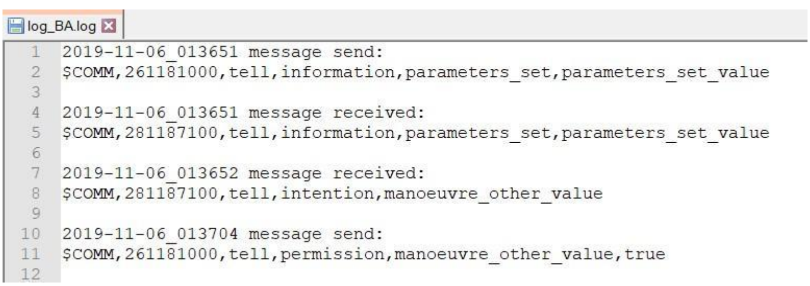


Fig. 8. Alfa and Beta trajectories



```
log_BA.log
1  2019-11-06_013651 message send:
2  $COMM,261181000,tell,information,parameters_set,parameters_set_value
3
4  2019-11-06_013651 message received:
5  $COMM,281187100,tell,information,parameters_set,parameters_set_value
6
7  2019-11-06_013652 message received:
8  $COMM,281187100,tell,intention,manoeuvre_other_value
9
10 2019-11-06_013704 message send:
11 $COMM,261181000,tell,permission,manoeuvre_other_value,true
12
```

Fig. 9. Message log from Baltic Ace (261181000)

Finally, Baltic Ace accepted thats intention. After the intended manoeuvre was executed, CPA increased to 1 Nm. Corvus J commenced a return manoeuvre, when Baltic Ace safely passed ahead of her (Fig. 11).

6. Discussion

Elements of the described systems can be used to automate communication processes in maritime shipping, but it is necessary to develop, inter alia, shipping-specific protocols, language, and inference models and mechanisms.

The paper presents specific protocols, suitable for maritime navigation, or more precisely, for collision avoidance. They were verified in a laboratory, based on simulated (scenarios 1 and 2) and real situations (scenario 3), quasi-real and real conditions.

To demonstrate the effectiveness of the presented approach, over 30 random simulations were carried out. After successful laboratory tests, over 100 scenarios were executed in quasi-real conditions and fully operational conditions. The results show that the presented inference process can be taken into consideration as a solution to be used in autonomous vessels. In all the test situations the vessels avoided a collision.

log_CJ.log

```
2019-11-06_013651 message received:
$COMM,261181000,tell,information,parameters_set,parameters_set_value

2019-11-06_013651 message send:
$COMM,281187100,tell,information,parameters_set,parameters_set_value

2019-11-06_013652 message send:
$COMM,281187100,tell,intention,manoeuvre_own_value

2019-11-06_013704 message received:
$COMM,261181000,tell,permission,manoeuvre_own_value,true

```

Fig. 10. Message log from Corvus J (281187100)

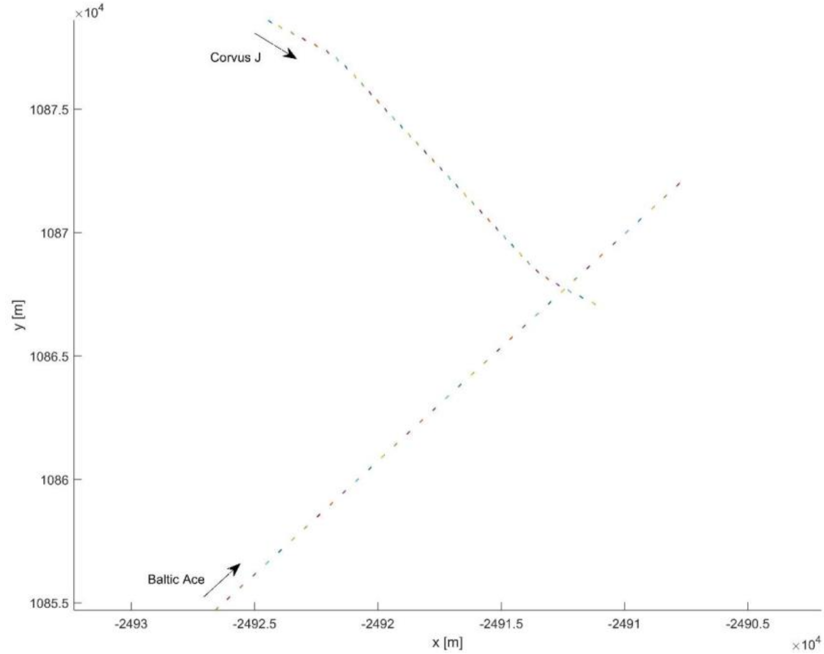


Fig. 11. Corvus J and Baltic Ace trajectories

In the following link, the implementation of the negotiation process in a quasi-real situation is presented: https://youtu.be/bvkdpnw_ypk.
As part of the project AVAL 82 successful random scenarios were performed, involving four vessels and 60 random scenarios with two vessels (Last Moment Manoeuvre). In each scenario, two vessels were autonomous and they carried out effective communication, managing to avoid a collision with other targets. Such implementation was not executed in the projects (MUNIN,2016; Mili-Ampre,2016; Ballstad,2018; ASTAT-link; Kongsberg,2018; Brekke et al., 2019). It is the subject of the projects (Yara Birkeland,2020; Ocean2020-link) where tests were carried out in 2021.
In September 2020 tests were carried out in real conditions on m/f Wolin (top of Figure 12) and m/f Gryf (bottom of Figure 12), two ferries that daily serve on the route from Świnoujście (Poland) to Trelleborg (Sweden). Two vessels were on a collision course. Following a negotiation process, a new trajectory for m/f Wolin was calculated (blue line with 4 waypoints). New courses taken by m/f Wolin enabled her to pass m/f Gryf at the predefined safe distance of 0.5 Nm.

Fig.12. Encounter situation in real conditions (blue line - suggested trajectory based on negotiation)

7. Conclusions

To summarize all test stages i.e. laboratory tests in random and predefined situations, quasi real and real condition tests, it is worth underlining that negotiations were carried out in each situation. The metric of success in each collision situation was CPA. It could not be smaller than the smallest CPA of all the participants in a meeting situation. Only in LMM situations it could not be smaller than zero. In all situations the metric was achieved. To provide communication metric i.e. safety and integrity of transmission during quasi-real and real condition tests, RipEX2 radio modems were used. These devices use digitally signed firmware, CRC32 data integrity control on a radio channel, backup routes, role-based access control, AES256 encryption, IPsec - encrypted end-to-end tunnel, Firewall - Layer 2 – MAC, Layer 3 – IP, Layer 4 – TCP/UDP and FEC, interleaving, proprietary data compression. All this makes the transmission much less susceptible to hacking attacks than, for example, AIS transmission. The contingency plan can be considered on at least two levels. The navigation level provides navigators with solutions at each ship encounter stage. If the navigators do not use the collision avoidance manoeuvre developed, they will still have three chances in the form of LMM1, LMM2 and LMM3. High quality equipment assured high reliability of the communication process. To increase safety, integrity and reliability of transmission, a backup system should be on hand.

The communication and negotiation system presented in the article was designed and developed specially for maritime navigation purposes. The reason was that solutions based on existing KQML and FIPA standards are characterized by a narrow scope of performed tasks and low flexibility. The authors believe that the presented solution can be one of many solutions implemented in autonomous shipping in the near future. They may complement the recently developed and deployed systems like STM https://www.seatrafficmanagement.info/projects/.

The presented models and inference mechanisms were developed for situations in open water, and the inclusion of other water areas requires the implementation of local regulations and, consequently, the rules of inference when moving to such a water area. An additional limitation of the current model is the assumed good hydrometeorological conditions and good visibility. Taking into account other conditions is the next stage of work on the model and on expanding the knowledge base.

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