The problem of cooperative divergence of uncrewed vessels

Sergey Smolentsev[1*], *Anatoly* Sazonov[1], and *Vladimir* Ivanov[1]

[1]Admiral Makarov State University of Maritime and Inland Shipping, 5/7 Dvinskaya Str., St. Petersburg 198035, Russian Federation

Abstract. The article deals with the problem of preventing ship collisions while at sea. When crewless ships meet at sea, it is necessary to ensure their safe separation. A formalization of setting the problem of safe divergence of a group of ships is given. Vessel subsets in various states in a group of ships are determined, and ship transitions from one state to another are described. The problem of a lack of mutual understanding between agents controlling unaccompanied ships is considered. A counter vessel may not perform the divergence manoeuvres that the agent controlling the uncrewed vessel expects. An analysis is made of the reasons contributing to this. The problem of detection of inadequate behaviour of a counter vessel or its violation of manoeuvring arrangements is offered. The criteria for detecting such behaviour and agent's actions to prevent collision in this case are considered.

1 Introduction

The development of the Crewless Vessel is now a promising direction in the development of the maritime industry. In the near future, numerous crewless ships will appear on the world's oceans. This will greatly influence many aspects of navigation, first of all navigation safety [1].

An important component of navigation safety is the problem of safe divergence of ships. The problem is summarised as follows. When ships are moving in such a way that there is a danger of their approaching at a distance less than the specified one, one or several ships must undertake manoeuvres preventing this approach. The principles of safe separation at sea are defined in the International Regulations for Preventing Collisions at Sea (COLREGs). Crewless ships must unconditionally comply with these rules for safe divergence. In [2, 3, 4], the issues of COLREGs in unmanned vessel control systems are outlined.

Active research is currently underway to develop systems for the safe divergence of uncrewed ships. An overview of current research in this area is given in [5]. In a situation of dangerous approach of several unaccompanied ships, there is a problem of cooperative maneuvering, i.e. carrying out joint actions of several ships for the purpose of safe divergence. Works [6, 7] are devoted to this question. In [8] the necessity of distributed

* Corresponding author: kaf_avt@gumrf.ru

coordination between all uncrewed ships is spoken, and in [9, 10] the distributed algorithms of the decision of a problem of safe divergence are considered.

The author [11] proposes an algorithm for solving the problem of safe divergence of ships at sea. In case of cooperative solution of divergence problem by crewless ships, it is natural to speak about working out and realization of collective decision by group of automatic machines, controlling these ships. Accordingly for the decision of this problem the theory of multi-agent systems (MAS) can be used. The similar approach to the decision of a problem of safe divergence was offered by the author in [12]. In this work, an agent is offered to use for the management of each uncrewed vessel. Accordingly, a cooperative decision on safe divergence is made by a group of agents that must be able to exchange information with each other. This article discusses the basic principles of interaction between agents controlling uncrewed vessels.

2 Methods and materials

This paper deals with the problem of cooperative manoeuvring of a group of ships. This problem occurs when two or more vessels in the group come dangerously close to each other. In this case, the actions of only one vessel cannot ensure safe divergence, or actions to diverge from the dangerous vessel can lead to a situation of dangerous convergence with other vessels. In this case, several ships in the group should perform coordinated manoeuvres to bring all ships in the group to a safe divergence. This means to solve the problem of safe divergence jointly (cooperatively).

Uncrewed (autonomous) ships controlled by agents are considered as objects. At the same time, all agents are universal and equal. That is, there is no central (or priority) agent in the group of agents that would coordinate the actions of other agents. Depending on the convergence situation and the status of the ship, each of the agents can play a different role in solving the specific problem of vessel divergence.

3 Problem statement

Consider the set (group) U of ships in a given water area. A subset of ships G can be defined in it, which contains objects of three classes:

- Class A - ships that go dangerously with other ships, but cannot manoeuvre (because of their privileges according to COLREG or other reasons);
- Class B - ships that sail dangerously with other ships and are required to manoeuvre;
- Class C - vessels that do not pose a danger to other vessels, but may manoeuvre;
- Class F - vessels that manoeuvre for the purpose of safe divergence.

Accordingly, $G = A \cup B \cup C \cup F$.

In addition, there may be class D ships in the water area: D = U/G. None of the ships of set D goes dangerous relative to any ships of U. Otherwise, these ships are similarly included in G. Vessels not included in G act as constraints on decisions made for ships in G.

Each vessel has an agent associated with it who manages that vessel. Each agent has its own interest (target function) - a given route of the vessel in the given water area.

The problem of cooperative maneuvering is that by the agents' actions it is necessary to resolve the conflict - dangerous convergence of ships within group G. For this purpose it is needed to change routes of the ships within the group, so that no situation of dangerous approach occurs between the ships, and the total deviation of all routes of the group from the initial ones was minimized. Principles of construction of sets A, B, C, D as well as algorithms of search of decision on safe maneuvering are suggested in [12].

In case of detection of a dangerous convergence situation with another vessel on an uncrewed vessel, the collision warning system solves the task of ensuring safe divergence. The solution to this problem is a new trajectory for the vessel required to give way in this situation. This trajectory is chosen to ensure that not only the dangerous vessel, but also all other vessels in the area are safely diverted.

However, when solving the problem of cooperative manoeuvring, the problem of lack of mutual understanding between different agents may arise. For simplicity, we will consider a meeting of two ships, although in a situation where several ships meet, the problem can only be exacerbated. Let us denote: A is the uncrewed vessel in question, operated by an automatic agent, and B is the oncoming vessel, operated by an agent, which can be both automatic (also uncrewed vessel) and the navigator.

If, in the present situation of a dangerous approach, vessel A should give way, it takes the manoeuvres calculated by it to safely diverge from vessel B. However, if the vessel giving way is an oncoming vessel (B), an uncertain situation may arise. This is because the agent controlling the uncrewed vessel A is not sure that the divergence solution he receives will be implemented by the oncoming vessel B. This is the situation that this paper will deal with.

The problem is that the manoeuvre for safe divergence is calculated by the agent controlling the uncrewed vessel A, and the divergence manoeuvre must be performed by vessel B (which in this case is required by COLREG to give way). However, the opposite vessel B may not behave as expected by the agent controlling the uncrewed vessel A, for various reasons, among which are the following:

1. The agent controlling vessel B may assess the approach situation differently and not define it as dangerous, because:

1.1. he uses other hazard criteria (shape and size of safety domains for himself and other ships, use of same safety domains for all ships, etc.);

1.2. the planned route of vessel B differs from the route predicted in the divergence system on vessel A and is in fact not dangerous.

2. Vessel B cannot perform the manoeuvre obtained in the divergence system A, because:

2.1. the parameters of the ship model B used to calculate the manoeuvre in the divergence system on ship A differ from the dynamic characteristics of the actual ship B;

2.2. external factors, which are not considered in the Divergence System on ship A when making recommendations (e.g. hydrometeorological conditions, depths, etc.) hinder execution of the calculated maneuver.

3. The agent controlling ship B plans to perform a different manoeuvre from the manoeuvre calculated by the divergence system on ship A, because in selecting the manoeuvre:

3.1. on vessel B the COLREG in that particular approach situation is treated differently;

3.2. A and B have differently configured safe divergence systems and accordingly produce different divergence decisions;

3.3. A and B have different sets of external conditions (e.g. when making a decision, either A or B does not take into account other ships, depth, visibility conditions, or other limitations on decisions in those conditions).

In the event of an encounter between two unmanned vessels, the agents controlling them must be able to communicate with each other to develop a common understanding of the current approach situation, unambiguously assess its degree of danger, and develop an agreed divergence decision. For this purpose, it is important for the automatic divergence systems on these ships to implement the use of the situation context proposed in [13], as well as to implement the information exchange protocol between the agents outlined in [14].

In case of encounter of unmanned vessel with vessel controlled by navigator the problem of uncertainty of counter vessel's actions becomes even more acute, because the agent controlling unmanned vessel A, will not be able to organize effective information exchange with the agent controlling vessel B (navigator).

In any case, it is important that the agent controlling the vessel knows exactly how the counter vessel is operated (by crew, remotely or autonomously). This information is proposed to be transmitted as mandatory in AIS.

4 Results

First of all, let us define the states in which each vessel of the group can be. To do this, we consider the process of formation of a dangerous approach situation and its resolution as a sequence of states of the set U. These states differ in the composition of its subsets:

$$U = A \cup B \cup C \cup D \cup F;$$
$$G = A \cup B \cup C \cup F;$$

$A \cap B = A \cap C = A \cap D = A \cap F = B \cap C = B \cap D = B \cap F = C \cap D = C \cap F = D \cap F = \emptyset.$

Let us list the states of the set U:

U1 - All vessels in the water area are moving safely:

$$A = \emptyset,\ B = \emptyset,\ C = \emptyset,\ D = U,\ F = \emptyset,\ G = \emptyset.$$

U2 - Situation of dangerous approach:

$$A \neq \emptyset,\ B \neq \emptyset,\ C = \emptyset,\ D = U/G,\ F = \emptyset,\ G = A \cup B.$$

U3 - Additional vessels are engaged to solve the problem of safe divergence:

$$A \neq \emptyset,\ B \neq \emptyset,\ C \neq \emptyset,\ D = U/G,\ F = \emptyset,\ G = A \cup B \cup C.$$

U4 - Manoeuvring for safe divergence:

$$A = \emptyset,\ B = \emptyset,\ C = \emptyset,\ D = U/F,\ F \neq \emptyset,\ G = F.$$

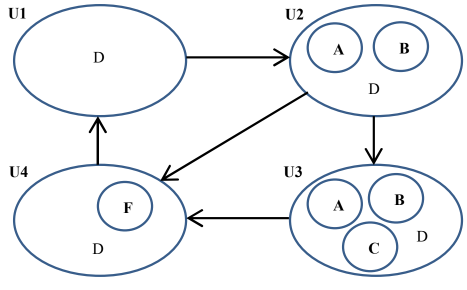

Fig. 1. State graph of the set U.

As mentioned in the previous section, when ships diverge, there is uncertainty in the behaviour of the opposite ship. And it is heightened if no effective exchange of information

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can be arranged between the agents controlling the ships, whereby they can agree on the implementation of an agreed manoeuvre for a safe divergence.

However, in any case, even if the manoeuvre is agreed, the agent controlling the vessel to which the way should be given way must monitor the implementation of the agreements reached. And all the more so if the agreement has not been reached. After all, if the vessel due to give way does not timely initiate a diverting manoeuvre, the vessel due to give way may (and then is obliged) under COLREG Rule 17 to take action for a safe diverting manoeuvre.

Therefore, after receiving (and preferably agreeing with the opposing ship's agent) a divergence manoeuvre, the agent of the ship to which the divergence is due should monitor the behaviour of the opposing ship and monitor its compliance with the manoeuvre. It is important to detect the failure to manoeuvre by the opposite vessel in time to assess the situation and recalculate the manoeuvring decision. Possibly already his own ship.

In case of agreed manoeuvre at meeting of two uncrewed ships and implementation of their interaction protocol for detection of situation of execution or non-execution of agreed manoeuvre by opposite ship B the agent of ship A has the following information (fig.2):

1. Initial trajectory, which is constructed by the prediction subsystem (predictor) on vessel A using the initial route of vessel B and its actual movement before manoeuvring.
2. The trajectory of manoeuvre of vessel B, which is constructed using the recommended route for safe divergence agreed by agents A and B.
3. The actual trajectory of vessel B, which is plotted from AIS and/or radar data.

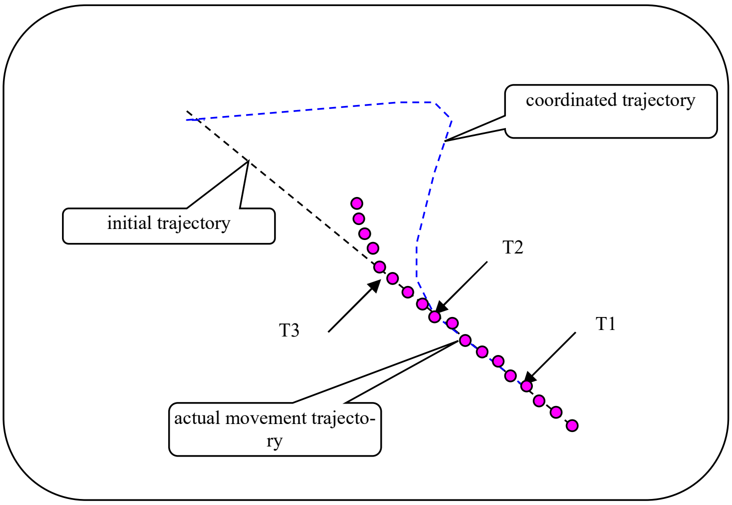

Fig. 2.

Fig. 2 shows:

T1 - The moment the uncrewed boat's agents reach agreement on manoeuvre of boat B;

T2 - The moment the vessel B is expected to start a new trajectory in accordance with the agreed divergence manoeuvre;

T3 - moment of actual deviation from previous trajectory in accordance with manoeuvre actually taken by ship B to diverge. Ideally it should be: T2 = T3.

The criterion for failure to perform an agreed manoeuvre is the deviation of the actual trajectory of vessel B from the trajectory determined as a result of the agreements reached.

In fact, it is the absence of change of trajectory parameters at the moment T2. However, it should be kept in mind that:

1. The position of ship B is determined with an error.
2. The trajectory of the ship B, even when complying with the arrangements, may not be exactly the same as the calculated trajectory due to a mismatch between the model of the ship B used in the calculation of the manoeuvre and the actual dynamic characteristics of the ship, as well as incomplete consideration of external sailing conditions.

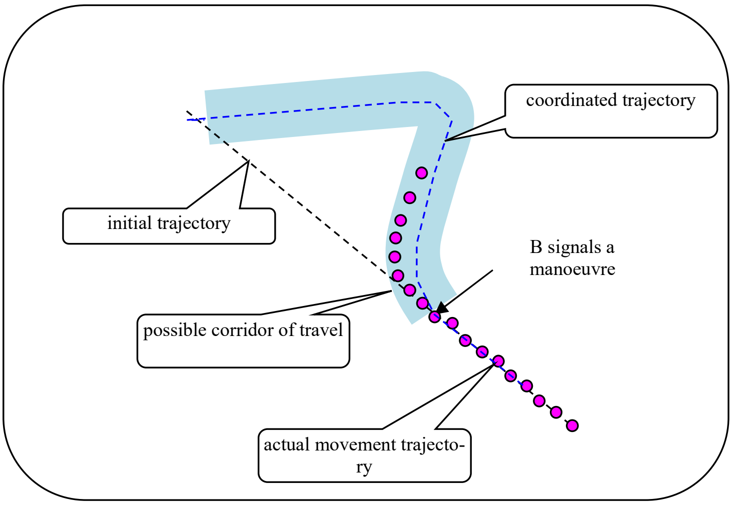

Fig. 3.

Thus it is possible for Agent A to falsely detect a violation of the arrangement. To solve this problem you can use (Figure 3):

1. Mandatory notification by the agent controlling ship B when he starts to perform the agreed manoeuvre.
2. Setting the value of the possible deviation of the real trajectory of the ship B from its real trajectory, taking into account the above-mentioned errors. Thus some "corridor" around the calculated trajectory of the maneuver is set, the movement inside which the ship B does not lead to false operation of the detector of non-compliance with the agreements.

In the case of an encounter between an unmanned ship A and a boat B controlled by the shipowner, the problem is exacerbated. In this case the agent controlling ship A cannot agree with the agent controlling ship B on an agreed manoeuvre in automatic mode. The agent controlling ship A cannot even know for certain that the agent controlling ship B (navigator) is in control of the situation, assesses it as dangerous, and plans to perform any maneuvers for safe divergence. In this case agent A's decisions must be based on the following assumptions about agent B's decisions:

- the decision about the degree of danger of the situation coincide with the decision of agent A;
- agent A's maneuvering decision coincides with COLREG.

The automatic divergence system installed on ship A can provide the agent of that ship with a manoeuvring solution that ensures a safe divergence. But if that decision concerns manoeuvring vessel B, there is no expectation that the pilot controlling vessel B will make the same decision. In addition, at the moment the manoeuvre is initiated, the ship B's

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navigator will not notify ship A's agent of this, which certainly complicates the task of tracking the execution of this manoeuvre.

In this case it is offered to use the following approach to the decision of a problem of detection of default of the maneuver on a divergence (Fig. 4).

1. To calculate the worst maneuver that ship B can perform to safely diverge from ship A. Usually it is the latest maneuver, when it is still possible to safely diverge by ship B alone.

2. To construct a sector of possible manoeuvres, limited to the worst manoeuvre found. 3.

3 The position of ship B is monitored and if it continues along its previous trajectory and leaves the sector of possible manoeuvres, the situation of failure to divert is detected and a decision is made whether manoeuvre A should divert.

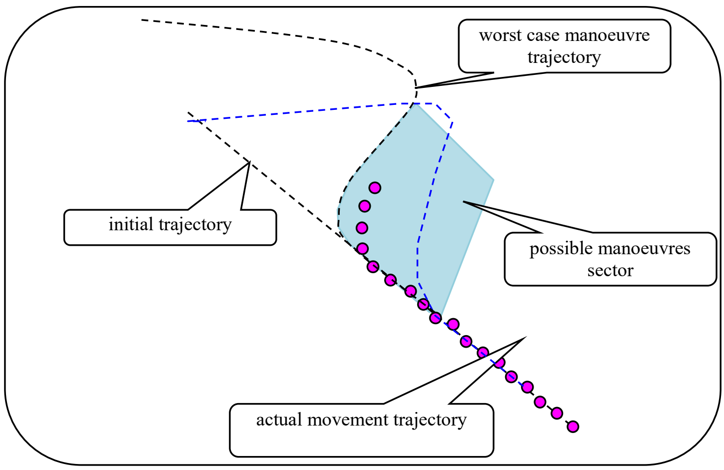

Fig. 4.

5 Discussion

If, using the methods described in the previous section, the oncoming vessel B is detected to be overstepping its manoeuvre area, the agent of vessel A decides that vessel B has failed to comply with its separation duty. He will then be forced to calculate such a manoeuvre to avoid a collision by the action of his vessel alone. Therefore, when determining this permissible area, both in the case of a corridor of possible movement for an unmanned ship and in the case of a sector of possible manoeuvres for a navigator-controlled ship, time and free water space should be provided for carrying out one's own manoeuvre.

Furthermore, when performing this forced manoeuvre, the agent of vessel A should take all possible steps to inform the agent controlling opposite vessel B of his intentions to perform the manoeuvre. In the case of uncrewed vessels, this can be done using a communication protocol between automatic agents. In any case, the uncrewed ship should signal its intention to manoeuvre by other means, such as the audible and visual signals required by COLREG regulation 34. Therefore, it will be able to give a warning of its intentions to the skipper of vessel B and to the skippers (agents) operating other vessels in the offshore area.

6 Conclusion

This paper considers the problem arising from cooperative manoeuvring of vessels in the process of divergence at sea. When crewless ships meet, it is necessary to control the manoeuvring arrangements made in the process of cooperative solution of the divergence problem. When a crewless vessel meets a vessel controlled by a navigator, the uncertainty of the manoeuvre increases considerably.

The approaches proposed in this work will solve the problem of detecting the situation of non-performance of the manoeuvre by the vessel, obliged in accordance with COLREG for giving way. This will allow timely decision on manoeuvring unmanned vessel to avoid collision.

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