Научная статья

Автономная система предупреждения столкновений безэкипажных судов: алгоритмы и программная реализация

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АННОТАЦИЯ

Столкновение судов – одна из наиболее серьезных проблем на международном морском транспорте. Поэтому вопрос безопасности судовождения является широко обсуждаемой темой исследования в специализированной научной литературе. На протяжении последнего времени технология безэкипажного судовождения постепенно находит все более широкое применение в области морской робототехники. В связи с этим исследуется проблема безопасности судоходства при управлении движением безэкипажных судов. Объектом исследования является процесс предупреждения столкновений безэкипажных судов. Предмет исследования – алгоритмы работы системы автономного принятия решений и программное обеспечение по предотвращению столкновения судов при безэкипажном судовождении. Основной целью является повышение безопасности безэкипажного судовождения путем разработки новых алгоритмов для автономного предупреждения столкновений безэкипажных судов в режиме реального времени с учетом Международных правил предупреждения столкновений на море и рекомендаций Федерального агентства морского и речного транспорта (Росморречфлот). Рассматриваются фундаментальная концепция и набор ключевых задач автономной системы предупреждения столкновений безэкипажных судов, которые являются морскими транспортными средствами, способными воспринимать окружающую среду и работать без участия человека. В контексте исследования особое внимание уделяется вопросу разработки алгоритма программного обеспечения по определению наиболее опасного препятствия, находящегося в радиусе 12 миль от безэкипажного судна (требования Росморречфлота), на основе геометрии предотвращения столкновений судов, оценки риска столкновения и характеристик препятствий. Кроме того, разработанные алгоритмы могут предотвратить столкновение и решать проблемы предупреждения столкновений безэкипажных судов в реальном времени. Результаты моделирования также демонстрируют перспективность применения предложенных алгоритмов для повышения безопасности безэкипажного судовождения. Тем не менее исследование дает возможность разработать новую информационную систему принятия решений для автономного предотвращения столкновений судов. В настоящее время информационная система находится в разработке и будет предложена позже.

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AUTONOMOUS COLLISION AVOIDANCE SYSTEM FOR UNMANNED VESSELS: ALGORITHMS AND SOFTWARE

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ABSTRACT

Ship collision is one of the most substantial concerns in the global maritime transportation industry. Hence, navigation safety is considerably cited topic in maritime literature. Recently, Unmanned Navigation (UN) technology is gradually becoming more widely used across in the field of marine robotics. The paper investigates the problem of navigation safety in the movement control of Unmanned Vessels (UVs). The object of the study is the process of avoiding collisions of UVs. The subject of the research is the algorithms of the autonomous decision-making system and software for preventing vessel collisions during UN. The intent of this article is to improve the safety of UN by developing new Decision-Making algorithms for autonomous collision prevention of UVs in real time, taking into account the International Rules for the Prevention of Collisions at Sea, 1972 (COLREGs-72) and the recommendations of the Federal agency for sea and inland water transport of the Russian Federation (Rosmorrechflot).In this article, the fundamental concept and the key functions set of the Autonomous Collision Avoidance System (ACAS) are carried out for UVs which are marine transport vehicles capable of sensing its environment and operating without human involvement. Along this line of research, this work focuses on the development of a software algorithm for determining the most dangerous obstacle located within a radius of 12 miles (recommendations of Rosmorrechflot) around an UV based on the principle of vessels collision avoidance geometry, collision risk assessment and the characteristics of obstacles. Moreover, the proposed algorithms can prevent the collision and address the issues of real-time collision avoidance for UVs. The simulation results also demonstrate the promising application of the proposed algorithms in studying the UN safety. Nonetheless, this study provides a way forward to conduct a new information decision-making system design for UVs collision avoidance. This is currently under development, and will be proposed later.

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Introduction

Improving the marine navigation and safety of sea transportation are a complex multi-level tasks, which are provided by the work of the International Maritime Organization (IMO), ship classification societies and administrations of governments involved in the development of world navigation. Analyzing vessel accidents, it can be noted that ship collisions, in particular, are one of the most common types of sea traffic accidents. Collision of vessels is the name given to an incident that occurred as a result of mutual contact between a vessel and another object during its movement and entailed loss of life or injuries, damage to the vessels and cargo, environmental pollution or other material damage.

According to official data from the Federal service for supervision of transport of the Russian Federation (Rostransnadzor), in the period from 2014 to 2020 collisions of vessels flying the State flag of the Russian Federation represent respectively 4.5 %, 1.4 %, 3.66 %, 7.14 %, 8.74 %, 3 % and 11.67 % of the total the number of accidents at sea. And also, were equal to 6.25 %, 11.83 %, 8.6 %, 8 %, 9.5 %, 6.3 % and 3.6 %, respectively, of the total accident rate on the inland waterways transport of the Russian Federation [1]. According to statistics overview annually issued by European Maritime Safety Agency (EMSA), over the 2014-2020 period, ship collisions represented 21.7 % of all casualty events [2]. When analyzing underlying factors leading to maritime accidents, safety investigations determined that 70% of safety investigations were related to "Human Factor" [3].

Enhancement of navigational safety in the world merchant fleet is carried out through a number of technical, organizational, economic, environmental and legal standards aimed at preventing the occurrence of casualty events, saving human life at sea and reducing environmental risks. In order to reduce or eliminate the need for human involvement in ship control systems and promote navigation safety in the maritime transport sector, Artificial Intelligence (AI) technology based on Machine Learning (ML) methods is being increasingly integrated into maritime transportation industry to create and implement the technology of Unmanned Navigation (UN), providing a reduction of the ship's operational costs, reduction in the ship crew size or complete elimination of the ship crew and a decrease in environmental impacts from direct emissions.

Recently, the technology of UN has become a widely discussed topic and one of the fastest growing field of maritime shipbuilding and marine robotics. Furthermore, techniques and methods of ML effectively addressed challenges of ensuring safe remote control of transport vehicles and intellectualization of complex systems. Taking this background into consideration, the development of an algorithm for the autonomous vessel collision avoidance system (ACAS) in UN is a new trend in the maritime sector and coming out of the growing field of marine robotics.

1. Unmanned vessel collision avoidance system characteristics

This section presents two main components that need to be established as the base for collision avoidance algorithm design, explained next. The first one is the conceptual framework of ACAS, which is the core of UN safety. The second one is UV collision avoidance principle, which defines the relative parameters that separate between UV and obstacle while sailing.

Autonomous decision-making system for vessels to avoid collision is fundamentally defined as a very technically and organizationally complex device that is designed to work in autonomous mode. With this understanding of the term of ACAS, the main goal is to detect potential hazards or obstacles, reduce the risk of collision between vessels in a close-quarters situation, prevent vessel from colliding into any obstacle present on their path and increase the safety of marine navigation by carrying suitable control actions in real time. This goal is achieved, in particular, by

improving sensor and data fusion modules, using marine digital navigation infrastructure (e-Navigation technology) and designing Decision-Making algorithms to solve the problem of avoiding collisions with obstacles in real time in UN.

The proposed block diagram of ACAS in UN is shown in Fig. 1. The main parts of the proposed system are data fusion block and Decision-Making block. The operation principle of ACAS is based on information measured in real time by sensors and navigation devices on-board (data fusion block), detecting obstacles and identifying their classes. Then, the data fusion block generates a vector of navigation situation parameters, which enters the Decision-Making block, where a set of intelligent algorithms for autonomous vessel collision avoidance is used.
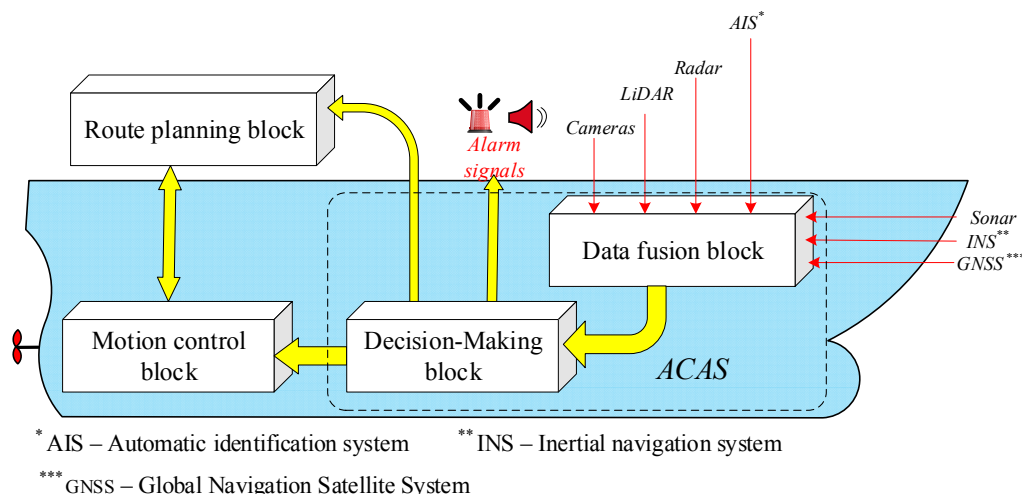
Fig. 1. Block diagram of autonomous collision avoidance system for unmanned vessels

In general, the key functions set of ACAS of UVs are:

▪ Fusion and integration of navigation data from different information sources (environment sensing).

▪ Automatic detection of static and moving obstacles (target objects).

▪ Automatic tracking a target's movement and predicting its position and other relevant information.

▪ Classification of obstacles according to their degree of danger.

▪ Situation analysis on marine navigation and minimization of collision risk, taking into account the International Rules for the Prevention of Collisions at Sea, 1972 (COLREGs-72).

▪ Navigational warnings other ships or alert them to collision hazard (as soon as a target object appears in a specific zone around UV, the ACAS should give sound and light signals).

▪ Automation of Decision-Making process for collision avoidance.

▪ Implementation of the recommended control actions in accordance with the appropriate COLREGs-72.

A scenario of UV encounter with target ship during the voyage is shown in Fig. 2. It can be seen from Fig. 2 that $X(E)$ and $Y(N)$ point to the east and north. The yellow ship represents the UV and the green ship represents the obstacle (target ship). Referring to Fig. 2, we designated (x_o, y_o), (x_g, y_g) and (x_M, y_M) to symbolized the positions of our own UV, obstacle and goal, respectively. The speed of our UV and target ship are represented as V_o and V_g. The movement course of UV and obstacle are ψ_o and ψ_g. The absolute azimuth of the obstacle and our own UV is a_g. The Distance to Closest Point of Approach (*DCPA*) can be calculated by using the following equation [4; 5]:

$$DCPA = \sqrt{(x_g - x_o)^2 + (y_g - y_o)^2} \times$$

$$\times \left| \sin \left(\cos^{-1} \left(\frac{V_o - V_g \cdot \cos(\psi_o - \psi_g)}{\sqrt{V_o^2 + V_g^2 - 2V_o \cdot V_g \cdot \cos(\psi_o - \psi_g)}} \right) - \alpha_g - 180 \right) \right|. \quad (1)$$

Time to Closest Point of Approach (TCPA) can be represented as [6; 7]:

$$TCPA = \frac{DCPA}{\sqrt{V_o^2 + V_g^2 - 2V_o \cdot V_g \cdot \cos(\psi_o - \psi_g)}}. \quad (2)$$
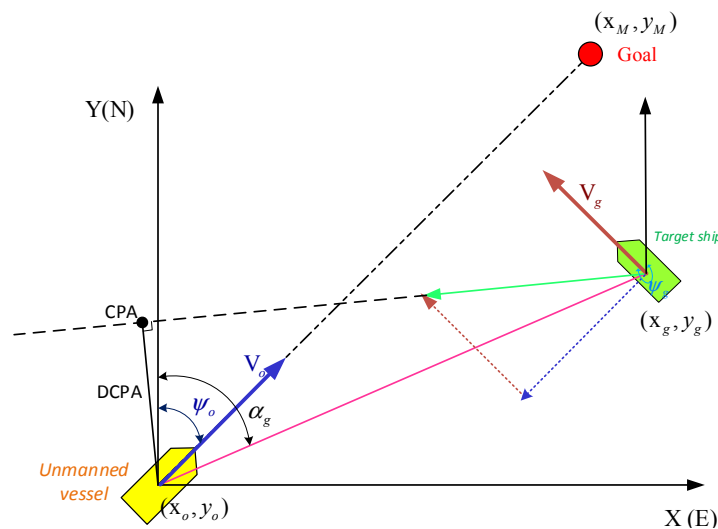

Fig. 2. Unmanned vessel collision avoidance kinematic

Using the recommendations of the Federal agency for sea and inland water transport of the Russian Federation (Rosmorrechflot) on the use of COLREGs-72 by autonomous ships in automatic control mode and the resolution No. 2031 of 5 December 2020 "on the regulations on conducting an experiment on the trial operation of autonomous ships under the State flag of the Russian Federation" by the Government Decree [10], the minimum allowable values of critical distance between vessels for avoiding collisions r_{per} are presented in the table below.

Minimum safe approach distances

| | | Unmanned vessel length, *m* | | |
| | | < 20 | 20 – 50 | > 50 |
		r_{per}, Cable length[*]		
Target ship length, *m*	< 20	3	4	5
	20 – 50	4	6	7
	> 50 or no information	5	7	10

[*]*where 1 Cable length = 185.2 Meter [m].*

Moreover, the concept of "Collision Risk Index" (*CRI*) is used as an important reference basis for determining the degree of collision risk. Where the relative movement parameters between UV and target ship are used to determine *CRI* according to fuzzy comprehensive evaluation method. It can be obtained as [8; 9]:

$$CRI = W \cdot U, \qquad\qquad (3)$$

where W and U are the weight vector and the membership vector of target ship factors, respectively.

Autonomous collision avoidance algorithms for unmanned vessels

The main objective of this paper is to develop a decision-making algorithm with the intent of optimizing the process of collision avoidance in UN. The typical algorithm of the ACAS operation is constructed as follows:

Step 1. Real-time navigation data collection.

Step 2. Maritime obstacles detection within 12 miles around an UV: if there are obstacles in the specified radius, then determine the number of obstacles; otherwise, go to the step 8.

Step 3. Determining the type of each detected obstacle: if the obstacle is movable, then determine its position, dynamic parameters and the possible encounter situation; otherwise, determine the position and statics parameters of obstacle.

Step 4. Collision risk assessment: if $CRI \geq 0.3$, then we will find the most dangerous obstacle based on the developed software algorithm built in accordance with the recommendations of Rosmorrechflot; otherwise go to the step 8.

Step 5. Give sound and light alert by emergency alert system.

Step 6. Decision-Making on the choice of obstacle avoidance actions (change of V_0 and/or ψ_o).

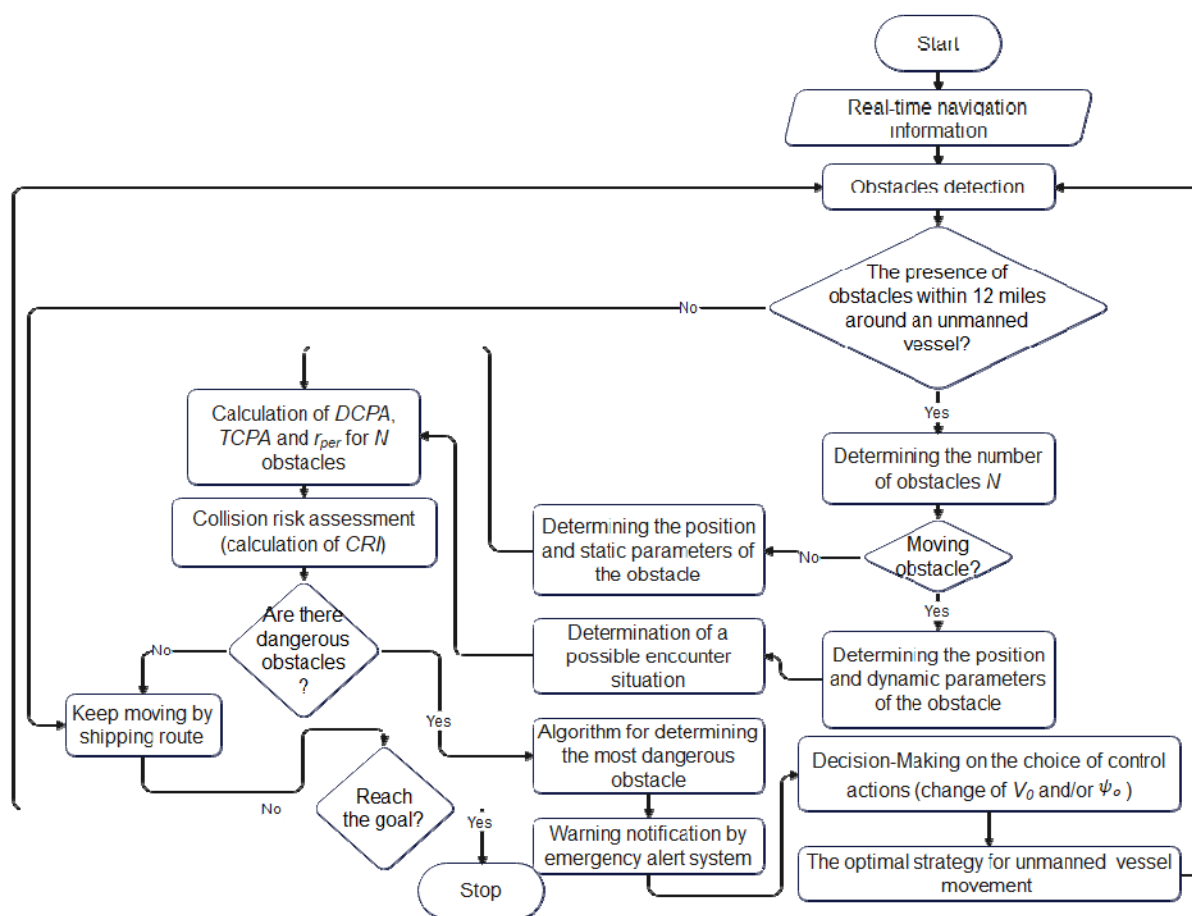*Step 7*. Planning a new route for an UV. Then return to step 2.

Fig. 3. Algorithm flowchart of proposed autonomous collision avoidance system

Step 8. Keep moving by shipping route (UV continues to sail): if the UV does not arrive at the destination (the goal), then return to the step2; otherwise, the voyage ends (the algorithm is completed).

The following flowchart (Fig. 3) summarizes the proposed algorithm.

According to the recommendations of the Rosmorrechflot on the use of COLREGs-72 by autonomous ships in automatic control mode, the algorithm for finding is mainly realized through the following 3 steps, and the flowchart is shown in Fig. 4.
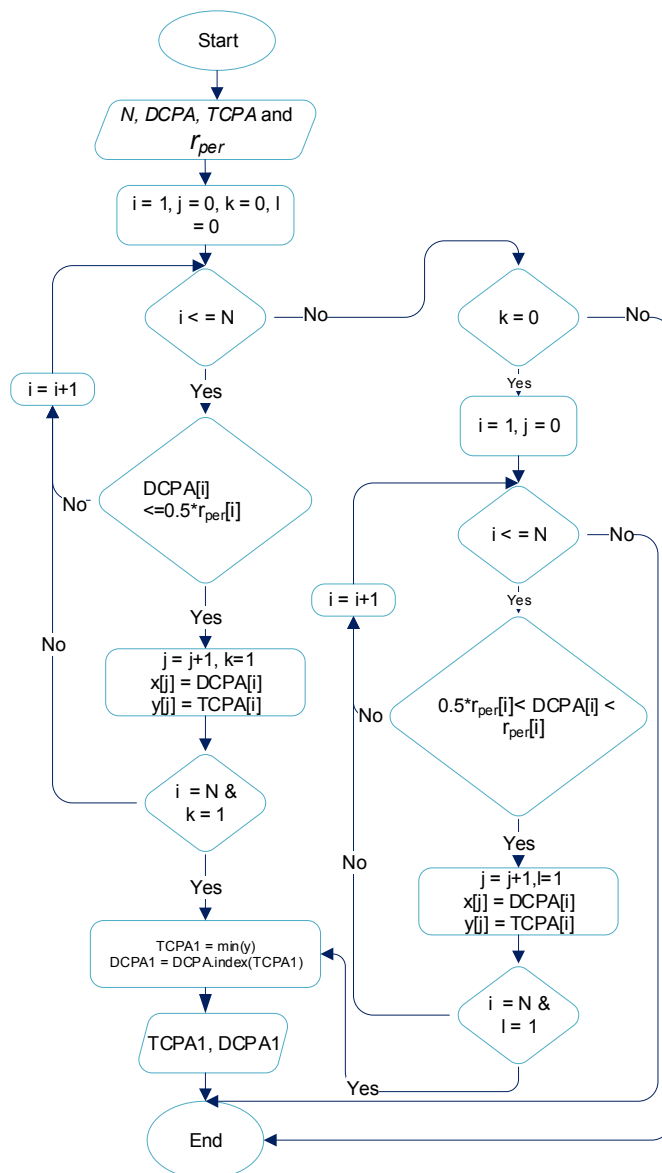
Fig. 4. Flowchart of the software algorithm
for determining the most dangerous obstacle

Step 1. Define the set of all obstacles located within a radius of 12 miles around an UV and having $DCPA < 0.5r_{per}$.

Step 2. If this set in not empty, then go to the step 3; otherwise, define the set of all obstacles located within a radius of 12 miles around an UV and having $0.5r_{per} < DCPA < r_{per}$ and go to the step 3.

Step 3. The most dangerous obstacle of this set will be the obstacle that will have the shortest *TCPA*.

Results and simulation analysis

Using the Visual Basic.NET (VB.NET) programming language in the Microsoft Visual Studio 2010 development environment, the performance of the proposed algorithm was implemented and tested under various scenarios. For these hazardous scenarios, a most dangerous obstacle located within a radius of 12 miles around an UV is defined. The simulation results are shown in Fig. 5. The red solid circles represent the obstacles. The green solid circle represents the UV. The simulation scenarios assume that UV and obstacles are sailing with specific movement courses ψ. The parameter settings of the UV and the relative navigational parameters are shown on the right side of the software interface.
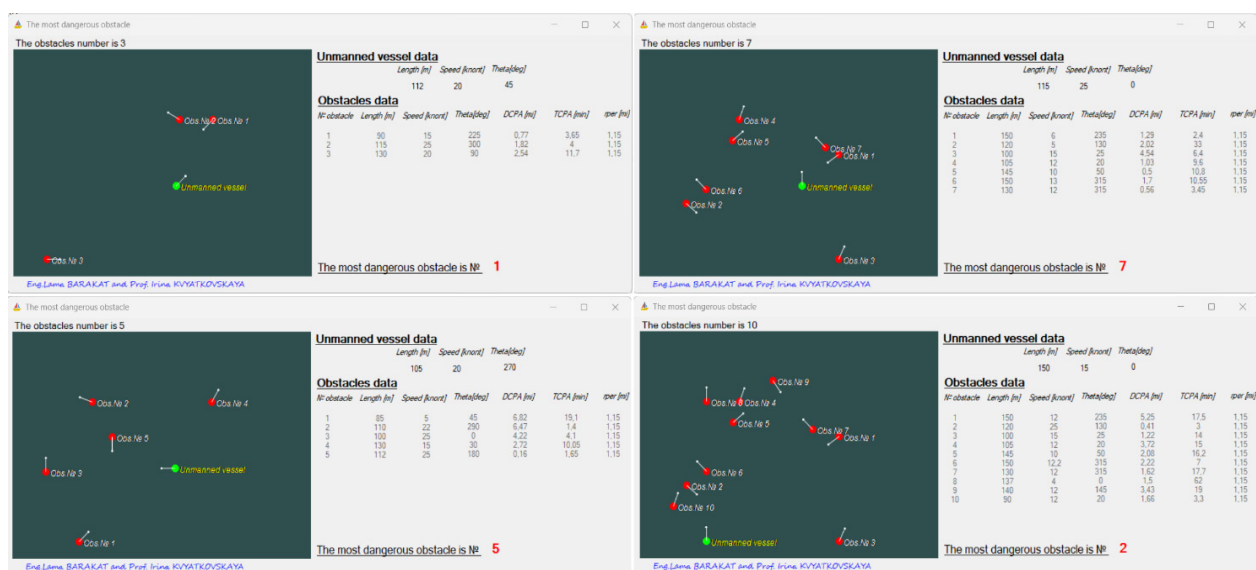
Fig. 5. Software interface "The most dangerous obstacle " under different encounter situations

The results presented above show that the algorithm is capable of defining the dangerous target ship fast, once the relative navigational parameters between UV and the obstacle are available. the application of the software algorithm for determining the most dangerous obstacle also meets the requirements of COLREGs and Rosmorrechflot.

Conclusions

The main contribution of this paper is to propose a novel autonomous collision avoidance algorithm for UVs. The algorithm constructs a collision avoidance model based on the type of obstacles and their static or dynamic characteristics, the relative parameters of an UV and the obstacle, vessel encounter situation while sailing, the recommendations of the Rosmorrechflot, COLREGs, and collision risk index. At the same time, the software algorithm to determine the most dangerous obstacle from the set of all obstacles located within a radius of 12 miles around an UV is established. The simulation results show that the proposed software algorithm can effectively determine the most dangerous obstacle under different encounter situations in real time, and it has an important practical application value. The proposed algorithms in this paper have a significant potential to solve the dangerous obstacle avoidance problem of UVs, and is thus suitable for a real application in UN.

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