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РАЗРАБОТКА МЕХАНИЗМА ПРИНЯТИЯ РЕШЕНИЙ ДЛЯ АВТОНОМНОГО ПРЕДОТВРАЩЕНИЯ СТОЛКНОВЕНИЙ ПРИ БЕЗЭКИПАЖНОМ СУДОВОЖДЕНИИ: НЕЧЕТКИЙ ПОДХОД

В ближайшем будущем безэкипажные суда будут иметь все большее значение, а также будут принимать решения без какого-либо вмешательства человека. Такая ситуация повышает риск столкновения безэкипажных судов с другими объектами. Анализируя аварийные случаи судов, можно отметить, что столкновения из-за нарушения Международных Правил Предупреждения Столкновений Судов в море, 1972 г. (МППСС-72), которые разработаны Международной морской организацией (ИМО), остаются лидером навигационных аварийных происшествий на водных путях. Поэтому автономное предотвращение столкновений на море будет играть основную роль в обеспечении безопасности при безэкипажном судовождении (БЭС). В данной статье рассматривается проблема автономного предотвращения столкновений в нормальных условиях видимости в открытом море. В связи с этим в работе на основании системного анализа существующих правил МППСС-72 разработан шестиэтапный метод устранения угрозы столкновения безэкипажного судна, включающий: механизм принятия решений на основе логической схемы для реализации стратегии, наилучшей в смысле выбранного критерия оптимальности (оптимальная стратегия) при управлении БЭС, где входными данными для системы нечеткой логики предотвращения столкновений судов являются навигационные параметры (скорость, курс, положение и т. д.). База нечетких продукционных правил МППСС-72 состоит из 17 правил предотвращения столкновений для определения наиболее подходящих управляющих воздействия в случае возникновения риска столкновения. Авторами работы в качестве функции принадлежности нечеткого множества была предложена трапециевидная форма, которая позволяет аналитическое представление о риске столкновения безэкипажного судна с препятствием в зависимости от признака ситуации (сектора встречи). Разрабатываемые в настоящее время информационные системы предотвращения столкновений добавило барьер безопасности, чтобы помочь предотвратить столкновения в море. Однако по-прежнему требовались дальнейшие исследования и усилия ученых многих *развитых стран мира. В рамках дальнейших исследований авторами планируется применение описанного метода для разработки информационной системы принятия решений при управлении движением безэкипажного судна.*

Безэкипажное судовождение; автономное предотвращение столкновения; принятие решения; риск столкновения; безэкипажное судно; управляющее воздействие.

L.A. Barakat, I.Y. Kvyatkovskaya

DEVELOPING A DECISION-MAKING MECHANISM FOR AUTONOMOUS COLLISION AVOIDANCE OF UNMANNED NAVIGATION: FUZZY APPROACH

In the near future, unmanned vessel (UV) will become increasingly important and will act without any human intervention. This situation raises the collision risk between UVs and general ships. Research on maritime accidents have shown that ship collision accidents due to violation of the International Rules for the Prevention of Collisions at Sea, 1972 (COLREGs-72), which were developed by the International Maritime Organization (IMO), remain the leader of navigational accidents on shipping waterways. In this respect, autonomous preventing collisions is critical for unmanned navigational safety at sea. Hence, in this paper, aiming at the problem of autonomous collision avoidance in open sea area under conditions of good visibility. To this end, a fuzzy logic system to obtain autonomous collision of UVs according to the rules of COLREGs-72 proposed in this paper. The proposed Decision-Making Mechanism (DMM) based on logical schema for the implementation of the strategy that is the best in the sense of the selected optimality criterion (optimal strategy) for unmanned navigation control. The inputs to the collision avoidance fuzzy logic system are the navigational parameters (speed, course, position, etc.). The rule base of the collision avoidance fuzzy logic system consists of 17 rules to avoid collisions. The authors proposed a trapezoidal membership function which allows an analytical representation of the collision risk of an UV with a target ship, depending on the situation feature (encounter sector). Currently, various information collision avoidance systems, which have been developed, added a safety barrier to help prevent collisions at sea. However, further research and efforts of scientists from many developed countries of the world were still required. As part of further research, the authors plan to use the described method to develop an information decision-making system for a movement control of an unmanned vessel.

Unmanned navigation; autonomous collision avoidance; Decision-Making; collision risk; unmanned vessel; control action.

Introduction. The Convention on the International Regulations for Preventing Collisions at Sea (COLREGs-72), which are the international navigational rules and regulations that define safe actions to prevent collisions between crewed ships, was adopted in 1972 and entered into force in 1977. Amendments to the convention on the COLREGs-72 introduced in 1981, 1987, 1989, 1993, 2001 ,2007 and 2012 are already in force on the international level [11]. In order to reduce the risk of collision between ships at sea, all maritime vessels are required to comply with all essential collision-avoidance requirements based on the COLREGs, which include 41 rules divided into six sections. In addition to these parts, there are four annexes which provide technical requirements for lights and sound signals.

COLREGs-compliant navigation of unmanned vessels. The advent of UV at present does raise questions across the shipping industry as to whether these vessels can strictly comply with the current requirement of the COLREGs-72, including on Rules 2 *(Responsibility)*, 5 *(Look-out)*, 8 (*Action to avoid a collision*) and 18 *(Responsibilities between vessels)*. Within the framework of Rule 2 of the COLREGS, the ship's owner, captain and crew are legally responsible for applying of COLREGs 72. But in an unmanned navigation, it will be difficult to determine the person responsible for infraction or violation of these rules of the COLREGS, since an UV can operate independently with no human intervention or interaction.

The first step of decision-making for autonomous collision avoidance is based on Rules *5* and *7(a)*, where an UV should constantly be able to carry out joint visual and auditory observation of the marine environment using microphones, daylight and IR cameras and all available means of observation, taking into account the need for coordination between the algorithms of "vision" and "hearing" in accordance with a trained observer. Therefore, the International Maritime Organization (IMO) needs to make appropriate changes, as well as additional clarifications to these rules.

Rule 7 *(Risk of collision)* emphasizes that on-time assessment of the risk of collision is a necessary condition for safe navigation. Therefore, in an unmanned navigation, continuous analysis of the navigation situation allows to sufficiently assess the risk of a collision and make effective decisions to prevent collisions.

Rules 13 *(overtaking)*, 14 *(Head-on situation)*, 15 *(Crossing situation)* and 18 (*Responsibilities between vessels*) are the main provisions defining behavior in dangerous encounter situations of vessels, and guidelines for decision-making. As shown in Fig. 1, each of UV and target ship in the head-on situation should avoid the collision in the direction of the starboard (see Fig. 1,a). The UV in the overtaking situation can set a course in the direction of the starboard of the target ship (see Fig. 1,b). The UV in the crossing situation must alter the course to the starboard (see Fig. 1,c). The target ship in the crossing situation must alter the course to the starboard (see Fig. 1,d).

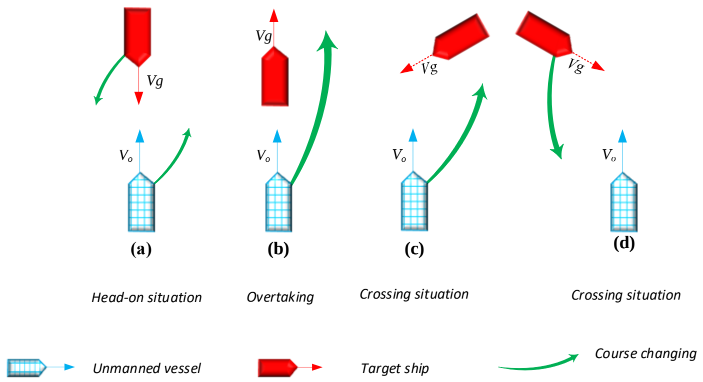

Fig. 1. Encounter situations of unmanned vessel and target ship

Rule 18 covers the relative responsibilities of various vessels on the principle of "who gives way to whom", unless any other rule requires otherwise. In this regard, a vessel with better maneuverability gives way to a vessel with less maneuverability. Each ship can be defined as a stand-on or give-way according to the COLREGs-72 rules [4].

An UV will be able to take early and decisive action to avoid collision in accordance with rules 16 (*Action by give-way vessel*) and 17 (*Action by stand-on vessel*). In fact, COLREG-72 is a system which is based on a set of fuzzy production rules about behavior. This system consists of (condition, action) pairs which mean, "If condition then action".

Problem formulation and approach. The model of intelligent decision-making for autonomous collision avoidance within the framework of COLREGs-72 is considered as a classification model, provided that the input factors are described in the form of linguistic variables characterizing the parameters of the automatic vessel motion control system, and establishing a correspondence between sets of fuzzy variables and elements of the set of control decisions for the implementation of the COLREGs-72.

Rule 8 includes maneuvering actions to be taken to prevent collisions with another vessel. This rule requires that the change in course and/or speed taken to prevent a collision should have a sufficiently large magnitude to be easily detected by other vessels. The effectiveness of the action shall be carefully checked until the other vessel is finally past and clear. In general, the order in which these actions are performed is given by the following hierarchy of the Decision-Making:

$$D_1 \rhd D_2 \rhd D_3 \rhd D_4, \quad (1)$$

where $\rhd$ is preference relation symbol; D_1 denotes vessel should alter course to starboard side; D_2 is vessel speed reduction to a full stop; D_3 denotes vessel should alter course to starboard with simultaneous speed reduction; D_3 denotes vessel should alter course to the port side.

Based on linguistics terminology description of actions included in the Rule 8 of COLREGs-72 and taken in various situations to prevent collisions of vessels a set of several utterances is given as follows:

$$Rule_n = IF \ «A_n» \ THEN \ «B_n», \quad (2)$$

where A_n, B_n are fuzzy utterances of linguistic variables which defined on the input and output values, respectively, for n = 1 to 4. Therefore, we can represent the actions included in the Rule 8 of COLREGs-72 to avoid collision in a fuzzy form:

Rule$_1$*: IF* «UV sail upon the high seas» *THEN* «change the course of movement by at least 30 – 90°».

Rule$_2$*: IF* «the vessel has turned to the port side for passing» *THEN* «it should be made much earlier than a possible change of course to the starboard side».

Rule$_3$*: IF* «there is sufficient space » *THEN* «movement course change alone may be the most effective action to prevent the close approach».

Rule$_4$*: IF* «it is necessary to prevent a collision » *OR* «allow more time to assess the situation» *THEN* «UV should slacken her speed» *OR* «stop completely».

A Decision-Making Mechanism for autonomous collision avoidance. As shown in Fig. 2, a hierarchy of rules was developed to formulate decision-making stages for autonomous collision avoidance in normal visibility conditions upon the high seas according to the part B (*Steering and Sailing Rules*) of COLREGs which establish internationally agreed system for safe navigation.

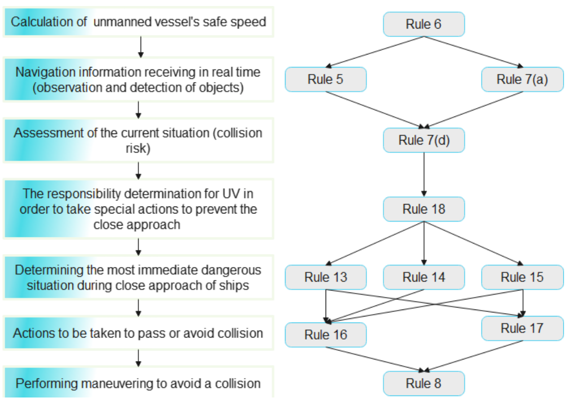

Fig. 2. Hierarchy of decision-making within the framework of the COLREGs

Based on these rules, in the context of fuzzy sets and fuzzy logic, a *Decision-Making Mechanism* has been developed in this paper to implement a Decision-Making strategy for unmanned navigation:

Stage 1. Check Rule 6 (*UV shall at all times proceed at a safe speed*).

Stage 2. Check Rule 5 (*keeping a lookout by camera and aural censoring equipment fixed to the ship*) and Rule 7(a) (*properly use all available means to determine in time if there is a risk of collision*).

Stage 3. IF «*Rule 5 is true*» AND «*Rule 7(a) is true*» THEN «*go to the step 4*» ELSE «go to step 1».

Stage 4. Check Rule 7(d) (*assessment of the current situation considering that UV will not create the potential for collision*).

Stage 5. IF «*Rule 7(d) is true*» THEN « *it is necessary to calculate the bearing among ships and fix its value*» AND «*go to the step 6*» ELSE «*collision hazard exists*».

Stage 6. Check Rule 18 (*Unmanned ship has a duty to avoid ships, such as ships not under command*).

Stage 7. IF «*Rule 18 is false*» AND « *collision risk exists in a traffic lane*» THEN « *the relevant Rules of navigation and maneuvering should apply*» ELSE «*go to the step 8*».

Stage 8. Check Rule 13 (*the rule for overtaking ships*), Rule 14 (*Head-On Situation*) and Rule 15 (*Crossing Situation*).

Stage 9. IF «*Rule 13 is true*» OR «*Rule 15 is true*» THEN « *check Rules 16 and 17*» AND «*go to the step 11*» ELSE « *go to the step 10*».

Stage 10. IF «*Rule 14 is true*» THEN « *check Rule 16*» AND « *go to the step 12*».

Stage 11. IF «*Rule 16 is false*» AND «*Rule 17 is false*» THEN «*collision hazard exists*» AND « *go to the step 12*».

Stage 12. Check Rule 8 (*take action very early to ensure there is no collision risk*).

Stage 13. Achieving the goal (avoiding the collision).

A Collision Avoidance Method for unmanned navigation. According to the recommendations of The Federal Agency for Sea and Inland Water Transport (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 [1], there are four zones in the area around the vessel as shown in Fig. 3.

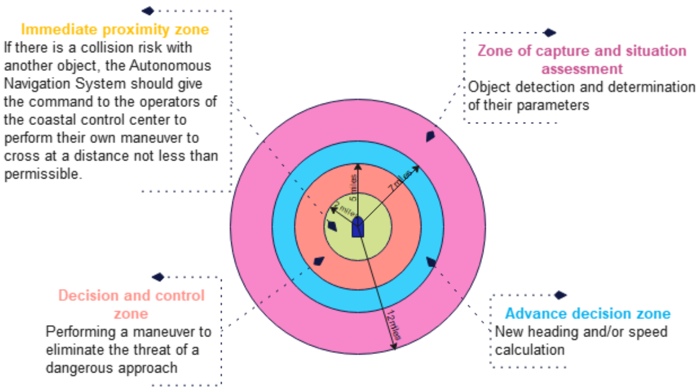

Fig. 3. Approximate zones around the vessel in case of dangerous approach in automatic control mode

Using a scenario that assumed that in the navigation area an UV and the target ship are at positions (x_o, y_o) and (x_g, y_g), respectively. The speed and movement course of each are represented as V_o, V_g, and ψ_o, ψ_g, respectively. Fig. 4 illustrates encounter situation of UV and the target ship while sailing to help understand the relative parameters of and their calculations.

The Distance to Closest Point of Approach (DCPA) can be obtained as follows [3]:

$$DCPA = D.\left|\sin\left(\psi_r - a_g - 180\right)\right|, \quad (3)$$

where D is the relative distance between the UV and the target ship which can be given as follows [2]:

$$D = \sqrt{(x_g - x_o)^2 + (y_g - y_o)^2}, \quad (4)$$

a_g is the azimuth of the detected obstacle (target ship).

ψ_r denotes the relative movement course which can be calculated as follows:

$$\psi_r = cos^{-1}\left(\frac{V_o - V_g.\cos\left(\psi_o - \psi_g\right)}{V_r}\right) \quad (5)$$

here V_r represents the relative velocity, which can be obtained using the following:

$$V_r = \sqrt{V_o^2 + V_g^2 - 2V_o.V_g.\cos\left(\psi_o - \psi_g\right)}. \quad (6)$$

Finally, Time to Closest Point of Approach (TCPA) can be obtained from [7]:

$$TCPA = DCPA/V_r. \quad (7)$$

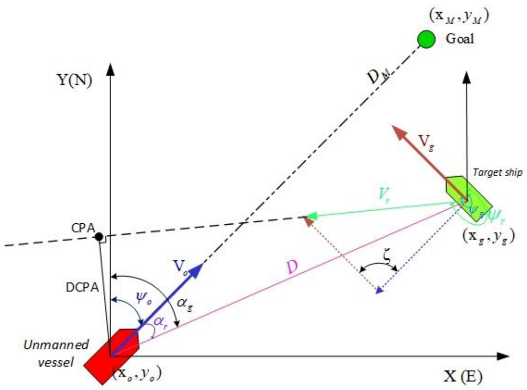

Fig. 4. Relative parameters of an unmanned vessel and the target ship encounter while sailing

(x_M, y_M) – goal position, CPA – Closest Point of Approach, ζ – the relative angle (angle less than 90) between the courses of the UV and the obstacle, D_M – the distance between UV and the goal, α_r – the relative bearing.

After identifying the main parameters, the next step is to avoid collision at sea. This paper proposes a six-step method for UV collision avoidance in accordance with COLREGs-72 at various positions with the target ship:

Step1. Dividing the zone at a distance of 12 miles (Rosmorrechflot's requirements) around each UV and target ship into eight sectors, the boundaries of which are determined by bearing, as shown in Fig. 5.

Step2. Determination of the set of sectors around the UV *I = (A, B, C, D, E, F, G, H).*

Step3. Definition of the set of sectors around the target ship *j = (a, b, c, d, e, f, g, h).*

Step4. Determination of the set of possible relative positions of a target ship with an UV (situation feature). In this case, for example, D_c means that the target ship is in the UV sector *D* and in its own sector *c*.

Step5. Analysis of the obtained set I_j to determine the recommended control actions in accordance with the appropriate COLREGs-72, depending on the relative approach speed $(V_K = V_g / V_o)$.

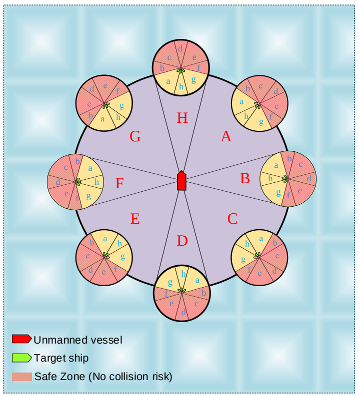

Fig. 5. Sectors used to classify encounter situations

Step6. Create a fuzzy set of the rule base of a Fuzzy Inference System (FIS) to prevent ship collisions which determines the necessary control actions to avoid a collision in the presence of a target ship at a distance of ≤ 12 miles around the UV.

Fig. 6 illustrates the basic building block of the inference process that is used to control speed, course and trajectory of UV to avoid a collision under conditions of uncertainty. The defuzzification technique for the proposed FIS can be the Center of Gravity method (CG method). The advantage of this method is that all active rules take part in the defuzzification process. However, the CG method has a number of systematic errors: a large cost of calculation, the narrowing of the range of defuzzification and the defuzzified value is relatively easy to calculate, but computationally rather complex and therefore results in quite slow inference cycles, and leads to unwanted results if the fuzzy set is not unimodal [21, 22]. These errors lead to the fact that accuracy of fuzzy systems decreases. It is possible to solve these problems and increase the accuracy of the fuzzy system, as noted in [23], through the method of areas' ratio (MAR) which can be used only for the triangular and trapezoidal membership functions.

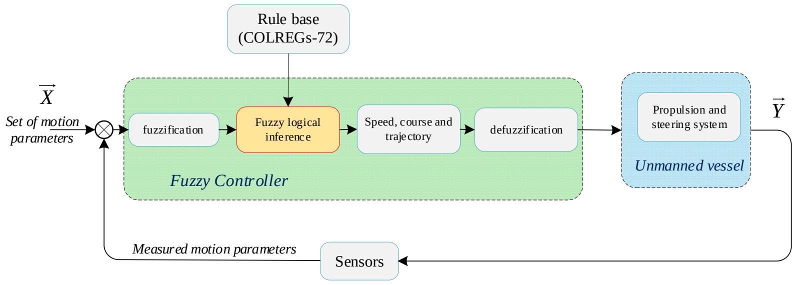

Fig. 6. Fuzzy Inference System to prevent ship collisions

Results and analysis. In general, the rule base is as follows:

$$Rule_n = IF \text{ «}I_j \text{ is true» } THEN \text{«control action»} \quad (8)$$

$Rule_1$: IF «A_b is true» OR «A_c is true» OR «A_d is true» OR «A_e is true» OR «A_f is true» OR «B_b is true» OR «B_c is true» OR «B_d is true» OR «B_e is true» OR «B_f is true» OR «C_b is true» OR «C_c is true» OR «C_d is true» OR «C_e is true» OR «C_f is true» OR «D_a is true» OR «D_b is true» OR «D_c is true» OR «D_d is true» OR «D_e is true» OR «D_f is true» OR «E_b is true» OR «E_c is true» OR «E_d is true» OR «E_e is true» OR «E_f is true» OR «F_b is true» OR «F_c is true» OR «F_d is true» OR «F_e is true» OR «F_f is true» OR

«G_b is true» OR «G_c is true» OR «G_d is true» OR «G_e is true» OR «G_f is true» OR «H_b is true» OR «H_c is true» OR «H_e is true» OR «H_f is true» THEN «no collision risk» AND «save the speed and course of the UV and the target ship».

$Rule_2$: IF «H_a is true» AND «$V_K \ll 1$» THEN «save the speed of the UV» AND « change the course of the UV to starboard» AND « save the speed and course of the target ship».

$Rule_3$: IF «H_g is true» AND «$V_K \ll 1$» THEN «save the speed of the UV» AND «change the course of the UV to the port side» AND « save the speed and course of the target ship».

$Rule_4$: IF («H_a is true» OR «H_g is true») AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «no collision risk» AND « save the speed and course of the UV and the target ship».

$Rule_5$: IF «H_h is true» THEN «change the course of the UV and the target ship to starboard» AND « save the speed of the UV and the target ship ».

$Rule_6$: IF «H_d is true», THEN «increase the speed of the UV» AND « change the course of the UV to starboard» AND «save the speed and course of the target ship».

$Rule_7$: IF («A_h is true» OR «A_g is true» OR «A_a is true» OR «B_h is true» OR «B_g is true» OR «B_a is true» OR «C_h is true» OR «C_g is true» OR «C_a is true» OR «D_h is true» OR «D_g is true» OR «E_h is true» OR «E_a is true» OR «E_g is true» OR «F_h is true» OR «F_a is true» OR «F_g is true» OR «G_h is true» OR «G_a is true» OR «G_g is true») AND «$V_K \ll 1$» THEN «no collision risk» AND «save the speed and course of the UV and the target ship».

$Rule_8$: IF «A_h is true» AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «reduce the speed of the UV » AND « change the course of the UV to the port side» AND « save the speed and course of the target ship».

$Rule_9$: IF «A_a is true» AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «save the speed of the UV» AND «change the course of the UV to starboard» AND « save the speed and course of the target ship».

$Rule_{10}$: IF («A_g is true» OR «B_h is true» OR «G_a is true» OR «B_g is true» OR «C_g is true») AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN « increase the speed of the UV» AND «save the course of the UV» AND «save the speed and course of the target ship».

$Rule_{11}$: IF («B_a is true» OR «C_h is true» OR «C_a is true» OR «G_g is true») AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «reduce the speed of the UV» AND « save the course of the UV» AND « save the speed and course of the target ship».

$Rule_{12}$: IF «G_h is true» AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «change the course of the UV to the port side» AND « reduce the speed of the UV» AND « save the speed and course of the target ship».

$Rule_{13}$: IF «D_h is true» AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «save the speed and course of the UV» AND « increase the speed of the target ship» AND « change the course of the target ship to starboard ».

$Rule_{14}$: IF «D_g is true» AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «save the speed and course of the UV» AND « increase the speed of the target ship» AND « change the course of the target ship to the port side»;

$Rule_{15}$: IF («E_h is true» OR «E_a is true» OR «E_g is true» OR «F_g is true») AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN « save the speed and course of the UV» AND «save the course of the target ship » AND « reduce the speed of the target ship».

$Rule_{16}$: IF «F_h is true» AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «save the speed and course of the UV» AND « reduce the speed of the target ship» AND « change the course of the target ship to starboard ».

$Rule_{17}$: IF «F_a is true» AND («$V_K \gg 1$» OR «$V_K \approx 1$») THEN «save the speed and course of the UV» AND « increase the speed of the target ship » AND « save the course of the target ship».

Moreover, the concepts of the collision risk degree can be formulated by the trapezoidal membership function which allows an analytical representation of the collision risk of an UV with a target ship, depending on the situation feature (encounter sector). The graphical representation of this membership function for is shown in Fig. 7.

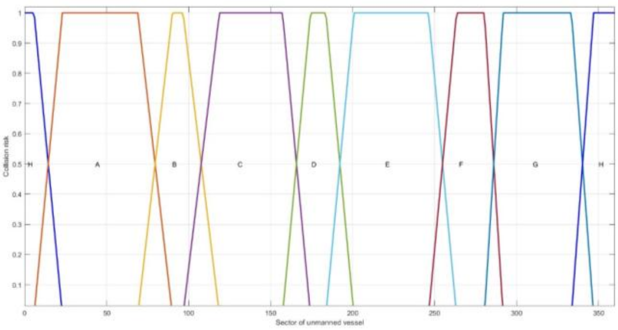

Fig. 7. Unmanned vessel encounter sectors membership function

Conclusions. In this study, we presented a fuzzy-logic approach for autonomous collision avoidance of unmanned navigation, since the International Regulations for Preventing Collisions at Sea is a system which is based on a set of fuzzy production rules about behavior and consists of (condition, action) pairs which mean, "If condition then action".

This paper proposed a six-step method for UVs collision avoidance considering COLREGs-72 rules at various positions with the target ship. In this method the rule base of a Fuzzy Inference System to prevent ship collisions is formed to determine the necessary control actions.

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