TransNav
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 17 Number 2 June 2023
DOI: 10.12716/1001.17.02.11

A COLREGs-Compliant Decision Support Tool to Prevent Collisions at Sea

M. Martelli[1], S. Žuškin[2], R. Zaccone[1] & I. Rudan[2]
[1] *University of Genova, Genova, Italy*
[2] *University of Rijeka, Rijeka, Croatia*

ABSTRACT: Groundings and collisions still represent the highest percentage of marine accidents despite the current attention on Maritime Education and Training and the improvement of sensor capability. Most of the time, a collision is caused by a human error with consequences ranging from moderate to severe, with a substantial impact on both environment and life safeguarded at sea. In this paper, a brief statistical data regarding human element as a root cause of marine incidents together with collision regulations misunderstanding is presented as a background chapter.
Furthermore, the present work discusses a decision support system architecture to suggest an appropriate action when the risk of a potential collision is detected. The proposed architecture system is based on various modules integrated with proper sensor input data regarding the surrounding navigation area.
As a result, the tool can support the Officers of Watch in the decision-making process providing an early suggestion in compliance with the COLlision REGulations. The proposed system is intended to be used onboard independently from the degree of automation of the ship, and it is based on AIS, which is mandatory, making it widely applicable. The proper use of the system can considerably reduce the number of collisions, as demonstrated by the obtained results.

1 INTRODUCTION

Most ship collisions derive from human error and have moderate to severe consequences on both environment and human lives. The International Maritime Organization (IMO) still defines shipping as a highly dangerous industry, as the number of accidents is still relatively high compared to other industries (IMO, 2003). According to Allianz Marine Insurance, human error is still one of the major causes of marine accidents and may vary from 80 to 96 % (Allianz Marine Insurance, 2023).

According to the collecting and studying data regarding navigation accidents and human actions accordingly, recent investigations showed us that misunderstanding of COLREGs is more severe than thought (Demirel and Bayer, 2015). Current ICT and sensor technologies can significantly reduce the misunderstanding and the number of collisions at sea. In particular decision support system based on the data coming from the onboard sensors is one of the best technology, suitable for several kinds of ships independently from the year of construction (Lazarowska, 2017).

A decision support system for ship navigation is a computer-based system that aids a ship's navigator in making decisions about the vessel's course and speed. It uses information from various sources, including electronic charts, satellite positioning systems, radar, and other sensors, to generate recommendations or alerts for the navigator. Such a system aims to improve the safety and efficiency of ship navigation by providing the navigator with timely and accurate information that can help them make informed decisions (Pietrzykowski et al., 2017). Some decision support systems for ship navigation also include route planning and risk assessment tools forming a collision avoidance system (COLAV). The COLAV is a safety system designed to help prevent collisions between two or more ships and rely on sensors to detect the presence and location of other objects and then use this information to calculate the risk of a collision and the evasive manoeuvre (Zaccone & Martelli, 2018). If the risk is deemed to be high, the system may issue an alert to the operator or take automated action to avoid the collision. Some examples of COLAVs used in the maritime industry include radar-based systems that can detect the presence of other vessels (Wilthil et al., 2018) and automatic identification systems (AIS) - based systems that can exchange information about a vessel's position and course with other ships in the same area (Jincan & Maoyan, 2015). CASs are an essential safety feature on many vehicles and can help reduce the risk of accidents and fatalities.

A COLREGs-compliant decision support tool for preventing collisions at sea, as a consequence of the maritime advanced technology development in navigation and the above-mentioned motivations, is indeed proposed by the authors for this transitional period where interaction between human interpretation and the help of a decision support system tool is inevitable and valuable. In particular, the paper structure is the following: in Section 2 statics on the collision at sea are reported to raise awareness of this specific type of accident. In section 3 the general architecture of the proposed system is shown with a detailed description of each sub-module and some examples. In the Conclusion, Section 4, the advantages and the future development of the system are drawn.

2 STATISTICS ON COLLISIONS

According to the Annual Overview of Marine Casualties and Incidents (EMSA, 2022), the percentage of reported accident events from 2014 to 2022 was obtained by counting each occurrence in the European Maritime Casualty Information Platform (EMCIP) for every event type (Figure 1).

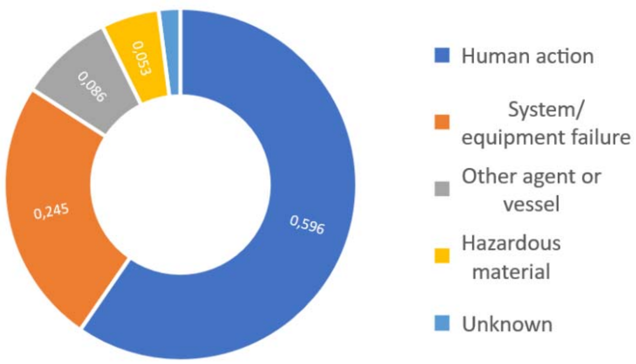

Figure 1. Percentage of accident events in the period 2014 - 2021 organized by accident event type (EMSA 2022).

During this period, human action accounted for the highest percentage of accident events at 59.6 %, followed by System/equipment failure at 24.5%, Other agents or vessels at 8.6%, Hazardous material at 5.3%, and Unknown at 2.0%. Similar trends were observed across all ship types with minor variations in the percentages; however, the Human factor remained the most common accident event type for all ship types.

According to the Safety analysis of EMCIP data regarding navigational accidents, the study examined 1,637 elements that contributed to navigational accidents, which were reported in 351 safety investigation reports (Figure 2).

Figure 2. Percentage of accident events for the period 2014 - 2021 organized by accident event type According to Safety analysis of EMCIP data - navigational accidents, 2022.

These factors were classified into nine safety issues. According to the findings, most of the issues raised were related to work/operation methods, organizational factors, and risk assessment, accounting for nearly two-thirds (66%) of the contributing factors. The main takeout of the analysis is that the top three safety issues, Work/operation methods and Organisational factors, are directly linked to COLREG rules which make up 55% of all contributing factors.

Table 1. Human action general conditions and interpretation. (According to Safety analysis of EMCIP data - navigational accidents, 2022)

Interpretation	Nr.	%
Delayed interpretation	70	27.5%
Local diagnosis - Wrong diagnosis	45	17.6%
Decision error - Wrong decision	41	16.1%
Local diagnosis -Incomplete Diagnosis	28	11.0%
Local prediction - Unexpected state change	16	6.3%
Local prediction - Process speed misjudged	12	4.7%
Wrong reasoning - Wrong priorities	11	4.3%
Wrong reasoning - Deduction error	9	3.5%
Decision error - Decision paralysis	8	3.1%
Wrong reasoning - Induction error	5	2.0%
Decision error - Partial decision	4	1.6%
Local diagnosis - Other	2	0.8%
Local prediction - Unexpected side	2	0.8%
Decision error - Other	1	0.4%
local prediction - Other	1	0.4%
Total	255	100.0%

According to the collecting and studying data from the abovementioned study, the action analysis includes 255 cases based on various types of human action interpretation errors. More than one-fourth (27,5%) of interpretation issues concern delays in interpretation, followed by wrong diagnosis (17,6%), and wrong decision (16,1%) that together makes more than 60% of all reported causes of cognitive functions. This can be exemplified by the Officer Of the Watch (OOW) monitoring the vessel's progress, considering the interpretation of data displayed from navigation instruments, alarms triggered by ECDIS, or the ship's motion during a manoeuvre.

According to EMSA analysis, out of significant occurrences of 8,800 navigation accidents, the following 370 cases have undergone safety investigations with a reported dataset suitable for the further required analysis.

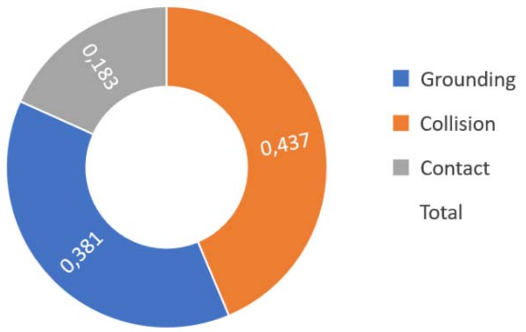

Figure 3. Navigation accidents are dealt with by safety investigations. According to Safety analysis of EMCIP data - navigational accidents, 2022.

Among these, collisions comprised the highest proportion (almost 44%), followed by groundings (38%) and contacts (18%). The analysis aims to contextualize navigation accidents by reviewing information from all relevant occurrences.

In addition to the navigation accident and human action data collected from the abovementioned studies, the MAIB investigation showed us that the misunderstanding of the COLREGs is more severe than thought. After analysing the MAIB database on collision investigation, it is evident that the highest number of cases had violated the following COLREGs' rules: Rule 5 (Look-out), Rule 7 (Risk of Collision), and Rule 8 (Action to avoid collision). Regarding Rule 5, it is evident from the MAIB's incident report that well-known, established international maritime standards are sometimes neglected. Regarding the risk of collision and action to avoid it, the complex COLREG misunderstanding is arising. Some recognized hazards are based on improper or delayed Rules interpretation, misunderstanding of vessel manoeuvring characteristics, a complacency of self-confidence and overreliance of the navigator, and reluctance to use ship propulsion in collision situations. Current state of art technologies can help in reducing notable human error, for example with Decision Support System (DSS).

3 DECISION SUPPORT SYSTEM ARCHITECTURE

The general architecture of the DSS proposed in the current paper is shown in Figure 4. The system can receive, as input, the data coming from several sensors. Have been hypothesized that the data coming from Automatic Identification System (AIS) and Global Positioning Systems (GPS) will be the starting point since these systems are installed on every ship. From AIS, the data of the vessels navigating in the surrounding are provided; among the several messages, the most relevant are targets' position, attitude, course over ground (COG), speed over ground (SOG), and navigation status. Moreover, the GPS provides the own ship's current position while the gyro provides its orientation. Furthermore, it is necessary to keep in mind that target acquiring is a major focus for COLREG Rule determination by using water-stabilized RADARs, which must be used for DSS systems. Also, the RADAR can be used as double-check for consistency. Additionally, ECDIS with an appropriate Electronic Navigational Chart (ENC) is needed as available layer information, especially for the position of safe waters, fixed obstructions, temporary notices, Traffic Separation Scheme (TSS), narrow channels, and other relevant information needed for safe navigation.

Data from sensors are the input of the detection module that constantly checks for collision risk; if a collision risk is detected, the module triggers the COLREG Classification Module that identifies the COLREG scenario and the rules involved. With this information, the Route selection module can suggest a course change to avoid the collision. Eventually, the final check on compliance with COLREG is done. The specific details on the functionalities of each module are provided in the following paragraphs.

Eventually, a Graphical User Interface (GUI), located in the bridge or any relevant space onboard, shows the outcome of the system. The Officer Of Watch (OOW) can indeed follow the suggestion provided by the DSS or decide by themself and then act on the Human Machine interface (HMI) to give the command on the rudder helm or set the autopilot. In the case of an autonomous ship, this action can be completely automatic.

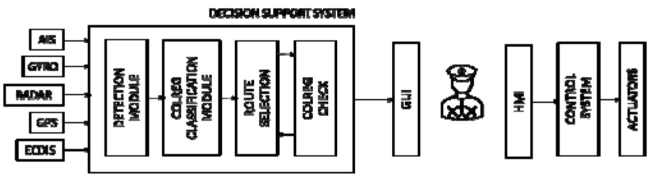

Figure 4. Proposed decision support system architecture.

3.1 *Detection module*

The detection module runs with a sample rate given by the slower sensor and runs continuously in the background. It is responsible for providing an alarm in case the risk of collision is detected.

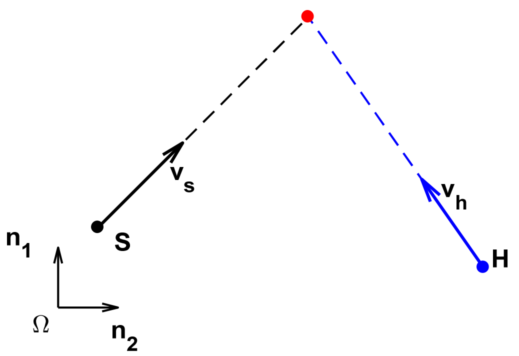

Figure 5. Reference frames.

Considering the scenario reported in Figure 5, consider the following variables in the earth-fixed reference frame $\{\Omega, \underline{n}_1, \underline{n}_2\}$: the ship initial position S, $\underline{\eta}_S(t_0) = x_S(t_0)\underline{n}_1 + y_S(t_0)\underline{n}_2$; and the ship current velocity, $\underline{v}_S = \dot{x}_S \underline{n}_1 + \dot{y}_S \underline{n}_2$.

Similarly, the kinematic variables of the target, initially detected in H, are assumed to be known:

$$\begin{cases} \underline{\eta}_H(t_0) = x_H(t_0)\underline{n}_1 + y_H(t_0)\underline{n}_2 \\ \underline{v}_H = \dot{x}_H \underline{n}_1 + \dot{y}_H \underline{n}_2 \end{cases} \tag{1}$$

The motion laws of both the ship and target are then known, assuming that the velocity and orientation of the two vessels do not vary in time:

$$\begin{cases} \underline{\eta}_S(t) = \underline{\eta}_S(t_0) + \underline{v}_S t \\ \underline{\eta}_H(t) = \underline{\eta}_H(t_0) + \underline{v}_H t \end{cases} \tag{2}$$

The Path Interception Point (PIP) is the geometric intersection of the two trajectories and can be expressed as $\underline{\eta}_{PIP} = x_{PIP}\underline{n}_1 + y_{PIP}\underline{n}_2$. It can be addressed by solving the following system, expressed in the matrixial form:

$$\begin{bmatrix} \dot{y}_S & -\dot{x}_S \\ \dot{y}_H & -\dot{x}_H \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \dot{y}_S x_S - \dot{x}_S y_S \\ \dot{y}_H x_H - \dot{x}_H y_P \end{bmatrix} \tag{3}$$

The system admits only one solution if the following condition (trajectory incidence condition) is ensured:

$$\det\left(\begin{bmatrix} \dot{y}_S & -\dot{x}_S \\ \dot{y}_H & -\dot{x}_H \end{bmatrix} \right) \neq 0 \tag{4}$$

The time needed to reach the *PIP* is denoted as *TPIP*. A collision occurs if both ships reach the *PIP* at the same time, or rather, at "excessively" close instants. As a matter of safety, considering actual operating conditions, ships should always keep a safe distance.

Therefore, one approach to collision detection is to require that the difference between ship and target *TPIP* is greater than a threshold time Θ. This parameter can, for example, be calculated as a function of safety distance by the following relationship:

$$\Theta = \frac{D_{safety}}{\min\left\{ \left|\underline{v}_S\right|, \left|\underline{v}_H\right| \right\}} \tag{5}$$

This corresponds to verifying that at the time the ship engages the *PIP*, the target is at a distance greater than the safe distance. However, there is no guarantee that the target will not violate the safety distance before or after that time. For such a reason is necessary to introduce the expression of the distance in the time domain between the ship and the target, *D(t)*, that should be lower than the threshold to provide an alarm:

$$D(t) = \left| \underline{\eta}_S(t) - \underline{\eta}_H(t) \right| \leq D_{safety} \tag{6}$$

The minimum distance over time (Closest Point of Approach, CPA) is so defined, using the previous expression, as:

$$\min_t D(t) = \left| \underline{\eta}_S(t_0) - \underline{\eta}_H(t_0) - \frac{(\underline{v}_S - \underline{v}_H)\cdot(\underline{\eta}_S(t_0) - \underline{\eta}_H(t_0))}{\left|\underline{v}_S - \underline{v}_H\right|^2} (\underline{v}_S - \underline{v}_H) \right| \tag{7}$$

The evaluated kinematic variables are reported in the GUI with an alert to the OOW, as reported in Figure 6.

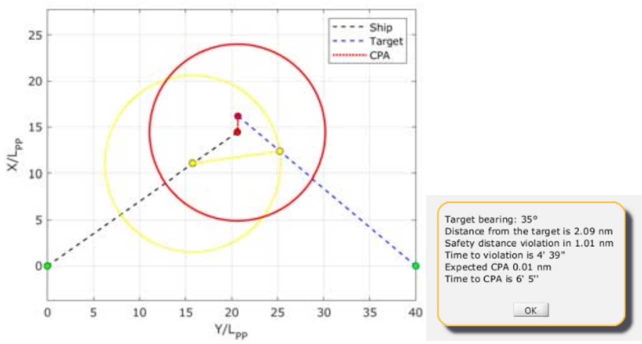

Figure 6. Example of the information coming from the detection module.

An example of the result is reported In Figure 6. The yellow circle represents the time when the violating the safety distance, D_{safety}. Thereafter, due to relative motions, the vessels will continue to move closer until they reach the CPA, identifying the minimum encounter distance with a red dashed line. The numerical information is reported in the pop-up windows.

3.2 *COLREG Classification module*

As some of the COLREG Rules are applied consecutively, it is necessary to find a way how to determine which rule is applicable at certain collision situations for the DSS proposed. According to (Sunmer, 2021) an individual approach to each COLREG Rules assessment is necessary for this approach. The key influencing factor is the attitude of a target concerning own vessel. It is essential to keep in mind that there are performance limits with sensory equipment on commercial vessels. For collision avoidance, it is only possible to ensure complete autonomy with audio and visual sensory equipment that can replace the human navigator's sight and hearing. Consequently, it is still necessary to involve human navigators in the Decision Support System (DSS) process.

The key element in the artificially intelligent and automated collision avoidance system is the COLREG Classification Module. This initial and critical step is the cornerstone of the decision process on which the collision avoidance architecture is based. The initial step of the COLREG Classification Module development relies on COLREG Rules description and elaboration together with the legal framework, empirical studies, case laws, and scientific survey analyses. This part is particularly sensitive due to past research that shows numerous accidents and COLREG misunderstandings. Nowadays, basic communication between vessels is established by using VHF which is not recommended according to the COLREG rules. Furthermore, electronic direct communication between other vessels will be developed in the near future where two ECDIS systems on board vessels, as primary means of navigation, will exchange relevant data regarding navigation safety. Also, a significant number of commercial ships that sail with navigators not knowing or not understanding the COLREGs is still a challenge that requires a global solution. After the initial step, the COLREG Classification Module development needs to be set without ambiguity and strong and concrete safety parameters that can later be encoded into COLREG verification Algorithms for the Module.

Considering the previous scenario, Rule 15 (Crossing situation), according to International Regulations for Preventing Collisions at Sea (2020) for the COLREG Classification Module development, is elaborated. The crossing Rule states that when two power-driven vessels are crossing, and there is a collision risk, the ship with the other ship on her own starboard side shall keep out of the way and, if possible, should avoid crossing the bow of the other vessel. Regulators did not restrict manoeuvring to starboard only. Still, if thinking about crossing from the starboard side, a vessel should alter to starboard and pass astern of the crossing vessel if the circumstances of the case permit.

Rule 15 assigns give-way and stand-on responsibilities among two crossing power-driven vessels, but only when there is a risk of collision. Even though the own threshold for collision risk might differ from the target vessel, the own vessel can act conservatively and risk-averse, which is always a good approach to avoid close-quarter situations. If thinking about other COLREGs geometries, it is noticeable that crossing includes any situation not classified as head-on or overtaking. Therefore, when the relative bearing of the target vessel is in the spectrum of [6°, 112.5°] and [247.5°, 354°], and if the trajectory is bringing the target vessel to the minimum CPA radius, then the navigator confirms that there is a risk of collision and then decides on the crossing action. Furthermore, in several Admiralty cases, the notion that a crossing give-way vessel should not cross ahead of the stand-on vessel has been confirmed (Benjamin et al., 2006); therefore, it is necessary to ensure that the crossing the stern is optimal behaviour when verifying generated trajectories. The following figure depicts the crossing where rule 15 is adopted.

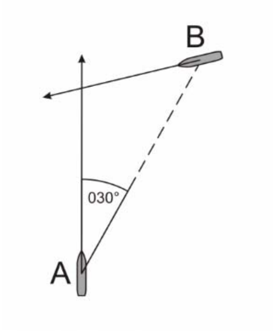

Figure 7. Rule 15 - Crossing situation. (Courtesy of: www.ecolregs.com).

In accordance with Rule 15 (Crossing situation), if the circumstances of the case admit, vessel A shall avoid crossing ahead of vessel B.

Furthermore, the COLREGs classification algorithm for the COLREG Classification Module focuses on the own vessel's and target's attitude, so course and speed through water are significant to determine which Rule will be appropriate for each collision situation. As stated before, it is necessary to keep in mind that the classification algorithm is developed including the interaction with human. On the contrary, it should be modified for future potential autonomous navigation applications. For setting the mathematical formulation for the COLREG Classification Algorithm, the following variables are used: H_o – heading of the own vessel taken from the gyro compass, *COG* – Course Over Ground for the own vessel taken from the GPS or radar, *CTW* – Course Through Water taken from the radar, *SOG* – Speed Over Ground taken from the GPS or radar, *RPM* – Revolutions Per Minute taken from the engine speed indicator directly, performance measurement monitoring, or conning display, *STW* – Speed Through Water taken from the speed log or radar, n_{OV} – GNSS north position of the own vessel, e_{OV} – GNSS east position of the own vessel, *h* – draught of the own vessel taken from the loadicator computer or manual input to verify safe waters, *D* – depth of water, *ECDIS info* – various ECDIS available layer information, especially position of safe waters, fixed obstructions, temporary notices, TSS, narrow channel, and other relevant information needed for safe navigation.

When tracking a new target T_n, the following information is of interest: H_T – heading of a target taken from the radar, COG_T – Course Over Ground for a target taken from the radar, CTW_T – Course Through Water of a target taken from radar, SOG_T – Speed Over Ground of a target taken from radar, STW_T – Speed Through Water taken from radar, n_T – GNSS north position of a target, e_T – GNSS east position of a target, AIS_T – various Automatic Identification System information of a target taken from the AIS receiver, $dCPA_T$ – distance to Closest Point of Approach (usually called simply a CPA) of a target in relation to the own vessel taken from the Automatic Radar Plotting Aid (ARPA), $TCPA_T$ – Time to the CPA of a target in relation to the own vessel taken from ARPA,

R_T – Range of a target taken from radar, θ_T – bearing of a target taken from radar, θ_{OV} – bearing of the own vessel from the perspective of a target (calculated after acquiring new target), and *BCR* – Bow Crossing Range taken from ARPA, which can be positive (bow crossing), or negative (stern passing).

COLREG Classification algorithm for the COLREG Classification Module is separate and now represents the first step before the collision avoidance algorithm with Route selection for DSS system in the next phase. The main function is utilizing vessels' water geometries and determining the appropriate attitude for accurate COLREGs Rule determination.

Considering the scenario reported, COLREG Classification Algorithm for Rule 15 is proposed:

Input: *H_0, COG, CTW, SOG, RPM, STW, n_{OV}, e_{OV}, h, D, ECDIS info, $T_{1,2,\ldots,n}$ (H_T, COG_T, CTW_T, SOG_T, STW_T, n_T, e_T, AIS_T, $dCPA_T$, $TCPA_T$, R_T, θ_T, BCR).*
Output: Display relevant COLREGs Rules
Every 10 seconds do:
  Rule 15
  verify information extracted from water stabilized RADAR
  for each T_n:
    read T_n (H_T, CTW_T, STW_T, n_T, e_T, $dCPA_T$, $TCPA_T$, R_T, θ_T, *BCR*)
    if 247.5° < θ_{Tn} < 354°, R_T<6 NM, *BCR*>0, and $CPA \leq CPA_{PREF}$:
      display: RULE 15 – T_n CROSSING BOW FROM PORT – STAND-ON
    end if
    if 247.5° < θ_{Tn} < 354°, R_T<6 NM, *BCR*≤0, and $CPA \leq CPA_{PREF}$:
      display: RULE 15 – T_n CROSSING STERN FROM PORT – STAND-ON
    end if
    if 006° < θ_{Tn} < 112.5°, R_T<6 NM, *BCR*>0, and $CPA \leq CPA_{PREF}$:
      display: RULE 15 – T_n CROSSING BOW FROM STARBOARD – GIVE WAY
    end if
    if 006° < θ_{Tn} < 112.5°, R_T<6 NM, *BCR*≤0, and $CPA \leq CPA_{PREF}$:
      display: RULE 15 – T_n CROSSING STERN FROM STARBOARD – GIVE-WAY
    end if
  end for
end

The proposed COLREG Classification Module will give directly four possible classifications related to Rule 15, taking into consideration the vessel's sensor parameters of the own vessel and target vessels. These four possibilities in the proposed Module represent significant information to determine give-way or stand-on vessel and to determine bow or stern crossing situation. Once the appropriate Rules have been classified, the collision avoidance algorithm exploits Rules classification as constraints and/or input parameters, which are then used for system design and decisions in the next phase.

3.3 *Route selection*

The route selection module will be enabled if the detection module detects that the safety distance is exceeded and suggests an evasive manoeuvre. The algorithm assumes a minimum course change, set in advance, towards the side established by the COLREG classification module and re-checks whether the safety condition is ensured. If the safety condition is achieved, the last course value is recommended; otherwise, a new course angle is assumed, iterating until the achievement of a safe solution. When the safety condition is assessed all the information will be displayed on the GUI both in graphical and textual form, an example is reported in Figure 8.

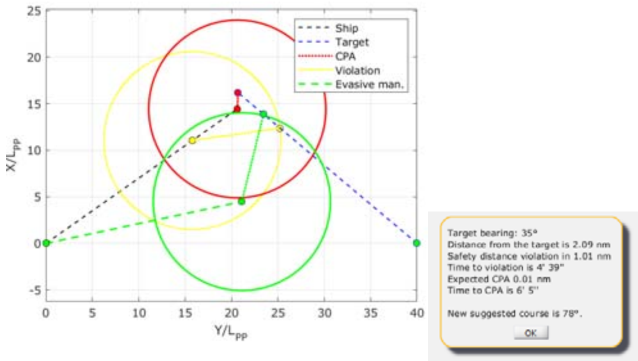

Figure 8. Example of suggestion of a new course in crossing scenario.

4 CONCLUSIONS

Groundings and collisions still represent the highest percentage of marine accidents caused by human error, with consequences on the environment and human life. The analysed statistical data regarding human element as a root cause of marine incidents and collision regulations misunderstanding show us that misunderstanding COLREGs is more severe than thought.

The proposed COLREGs-compliant decision support tool for the end-users (OOW and Masters) provides an early suggestion in compliance with the COLlision REGulations in raising navigation safety. As suggested, the critical element in an automated collision avoidance system technology is the COLREG Classification Module. Therefore, future work will be based on all COLREGs - individual Rules' assessment together with COLREGs implementation and compliance by the legal framework for establishing COLREG Classification Module. Also, as a result of future steps regarding individual COLREG Rule assessment, safety parameters need to be established and elaborated as input parameters for the DSS system.

Furthermore, a detection and tracking module for a DSS system can also rely on data coming from sensors not fully exploited for navigation purposes, such as LiDARs and cameras. This data, especially if elaborated by a data fusion algorithm, could help classify the objects when data coming from AIS are unavailable (e.g., yacht, AIS switched off, etc.) or for floating obstacles. Moreover, in the perspective of a completely autonomous vessel, the proposed approach can be further developed by providing a complete evasive manoeuvre that can be directly actuated by the track keeping and motion control system, with humans that only supervise the process; this will be the object of further studies.

Nevertheless, the properly established and proposed DSS system can considerably reduce the number of collisions in raising navigation safety and environmental protection.

ACKNOWLEDGEMENTS

This research was partially funded by European Union's Horizon Europe under the call HORIZON-CL5-2022-D6-01 (Safe, Resilient Transport and Smart Mobility services for passengers and goods), grant number 101077026, project name SafeNav. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

REFERENCES

[1] Allianz Marine Insurance. Archived on 10-March-2023. Retrieved from https://www.agcs.allianz.com/global-offices/united-states.html#marine

[2] Annual Overview of Marine Casulties and Incidents – European Maritime Safety Agency (EMSA) 2022. Archived on 25-March-2023. Retrieved from https://www.emsa.europa.eu/accident-investigation-publications/annual-overview.html

[3] Benjamin, R.M. Multi-objective autonomous vehicle navigation in the presence of cooperative and adversarial moving contacts. In OCEANS'02 MTS/IEEE, volume 3, pp. 1878-1885. IEEE, 2002.

[4] Benjamin, R.M., and Curcio J. Colregs-based navigation of autonomous marine vehicles. IEEE/OES autonomous underwater vehicles pp. 32–39, 2004.

[5] Benjamin, R.M., Curcio, J.A., Leonard, J.J., and Newman, P.M. Navigation of unmanned marine vehicles in accordance with the rules of the road. In Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICFA 2006., pp. 3581-3587, May 2006.

[6] Demirel, E, and Bayer, D. Further studies on the COLREGs (collision regulations). Transnav-International Journal on Marine Navigation and Safety on Sea Transportation (2015).

[7] Ecolreg. Archived on 03-March-2023. Retrieved from https://ecolregs.com/index.php?lang=en

[8] EMSA, 2022 Annual overview of marine casualties and incidents 2022.

[9] Lazarowska, A. "A new deterministic approach in a decision support system for ship's trajectory planning." Expert Systems with Applications 71 (2017): 469-478.

[10] IMO. Human Element Vision, Principles and Goals of the Organisation. International Maritime Organisation, Resolution A.947(23). Adopted on 27 November 2003.

[11] International Regulations for Preventing Collisions at Sea (Consolidated edition, 2018). Archived on 03-March-2023. Retrieved from https://www.samgongustofa.is/media/log-og-reglur/COLREG-Consolidated-2018.pdf

[12] Jincan, H., & Maoyan, F. (2015, June). Based on ECDIS and AIS ship collision avoidance warning system research. In 2015 8th International Conference on Intelligent Computation Technology and Automation (ICICTA) (pp. 242-245). IEEE.

[13] Pietrzykowski, Z., Wołejsza, P., & Borkowski, P. (2017). Decision support in collision situations at sea. The Journal of Navigation, 70(3), 447-464.

[14] Safety Analysis of EMCIP Data. Analysis of Navigation Accidents - European Maritime Safety Agency (EMSA) 2022. Archived on 25-March-2023. Retrieved from https://www.emsa.europa.eu/publications/item/4830-safety-analysis-of-emcip-data-analysis-of-navigation-accidents.html

[15] Sunmer, M. Dynamic Collision Avoidance for Sea Surface Vehicles with a Hidden Markov Model. doctoral dissertation. University of Rijeka, Faculty of Maritime Studies, Rijeka 2021.

[16] Wilthil, E. F., Flåten, A. L., Brekke, E. F., & Breivik, M. (2018, March). Radar-based maritime collision avoidance using dynamic window. In 2018 IEEE aerospace conference (pp. 1-9). IEEE.

[17] Zaccone, R., & Martelli, M. (2018, October). A random sampling based algorithm for ship path planning with obstacles. In Proceedings of the International Ship Control Systems Symposium (iSCSS) (Vol. 2, p. 4).