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RESEARCH ARTICLE

Dynamic Tabu Search for Collision Avoidance in Autonomous Maritime Ships

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ABSTRACT This article presents an innovative approach to maritime collision avoidance, featuring a redesigned tabu search algorithm that creates effective solutions across various sea regions by incorporating COLREG, regional rules, ship capability, and good seamanship. The algorithm's dynamic memory adapts solution spaces to changing conditions, ensuring optimal outcomes by modifying tabu, avoiding local minima, and initiating searches in probable solution regions. Notably, the method generates multiple evaluated solutions considering criteria such as risk, implementation cost, legality, and applicability. The proposed comprehensive approach promises to enhance maritime safety and operational efficiency through adaptable collision avoidance strategies.

INDEX TERMS Autonomous navigation, collision avoidance, COLREGs compliance, maritime autonomous surface ships, maritime safety, Tabu search.

I. INTRODUCTION

Maritime transportation accounts for a significant portion of global trade due to its low cost. However, accidents are the most common risk factor in maritime transport, as collisions account for 60% of accidents and 80% of collisions are caused by human error [1]. Autonomous Collision Avoidance (CA) is critical to mitigate human error, reduce the associated negative impacts to avoid the consequences for people and increase the efficiency of the maritime trade system.

Maritime Autonomous Surface Ships (MASS) have emerged as a transformative technology in the realm of maritime innovation. Despite their potential, the lack of a coherent legal framework has restrained their progress beyond the testing phases but a forthcoming milestone looms. The International Maritime Organization (IMO) is poised to introduce regulations in 2024 [2] clearing the way for MASS to transition from prototype to reality. The autonomous navigation or e-navigation [3] system a defining characteristic separating MASS from traditional vessels is at the center of this evolution so perfecting CA is paramount to realize their potential. Autonomy presents both opportunities and challenges for the future of maritime transportation. It reduces overall transport costs by lowering personnel expenses, enhances the resilience of the global supply chain against potential pandemic-like shocks, and creates suitable conditions for the slow-steaming navigation recommended by the IMO to reduce greenhouse gas emissions.

Delving into the prevailing regulations and scholarly studies indicate that an effective CA maneuver must adhere to a set of distinct characteristics briefly defined below.

- The main goal of these practices is to keep costs low while increasing the safety of life and property. This is achieved by reducing the risk of conflict in a cost-effective manner.

- International Regulations for Preventing Collisions at Sea (COLREGs, 1972) are a set of rules that determine which ship has the right of way and the responsibilities of the ships in the maneuver to be carried out for avoidance, taking maneuverability, area, bearing, and other factors into account in the encounter. Currently, ships execute the avoidance maneuver by COLREGs while the CA method should do the same thing.

- An appropriate solution must be found to minimize damage and losses in an event where a collision is unavoidable.

- The Target Ship (TS) may not fully comply with the COLREGs or there may be a problem with ship control for any reason. In such a case, the method should correctly identify the TS and find a solution under all circumstances.

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- As the alteration in speed poses risks of damaging machinery systems and is inherently slow, particularly in large tonnage ships, efforts should be performed to minimize its occurrence. Additionally, speed reduction is advisable when it is identified that the speed surpasses the safe limit as specified in COLREGs or when time is essential for conflict resolution.

- The maneuverability of ships is significantly affected by their size and design so IMO has established the minimum maneuvering characteristics that a ship should have [4]. These requirements include the ability to turn and stop the ship depending on its size and tonnage. The maneuvering capability of the ship should be considered for an appropriate and accurate CA solution.

- The solution must be quick for two reasons. First of all, the situation is dynamic, so if a solution takes a long time, then the conditions under which you achieve the result may change and lose their effectiveness. Secondly, it may require to respond quickly when the TS is detected at close range.

- COLREGs cannot account for what to do in the case of multiple TS so the problem should be divided into smaller parts with individual solutions being developed for each while the overall solution interconnects with the main objective.

- There is no need to apply regulations for objects that are not subject to the COLREGs rules so the CA method may find different solutions for them.

- Seamanship is a profession with a high level of tradition and experience so good seamanship traits should be included in the CA method.

- By starting the avoidance maneuver as early as possible, there is no need to change speed, the deviation from the course is minimized, and the amount of turns needed is reduced. For these reasons, the CA maneuver should be started as early as possible.

- In areas close to shore and with heavy traffic, a low-risk solution may not be obtained due to the lack of sufficient sea space. In this case, the CA method should find and implement a solution with optimum risk.

- Although CA methods are not at the desired levels, they should find and implement solutions for all risky encounters, since acting on the principle that the worst decision is better than no decision.

- Meteorological conditions have a significant effect on ship maneuvering so taking the waves from the ship's broadside in high-sea state conditions may cause the ship to yaw and risky situations for passengers or freight. Therefore, the CA method should find results by considering the meteorological conditions.

The method must meet the specified requirements to a high degree while seeking a CA solution. Any deviation from it can negate the benefits provided. A literature review reveals that many methods only partially satisfy the requirements. Additionally, studies by the IMO indicate that new regulations may be introduced or existing ones could be modified. Therefore, adaptability to these changes is essential. According to the autonomy levels defined by the IMO, an operator will be responsible for navigational safety either onboard the ship or at a Remote Operations Center (ROC). For this reason, the method must interact with the operator and allow him to make decisions when necessary.

Analyzing the characteristics of the CA problem, there are dynamically changing prohibitions, constraints, limits, and directives arising from the rules, the region, meteorological conditions, and ship capability. The literature shows that most methods adhere to COLREGs only to a limited extent, fail to incorporate good seamanship principles, and do not account for factors such as meteorology and maneuverability that constrain the problem. Additionally, these methods exhibit low flexibility in adapting to changing rules and conditions. While it appears unlikely that any single method can fully satisfy all requirements, an optimal solution could be achieved through a heuristic search considering these various factors. A common solution to such problems is the use of meta-heuristic search methods. In this study, the Tabu Search algorithm [5], which is a meta-heuristic search method, has been restructured to suit the solution of the CA problem. It can search locally and globally as well as does not get stuck in local minima when searching the entire state space. The main component of the method is its adaptive memories. By shaping them, flexible and customized searches can be performed. The search starts in the region where the solution is most likely according to the rules. Prohibitive rules shape the tabu memory, directive rules shape the search vector, and ship limits and geographic structure determine the search space. By the proposed solution, long-term memory is created to diversify the search to obtain alternative solutions and not to get stuck in the local minimum. The generated solutions are evaluated according to numerous criteria such as risk level, implementation cost, amount of tabu violated, legality, and applicability. The method has successfully passed the tests carried out in a computer-based and realistic navigation simulator.

This study has four major contributions. First of all, the technique creates appropriate solutions in various sea areas (open sea, coastal waters, narrow channels, etc.) using a single method that takes into account COLREGs, regional rules, ship capability, and good seamanship features. Secondly, thanks to its dynamic memory, it can adapt the solution space to changing circumstances and conditions, remove or modify the tabu assigned to certain restrictions, shape the space by adding new tabu, and find the best solutions without getting stuck in local minima when the requirements cannot be met. Thirdly, the search starts in the region where the solution is most probable by considering the situation and the rules. The optimal solution is reached as soon as possible by moving in the appropriate direction with the created dynamic search vector. Finally, the method generates multiple solutions with alternatives. The solutions are evaluated according to numerous criteria such as risk, cost of implementation, amount of tabu violation, legality, completeness, and applicability.

II. LITERATURE REVIEW

In anticipation of the essential role of MASS in the future of maritime activities, comprehensive studies such as MUNIN [6], MONALISA, IHO MASS PT, and EfficientSea have been conducted to establish their theoretical framework. Technological advancements in power, communication, and position determination have facilitated the realization of MASS by leading to the construction of numerous test-purpose vessels.

As MASS is expected to become a primary element in the maritime sector in the future, CA methods have recently been tested on both commercial and military vessels beyond academic studies. However, due to the lack of legal authorization for actual use, tested MASS cannot be commercially utilized. To fill this gap, the IMO is conducting studies to establish the necessary regulations and capabilities required for compliance. The rules that will come into effect as a result of these studies also directly impact the resolution methods for the CA problem. Currently, methods that operate in accordance with existing regulations are being developed, implemented, and assessed for deficiencies. Methods employed in the previous studies can be tested and their suitability evaluated with the widespread adoption of realistic simulations.

The variables that influence the problem of CA are successively the COLREGs, good seamanship practice, the rules specific to the area being sailed, the maneuverability of the vessels, the meteorological conditions, and the geography of the area being sailed. CA studies in the literature generally include developed methods, improvements to solutions based on variables, and efforts to correct deficiencies. The methods commonly used in such studies are briefly outlined and described below.

A single rule cannot address every encounter in a dynamic environment so multiple rules are taken into consideration. However, the methods do not guarantee effective CA since they are impractical to use rules for all scenarios. If an event has not been previously experienced or studied, then the method may not find a suitable solution. For this reason, COLREGs and good seamanship rules are incorporated into the calculation in general. Rule-based methods are often based on artificial neural networks [7], fuzzy logic [8], and Bayesian networks [9]. Fuzzy logic [10] is a suitable and effective method for dealing with linguistic representation and subjective concepts. It facilitates the translation of all applicable rules into software as they are written in a way that is interpretable by humans. Additionally, it can be utilized in this method for aspects with relative considerations, such as ship capabilities and risk levels, which do not have precise boundaries [11].

Artificial neural networks are trained using these data to make decisions about encountered situations when sufficient data is available. The decision to be made varies depending on the quality of the data used in training. Video cameras, LIDAR [12], and similar sources play a vital role in designing COLREG-compliant MASS and CA processes. At this point, Convolutional Neural Networks (CNN) [13] are a commonly used method for visual data processing. When the type of TS (sailing, fishing, power-driven vessel) is accurately identified visually, the requirements of the rules can be implemented precisely.

The Artificial Potential Field (APF) [14] is based on two generated forces called attractive and repulsive. The attractive force is created by the target position while the repulsive force is created by obstacles. It has two main problems. The first one is its tendency to converge to a local minimum when close to obstacles [15] while the other one is the decrease in attractive force and increase in repulsive force when obstacles as well as the target are close to each other. The Virtual Force Field [16] and the Limited Cycle Method [17] also achieve an optimal solution by creating force lines with a similar logic.

The Decision Disk (DD) approach selects route and speed as control inputs for the ship and presents the solution space as a disk [18]. If this trajectory is collision-free, then the control is reserved while the control is rejected otherwise. Subsequently, collision-free controls are directly presented to the operators or an optimal solution is selected through optimization from these collision-free solutions. The primary drawback of these studies is the neglect of the kinematic and dynamic constraints of the operating system, which may lead to the failure of the method to prevent collisions in close encounters [19].

Graph search algorithms aim to create tree-like paths to reach a target. These algorithms perceive the environment as nodes and corners. Dijkstra's algorithm [20] is one of the earliest graph search path planning algorithms. The goal of this algorithm is to find the shortest path between two nodes. Voronoi diagrams in addition depict proximity information between a set of points or objects within a specified region while dynamic solutions can be obtained in regions with dense land using this method [21]. The A* search algorithm [22] is an intuitive line traversal and pathfinding algorithm. It is known for its completeness, optimality, and high efficiency. The disadvantage lies in its high memory requirement and processing cost since it keeps all nodes in memory. A* and its variations have been studied in various forms, such as safety-zoned [23], COLREG-compliant [24], and applications in a constrained search space [25]. Adding the feature of speed change alongside the classical route alteration can be a fast and robust method for collision avoidance.

The Dynamic Window (DW) [26] consists of two steps. First of all, all pairs that the Owns Ship (OS) can reach within a specific time step are selected as the initial DW by considering speed and acceleration constraints. Secondly, the initial DW is reduced by retaining pairs that allow the vehicle to come to a stop before colliding with obstacles. The drawbacks of the original DW include sensitivity to local minima, the assumption of circular paths, and freezing time at each step. In addition, methods that do not use circular paths [27] and approaches that do not get stuck in local minima [28] have been developed.

Brute-force search is a general problem-solving technique that involves creating a list of all possible candidates for a solution and testing the validity of the candidates. The computational load is high so a specific range is defined to initiate the search for CA solutions where the first solution found is implemented [29].

The Ship Safety Domain (SSD) [30] is the area around the ship where the entry of other vessels is not desired. SSD dimensions are determined as both fixed and instantaneously variable based on numerous parameters [31]. The efforts are performed to prevent conflicts in various scenarios, such as avoiding the violation of OS's domain [32], ensuring that TS's domain is not violated, preventing violations of either OS or TS's domain, or domains do not overlap. The positions of ships within SSD can be adjusted according to the encounter situation for compliance with COLREGs [33], [34], [35].

Velocity Obstacle (VO) [36] is the set of all velocities of a ship at a given instant that would result in a collision with another TS. It assumes that the TS maintains its current speed and heading. If OS selects a velocity inside the VO, then a collision occurs between the two ships. On the other hand, such a collision does not occur if it selects a velocity outside the VO. In addition, the method has been successful in scenarios involving multiple Target Ships (TSs) [37]. The advantages of the method include low computational load, long-standing familiarity among captains, and the ability to provide visual output to the captain.

Route planning for CA is an optimization that adheres to the rules with the lowest possible turn without extending the path. In this regard, it exhibits a problem-solving characteristic through constrained optimization. Successful results have been obtained using optimization methods such as evolutionary algorithm [38], ant colony algorithm [39], and genetic algorithm [40]. Their main advantages lie in obtaining quick results compared to many methods due to their intuitive search capabilities.

The Lattice-Based Search (LBS) method allows control inputs to change at every time step by making it time-consuming. To shorten the time, it searches for some representative candidates since it performs searches in multiple directions in a one-time step. The main advantage of this method is to produce an accurate solution while the disadvantage is searching all branches in the graph can be computationally expensive and may not be suitable for real-time CA [41], [42].

Widespread adoption of automatic CA systems is achieved by meeting safety expectations and making the most accurate decisions in compliance with existing regulations. A collision resulting from an error in the MASS negates all the benefits it provides in a single incident. To meet the safety requirements of the CA method and to avoid being blamed in the event of an accident, it is necessary to apply not just some but all COLREGs, regional rules, and good maritime practices. When examining the studies in the literature, it is observed that some methods do not include rules in their calculations whereas those that use rules are designed to apply only a few rules. Good maritime practices are rarely applied. The studies by Ozturk et al. [43] and Huang et al. [44] illustrate this situation. It is predicted that many methods that comply with the rules become unusable in the future due to changes in regulations. In this study, a fast, realistic, and easily adaptable method was developed that covers as much regulation as possible.

III. METHOD

Tabu Search is a meta-heuristic search method developed by Glover in 1986 [5]. It employs a local or neighborhood search process to continually transition from one potential solution to a better one within the nearby vicinity. By enabling navigation within the specified search space, a global search can be conducted without becoming trapped in local minima so it can perform global searches while not getting stuck in local minima when searching the entire state space. The main component of the method is its adaptive memories. By shaping these memories, a flexible and desired search can be performed. The most commonly used basic definitions and memories of the TA method are presented in this study.

Tabu list specifies areas that should not be visited or actions that should not be done while achieving results. Search space is the state space in which the most optimal solution is explored. Tabu tenure refers to points that have been recently visited and should not be visited again during the established period. When its criteria are fulfilled, the point can be revisited with a reduced or renewed list of tabu to improve the solution. Aspiration criteria, the area, criteria, or movement identified as tabu is removed from the tabu list to become usable if the specified conditions are fulfilled. Tabu is usually terminated when a suitable solution is not achieved despite performing a certain number of iterations or when a tabu is encountered while advancing in a suitable direction. Long-term memory facilitates the discovery of the global minimum by executing jumps to prevent the search from getting stuck in a local minimum. Solution Memory, in addition, is the repository for solutions that meet predefined criteria, primarily encompassing the best and most recent solutions. Objective value/function represents the function or desired criteria for which the optimal value is sought. The stopping criterion refers to the conditions that terminate the search when one of the predefined criteria such as the number of iterations, a specific error threshold, a maximum runtime, the attainment of a solution, evidence of reaching the best solution after a certain iteration, or similar criteria is met.

The general characteristics of the tabu search method are as follows. It always selects the best neighbor for processing although the resulting solution may not necessarily be better than previously obtained ones. Besides, regions that have been visited and processed are not revisited within the defined criteria but the tabu list can be modified based on visited points. In addition, tabu can be removed from the list after a certain duration while the search space can be expanded by adjusting the tabu tenure and modifying the tabu list.

Memories serve as the cornerstone of the tabu search method, thereby, the greater the efficiency and optimization of these memory structures, the swifter and more precise the solution discovery process becomes. Adhering to the principles delineated by Glover et al. [45] during the establishment of these memory constructs plays a pivotal role in attaining an effective solution. Tabu lists are also supposed to exhibit adaptability to changing circumstances while allowing for the creation of distinct tabu lists that align with specific conditions. This practice ensures the maintenance of concise tabu lists that contribute to the algorithm's enhanced operational speed. Continuously updating the lists guarantees accurate neighborhood delineation and ensures that the search is executed within the appropriate spatial context. It is advisable to initiate multiple random searches from different starting points to promote solution diversification and explore various points within the search space. Additionally, it is important to define penalty regions with sufficient size to ensure the exploration of diverse regions and avoid convergence to local minima. Additionally, the existing tabu list can enhance solutions by revisiting previously successful outcomes. The generation of new memories tailored to a specific problem or problem area can yield solutions that are well-suited to the given context as this approach enables flexible exploration and facilitates the attainment of context-appropriate solutions.

A. OUTLINE OF THE METHOD

The method collects information from four different sources (1) Own ship platform data, (2) TS data obtained from the own sensor, (3) Data received from the Automatic Identification System (AIS) and control center, and (4) Visibility and sea state. Then it interprets them according to COLREG as the data is used for conflict risk calculation and determination of the CA maneuver required. If the risk of collision is below the threshold level, then moving forward is continued without any change while they are sent to the tabu search method to calculate an avoidance route for contacts with conflict risk above the threshold level. The CA method calculates the risk of each solution to evaluate it. Risk calculation is one of the two main sub-components of CA and it also enables the CA method to make an accurate assessment of the optimal solution. In this study, the risk calculation method developed by the authors is used to catalyze the risk by examining the risk from multiple aspects. The general algorithm of the method is presented in the Fig. 1.

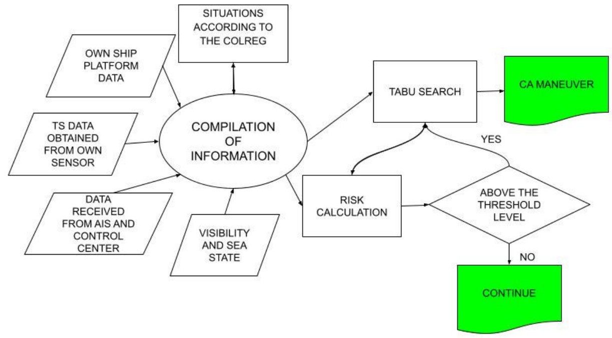

FIGURE 1. General algorithm of the method.

The compiled information is interpreted according to COLREG. In this section, firstly, the type of encounter situation is determined based on Rules 13, 14, 15, and 16. Secondly, considering the maritime areas specified in COLREG rules 1, 9, and 10, it is established that the vessel has the right of way as well as taking into account the responsibilities between vessel situations outlined in COLREGs rule 18. Depending on it, calculations are performed for a point in the search space where the solution is most likely possible and is selected as the initial point to get the results accordingly. If the desired results are not achieved within the defined search limit, then some of the tabu are broken and the search is continued by updating the memories while the search is terminated if the result meets the requirements or one of the termination criteria is met. The tabu search algorithm for solving the CA problem is depicted in the Fig. 2.

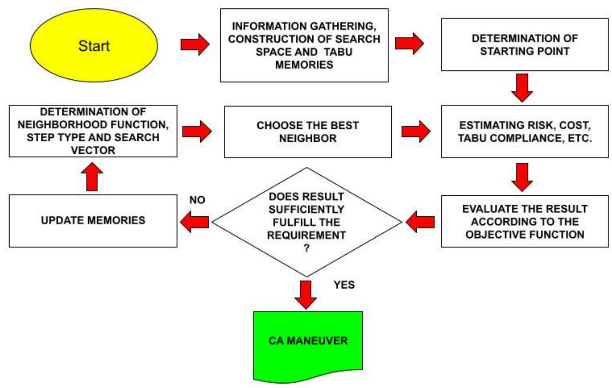

FIGURE 2. Tabu search algorithm for solving the CA.

B. CREATION OF METHOD COMPONENTS

The TS is reinterpreted to obtain solutions following general, local and, good maritime rules. The main difference of the regulation-compliant tabu search method is to shape the memories according to the rules, conditions, and capabilities of the ship. Prohibitive regulation creates a long-term tabu list and this continues unless aspiration criteria are met. Besides, ship capability and navigable sea area are used to determine the search space. The COLREG defining the course of action comprises the neighborhood vector so a rule-compliant search in the correct direction is performed. Emergency rules become long-term tabu-termination criteria because they abolish the rules that ordinarily are in force. Recently visited points are saved in the short-term tabu memory and repeat visits are prevented. The solution memory contains the best, last, initial, and unique solutions. The method, which is constructed by placing the rules in appropriate tabu memories, produces a highly efficient, optimal, fast, and dynamic solution in a limited search space. The starting point is in the region where the solution is most likely according to the rules. The evaluations are based on the risk, cost, tabu compliance, objective function, and validity of the solution. The search is terminated if one of the termination criteria, such as the defined number of iterations, the changes that improve the solution only slightly, the best solution does not change, etc. is present. The tabu list used in classical TS, which contains recently visited points, is called the short-term tabu list in this study and is used in the same way. Long-term memory facilitates jumps between search regions to prevent the search from getting stuck in a local minimum. The method uses dynamic tabu tenure that can vary for different types or combinations of attributes as well as over different intervals of time or stages of the search.

The memories to be used in the method can be changed according to the rules of the cruising region. This feature allows the method to work effectively in all conditions and regions. It is foreseen that the rules in force may change with the widespread use of autonomous ships and the method can be used effectively with minor modifications depending on changing regulations. The rules that are considered to be good features of seamanship and desired solutions are placed in the appropriate memory.

1) SEARCH SPACE

A search space is the domain through which a tabu search algorithm seeks. When a TS with a risk of conflict is detected, the proposed method creates an intermediate waypoint and proceeds to this point with the determined speed. The search space consists of points and the velocity domain. Due to the fact changing the speed is tabu, the search is conducted initially in the point domain. If tabu for speed change is terminated, then the search is also conducted in the speed domain. Factors limiting search space for the optimum size of the search space are presented below.

- Land and shallow sea area determined according to the ship's draft.
- Sea area around buoys, cardinals, laterals, etc.
- Sea area around moored boats.
- Areas prohibited for navigation by NOTAM NOTMAR etc.
- Between stop and maximum speed.

2) STARTING POINT AND NEIGHBORHOOD VECTOR

The search starts from the area where the optimum result is most probable and it proceeds in the proper direction according to the situation by interpreting the rules. The algorithm jumps to different regions of the solution space to avoid getting stuck in the local optimum. In the tests performed, the solution is obtained much faster than searching randomly starting from a randomly chosen initial point.

To perform the search, the solution is considered by taking the current speed into account in the first step. The search direction is mostly in the opposite direction of SSD. If a solution is not obtained despite searching in the region for the specified amount of time, then a new region is entered. The direction takes place where the solution improves the most. In the case of multiple TSs, the starting point and search vector are determined according to the target with the lowest TCPA.

In cases where the solution needs to be diversified and the starting point does not meet the requirements, a new starting point needs to be set. In such a case, it is restarted from the point that was not searched since it is possible to be on the opposite side of the target. Since some of the tabu are set according to the TS, some of the solutions for multiple TSs may be appropriate for one target but not for others. For this reason, the results are evaluated in multiple aspects to determine the optimum solution. The starting point and neighborhood vector determined for the method are presented in Table 1.

TABLE 1. Starting point and neighborhood vectors depending on the situation.

SITUATION	STARTING POINT	NEIGHBORHOOD VECTOR
Head-on situation	The first point on the starboard side of the estimated SSD.	Starboard side
Crossing situation (TS on the starboard side)	The first point on the starboard side of the estimated SSD	Starboard side
Crossing situation (TS on the port side)	The first point on the port side of the estimated SSD	Port side
Overtaking vessel situation	The first point on the port side of the estimated SSD	Port side
Overtook vessel situation	The first point on the starboard side of the estimated SSD.	Starboard side
Contact that is not subject to COLREG	Start from the starboard and port side and continue from the most appropriate point.	Proceed to the designated side

3) LONG-TERM TABU LIST

What should not be done according to the general, local, and good seamanship rules is kept at this point and remains until the termination criterion is fulfilled. The tabu list, mostly determined by the current rules, also establishes termination criteria according to these rules. The tabu, their bases, and termination criteria are presented in Table 2. Variables in this list can be changed optionally to provide a dynamic and flexible search.

The tabu list, prepared by the authors as an example to demonstrate the functionality of the method, is constructed from COLREGs rules, good maritime practices, and regional regulations. The number of elements in the list can be increased as desired. For instance, new rules can be defined when a specific ship type or activity is involved, in case of the introduction of new rules, or changes to existing rules concerning MASS. The tabu list is flexible in this regard.

In the method developed, a solution without using long-term tabu is explored. The aim is not to violate any tabu but in the case of high traffic, limited sea space, or nearby detected contact, a tabu-free solution cannot be found. In such

TABLE 2. Long-term tabu list, basis, and termination criteria.

NO	TABU	BASIS	TERMINATION CRITERIA
1	Getting inside the estimated Ship Safety Domain (SSD).	COLREG Rule 8 (d)	Absence of a solution that meets the requirements at the end of the defined iteration limit and detection at a very close distance.
2	Altering the course and speed while having the right of way.	COLREG Rule 17 (a) (i)	The give-way vessel does not make the necessary movement.
3	Changing course to port in case of a head-on situation.	COLREG Rule 14 (a)	Absence of safe route at starboard side.
4	Speed change.	Good seamanship	Absence of a solution that meets the requirements at the end of the defined iteration limit and detection at a very close distance.
5	Crossing ahead of the other vessel.	COLREG Rule 15	TS is a towing vessel or too close distance.
6	A succession of small alterations of course and/or speed.	COLREG Rule 8 (b)	Before the risk commences
7	Areas outside own line, when a traffic separation scheme is in place.	COLREG Rule 10	Absence of a solution that meets the requirements at the end of the defined iteration limit and detection at a very close distance.
8	Courses and speeds that are considered to cause the ship to roll due to sea conditions.	Good seamanship	Absence of a solution that meets the requirements at the end of the defined iteration limit.
9	Crossing the stern area of a towing, fishing vessel.	Good seamanship	Emergence situation.
10	Proceeding above the speed set for the region or safe speed	Local rule and COLREG Rule 6	Emergence situation.

a case, the tabu is terminated when the termination criteria are met. Each time a tabu is terminated, the search is repeated to obtain the result. An example is a speed change tabu so that a solution is tried to be found with only a course change in the first place. The termination criterion of the tabu is that the desired result is not obtained without changing the speed. When the maximum iteration is reached and no result is obtained, the tabu is terminated and the search continues to find solutions with different speed values.

4) SHORT-TERM TABU LIST

Short-term tabu is applied like classical tabu search where recently executed actions are recorded in the tabu memory. When a new action is performed, its tabu status is assessed by checking against a tabu list, which is constructed in a way of the classical tabu search approach. It is structured as a matrix, automatically refreshed with an increase in the number of iterations. The size of it is determined empirically so if the size is too small, then a cycling event may occur. On the other hand, the search process may deviate from the optimum when it is too large. The optimal size of the tabu list should strike a balance, being long enough to avoid cycles and short enough to facilitate the search within the continuous solution space.

5) TABU TENURE (TT)

The tabu tenure is the count of iterations that a movement remains in the tabu list. In the proposed method, there are two types of tabu as long and short-term tabu. Long-term tabu, which is developed specifically for the proposed method, persists unless the destruction condition is met. TT determines the period of short-term tabu.

6) LONG-TERM MEMORY (LTM)

In long-term memory, the searched points, the best point, the development rate, and the tabu in the regions are recorded. When conditions such as trying all regions, reaching the set number of iterations, slow-progressing, or points containing tabu occur in the region, location change is performed to avoid getting stuck in a local minimum. When a new search is made in the searched region due to the breaking of a tabu, the search is accelerated by starting with the best point since the best points are recorded in all regions.

The best points in different regions generate alternative solutions. If the decision made is deemed risky by the operator, then alternative solutions are presented and the solution chosen by the operator is implemented.

C. EVALUATION

The solution undergoes a two-stage evaluation procedure. In the first stage, the legality, feasibility, and risk of the solution are assessed. If tabu is found in the solution for the control of COLREGs, then it is deemed unlawful. The search space is defined according to the standard limit of the vessel, for instance, a solution that includes a turn that poses a risk on high seas, a change in limitation due to malfunctions, or conflicts with the restrictions set by the operator is considered unfeasible. A solution that exceeds the risk threshold set by the operator is considered risky. In the second stage, solutions that pass these tests and meet the requirements are subjected to the calculations outlined below. The solution with the lowest value becomes the best solution and is provided as the output.

1) RISK

It indicates the risk (Current Route Risk-CRR) of collision if a ship navigates the calculated course and speed without any change. The risk is determined proportionally to how much the calculated SSD is violated. The method uses the SSD designed by Kijima and Furukawa [46]. The SSD consists of two ellipses located at the bow and the stern. The dimensions of the ellipses are determined using ship length, speed, and time to a 90-degree course change. The shape of the SSD and the parameters used in the CRR calculation are presented in Fig.3.

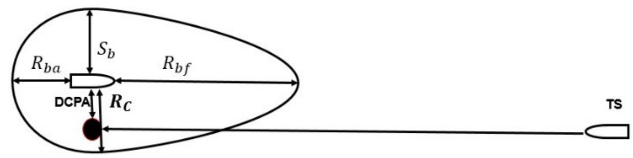

FIGURE 3. Current route risk (CRR).

The formula for calculating CRR is as follows.

$$CR = 1 - \left(\frac{DCPA}{R_c}\right)^2 \tag{1}$$

where R_c is the distance to the SSD border at the moment of the Closest Point of Approach (CPA) while the Distance at the Closest Point of Approach (DCPA) is the distance at which the TS is closest to OS. The greater the number of domain violations committed by the target, the higher the risk level compared to its square.

2) COURSE ALTERATION RATE (C)

Szlapczynski et al. [47] observed in a simulated scenario that a 90-degree turn with no speed reduction averted collisions except at close distance. In this study, the cost of the evasive maneuver is determined by the number of turns required to reach the defined route leg. The cost is calculated as the ratio of the required amount of rotation (T) to 90 degrees and is presented in Equation (2).

$$C = \frac{T}{90} \tag{2}$$

3) TRAVEL DISTANCE INCREMENT (D)

Travel Distance Increment (D) is the parameter that indicates how much the performed maneuver extends the distance to be traveled. When a course alteration is performed to avoid the ship encountered, $a + b$ distance is traveled in total, subtracting c, the distance normally traveled, provides the increase in the distance to be traveled. The calculation of D is presented in Equation (3) and depicted in Fig. 4.

$$D = (a + b) - c \tag{3}$$

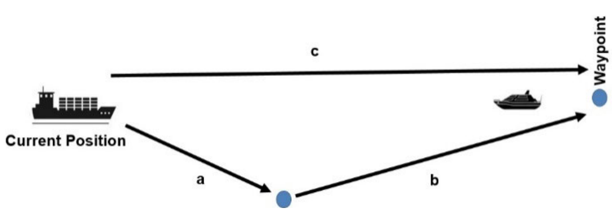

FIGURE 4. Travel distance.

4) TABU-BREAKING STATUS (TBS)

Although the desired state is to obtain a solution without tabu breaking, it may occur depending on the circumstances. Tabu breaking status (TBS) is calculated as the ratio of the amount of tabu broken (T_b) and the amount of long-term tabu (T_t) as follows.

$$TBS = \frac{T_b}{T_t} \tag{4}$$

5) OBJECTIVE FUNCTION

Objective Function (F_o) is the sum of risk, cost, and tabu-breaking status. The method strives for this function to be close to zero while the formulation is provided in Equation (5).

$$F_O = \alpha\, CR + \beta\, TBS + \rho\, C + \sigma D \tag{5}$$

where α, β, ρ, and σ are coefficients of the cost function elements to shape the solution. In Equation (5), the coefficient α determines the importance of the risk value in the solution, the coefficient β indicates compliance with the rules, the coefficient ρ determines the significance of the turning amount to be made, and the coefficient σ indicates the significance of distance increase. By increasing the coefficient of the prioritized element, the results can be adapted to the operator's requirements.

D. DEMONSTRATION OF THE WORKING MECHANISM OF THE METHOD WITH SIMPLE SCENARIOS

In this section, the method search is described using the five basic common encounter situations as well as the results obtained in computer simulation are presented. The calculation in the case of multiple targets with the scenario is also described.

The scenario where TS approaches OS from the bow is termed as the head-on encounter condition and is illustrated in Fig. 5. In this situation, COLREG dictates that vessels must not alter their course to port. Therefore, when a solution takes place in the red-dotted area on the port side of our vessel it violates long-term tabu-3, increases the cost calculated, and also it is deemed unlawful in the initial evaluation stage. The yellow-dotted area represents the region where turning is not feasible with the current speed and standard rudder angle. The black-dotted area specifies the expected area of SSD at the CPA time, and solutions within this area violate long-term tabu-1. The point presented in gray is the starting point determined based on the encounter situation where the search begins from this point. All tabu list is examined for each selected point and the total score is determined by calculating how much turn as well as distance are needed to reach that point. The best point within the neighborhood is selected before the search continues. This process endures until the termination conditions are met and the point with the lowest score obtained is the best solution. The colored dots in the figures are visualized for the most common COLREG rules so similar applications are performed for other rules as well.

The scenario depicted in Fig. 6 showcases the situation where the TS approaches from the starboard side posing a risk of collision. The red and black-dotted areas in the figure represent tabu, the yellow dots denote regions where turning with a standard rudder angle without altering speed

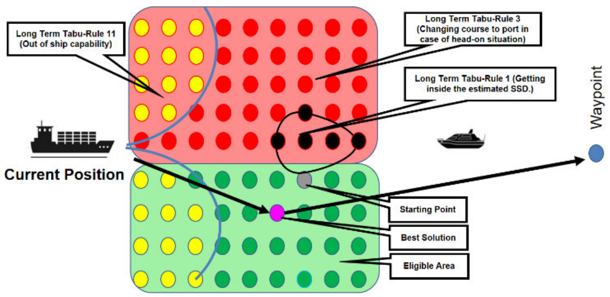

FIGURE 5. Head-on situation.

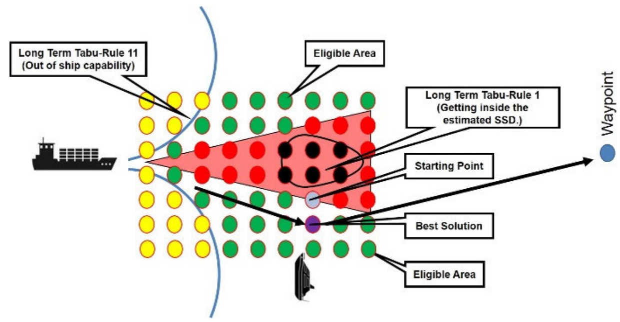

FIGURE 6. Crossing situation (starboard side).

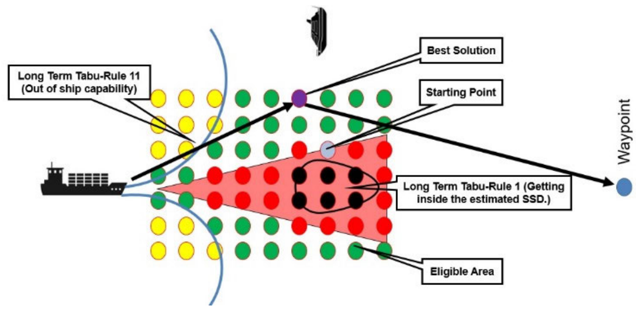

FIGURE 7. Crossing situation (port side).

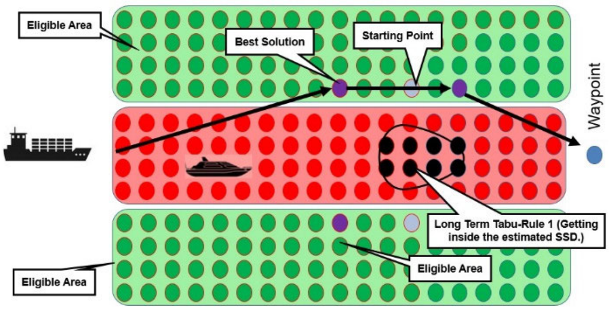

FIGURE 8. Overtaking.

is unfeasible, and the green dots designate priority search zones. Consistent color codes are utilized in other figures for clarity. Given the right of way to the TS, the give-way ship (OS) initiates maneuver promptly and distinctly under COLREG when the risk arises. The method identifies the starting point based on the "Crossing situation (TS on the starboard side)" definition in Table 1.

The grey-shaded starting point is positioned on the starboard of the SSD by aligning with the estimated CPA position. Subsequent search efforts follow the search vector and neighborhood rules are specified in Table 2. In the initial region, an optimum solution is swiftly reached by meeting all conditions. However, as solutions in the green area northward intersect with the TS's bow, violating long-term tabu-5, jumping to this area does not yield a satisfactory solution.

The scenario of posing a risk of collision illustrates the approach of the TS from the port side in Fig. 7. In response to the emerging risk, the give-way ship (TS) adheres to COLREG where OS maintains its course and speed due to the right of way. Once the risk surpasses the predetermined threshold level, the long-term tabu-2 is broken by prompting the initiation of maneuvers. The method identifies the starting point based on the "Crossing situation (TS on the port side)" in Table 2. The grey-shaded starting point is positioned on the port side of the SSD as it aligns with the estimated CPA position. Subsequent search efforts follow the search vector and neighborhood rules specified in Table 2. Given the attainment of a solution meeting all conditions in the initial region, the method efficiently reaches the optimum solution.

The scenario with the TS in the current bow, posing a risk of collision is provided in Fig. 8. As the TS has the right of way, OS initiates early and clear maneuvers in compliance with the COLREG rules as soon as the risk of collision emerges. In the case of the open sea, the TS can be passed from both sides. The determining factor for selecting the passing side relies on the cost, with the optimal solution identified on the side where the cost is lower. In scenarios involving channels or passages, a solution is generated to leave the TS on the starboard side with a provided suitable area.

E. SOLUTION OF MULTIPLE TS

When encountering a single TS, a solution involving tabu or risks may result in a high cost so it is not designated as the optimal solution. Thus, using the method in situations where only a single TS is encountered has a very high probability of obtaining a risk-free solution that complies with all rules. In the case of multiple-TS, as COLREG rules do not specify the maneuver style for multiple TS, the applied maneuver may be compliant for some ships while violating the rules for others. Consequently, there may be tabu violations, the method must achieve an optimal solution under these conditions. When the number of TSs increases, there is a possibility that the solution may involve rule violations for some ships as it is also the case in real-world scenarios.

In scenarios with numerous ships in close proximity, defining a new route exclusively for the risky ship can lead to risks for other ships. To mitigate this, it is imperative to include all ships within the specified area in the calculation. Only through this comprehensive approach can a complete and optimal solution be achieved. The proposed method includes all ships within the calculation range defined in the study by the authors. When identifying a risky ship, the initial solution is generated based on the most dangerous vessel once the necessary conditions for initiating a maneuver are met. From this starting point, the tabu search method performs similar calculations to those for a single target. The key difference is that the cost is calculated for all ships within the calculation area and the total cost value of the identified point is determined by aggregating the individual costs. F_o for multiple TS is described in Equation (6).

$$F_O = \sum_1^n (\alpha.CR_n + \beta.TBS_n) + \rho.C + \sigma D \qquad (6)$$

In scenarios involving numerous ships, the computational processes become more time-consuming for two primary reasons. Firstly, an extensive search is conducted across various regions with jumps in the state space upon identifying a TS in the vicinity of the initial solution as potentially posing risks to other ships. Secondly, the inclusion of all ships within the vicinity adds to the processing load and complexity of the calculations.

The scenario involving multiple TS is depicted in Fig. 9. Beginning with the ship with the lowest TCPA value among the TSs at risk of collision, the starting point (grey point) is determined according to Table 2, initiating the search along the designated search vector. In this scenario, tabus are prevalent across nearly all points within the calculation area by prompting a search strategy involving jumps between regions with the best solution from each region being recorded. Ultimately, the optimum solution is identified as the one with the lowest cost among those passing the initial evaluation stage (feasibility, legality, risk threshold). In scenarios unable to progress beyond the first evaluation step, the solution with the lowest cost is directly selected as the optimum solution by bypassing the initial evaluation.

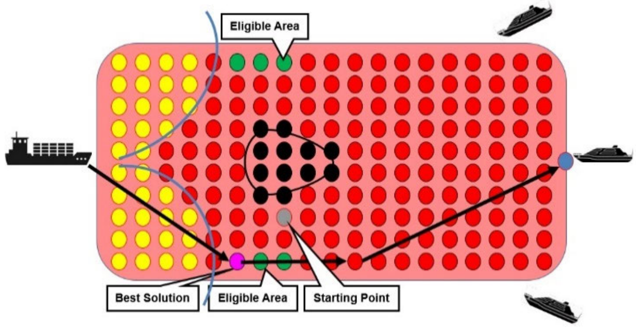

FIGURE 9. Multiple TS.

F. VISUAL OUTPUT TO THE OPERATOR

The regulations under development by the IMO intended to establish the legal framework for MASS in the future. It emphasizes that, even at the highest level of autonomy, an operator retains control over ship movements and bears responsibility for the decisions made. It is anticipated that the operator controls more than one ship at the same time. So, if a risky situation is detected, then the operator should be able to quickly grasp the incident and find a solution.

The system is designed to identify and alert the operator to risky situations as the operator assumes responsibility for potential accidents. For instance, if the decision generated by the CA system fails to pass the initial evaluation stage as an indication of non-compliance with fundamental conditions (legality, feasibility, and risk), then the system promptly notifies the operator. Additionally, the conflict risk detection module is capable of identifying risky situations or the operator can independently detect such scenarios. Furthermore, the operator is empowered to assume direct control of the ship in situations where the system cannot find a suitable solution to a conflict.

In addition to identifying the optimal solution through jumps within the computational domain, the method retains the best solutions from various regions in long-term memory to serve as alternative solutions. Alternative solutions stored in long-term memory are presented to the operator to facilitate prompt decision-making for the best course of action in situations where the solution determined by the method is not deemed suitable by the operator.

The Fig. 10 illustrates two alternative modes of motion. The one highlighted in green is the primary mode of motion, which will be implemented if left to the system. In the event of the operator taking control of the vessel, any of the two can be selected.

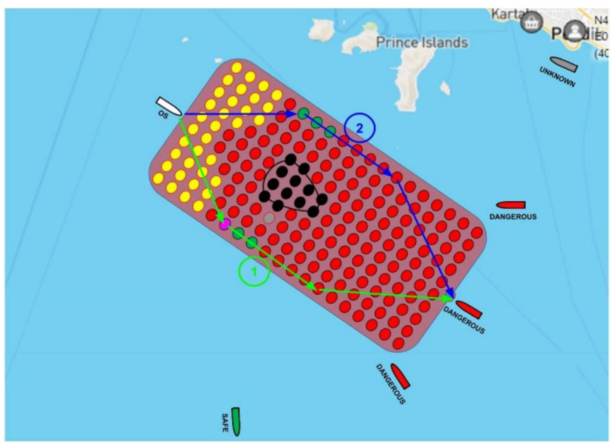

FIGURE 10. Visual output.

IV. CASE STUDY

The methodology underwent testing using MATLAB and a navigation simulator. The characteristics of the Matlab-created simulation are provided in this section. In line with the Fossen method [48], OS has been developed with three degrees of freedom. Its standard helm angle is set to fifteen degrees while the ship's tactical diameter is 1920 yards at ten knots. There are available tactical diameters and turn times for every ship's speed. In one minute and fifty-four seconds, the OS completes the 90-degree turn at a speed of 10 knots. During the tests, the ship moves along a path designated for this purpose to arrive at a predefined waypoint. PID control has been used to track the path. A total of 20 scenarios with one TS, 78 scenarios with two TSs, and 80 scenarios with three TSs were tested in MATLAB and the method successfully passed. Subsequently, the same scenarios were replicated in the navigation simulator where OS was controlled by the developed method and the TSs were operated by individuals in three different modes of maintaining a fixed course, speed, and maneuvering by COLREG deliberately to increase the severity. A collision occurred when the TS was operating at high speed and took actions to increase the danger while other scenarios were successfully navigated. The results of the tests conducted in MATLAB and the navigation simulator are presented in Fig. 11-14. The track of OS is indicated in blue, while target ships are depicted in red, green, and black. When a risky contact is detected, a new waypoint indicated in green is set by considering all contacts in the calculation, and the vessel proceeds towards it. Upon the cessation of the risk, the vessel returns to the main route following the optimum path.

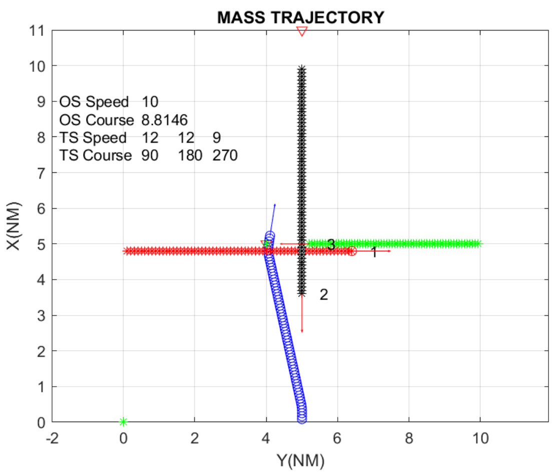

FIGURE 11. Simulation test-1.

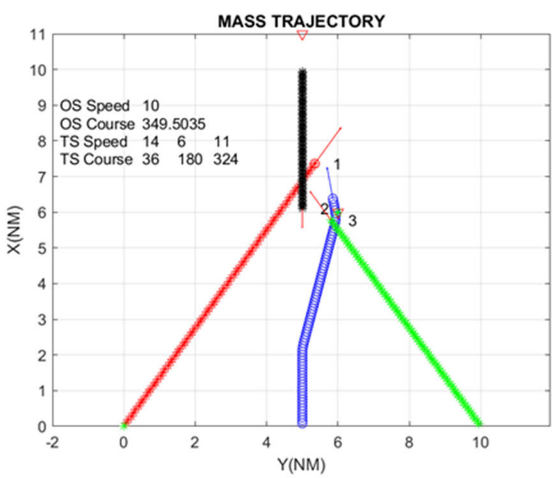

FIGURE 12. Simulation test-2.

The performed experiments show that optimum and fast solutions are obtained in accordance with the rules. In the future, in case of changes in the rules, the method can

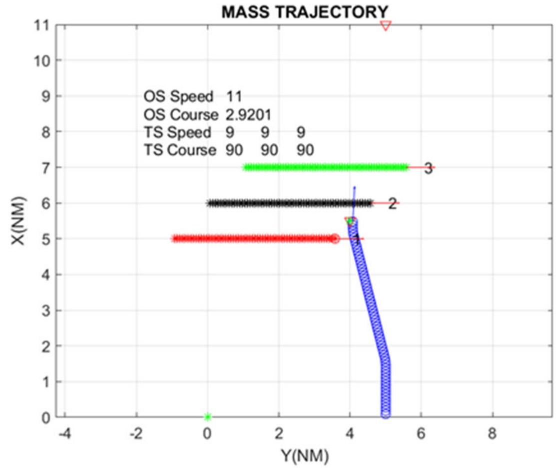

FIGURE 13. Simulation test-3.

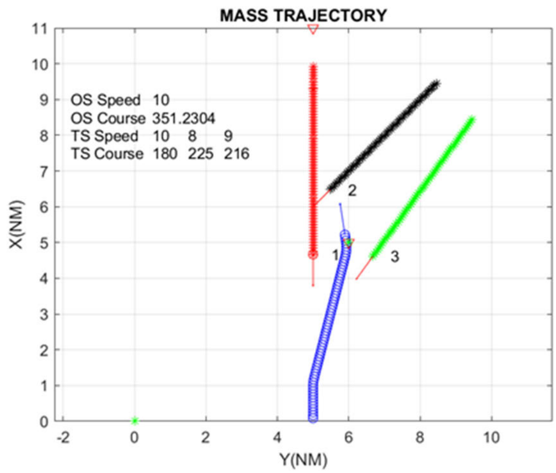

FIGURE 14. Simulation test-4.

be easily adapted to the new conditions by modifying the relevant memory of the method. Similarly, when there are local rules in the region, the method can be adapted to the requirements by placing rules in the appropriate memory. The computation time for each TS was obtained to be 0.04 seconds as it allows for real-time calculations for up to 20 TS. This comprehensive approach promises to enhance maritime safety and operational efficiency through adaptable collision avoidance strategies.

There is no standardized procedure for evaluating CA methods. These methods are assessed in the literature based on several criteria such as their ability to avoid single or multiple target ships, the specific COLREG rules applied, the tested environment, the sea area used, the type of output generated, the environmental data types utilized, the type of method employed, whether decision-making is centralized, the type of target ship, and vessel dynamics. The presented method generates solutions for multiple target ships and applies COLREG rules 5, 7, 8, 9, 10, 13, 14, 15, 16, 17, and 18, as well as good seamanship and local rules. It has been tested in specialized simulations created in MATLAB and navigational simulations. The method is designed for use in open seas and heavy traffic areas. Its primary output is waypoints but also suggests speed changes in challenging situations. The method also considers the sea state and direction from environmental conditions. Decisions are made on a ship-specific basis rather than centrally, and the targets are dynamic.

V. CONCLUSION

In conclusion, as the maritime industry anticipates a rapid proliferation of autonomous ships and a concurrent evolution in rules and regulations, CA methods must keep pace. This study has introduced a redefined tabu search algorithm that addresses the dynamic nature of the maritime environment. Unlike previous methods, which were often limited to specific rules and geographic areas, this technique provides a comprehensive approach that considers COLREG, regional rules, ship capabilities, and seamanship principles, ensuring.

One of the key strengths of this algorithm is its adaptability to evolving conditions and the ability to navigate complex rule changes. By incorporating a dynamic memory system, it can efficiently adjust its solution space, remove or modify tabu, and incorporate new restrictions as needed. This adaptability allows it to escape local minima and find optimal solutions even in challenging situations where all requirements cannot be met.

The approach offers multiple alternative solutions, allowing for a comprehensive evaluation process based on various criteria, including risk assessment, cost implications, tabu violation, legality, and practicality. By starting the search in the most probable solution region and employing a dynamic search vector, this method minimizes the time required to reach an optimal solution while ensuring compliance with the relevant regulations.

In an era of shifting maritime landscapes, the redefined tabu search algorithm presented in this study holds great promise for enhancing CA in an environment where autonomous ships and changing rules are set to become the norm. Its adaptability, comprehensiveness, and efficiency make it a valuable tool for safeguarding maritime traffic in the face of future challenges and developments.

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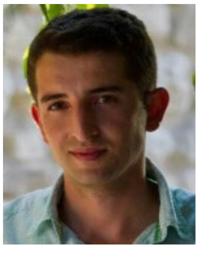

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