Isochrone-Based Collision Avoidance for Enhanced Ship Safety in Confined Waterways

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ABSTRACT

Collision avoidance is one of the most critical issues in ensuring a ship's safety. Ship maneuvering for collision avoidance first demands high real-time performance and rapid response from algorithms. In practical applications, arrival time constraints also need to be taken care of. This paper proposes an optimization algorithm to address collision avoidance challenges. Based on the traditional Isochrone method, it optimizes sailing safety while possessing computational efficiency and incorporating sailing time considerations. Its grid partition strategy can adapt to complex and changing terrains for sailing in confined waterways, while also considering regulation compliance e.g. with COLREGs. The effectiveness of the proposed algorithm is demonstrated by simulations of multiple obstacles collision avoidance in different sailing scenarios. The computation and reaction of the algorithm is within 10 seconds which allows for real-time usage.

KEYWORDS: Algorithm; collision avoidance; COLREGs; confined waterway; Isochrone; voyage optimization.

INTRODUCTION

Background

Collision avoidance (CA) has been the top priority to ensure ships' safety at traffic, especially for coastal and inland ships where the transportation activities are dense, leading to a complex sailing environment. However, such a task has always been challenging. The processes of CA typically can be divided into three phases: motion prediction, collision detection, and collision resolution (Huang et al., 2020). The performance of each phase significantly impacts the overall effectiveness of CA. The optimization algorithm in collision resolution, as it is responsible for decision-making, is an essential component.

The optimization algorithm is challenged by the ship's rapidly changing and complex surrounding environment, whose perceptions are performed in real-time during operation. The dynamic factors include moving obstacles (e.g. other ships), ship maneuverability, and environmental disturbance (wind and current). The computational efficiency and robustness of the algorithm is therefore crucial to ensure its effectiveness (Johansen et al., 2016). Numerical research has contributed to resolving CA issues focusing on the algorithm's development. Those who are interested can refer to these comprehensive review papers (Huang et al., 2020; Zhu et al., 2024).

In general, based on their input variables (solution space), they can be divided into **continuous** and **discrete** search methods. And each search method based on their processes can further be divided into global or stepwise search: the **global** search first identifies a collision-free space and then optimizes within this identified space; and the **stepwise** search proceeds with collision check step by step iteratively towards the destination. Examples of 1) continuous space with global search include velocity obstacle algorithm (Alonso-Mora et al., 2018; Fiorini and Shiller, 1998; Zhuang et al., 2016) and vision cone (Chakravarthy and Ghose, 1998; Fan et al., 2019). 2) Examples of stepwise search in continuous space include model predictive control (MPC) based CA (Abdelaal et al., 2018; Chen et al., 2018). Discrete search algorithms employ discrete input to limit the variations in optimization, to opt for computational efficiency and rapid reaction of algorithms. 3) With discrete input, examples employing stepwise search process include the dynamic window approach (Fox et al., 1997; Serigstad, 2017), and MPC based CA (Johansen et al., 2016; Li et al., 2018). 4) Those employing global search include grid-based methods (Shah et al., 2016; Svec et al., 2014). 5) In addition, there are also algorithms that can be applied regardless of continuous or discrete input types, such as artificial potential field, or more recently, machine learning (ML) such as reinforcement learning algorithms.

Table 1. Examples of different methods used in collision avoidance.

	Global	Stepwise
Continuous	Velocity obstacle algorithm, vision cone	MPC-based CA
Discrete	Grid-based methods	Dynamic window approach, MPC based CA
Others	Artificial potential field, ML (reinforcement learning algorithms)	

Global search algorithms often outperform in their comprehensive considerations during optimization, especially for complex environments. However, they may struggle to keep efficiency with their optimality at the same time to assist real-time operations. And on the contrary, the main challenge for some stepwise search algorithms lies in the limited choices of possible solutions and commonly used greedy search strategies, both may lead to suboptimal solutions. But as they deliberately give up excessive computation, they are crafted to run much faster than the global ones.

Challenges and motivations

To more effectively conduct collision avoidance to assist the operation, some practical considerations are essential to incorporate in the optimization algorithm. First, transportation usually has requirements for on-time delivery to ensure its shipping efficiency and performance. Inland and costal transportation has to consider timely arrival and accurately estimated time of arrival (ETA) as essential sailing objectives (Lei et al., 2024). Second, its computational efficiency must allow for real-time applications while ensuring the optimization outcomes remain practical for operation. Third, traffic regulations must be considered and independently incorporated in the decision-making process of the algorithm. All the ships' behaviors at traffic must comply with traffic regulations, such as COLREGs that were proposed in 1972 (IMO, 1972). However, these rules are very general with no quantified requirements are clearly given by COLREGs (Huang et al., 2020; Maza and Argüelles, 2022). In addition, in many specific regions, there can be regional regulations given by local authorities for bypassing ships to comply. This also poses challenges in the implementation of collision avoidance algorithms. To better consider the ambiguity and uncertainty from traffic regulations, the CA algorithm needs to separate the regulation module, ensuring that the method's effectiveness remains unaffected while allowing flexibility in modifying the regulation module.

Contributions

The paper contributes to the following aspects. 1) An optimization algorithm based on the Isochrone algorithm is first proposed to address the CA problem. The Isochrone algorithm has been well-known for its computational efficiency, while being developed to ensure an accurate ETA for weather routing. In this paper, it is improved to address collision avoidance (CA) problems to leverage its efficiency and consideration of ETA. By changing the grid partition strategy, the proposed Isochrone-based CA method fits well in the confined inland waterways, while the original version did not account for land avoidance. 2) The proposed method incorporates COLREGs rules for collision avoidance maneuvering and defines them as a separate module to guide the search. This ensures future adaptations for local regulations and generalization of methods to apply at any other specific region. 3) Finally, the cost function is also refined to achieve multi-objective optimization, minimizing the risk of collision while also considering ship's maneuverability and sailing distance, to generate a safe and smooth voyage for ships to follow, and adapt it to the dynamic traffic in real-time.

OVERVIEW OF THE COLLISION AVOIDANCE PROBLEM

Fig. 1 presents a general collision avoidance problem. As an optimization problem, the constraints usually considered in CA are avoiding riverbank or shallow water, obstacles, and regulation compliance. By satisfying constraints, the collision-free voyage is also optimized for sailing safety, estimated time of arrival (ETA), or energy costs, etc.

The processes of CA are further shown in Fig. 2. Assume the Own Ship (OS) is currently located at departure $\boldsymbol{P_0}$ and targets the destination $\boldsymbol{P_f}$. There will be three main processes: motion prediction, collision detection, and collision resolution. First, based on the observation data, motion prediction process predicts the trajectories in the upcoming time period. This includes two objects, predicting the moving of OS (i.e., coordinates of $\boldsymbol{P_1}$ including the grey dashed line) and the other Target Ships (TS) (the orange dashed lines) as shown in Fig. 2(a). The details for motion predictions will be introduced in the following sections. Based on the predicted trajectories of OS and TS, collision detection determines whether a collision is likely to occur or if any evasive action is needed, etc. If there is found to be such a risk, the collision resolution will react to computing and generating a collision free trajectory as shown in Fig. 2(b), i.e., which grey dashed trajectory is the optimal for CA. This updated trajectory will then be provided to actuators for ship to follow.

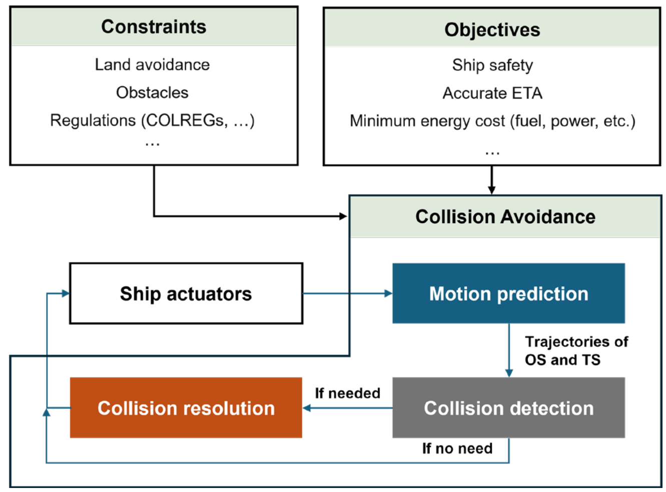
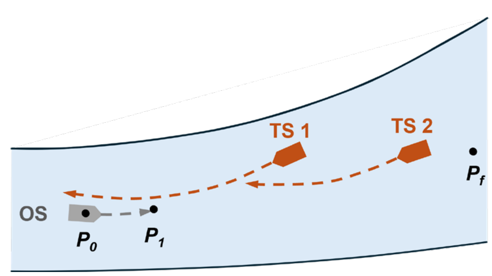


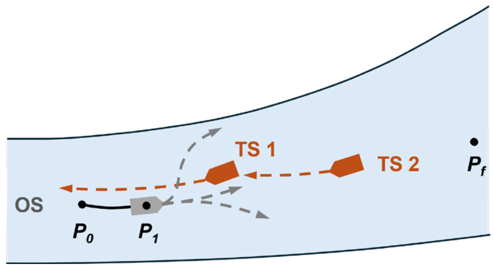
Fig. 1: Overview of a collision avoidance problem.

Table 2. The input, optimization formulation, and output of the proposed CA method.

Input	
Departure	$\boldsymbol{P_0} = \{x_0, y_0, t_0\}$
Destination	$\boldsymbol{P_f} = \{x_f, y_f, t_f\}$
Parameters	Listed in Table 3
Optimization formulation	
Variables	Ship heading θ
Objectives	Lowest collision risk, accurate ETA and shortest travelling distance
Constraints	Shallow water, static obstacles, COLREGs rules
Cost functions	Collision risk OR travelling distance OR deviations from reference route (depend on sailing situations)
Output	
Optimal voyage	$\boldsymbol{\theta}^* = \{\theta_0^*, \theta_1^*, \ldots, \theta_i^*, \ldots\}$ which gives $\boldsymbol{R}^* = \{\boldsymbol{P_0}, \boldsymbol{P_1}^*, \boldsymbol{P_2}^*, \ldots, \boldsymbol{P_i}^*, \ldots, \boldsymbol{P_f}\}$



(a)



(b)

Fig. 2: Graphical illustration of collision avoidance processes.

In this paper, the main contribution of the proposed algorithm is in collision resolution of CA. The collision resolution is formulated as an optimization problem as presented in Table 2, where $\boldsymbol{P_1}^*$, $\boldsymbol{P_2}^*$, and $\boldsymbol{P_i}^*$ indicate optimal waypoints at each stage consisting of the final optimal voyage $\boldsymbol{R}^*$. θ_0^*, θ_1^*, and θ_i^* are optimal ship headings between adjacent optimal waypoints, forming the optimal heading set $\boldsymbol{\theta}^*$. And $\boldsymbol{\theta}^*$ is the final output of the proposed algorithm.

MOTION PREDICTION

Own ship

The trajectory prediction of OS (the grey dashed line in Fig. 2) is relying on a ship dynamic model. This model predicts the ship's motion in the upcoming period, under specific control commands and environment disturbances (wind and current). A linear maneuvering model is adopted in this paper, which is classic for describing the basic maneuverability of ships under hydrodynamic forces. Proposed by Clarke et al. (1983), this model assumes that the ship's maneuvering motion is linearized under small perturbations, while considering only 3 degrees of freedom in surge, sway and yaw in the horizontal plane (Fossen, 2011):

$$(M_{RB} + M_A)\,\dot{v}_r + (C_{RB}^* + C_A^*)\,v_r = \tau + \tau_{wind} \qquad (1)$$

where v_r represents the relative velocity of the ship body with respect to the current. Respectively, M_{RB} and M_A indicate the rigid-body and added mass matrix, and C_{RB}^* and C_A^* indicate Coriolis and centripetal matrix of rigid-body and added mass. τ represents the thrust force and τ_{wind} is the force from wind. Each matrix is linearized based on the assumptions that non-linear and unknown terms are negligible. Eventually, this ship's dynamic model establishes a relationship between the ship thrust (power, RPM, etc.) to the sailing speed and locations, under the specific local sea conditions.

This ship model is based on Fossen's Python toolbox (Fossen), which also accounts for the dynamics of the propulsion and steering systems. After specifying a reference heading, the ship model considers the dynamic following process of the ship as well as course changes during the maneuver. It can provide a more real trajectory that includes the effects of the control system following the desired heading.

Target ship

The target ship's trajectory prediction (the orange dashed lines in Fig. 2) is different from OS, as they are considered as moving obstacles where their characteristics are unknown to OS. The OS establishes a dynamic model from thrust forces to kinematic parameters (e.g., velocity and acceleration) based on its characteristics and control commands, to predict its own motion. However, from the perspective of the OS, the motion of the TSs can only be estimated externally.

Several approaches are available as follows to predict the obstacles movements: physical-based methods which are based on physical principles of ship motions, learning-based methods which predict based on their historical motion data, and interaction-based methods which are based on communication and information exchanges between ships. For interaction-based methods, the motion information is provided directly by each TS itself, which is considered to offer better accuracy compared to predictions made from external perspectives. However, this approach poses challenges in communication efficiency during operations (Huang et al., 2020).

In this paper, the motions of TSs are assumed to be known by OS through communications and interactions. The moving trajectories of target ships are therefore generated based on simulations as known conditions during the whole optimization period.

COLLISION DETECTION

The collision detection is responsible for determining if a collision will occur and when evasive actions are needed based on the predicted motion information. Specifically, this involves 1) assessing the risk of collisions and 2) determining the risk threshold at which evasive actions should be taken. Both aspects rely on how to assess the collision risk. This risk can either be calculated in a numerical value or presented graphically. In this paper, graphical representations by ship arena and domain are adopted to identify collision. The calculation of a collision risk index (CRI) is also employed to offer a numerical representation of the risk level. However, CRI will be integrated into the cost function to further identify the safest voyage with minimal risk. The calculation of CRI will be introduced in the following section.

Ship arena and domain is an individual research topic and those who are interested can refer to this comprehensive review (Szlapczynski and Szlapczynska, 2017). The ship domain defines a minimal safe region around the ship, indicating that any obstacle entering this region is considered a certain danger for collision (Fujii and Tanaka, 1971). The ship arena is an extended ship domain, indicating that any violation will necessitate CA actions (Davis et al., 1980). These two regions should be determined based on factors that influence risks, such as relative movements between two moving objects, the encountering scenarios (overtaking, head on, etc.), and environmental conditions, in addition to individual ship's characteristics. Thus, comprehensive considerations of the ship domain/arena may give dynamic regions that adjust in response to the relative movements between TS.

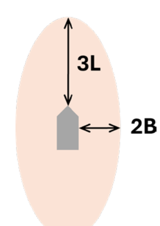


Fig. 3: Adopted definitions of ship domain in CA simulations.

In this paper, the ship domain is constructed following Coldwell (1983)'s definitions and simplified into a static ellipse, as the orange ellipse presented in Fig. 3. L and B represent the length and width of OS. This static ship domain is used to identify collisions of OS with static obstacles in the waterways, i.e., no static obstacle can appear inside this domain. For ship arena, it is defined in a dynamic way using DCPA and TCPA:

$$0 < \text{DCPA} < 6\text{L AND } 0 < \text{TCPA} < 120\text{s}$$

This means that if any TS is found to approach OS closer than 6L within 120 seconds, the OS must take actions to avoid such a situation. Meanwhile, the ship domain cannot be violated during the avoidance.

COLLISION RESOLUTION

A flowchart of the proposed algorithm is presented in Fig. 4. Besides, some initial parameters also need to be defined as given in Table 3.

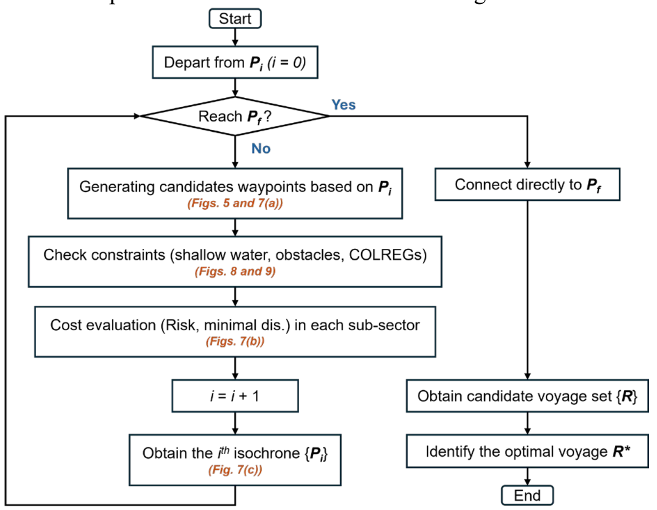


Fig. 4: Flowchart for the proposed Isochrone-based CA algorithm.

Table 3. Parameters to be determined for algorithm initialization.

Parameters	
Δt	Time interval in each isochrone [s]
$2r$	Number of sub-sectors [-]
$\Delta\theta$	Increments in heading [°]
$2m+1$	Number of candidates generated for one waypoint [-]
Thrust power	Constant thrust in each time interval [N]

Starting from $\boldsymbol{P_0}$, the algorithm is conducted as follows:

1) Determine the time interval (Δt) and a constant ship power/RPM during the time interval.
2) If the stop condition ($\boldsymbol{P_f}$ is reached within the time less than Δt) is met, connect to $\boldsymbol{P_f}$ and terminate the process; otherwise continue.
3) Based on each waypoint in the current isochrone $\{\boldsymbol{P_i}\}$, generate candidate waypoints for the next isochrone $\{\boldsymbol{P_{i+1}}\}$. The detail is given in the Fig. 5 and Fig. 7(a).
4) For generated candidates, check if the constraints are satisfied, i.e., shallow water, static obstacles (Fig. 9), and COLREGs compliances if there is any TS (Fig. 8).
5) Divide the waterway into $2r$ parallel sub-sectors given in Fig. 6. In each sub-sector, retain one optimal candidate waypoint as shown in Fig. 7(a) - Fig. 7(c).
6) The retained candidates form the next isochrone $\{\boldsymbol{P_{i+1}}\}$. Continue to repeat step 2).

The stopping condition is set using a specific location $\boldsymbol{P_f}$, but it can also be replaced with other conditions, e.g., no upcoming TSs and OS converges back to the original reference voyage (such as the centerline of the river).

Generation of isochrones

Based on the initial starting point $\boldsymbol{P_0}$ (considered as the 0^{th} isochrone), the candidate waypoints are generated iteratively as shown in Fig. 5:

1) A reference heading θ_{ref} needs to be determined based on the flow and topography of the river, i.e., the tangent direction of the river centerline at the current location.
2) At $\boldsymbol{P_0}$, based on θ_{ref}, $2m+1$ candidate waypoints can be obtained following the headings $\theta = \theta_{ref} \pm j \cdot \Delta\theta$ $(j= 0,\ 1,\ \ldots,\ m)$. These consist of the 1^{st} isochrone $\{\boldsymbol{P_1}\}$.
3) From $\{\boldsymbol{P_1}\}$, repeat step 2) for each waypoint. Candidate waypoints for $\boldsymbol{P_2}$ can again be obtained.

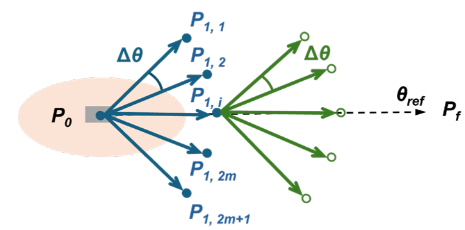


Fig. 5: Generation of candidate waypoints for the next isochrone.

Parallel sub-sectors

The parallel sub-sectors partition is illustrated in Fig. 6. It should be noted that the black lines aside outline the area which excludes shallow water, instead of indicating the riverbank. The shallow water effect has an impact on ship's maneuverability and should be considered comprehensively through an inland ship dynamic model. In this paper, it is assumed that the waterway included in the sailing area has sufficient depth through a bathymetry check.

The partition of the parallel sub-sector is based on the width of the river. The river width is evenly divided into $2r$ intervals, with two purposes: 1) It is impractical to maintain exponential growth in the number of points as the original Isochrone method. By introducing sub-sectors, the number of points in each generation of the isochrone can be reasonably controlled. 2) Optimal points are selected based on their positions by sub-sectors. While limiting their total number, the candidates maintain a certain level of diversity to avoid local optimum.

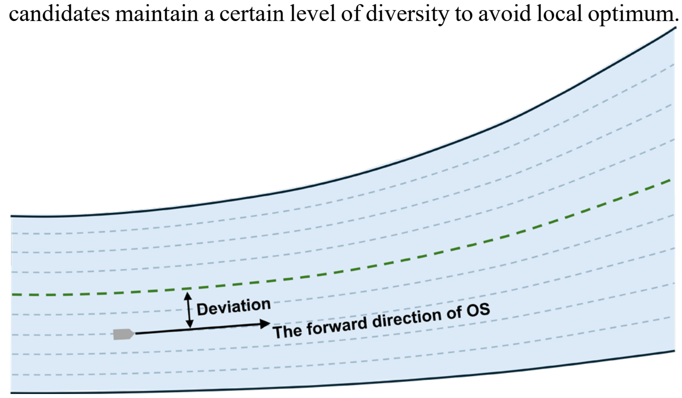


Fig. 6: Illustration of parallel sub-sectors based on topography of confined waterways.

Table 4. Waypoint evaluation criteria in subsectors to achieve the optimization objective.

Scenarios	Open area	Confined waterway
No encountering	Shortest distance to $\boldsymbol{P_f}$	Least deviation to waterway's centerline
Encountering	Lowest collision risk	Lowest collision risk

In each sub-sector, the optimal waypoint is selected based on the criteria listed in Table 4. It is worth noting that in the confined waterway, ships typically sail along their designated traffic lanes following a reference route (Cheng et al., 2021). In this study it assumes that the ship prefers to sail along the center of the river when there is no need to avoid any objects, i.e., assuming the center line is the reference route of OS, which can be flexibly replaced if other reference data is available.

Thus, when sailing in a confined waterway as shown in Fig. 6, and no collision is detected, the waypoint is chosen as the one with the least deviations from the centerline towards $\boldsymbol{P_f}$; while avoiding the collision, the waypoint is chosen as the one with the lowest CRI. If sailing in an open area, the subsector is used based on a previous study (Chen and Mao, 2024). When there are no potential collisions, the waypoint is chosen as the shortest distance to $\boldsymbol{P_f}$, and the one with the lowest CRI when avoiding collisions.

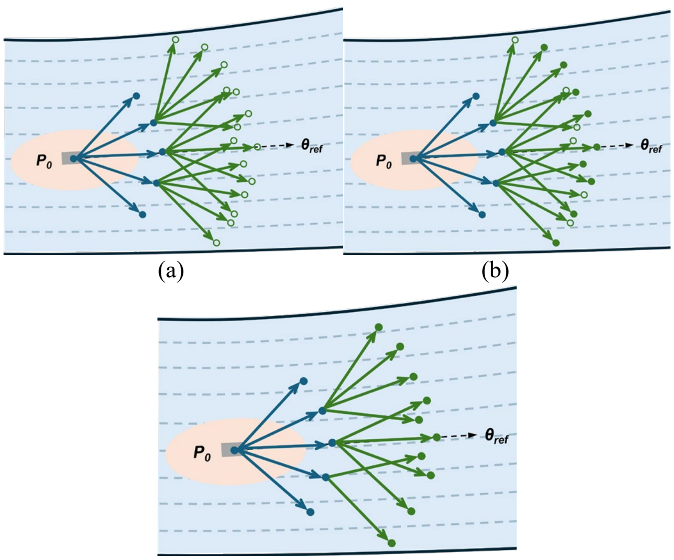


Fig. 7: Waypoint selection in each sub-sector based on cost evaluations.

Collision risk index

To assess the collision risk, the two indices are adopted: Distance to the Closest Point of Approach (DCPA) and Time to the Closest Point of Approach (TCPA). They are calculated using the relative movement of OS with respect to each TS. A collision risk index (CRI) is further calculated based on DCPA and TCPA, referring to the research in Hu et al. (2020).

COLREGs rules

Currently, COLREGs do not provide very clear and specific definitions, and there are varying interpretations on how to comply with them during CA. (Maza and Argüelles, 2022). From this perspective, how to incorporate COLREGs is method dependent. The main rule in COLREGs to be considered is Rule 6, 8, 13, 14, 15, and 16. Among which, Rules 13, 14, and 15 define collision avoidance maneuvering behaviors, and the rest can be achieved through parameter adjustments, definitions of ship domain and arena, etc. In this paper, the COLREGs compliance follows the research from Johansen et al. (2016).

It is worth noting that different regional rules regulate inland waterways in practice (UNECE, 2015). Developing CA algorithms applicable to all inland waterways has been a challenging and ongoing task. This paper considers the common COLREGs rules. In the meantime, regulation compliance is incorporated separately in the constraints or feasibility conditions. Each waypoint is evaluated independently for feasibility, returning a Boolean variable (True or False). Changing the regulations does not affect the effectiveness of the algorithm.

An example is shown in Fig. 8 for waypoints generation complying COLREGs. If a potential collision is detected, the encounter scenario will then be identified, e.g., head-on or over-taking, etc. For head-on situations, OS are required to turn towards starboard to avoid collision while also keeping a safe distance, i.e., outside the ship domain of TS. Those candidate waypoints violate the COLREGs are therefore removed (appears transparent in Fig. 8(b) compared to Fig. 8(a)).

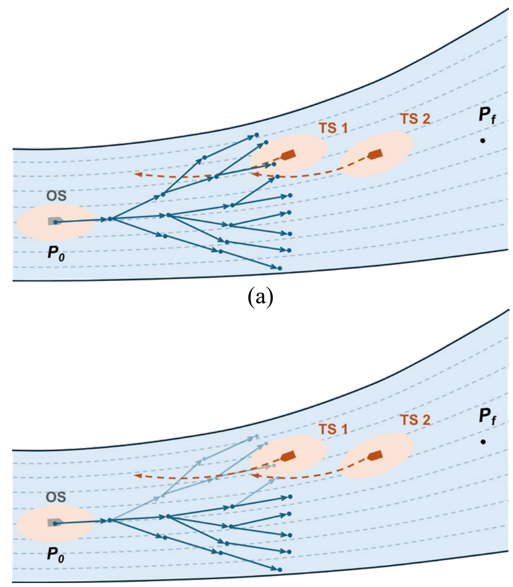


Fig. 8: Graphical illustration of COLREGs compliance for head-on encountering scenario in CA.

Static obstacles

The process to avoid static obstacles is presented in Fig. 9. Similarly, black line indicates the area considering an additional safe distance with obstacles or excluding shallow water area around the obstacles. For the newly generated waypoints, crossing any land or obstacles must be checked. If any sub-route overlaps with land or obstacles, the waypoints along the sub-route will be removed (the waypoints appeared transparent around the static obstacles in Fig. 9 indicate the removed ones).

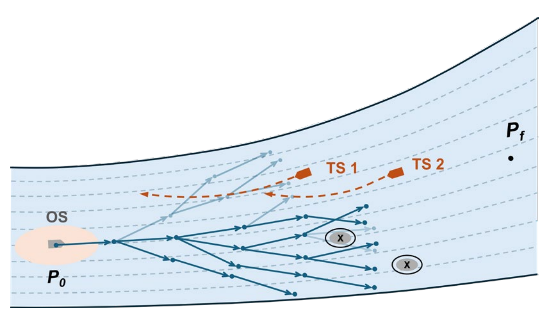
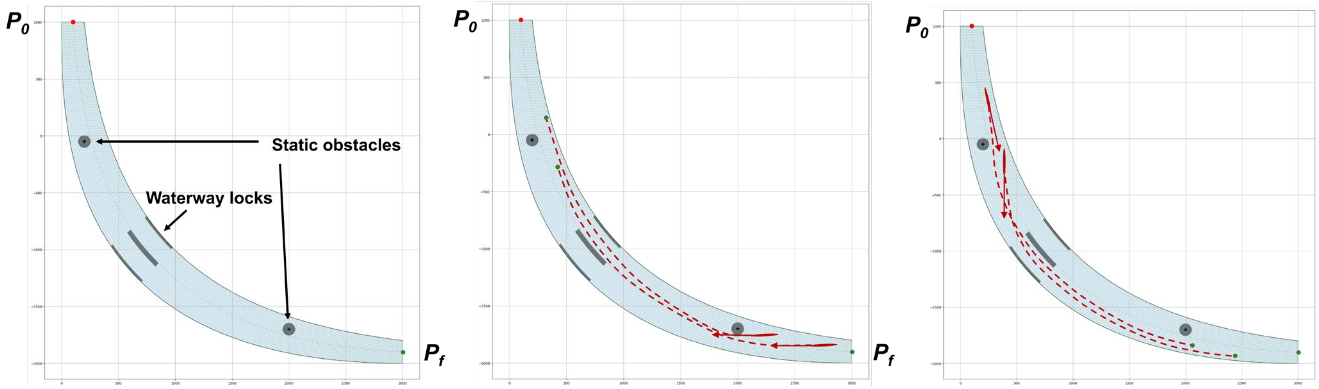


Fig. 9: Graphical illustration of avoiding static obstacles in CA.

RESULTS

To validate the proposed method, simulations are conducted in two scenarios: open water and a confined waterway. Validations in open water areas focus on demonstrating the effectiveness of the proposed algorithm in complying with COLREGs. Further validations in the



(a) (b) (c)

Fig. 10. The simulation environment of confined waterway with water waterway locks in (a), and TS's trajectories information in (b) and (c).

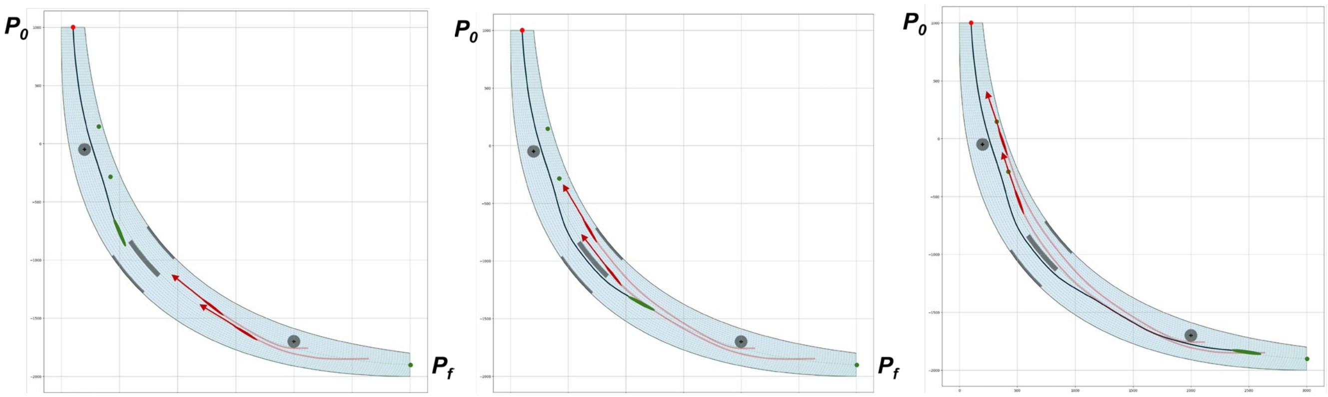


Fig. 11. Simulations of head-on in confined waterways using the proposed CA methods.

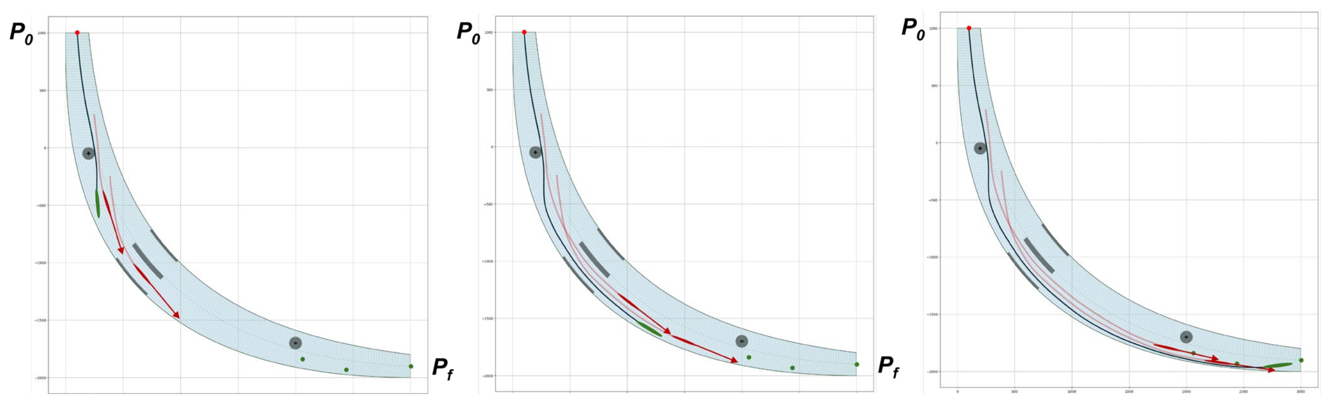


Fig. 12. Simulations of overtaking in confined waterways using the proposed CA method.

confined waterway scenarios highlight the proposed algorithm's CA capabilities in narrow spaces, taking into account both COLREGs and land restrictions, as well as other inland waterway infrastructures. The OS and TSs are assumed to be 100 meters in length and 9 meters in width.

The parameters listed in Table 3 should be determined to initialize the proposed method. Increments of the heading, i.e., $\Delta\theta$ limits the changes of ship's reference heading, so to consider the ship's maneuverability and generate smoother routes. Thus, this can be set based on specific ship's maneuverability or other moving requirements. And according to the ETA, Δt can be decided to divide the whole process into 20 - 30 time stages. To achieve an accurate ETA and ensure on-time arrival as required, the sailing speed and corresponding thrust power can then be determined based on the remaining distance to the target point. Subsequently, real-time adjustments can be made to modify the route if any significant deviations occur. The rest of the parameters, m and r, can be determined based on performance. Higher numbers of m and r may result in higher computational loads and local optima, and lower numbers may lead to insufficient search. 10 – 20 can be sufficient to common cases.

Collision avoidance in open water area

In this section, the proposed method is first validated in an open water area with no obvious constraints from land, e.g., the terrain of river. Only static obstacles are present within the sailing area along with three TSs. Static obstacles are simulated as circles with a diameter of 10 meters, and the additional safety distance is set to 50 meters.

It can be seen in Fig. 13 that the behavior of OS is complying with COLREGs regulations in each encountering scenarios. For example, the OS turns starboard as head-on situations require, and the evasion behaviors are taken well in advance (Fig. 13(a)). In the all-crossing scenario, it is worth noting that TSs are simulated as moving obstacles, thus they cannot take CA responsibilities even if they are required to give way as for the first and third TS (Fig. 13(b)). And for the second TS, OS crosses in the front as it is not close enough to the TS for their interaction to be considered as an encounter. And for the last over-taking situation, turning starboard is prioritized than turning port even if they are both allowed to (Fig. 13(c)), as starboard turning is preferred by using weighted coefficients in the cost function.

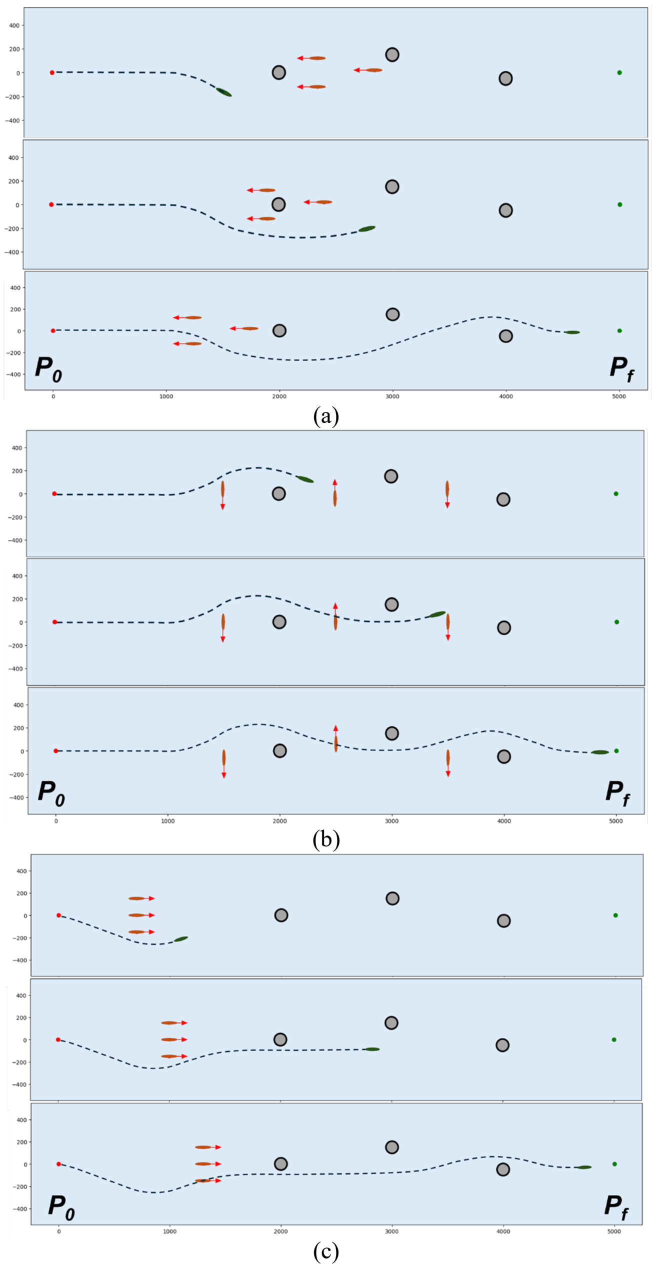


Fig. 13: Collision avoidance simulations for head-on (a), all-crossing (b) and over-taking (c) scenarios using the proposed methods.

Collision avoidance in confined waterways

Further, the proposed method is validated in a confined waterway presented in Fig. 10. The river width ranges from 200 to 400 meters. In addition to static obstacles, the same as given in Fig. 13, a waterway lock is also simulated with a length of 250 meters and a width ranging from 10 to 20 meters. It corresponds to the general dimensions of small to medium-sized locks and is positioned along the riverbank and centered within the waterway as given in Fig. 10 (a), occupying a total of 20% of the river's width. As in inland traffic it is uncommon to see a ship crossing the river widthwise, only head-on and overtaking scenarios are simulated in this confined waterway. The moving trajectories of TSs, as mentioned above, are assumed to be known in advance by the OS. The trajectories of TSs are presented in Fig. 10 (b) and (c) for the head-on and overtaking situation respectively, where the green points indicate the target points.

The processes to avoid head-on TSs are given in Fig. 11. It can be seen that OS first follows the centerline when no collision is detected. To avoid the collision as well as considering maneuvering preference of turning starboard, the OS pass the center waterway lock from its own starboard side. And after passing the lock, the two TSs already left the nearby waters, thus the OS turned back to the center line continuing the sailing towards the target point $\boldsymbol{P_f}$. Similarly, the CA processes for overtaking two TSs are also given in the following Fig. 12. The TSs sail slower than OS in the right part of the river. And the OS, similarly, first follows the centerline and avoids an obstacle. After passing the static obstacles it starts to turn starboard and overtakes the two TSs from the right. This happens when sailing inside the waterway locks. And after finishing the overtaking, the OS turns back and converges to the target point $\boldsymbol{P_f}$ with a relatively smooth turn. These two validated cases in narrow confined waterway also demonstrate the CA capabilities of the proposed algorithm, complying COLREGs while considering the terrain constraints of the waterway.

In summary, for the above validated cases sailing in open areas and confined waterways, the evasive maneuvers of the OS first result in effective avoidances of both static and moving obstacles. In addition, they also comply with the COLREGs rules, and the suggested routes are smooth with no harsh turns, making it applicable for real operations. Meanwhile, the runtime for these cases is on average less than 10 seconds including the trajectory prediction using ship dynamic models. This trajectory prediction computation costs can further be improved by deploying parallel computing techniques, meaning that the runtime can be even shorter with good real-time potential.

CONCLUSIONS

In this paper, an Isochrone-based collision avoidance algorithm is proposed to ensure ship's safety, assist real-time operations and punctual arrival needs in practice. In addition to leveraging computational efficiency and ETA considerations of the traditional Isochrone algorithm for voyage optimization, it is further enhanced with land avoidance capabilities to account for the terrain/bathymetry. Thus, it is improved to be suitable for applications both in confined inland waterways and open water areas. Following that, compliance of traffic regulations such as COLREGs is incorporated into the proposed method as a separate module, allowing for also adaptations to varying local regulations. The simulation results show that, based on terrain-adaptive and rule-compliant requirements, the proposed method can suggest smooth routes with optimized safety for collision avoidance and short distance sailing. Furthermore, the algorithm can be executed in an average of 10 seconds allowing for real-time operations.

However, the current work is based on some assumptions. First, the ship dynamic model is linearized which can later be replaced with a more accurate dynamic model specifically tailored for inland ships, such as one that considers shallow water effects on the ship's movements. In addition, the ship domain is assumed to be static, whereas it should adapt dynamically based on situations such as encounters with other ships. The TSs' motions with trajectories are also assumed to be known to the OS.

However, in practical situations, more reliable solutions could be considered such as using AIS data for trajectory prediction. Finally, as the shallow water effect is not comprehensively analyzed, energy consumption for sailing cannot be comprehensively estimated to be as an optimization objective. The current approach uses the short distance as a simplified method to estimate the energy cost. Thus, based on an inland ship dynamic models, the future work could be considered to optimize towards energy efficiency in addition to ship's safety in collision avoidance.

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