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RESEARCH ON COLLISION AVOIDANCE DECISION-MAKING OF HYBRID OPTIMIZATION ALGORITHM BASED ON *K* AND *T* INDEX

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To address the situation where ship pilots may encounter ineffective collision avoidance or even ship collisions during the process of maneuvering ships, leading to economic losses, marine pollution, and even threats to human safety, a ship decision-making based on a hybrid optimization algorithm is proposed. The hybrid optimization algorithm includes two optimization processes, genetic algorithm (GA) and fmincon. This research is based on Nomoto model to establish a ship paths model utilizing the ship's turning ability index K and the tracking ability index T. The constraint function ensures safety navigation between ships and the objective function ensures the minimum loss of voyage throughout the entire collision avoidance process. Hybrid optimization algorithm ensures the achievement of global minimum values and computes the decision data including steering time and steering angle, which can assist ship drivers to make a more reasonable decision. The results of this research are of great significance for improving navigation safety and provides reference and support for the future development of intelligent navigation technology.

Keywords: collision avoidance decision-making; *K* and *T* index; path planning; genetic algorithm; fmincon

1. Introduction

With the growth of maritime trade, the trade in the maritime market accounts for 84% of the total world trade. However, with the development of large and diversified ships, major collision accidents occur from time to time. Collision avoidance has always been the focus of many researchers [1]. As the density of maritime traffic and vessel speed increase, the decision time in taking reasonable actions is becoming shorter, which increases the risk of ship accidents. At present, collision avoidance of ships during navigation mainly depends on the experience and judgment of ship drivers. Through further improvement of TFIDF algorithm, Ma [2] deduced that human factor is the first factor that causes the risk factor of ship collision accidents. For enhancing maritime safety, minimize loss of life and property, reduce ship driver decision-making burdens, and eventually achieve automation collision avoidance decision-making systems, researches on the field of shipping safety have become an urgent topic. [3]. On May 10, 2022, Reportlinker released the "Global Smart Ship Industry" report, which said that the global smart

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ship market would reach 10.1 billion US dollars by 2026. Thus, researching ship decision-making is highly important. Ship auxiliary decision primarily addresses two issues: first, ensuring that the ship effectively avoids other ships and navigates safely, that is, ship collision avoidance. Second, the ship chooses the best path in the process of navigation, that is, path planning [4]. The ship aided decision-making based on collision avoidance and path planning has the advantages of all-weather, fast response and no fatigue. Intelligent algorithms development has promoted the path planning problems of researchers in ship collision avoidance, and various models and methods have been studied to address the aforementioned issues [5]. Tsou, et al. [6] adopted the parameters of collision avoidance time, steering angle, original passage recovery time, navigation recovery angle and other parameters as the basis of genetic algorithm genetic coding. While, the ship's turning process is not mentioned, which reduced the its applicability of large ships. Li, et al. [7] studied multitudinous documents and expertise to compare the differences between theoretical research and real shipping, which is conducive to other researchers in the field. Zhang et al. [8] preprocess and reconstruct AIS data, build a scene similarity model, and use Delaunay triangulation to fuse the ship tracks of similar scenes to generate a feasible collision avoidance path. Liu, et al [9] investigated collision avoidance decisions of conventional and intelligent ships in complex water scenarios. The corresponding simulation experiments are also conducted to verify the validity of the research. Rongcai et al. [10] proposed a ship navigation safety system based on fuzzy theory by combining the marine environment model and the ship three-degree-of-freedom motion model and completed the simulation experiments on the system. The above-mentioned research studies have made many achievements in the of decision-making field, But the above research studies did not provide ship drivers with references of rudder angle and steering time. In this paper, while referring to the excellent research methods, new ideas are also incorporated. Firstly, the path is planned by using K and T indexes based on optimized Nomoto model, and the steering processes of the ship is considered to reduce the position error. Ship collision avoidance path planning needs to calculate collision avoidance actions while simulating ship navigation, which requires a large amount of computation. The ship path model based on the K and T index is simpler than the MMG model, and can ensure high accuracy in simple system simulation [11]. So, path based on K and T index makes decision more efficient. The gyration index K is a parameter determined by the ratio of the turning moment coefficient and the damping moment coefficient after steering. If K value is large, ship’s gyration is good. The tracking index T is a parameter determined by the ratio of the ship's moment of inertia about the longitudinal axis of the center of gravity to the damping moment coefficient. This research provides not only the reference of the new heading but also the steering angle. Secondly, hybrid algorithm solves the problem that GA and fmincon can only find the local optimal solution. Hybrid algorithm also make it possible to estimate the starting point of fmincon. The hybrid algorithm can determine the values of multiple decision variables when finding the optimal solution precisely, and calculate the decision data under different encounter situations to ensure that the ship passes safely from the target ship and returns to the original course at the end of collision avoidance, ensuring the minimum amount of the ship's voyage loss at the same time. Taking the bulk ship model of Danish Institute of Navigation as an example, this research carried out simulation experiments and realized the visualization of ship collision avoidance path. In theory, this research results can be applied to all ships by modifying the K and T index, which marks a significant advancement. At the same time, the research has established a collision avoidance decision-making system that includes ship risk warning, collision avoidance, and yaw warning. This is highly significant in promoting the advancement of intelligent ships and ship maneuvering simulator.

2. Division of ship encounter situation

According to COLREGS, path planning will only be initiated when a ship needs to take action in an encounter situation. The classification principle of situation is based on the analysis results of COLREGS, navigation experience. et al. When two ships meet each other at sea, COLREGS lists three situations: head-on situation (I), crossing situation (II,IV) and overtaking situation (III) [12], As shown in Fig. 1. Ships from areas I and II are regarded as stand-on ships, maintaining original navigation situation. While for ships from III and IV areas, is liability ship, and it shall take actions to keep stand-on ship clear.

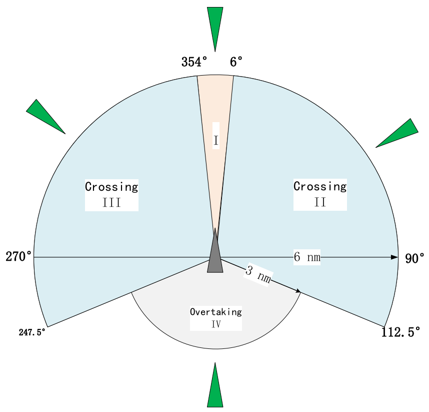


Fig. 1. Division of ship encounter situation

3. Collision risk detection

Ship collision risk detection is achieved by assessing the d_{CPA} (distance of the closest point of approach). If d_{CPA} meets the requirements of safety, considering that ships can pass safely without collision warning. Otherwise, a collision warning with visual alarm will be issued to remind the driver to take actions. The ship driver can set the threshold of d_{CPA}. The calculation of d_{CPA} need to establish d_{CPA} calculation model. Ship collision warning data comes from the following Nautical Instruments.

ARPA (Automatic Radar Plotting Aid) is based on electronic computer technology and combined with marine radar, log and compass. It can manually or automatically capture multiple targets, automatically track the target after capture, and display target ship's course, ship speed, orientation, d_{CPA}, and time to the closest point of approach (t_{CPA}) on display screen [13]. ARPA can obtain distance and relative bearing of the two ships. While ARPA can provide information, its accuracy is affected by various factors such as signal interference, data transmission errors, and, weather conditions. When target ship turns, it takes 1 to 3 minutes to get the d_{CPA} data, so there are risks in using ARPA alone as an early warning. Therefore, this research has established a d_{CPA} calculation model with Automatic Identification System (AIS) as an auxiliary data source. AIS (Automatic Identification System) is a broadcast communication system for automatic and autonomous exchange of navigation data. It is an effective means to obtain traffic information without radar detection, and can effectively reduce ship collisions [14]. Information such as speed and course are obtained by AIS because the data accuracy obtained through AIS is higher.

d_{CPA} calculation model is based on distance function($D(t)$). Cartesian coordinate system is established with own ship's initial position as the coordinate origin. course of the ship as Y-axis is the same with own ship original course, seeing Fig.2 for more information. The calculation principle of d_{CPA} is to establish the functional relationship between the distance between two ships and time in Cartesian coordinate system. The minimum result of $D(t)$ is d_{CPA}. When the minimum result of $D(t)$ is obtained, the result of corresponding independent variable is t_{CPA} [15]. The d_{CPA} calculation model is applicable to all situations, simplifies the solution process and meets the needs of ship risk assessment. Own ship's initial coordinate (x_o,y_o) is (0,0) and course is θ_o, speed is v_o. The model uses distance and relative bearing to calculate coordinates relative to own ship position. In Fig. 2., β is relative orientation, the distance of two ships is d, x_t and y_t are the horizontal and vertical coordinates of the target ship relative to own ship, θ_t is target ship's course, θ_{tr} is target ship's course relative to own ship.

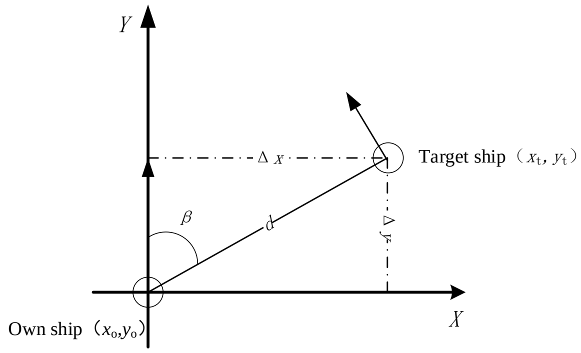


Fig. 2. Distance- d_{CPA} calculation model based on the distance function between two ships

$$\begin{cases} x_t = d\sin\beta \\ y_t = d\cos\beta \end{cases} \tag{1}$$

$$\begin{cases} \theta_{tr} = \theta_t - \theta_o \\ \text{if} \quad \theta_{tr} < 0° \\ \theta_{tr} = \theta_{tr} + 360° \end{cases} \tag{2}$$

v_{rx} and v_{ry} are the difference between the speed in the horizontal and vertical coordinate directions:

$$\begin{cases} v_{rx} = v_{tx} - v_{ox} \\ v_{ry} = v_{ty} - v_{oy} \end{cases} \tag{3}$$

*D(t)*is the functional relationship between *D* and *t*, $D'(t)$ is the derivative function of *D(t)*:

$$\begin{cases} D(t) = \sqrt{(x_t + v_{rx}t)^2 + (y_t + v_{ry}t)^2} \\ D'(t) = \dfrac{(v_{rx}{}^2 + v_{ry}{}^2)t + v_{rx}\Delta x + v_{ry}\Delta y}{\sqrt{(x_t + v_{rx}t)^2 + (y_t + v_{ry}t)^2}} \end{cases} \tag{4}$$

As shown in formula (4), the denominator part of the function is always greater than 0 and the molecular part of the derivative is a primary increasing linear function of the variable *t*, so the derivative has only one zero point, t_{CPA}, and the function at the zero point takes the minimum value, d_{CPA}.

$$\begin{cases} t_{cpa} = -\dfrac{v_{rx}x_t + v_{ry}y_t}{v_{rx}{}^2 + v_{ry}{}^2} \\ d_{cpa} = \sqrt{(x_t + v_{rx}t_{cpa})^2 + (y_t + v_{ry}t_{cpa})^2} \end{cases} \tag{5}$$

4. Method for collision avoidance

The own ship is sailing in the open water according to the planned path. ARPA is set to automatically capture other ships, obtaining distance, d_{CPA} and other data, providing d_{CPA} alarm. The system reads the distance and relative bearing data of target ship from ARPA. System establishes auxiliary alarm watch based on d_{CPA}. In case of d_{CPA} alarm is on, users identify encounter situation, and then judge the obligation of own ship. If own ship is a give-way ship, the auxiliary decision data information including the rudder angle, steering angle and sailing time at each stage of own ship is calculated by GA for the reference of the users. At the same time, the system can give a yaw alarm. If the ship's position deviates from the original path beyond the allowable range while completing actions, the system will give a yaw alarm. Fig. 3 shows the framework of collision avoidance decision-making system.

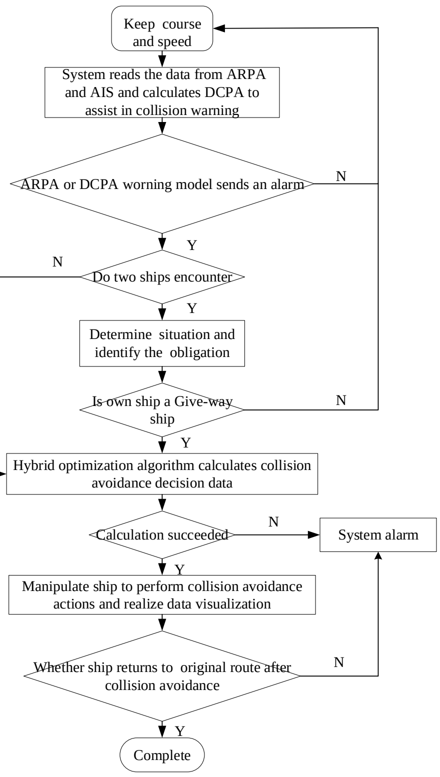


Fig. 3. The framework of collision avoidance decision-making system.

This research establishes a path model using K and T index. In order to compare the advantages of different ship's maneuverability, K value will be converted into the dimensionless quantity K', $K'=K\mathrm{L}/v_s$. Ship's length is L and v_s is the initial speed of the gyration. If the value T is small, this means that the steering effect is good. *T'* is a dimensionless quantity of *T*. The *K* and *T* index decrease with the increase of rudder angle. Based on the SIHC simulation platform [16], Zhang, et al [17] selected the ship model of the Danish Maritime Institute to calculate the *K* and *T* indexes under different rudder angles(δ). In this research, the data were fitted by EXCEL to obtain the relationship curve between rudder angle and *K'* and *T'* as shown in Fig. 4.

$$\begin{cases} K = -3.1556e-06\delta^3 + 0.00023824\delta^2 - 0.0063985\delta + 0.086671 \\ T = -0.0024556\delta^3 + 0.16795\delta^2 - 4.1359\delta + 83.264 \end{cases} \tag{6}$$

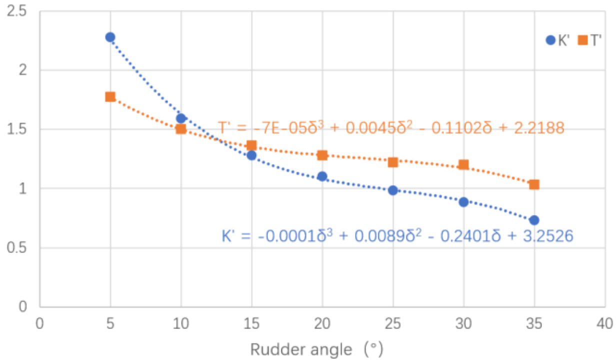


Fig. 4. Relationship curve between rudder angle and *K'* and *T'*

Nomoto model is currently the most widely used linear mathematical model in the field of ship motion control, and Nomoto model can ensure high accuracy in the design of linear controllers and simple system simulations. Based on the Nomoto model, the position coordinates(x,y) of the ship at any moment after turning are deduced using the ship maneuverability indices *K* and *T*. Based on Nomoto model, the ship path is simulated using MATLAB. It is found that the Nomoto model consumes about 500s for the calculation of the ship path in simulation scenario 1, which is less efficient. In this research, the collision avoidance path is optimized based on *K* and *T* index, reducing calculation time 99.7%. Comparison of optimized path with path based on Nomoto model is shown in Fig. 5. From Fig. 5(a), it can be seen that the two paths are highly overlapping. Fig.5(b) 7 shows the Euclidean distance deviation of the path at each moment. The maximum position deviation of the optimized path model is about 80m, and this error can ensure the safety of ship navigation in open water.

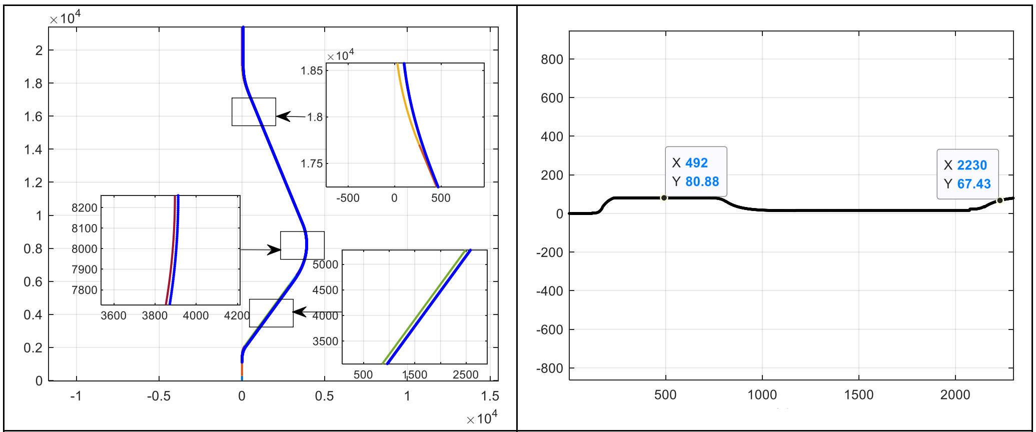
The following three points are the premise assumptions of the path model:

1). The propeller speed remains the same, and the ship's speed decreases by 20% during steering due to the influence of slanting resistance [18];

2). During the time of $T+t_r/2$ (t_r is rudder angle) after steering, the ship keeps sailing on the original path and the sailing distance is equivalent to the reach distance (Re). After $T+ t_r/2$, ship enters the steady cycle stage, with $\omega=K\delta$ (δ is rudder angle).

3). The time rudder turning from certain angle to Midships is t_0. During this time, the ship is still sailing in the original circle. The ship will sail in a straight line after Midships.

In order to make it convenient for ship driver to observe the ship's movement on the simulation display platform, own ship's initial course is the same with Y-axis.



a). comparison of path	a). distance offset

Fig. 5. Comparison of optimized path with path based on Nomoto model

Initial position of own ship (x_o, y_o), course θ_o. Ship’s speed is v_o, t_0 is the decision-making calculation time. So, relationship between the subsequent position (x_p, y_p) and the time t_1 before turning is:

$$\begin{cases} x_p = x_o + v_o\left(t_0 + t_1\right) \\ y_p = y_o + v_o\left(t_0 + t_1\right) \end{cases} \tag{7}$$

The ship's steady time after turning is t_2, Ψ is the turned angle of the ship, t_{r1} is the time if first turning rudder. So, the relationship between the subsequent position (x_q, y_q) and the time t_2 is:

$$\begin{cases} x_q = x_p + v_o \sin(\theta_o)(T_1 + \frac{t_{r1}}{2}) \\ y_q = y_p + v_o \cos(\theta_o)(T_p + \frac{t_{r1}}{2}) \\ \Psi(t) = \int_0^t \theta_o + K\delta_1 t dt \\ x_{q+1} = x_q + \int_0^{t_2+1.5t_{r1}-T_1} v_o \sin[\Psi(t)]dt \\ y_{q+1} = y_p + \int_0^{t_2+1.5t_{r1}-T_1} v_o \cos[\Psi(t)]dt \end{cases} \tag{8}$$

The following path model of the ship is consistent with the above and will not be repeated.

5. Hybrid optimization algorithm

GA uses the power of evolution and optimization to solve a large number of tasks, and can determine the value of multiple decision variables when finding the optimal solution [19]. GA establishes a population including multiple individuals, and iteratively updates them by selection, crossover, and variation to improve the individuals and the population, which eventually converges to the optimal solution after evolution.

In this research, GA uses real number encoding. The number of individuals in this research is 9, t_1~t_6, δ_1~δ_3(t_i is the time of each voyage and δ_i is the rudder angle). Population is a collection of individuals, and here the population size is 200. Fitness function (objective function) is a measure of optimization, the smaller of the value, the higher of the fitness. Rank ordering is used to calculate the fitness value. In each iteration, after calculating the fitness of each individual, the good individuals in the population are randomly and uniformly selected by the fitness function value to form the next generation population. Two parents pass the good genes to the offspring through crossover, so that the algorithm proceeds in the direction of optimization. Variation ensures the diversity of individuals in the next generation, which is more likely to find the global optimal solution. The objective function f_o is the lost voyage in collision avoidance, it is the sum of the range of each segment deviating from the original course minus the straight-line distance sailed on the original heading. In this research, 7 segments of the range are deviating from the original course. y_{o_p} and y_{o_end} are the ordinate at the beginning of the turn and returning to the original route. L_k is the distance of each segment:

$$f_o = \min\left[\sum_{k=1}^{k=7} L_k - (y_{o\_end} - y_{o\_p})\right] \tag{9}$$

Establishment of constraint functions keep own ship away from danger. In related research, Jiang et al. [20] used d_{CPA} as a constraint function for safe passage. This research considers the actual operation performance of the ship and simulates the ship turning process. The combination Euclidean distance d_{CPA} is as the constraint function (f_c). The distance formula between two points can be used to establish the functional distance relationship between ships with respect to time. Establish the constraint function taking the distance between ships as the risk assessment standard. Wherein, [$x_j(t)$, $y_j(t)$], [$x_{tj}(t)$, $y_{tj}(t)$] are the coordinate point of ship at the time t in j-segment voyage. Time t starts from 0. R_j and R_l are the safety distance requirement to be met in the j-segment and l- segment. (x_k, y_k) is the coordinate of own ship returning to the original path. θ_o is initial course of own ship. θ_k is the ship's course back to the original path. $D_j(t)$ is the distance between ships at time t in section j voyage. x_{o_p} and x_{o_end} are the abscissa at the beginning of the turn and returning to the original route. i is a parameter that represents the accuracy of the constraint function. The larger the value of i, the higher the accuracy. In this research, the value of i is 5.

$$D_j(t) = \sqrt{(x_{tj}(t) - x_{oj}(t))^2 + (y_{tj}(t) - y_{oj}(t))^2} \tag{10}$$

$$s.t. \begin{cases} f_{c1}(n) = S_j - D_j\left(n\dfrac{t}{i}\right), \\ f_{c1}(n) < 0, n = 1, 2, 3 \ldots i \\ f_{c2} = S_l - d_{\mathrm{CPA}\,l},\ f_{c2} < 0 \\ f_{c3} = x_{\mathrm{o\_end}} - x_{\mathrm{o}},\ f_{c3} = 0 \\ f_{c4} = \theta_{\mathrm{o}} - \theta_{\mathrm{o\_end}},\ f_{c4} = 0 \end{cases} \tag{11}$$

This research also uses fmincon optimization toolbox in MATLAB to solve the above problems by the use of interior point algorithm. Fmincon can get better results in less time than GA. From this perspective, fmincon is more optimal. However, fmincon needs to input the iteration starting point. If the selection of the starting point is close to the optimal solution, fmincon can quickly and accurately find the global optimal solution. Otherwise, it cannot calculate the optimal solution or even obtain a solution that meets the constraint conditions. The range of the input initialization population is not a necessary condition for GA, and from this perspective, GA is more optimal.

This article found a hybrid algorithm solution that can accommodate the advantages of both algorithms: prioritize using GA to calculate the local optimal solution, and then use this optimal solution as the starting point for the fmincon iteration calculation. The algorithm process is shown in Fig.6.

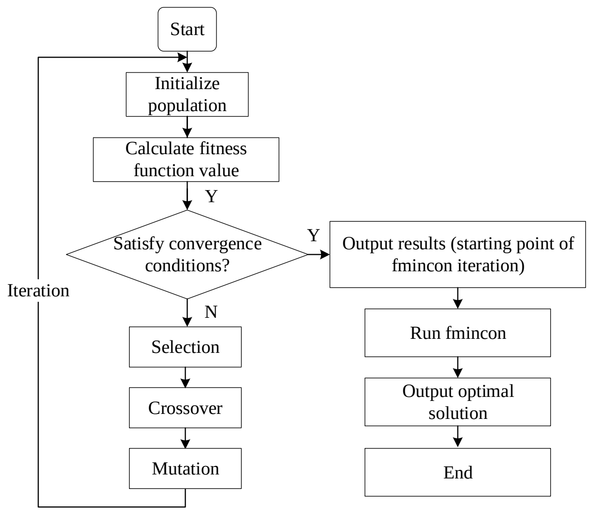


Fig. 6. A hybrid optimization algorithm based on GA and fmincon

Through simulation experiments, it has been proven that the hybrid algorithm is stable and effective.

6. Validations with simulations

Taking M/V La Cordillera bulk of Danish Maritime Institute as an own ship example, ship data are in Table 1.

Table 1.

M/V La Cordillera parameter

Length overall(m)	Breadth moulded(m)	Displacement(m^3)	C_b	Tactical diameter(m)
289.6	44.2	150100	0.804	1296

This research simulates the situation of crossing, heading, overtaking and multi-ship involved in COLREGS. All actions to avoid collision comply with the COLREGS. Among them, the requirements of COLREGS for the giving way ships are taking substantial collision avoidance actions so that the keep way ships are easy to detect by the vision or radar. Therefore, the rudder angle for the first turning is set to be greater than 20°. Table 2 is target ship information in simulation scenarios.

Table 2.

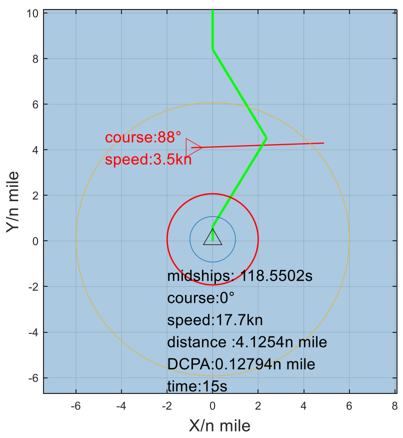
Target ship information and system parameter setting

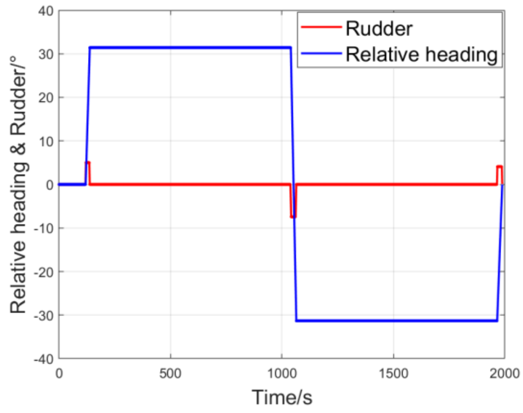
Target ship NO.	1	2	3
Situation	crossing	crossing	heading
Distance(n mile)	4.2	5.53	5.17
Course(°)	272	115	359
Speed(kn)	3.5	20	20
RB(°)	347°	64.4	356
d_{CPA}(n mile)	0.12	0.66	0.32
t_{CPA}(mins)	14	15.3	7.7
Safe distance(n mile)	2 n mile	1852m	1852m
Start point of fmincon	[200 100 500 300 500 200 21 15 15]		
t_1～t_6, δ_1～δ_3 range	lb:[0 25 10 10 10 10 20 3 3] ub:[500 75 900 500 900 500 30 30 30]		

This decision-making system is based on AMD Ryzen 7 5800H. and the calculation time is 15s on average.

Simulation scenario 1: Container ship YM MUTUALITY collided with Minzhao Fishing 60969 at 0312 local time, YM heading 184 °, speed 17.7 kn, Minzhao Fishing 60969 heading 272°, speed 3.4kn, distance of 4.2 n miles. COLREGS, YM is the giving way ship.

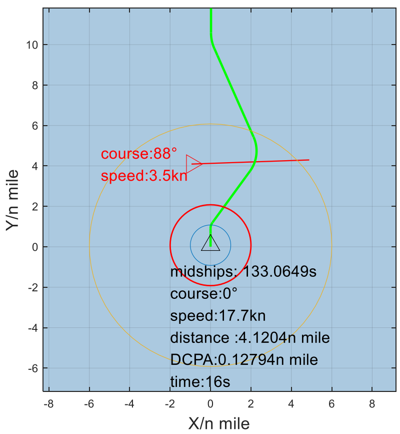
Related studies extremely simplified the ship turning process in ship collision avoidance path planning, only considering the turning time, new heading, and time to restore the original heading, as is shown in Fig.7.This research simulates the related studies path by increasing the cyclicity index *K* and decreasing the *T* index. Expanding the K value to 10 times the corresponding value in the experiment can enable the ship to quickly reach a new heading after turning. At the same time, T index is reduced to 0, which means that the ship starts turning immediately after turning the rudder.as shown in Fig.7.

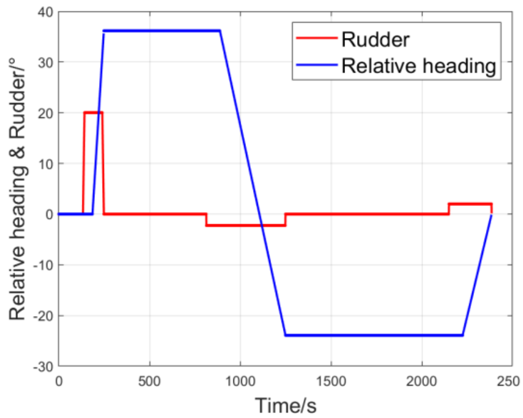




a). collision avoidance path b). relative heading and rudder angle

Fig. 7. Collision avoidance simulation of relevant research



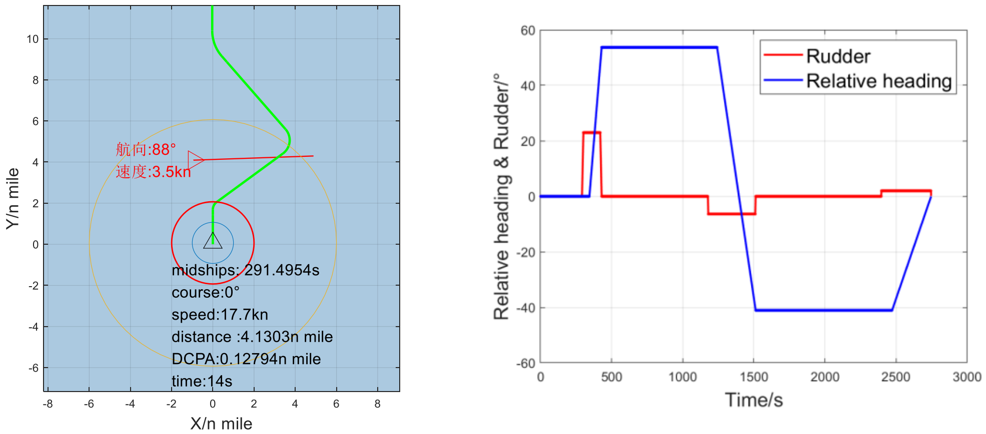


a). collision avoidance path b). relative heading and rudder angle

Fig. 8. Collision avoidance simulation based on GA

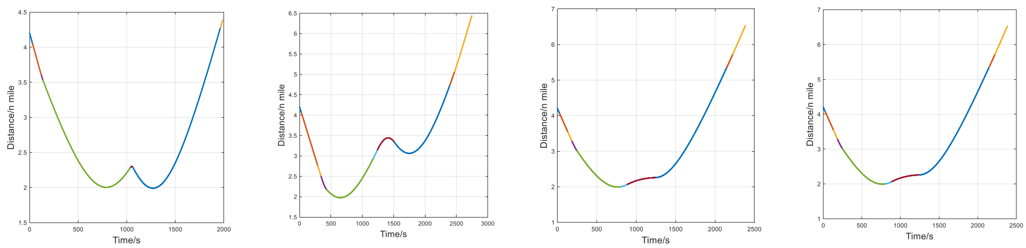
Fig.8. is collision avoidance simulation based on GA. Fig. 9. is collision avoidance simulation based on hybrid optimization algorithm. Fig.10. shows the distance relationship between two ships. In this experiment, fmincon obtains the

same results as the hybrid optimization algorithm. Table 3 shows a comparison of the four methods in terms of voyage loss and time. Fig.11.shows current function value of fmincon and hybrid optimization algorithm.



a). collision avoidance path b). relative heading and rudder angle

Fig. 9. Collision avoidance simulation hybrid optimization algorithm



a). relative research distance b).GA distance a). fmincon distance a).hybrid optimization algorithm distance

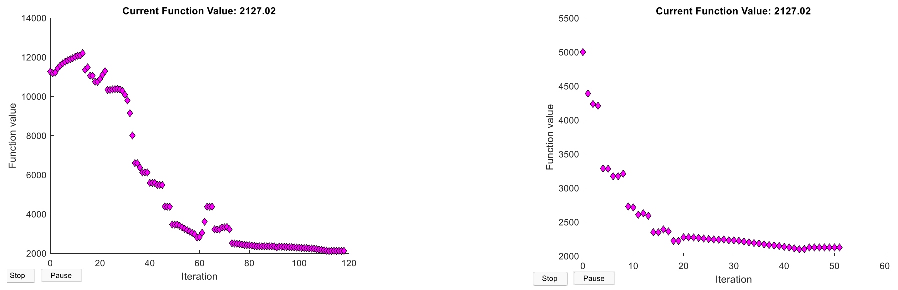
Fig.10. Distance relationship between two ships

Table 3.

Comparison of the four methods in terms of voyage loss and time

Algorithm	Related research	GA	fmincon	GA&fmincon
Voyage loss(m)	2426	5759	2127	2127
Time(s)	1988	2746	2385	2385
System calculation time(s)	6.7	13.3	4.7	14.1

Fmincon and hybrid algorithm get the same results, but this ideal optimization result cannot be stably obtained in every scenario. After local optimization by GA, hybrid algorithm can use less iterations to find the global optimal solution.

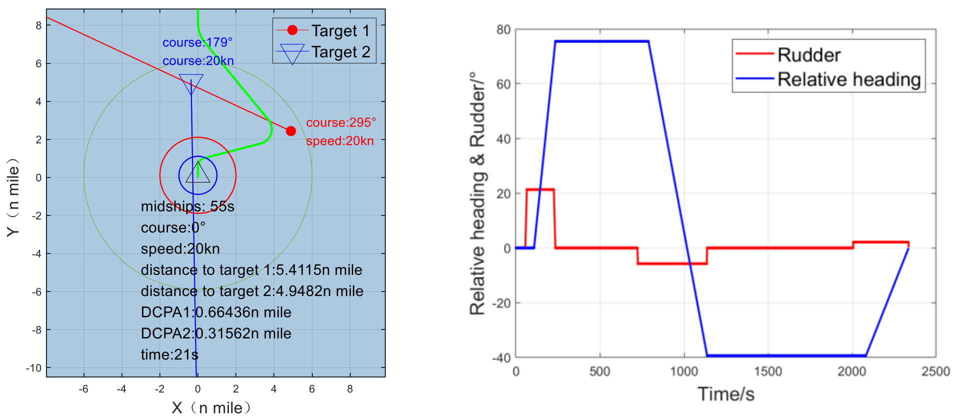


a). fmincon b). hybrid optimization algorithm

Fig.11.Current function value of fmincon and hybrid optimization algorithm

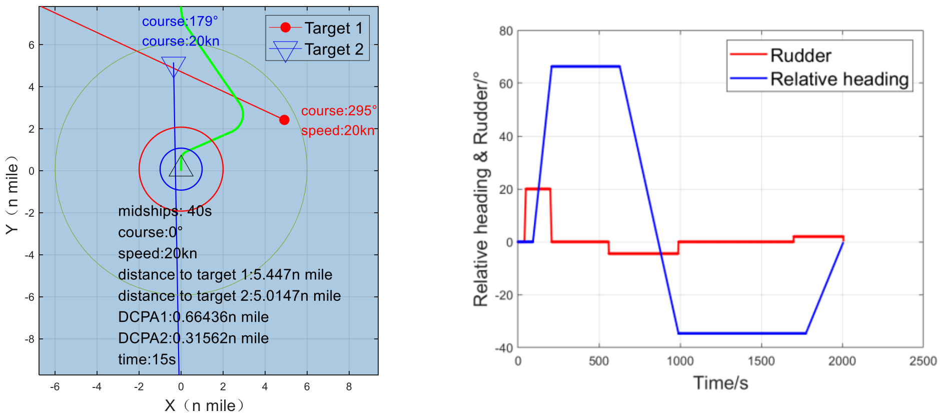
Simulation scenario 2: Simulation of three ships meeting. Own ship course 180°, speed 20kn. Fig.12. is collision avoidance simulation based on GA. Fig. 13. is collision avoidance simulation based on fmincon. Fig. 14. is collision avoidance simulation based on hybrid optimization algorithm. Fig.15. shows the distance relationship with target ships. Fig.16.shows current function value of fmincon and hybrid optimization algorithm. Table 4 shows the comparison of the three methods in terms of voyage loss and time.

In simulation scenario 2, as is shown in Fig.16(a), fmincon has fallen into local optima. The setting of algorithm parameters is the default value of the optimization toolbox. Display of operation result is “fmincon stopped because it exceeded the function evaluation limit, options: Max Function Evaluations = 3000 (the default value)”. In this situation, Changing Max Function Evaluations does not solve the problem, The problem was effectively solved through combinatorial algorithm, seeing Fig.16(b). Fig.17. shows detailed ship collision avoidance decision data based on hybrid optimization algorithm.



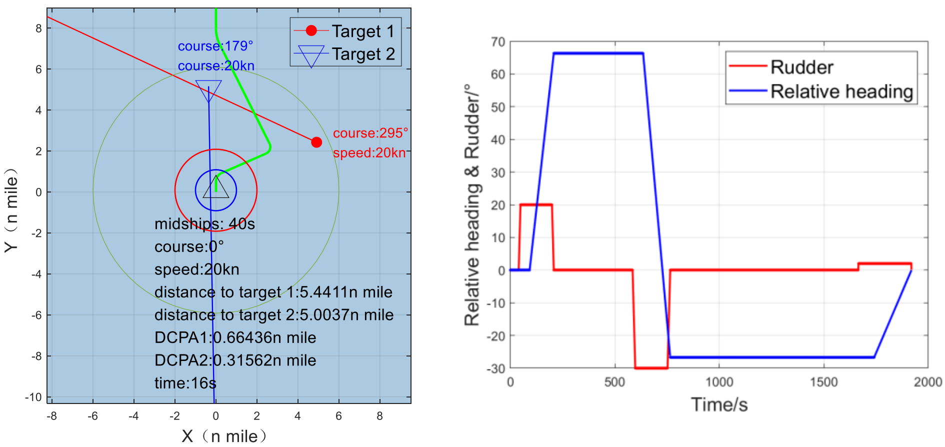
a). collision avoidance path b). relative heading and rudder angle

Fig. 12. Collision avoidance simulation based on GA



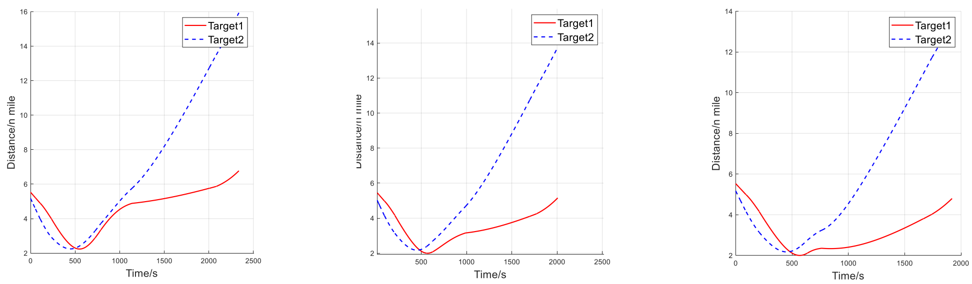
a). collision avoidance path b). relative heading and rudder angle

Fig. 13. Collision avoidance simulation based on fmincon



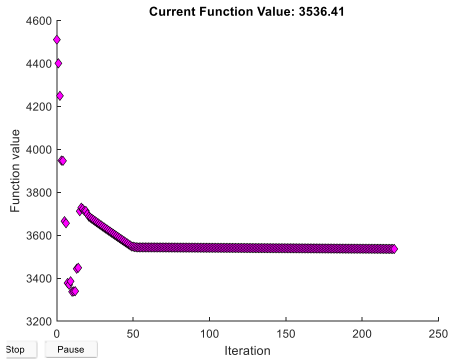
a). collision avoidance path b). relative heading and rudder angle

Fig. 14. Collision avoidance simulation based on hybrid optimization algorithm

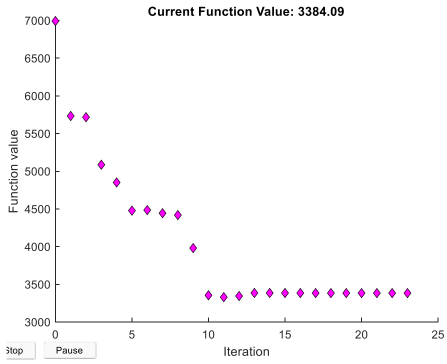


a). GA b). fmincon b). hybrid algorithm

Fig.15.Distance relationship between target ships



a). fmincon



b). hybrid optimization algorithm

Fig.16.Current function value of fmincon and hybrid optimization algorithm

Table 4.

Comparison of the four methods in terms of voyage loss and time

Algorithm	GA	Fmincon	GA&Fmincon
Voyage loss(m)	6243	3536	3353
Time(s)	2337	2007	1919
System calculation time(s)	16.1	5.9	13.5

	midships	starbosad:20	steady	midships	steady	port:...	steady	midships	steady	starbosad:2	steady	midships	complete
Time(s)	40	8.58	150.5...	8.58	377.0...	12.87	154.3258	12.87	900	0.858	252.7238	0.858	/
Accumulated time(s)	40	48.58	199.1...	207.7564	584.8...	597.7...	752.0431	764.9131	1664....	1665.7711	1918.49...	1919.3529	/
Relative course(°)	0	0	/	/	66.3059	66.3059	/	/	333.3...	333.3341	/	/	2.2794e-10
True course (°)	180	180	/	/	246.3...	246.3...	/	/	513.3...	513.3341	/	/	180
DCPA (n mile)	0.66436\...	/	/	/	/	/	/	/	/	/	/	/	1.6084\0.2921
TCPA(s)	920\464	/	/	/	/	/	/	/	/	/	/	/	-757\-1212
Voyage loss(m)	3353.5648	/	/	/	/	/	/	/	/	/	/	/	/

Fig.17. shows detailed ship collision avoidance decision data based on hybrid optimization algorithm

Take Fig. 17. as an example, to illustrate the output data of the decision-making system:

1). When collision risk detection sends an alarm, click the start calculation button immediately, and the collision avoidance decision data will be obtained after several seconds (not exceeding 30s), which is reliable;

2). Time from clicking the start calculation button, and the ship will continue to sail at the original course for 40.0s;

3). After that, starboard 20.0°, taking 8.6s, and steady on the rudder angle for 150.5s;

4). After that, midships, and then steady on midships for 377.0s;

5). Then, port 4.99°, steady on port 30.0° for 154.3s;

6). Midships, and then steady on midships for 900.0s;

7). Starboard 2.0° and steady on starboard 2.0° 252.8s;

8). Midships, complete.

The whole process takes 1919.4s, and the loss voyage is 3353.6m.

6. Conclusions

This research makes decisions based on the path established by *K* and *T* index, which makes the decision data more practical. Hybrid optimization algorithm helps system find global optimizer. This research provides users with decision-making references of rudder angle, steering time, reducing human error and increasing decision accuracy. Visualization module helps preview the dynamic position relationship, distance between ships, as well as rudder angles. At present, intelligent ships are not yet popular and ships still requires manual operation. The research results can play a huge role in providing the ship drivers with steering angle, steering time and other collision avoidance decision-making information, which simplifies the ship driving task and reduces human decision-making errors. In the future, with the help of the shipping Internet of Things, the research results can realize the remote collision avoidance and control of ships, and can also be integrated into the intelligent ship system as an automatic collision avoidance path planning module to realize the autonomous control of ships. While this research does not consider the situation of ships in restricted water and the influence maritime conditions. In order to increase the reliability of the decision-making system, the *K* and *T* values should be adjusted according to ships' different loading conditions and maritime situation.

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