A multi-objective routing optimization model for ship intelligent navigation

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Abstract—In order to solve the problem of ship route planning in the autonomous navigation and decision-making of ships, based on the electronic chart display and information system (ECDIS), the meteorological conditions of ocean-going ships were analyzed and the grid method was used to establish an environmental model. The voyage time, fuel consumption and navigation safety were taken as optimization goals, and a multi-objective ship route optimization model was established, then the non-dominated sorting genetic algorithm with elite strategy (NSGA-II) was applied in the optimization route searching to realize the solution of the optimal ship route.

1. INTRODUCTION

With the rapid development of technologies and theories such as Internet information technology, artificial intelligence, neural networks, and deep learning, the global industrial industry is moving in the direction of informatization and intelligence. The construction of the automated control of ships and the integration of ship-shore information systems is moving further towards intelligence. With the rapid improvement of ship intelligence, the research and development of intelligent ships has become the consensus of the ship-building industry [1].

As an important functional module of smart ships, autonomous route planning and decision-making plays a vital role in the development of intelligent ships. At present, route planning based on weather information technology has become a hot research area in ship autonomous route planning and decision-making. Weather routing focuses on designing an optimal weather route for the ship based on the received accurate ocean and weather forecasts and the ship’s own performance. With the in-depth attention of IMO to green shipping and the increasing requirements of weather routing for ocean ships, the problem of ship route optimization is no longer a dynamic single-objective problem, but a dynamic multi-objective optimization problem with multiple objectives, multiple constraints and high-dimensional decision variables.

For ship route optimization, many scholars around the world have made great efforts and carried out some achievements. The traditional single-objective route optimization lacks in-depth study on the problems that ocean-going ships may encounter. In recent years, the idea of multi-objective optimization has been introduced into ship route optimization, and has been integrated with many intelligent algorithms, which has achieved remarkable research results. For example, Joanna et al proposed a new multi-objective evolutionary algorithm based on a trade-off by introducing decision-maker preferences in multi-objective optimization problems [2]. The preference of the decision maker is distributed to all the targets through the configurable weight interval, and the multi-objective is normalized to improve the efficiency of the algorithm. WANG et al proposed a genetic algorithm based on real coding of route path points to find the optimal route [3], and in order to avoid the route optimization trapping into local optimization.
and improve population diversity, the fitness calculation and relevant operators were transformed. Lijia Chen et al took electronic chart display and information system (ECDIS) as the platform, the various factors affecting the weather route design was analyzed, the network navigation environment model was set up, and a kind of constraint route generation algorithm under dynamic environment was realized in their research [4]. Aiming at the minimum fuel consumption and the shortest sailing time respectively, Huachuan Zhao et al proposed a dynamic route design method based on real weather information and carried out an applied simulated annealing method for ship route planning [5]. Mingfeng Li et al presented a reliable ship weather routing algorithm by combining the strength Pareto multi-objective genetic algorithm, in which the time and fuel consumption were taken as the optimization goals, the routes to point and interval speed were taken as the optimization objects [6]. Li et al set up a model with voyage time and safety as its optimization objectives, and adopted non-dominant sequencing genetic algorithm-II (NSGA-II) to optimize the design of route conversion points and improve the optimization efficiency [7].

In this work, the environment grid model is established as the basis, a multi-variable and multi-objective ship route optimization method is proposed.

2. A GRID METHOD TO BUILD THE ENVIRONMENT MODEL

Ships will encounter obstacles such as islands, submerged reefs, shallow water areas, and dynamic weather warning zones caused by harsh environments during their voyage. If the environmental model cannot be established accurately, most ship route searching algorithms cannot be used directly, so the problem of environmental model must be solved. Rasterizing the marine environment is a useful way to build the environment model, so the grid method is used in this research, which is helpful to improve the computational efficiency of the algorithm [9].

In order to reduce the interference of other external areas, the starting point \( S(\lambda_s, l_s) \) and the target point \( E(\lambda_e, l_e) \) on the electronic chart are framed in a rectangular area. In the rasterization, an appropriate rectangular area is selected and divided into equal proportions by designing an appropriate grid size. After quantizing the electronic chart into grids, the grids in the environmental model area are numbered.

Static obstacles can be directly filled with black, which referred to as obstacle grid collectively. The grids that do not contain obstacles in the area are shown in white, which called free grids. The starting point in the grid area is set as the starting grid \( 1 \), then each grid is numbered successively from bottom to top and from left to right, until target point is finally numbered as the last number \( N \). The ship route can be regarded as composed of waypoints, which can be expressed in turn as \( 1(\lambda_s, l_s) \rightarrow 2(\lambda_s, l_s) \rightarrow \cdots \rightarrow N(\lambda_e, l_e) \). After being rasterized, the space of the ship’s possible driving environment is transformed into a grid map. The route optimization problem is transformed into the problem of finding the optimal route between two grid nodes. The established grid model is shown in Figure 1 below.

![Figure 1. The established grid model](image-url)
3. MULTI-OBJECTIVE OPTIMIZATION MODLE OF SHIP ROUTE

With the development of modern science and technology, shipping companies put forward new requirements for the intelligentization of ocean-going ships. In the process of ocean voyages, ships will encounter the influence of multiple uncertain factors such as severe weather, resulting in the failure of established routes to meet the sailing needs. In the case of comprehensive consideration of various factors, this work establishes a model to obtain an optimal route, which is taken the minimum voyage time, minimum fuel consumption and maximum safety as the multiple optimization objectives.

3.1. Minimum voyage time

The minimum voyage time is the design of a route with the shortest sailing time between the ship's departure point and the destination point, within the ship's own pressure range and the limits of constraints. In the optimization design process, ship routes can be divided into route segments between certain two grid points. The voyage time between the departure point and the destination point is approximated as the sum of the sailing time between the route segments, as presented by (1):

\[ f_1 = \sum_{i=1}^{n} R_i / V_i \]  

where \( f_1 \) is the total sailing time, \( R_i \) are the voyage between each segments, \( V_i \) are the speed of the ship on each route segment.

3.2. Maximum navigation safety

Ships will encounter sudden and severe weather when they are sailing. The occurrence of severe weather will bring about the interaction of various factors such as waves, wind and tidal currents, which makes the operating environment of ships become complex and changeable. When the wave height exceeds the ship's acceptable range, it will be more difficult to control the ship and affect the safety of ships [8].

In actual operation, the weather grid data is applied to analyze wave height. The grid points whose wave height are greater than the highest value the ship can bear are assigned as the value of 1, and those within the acceptable range are assigned as the value of 0. The value 1 represents the highest level of risk, and 0 represents the lowest level of risk. Finally, the value of each node passed by the route is added to obtain a navigational safety objective function \( f_2 \).

3.3. Minimum fuel consumption

The green shipping is advocated currently. Now, more and more ocean-going ships still use diesel fuel as the main fuel and exhaust emissions, which have many adverse effects on the environment. If the fuel consumption can be minimized, this will greatly improve the air quality.

The function for fuel consumption calculation is present by (2):

\[ f_3 = \sum_{i=1}^{n} V_i \]

Where \( f_3 \) is the sum of fuel consumption of each voyage of the ship, \( V_i \) are the speeds of the ship on each route segment.

3.4. Establishment of constraint conditions

In ship route optimization, constraints generally include static restricted navigation zone constraints and dynamic restricted navigation zone constraints. Static constraints mainly include islands, shallow waters, and military restricted navigation zones, while dynamic constraints mainly refer to severe winds and waves caused by severe weather that make ships impassable. Record the entire grid area as \( U_0 \) and the navigable area as \( U_i \). \( \lambda \) is the possible latitude coordinates set of the navigation area, \( l \) is the possible longitude coordinates set that the navigation area can take, \( \lambda_{\text{max}} \) and \( \lambda_{\text{min}} \) are the maximum and minimum
values of the latitude coordinates of the navigable area, $l_{\text{min}}$ and $l_{\text{max}}$ are the maximum and minimum longitude coordinates of the navigable area. The selectable areas $U_i$ is represented by (3):

$$U_i \subseteq \{ (\lambda, l) | \lambda_{\text{min}} \leq \lambda \leq \lambda_{\text{max}}, l_{\text{min}} \leq l \leq l_{\text{max}} \}$$

(3)

When a ship sails in each section, the static water velocity of the ship is limited to a certain range $[V_{\text{min}}, V_{\text{max}}]$, where $V_{\text{min}}$ is the minimum static water speed and $V_{\text{max}}$ is the maximum static water speed. Therefore, the ship's speed in still water satisfies the following inequality (4).

$$V_{\text{min}} \leq V_i \leq V_{\text{max}}, i = 1, 2, 3, \ldots, n$$

(4)

3.5. Multi-objective model of route optimization

When taking the ship's own factors under considering, the navigation time, fuel consumption and navigation safety can be taken as the optimization goals, and the static and the non-navigation zones can be taken as the constraints. The route optimization model can be established, as presented by (5):

$$\begin{align*}
\min f &= \min(f_1, f_2, f_3) \\
\text{satisfy } & (\lambda, l) \subseteq U_i, V_{\text{min}} \leq V \leq V_{\text{max}}
\end{align*}$$

(5)

where $f$ is the objective function.

4. IMPROVEMENT AND REALIZATION OF ROUTE PLANNING ALGORITHM

Multi-objective optimization problems are generally solved under constraints corresponding to multiple objective functions. The final solution is a solution set, which is called the Pareto optimal solution. The non-dominated sorting genetic algorithm with elite strategy (NSGA-II) is a non-dominated sorting genetic algorithm based on the Pareto optimal concept, which is proposed on the basis of the genetic algorithm. It also simulates the process of biological genetics and evolution in nature, carries out random search and optimization of the target space, and finally achieves the effect of approaching the optimal solution. The specific route planning algorithm flow can be seen in the Figure 2.

![Route Planning Flowchart](image)

The algorithm based on NSGA-II is a method to construct the Pareto solution set quickly, it sorts populations of any size according to the non-dominated level. Each solution needs to be compared with other solutions, and all population individuals rearrange to get rank whether it is dominated or not. Then, the parent population can be selected from the individuals according to the result of crowding degree.
distance sorting, and a new generation of the population is generated through selection, crossover and mutation operations. Repeated iterations finally obtain the Pareto optimal solution that meets the conditions.

4.1. Generation and coding of the initial population
After the solution target space is rasterized, each grid point is assigned a specific number. The generation of the initial population will not cover the grid points in the entire target area, and the threshold of the grid nodes in the static restricted navigation zone can be set relatively large, so that they can be filtered directly when the population is initialized. Generally, an appropriate size of population individuals (adjustable by experiment) is selected, which will not only reduce the complexity of calculation, but also improve the efficiency of subsequent operations of the algorithm. Compared with binary-coded method, the real-coded method saves the decoding process and improves the operation efficiency.

In this work, based on the rasterization and labeling of the navigation area, the population is real-coded. The ship route can be regarded as a vector connection of waypoints. After the navigation area is initialized, the grid nodes (including latitude and longitude position information and weather conditions) are encoded into the vector, which can be expressed as \( Y = \left[ Y_1, Y_2, Y_3, \ldots, Y_n \right] \) to represent a chromosome.

4.2. Population renewal and evolution
In traditional genetic algorithms, the generation of parents is simulated by selecting individuals with greater fitness. The formation of offspring is simulated by crossover and mutation operators. The marine environment is complex and changeable. In the process of evolution, consider the influence of static and dynamic obstacle zones on basic operator operations is necessary. Therefore, the operators need to be improved accordingly.

The process of selection is based on traversing the fitness of various groups. Individuals with greater fitness are chosen as the parents with good traits, which can be passed to the next generation.

For the minimum navigation time, maximum safety and minimum fuel consumption of route optimization, the formula (6) can be used to calculate the fitness value:

\[
\text{eval}(f_i) = \frac{1}{f_i}
\]  

where \( \text{eval}(f_i) \) is the fitness value of each individual.

4.2.1. Selection operation: Using the roulette method of selection, individuals with high adaptability are more likely to be selected as parents and pass on excellent traits to the next generation.

The total fitness value of the population can be calculated as shown in the formula (7):

\[
F = \sum_{i=1}^{n} \text{eval}(f_i)
\]  

The probability of each corresponding individual being selected can be calculated as shown in the formula (8):

\[
P_i = \frac{\text{eval}(f_i)}{F}
\]  

The cumulative probability of each chromosome \( Y_i \) can be calculated as shown in the formula (9):

\[
Q_i = \sum_{j=1}^{i} P_j
\]  

In the actual selection process, the algorithm generates a random number between 0 and 1. If \( r \leq Q_i \), chromosome \( Y_i \) was chosen; otherwise, \( k \)-th chromosome \( Y_k \) was chosen.
4.2.2. **Crossover operator:** The diversity of the population can prevent the algorithm from falling into the local optimal, but it will slow down the evolution speed and lead to the decrease of the overall performance of the algorithm. In order to resolve this contradiction as much as possible, and speed up the evolution of the population without destroying the diversity of the population, the randomly selected parent population are crossed \( n \) times according to the arithmetic crossover method, so that offspring individuals will be generated. The offspring individuals will be sorted according to their fitness, and the individual with the best fitness is selected and repeated randomly until the set number of offspring is generated. Arithmetic crossover is the linear combination of two individuals into two new individuals. Supposing that an arithmetic crossover is performed on two individuals of \( Y_A \) and \( Y_B \), the new generated individuals are shown in the formula (10):

\[
Y_A^{t+1} = \alpha Y_A + (1-\alpha)Y_B \\
Y_B^{t+1} = \alpha Y_B + (1-\alpha)Y_A
\]  

(10)

4.2.3. **Mutation operator:** In the process of biological genetic evolution, the change of living environment or internal factors will lead to gene mutation and change of species characteristics. The mutation operation of a genetic algorithm is to imitate this operation to improve the diversity of the population and the ability of local search without losing key information. The mutation operation mutates a grid point of the \( i \)-th individual randomly according to a certain probability. In the way of uniform variation, the original gene value on a certain locus in individual coding is replaced by random number with uniform distribution in a certain range and a certain probability.

5. **CONCLUSION**

This work combined environmental modeling with the ship's autonomous route decision-making system, and proposed a new type of multi-objective ship weather route planning method based on the NSGA-II algorithm. Integrating voyage time, fuel consumption and navigation safety into the objective function, the final generated route in this work can not only ensure the safety of the ship's navigation, but also save the operating cost of the ship company and mention economic benefits.

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**REFERENCES**

[1] Guan Wei, Zhou Haotian, Su Zuojing, Zhang Xianku, Zhao Chao. Ship Steering Control Based on Quantum Neural Network[J]. Complexity,2019,(05):1-10. https://doi.org/10.1155/2019/3821048.

[2] Joanna Szlapczynska, Rafal Szlapczynski. Preference-based evolutionary multi-objective optimization in ship weather routing[J]. Applied Soft Computing,2019,(84):58-64. https://doi.org/10.1016/j.asoc.2019.105742.

[3] Hong-Bo Wang, Xiao-Gang Li, Peng-Fei Li, Evgeny I. Veremey, Margarita V. Sotnikova. Application of Real-Coded Genetic Algorithm in Ship Weather Routing[J]. The Journal of Navigation,2018,71(04):989-1010. https://doi.org/10.1017/S0373463318000048.

[4] Lijia Chen, Liwen Huang, Mei Cui. Ship multi-constrained optimal route design based on improved ant colony algorithm[J]. Journal of Shanghai Maritime University,2017,(04):11-15.

[5] Huanchuan Zhao. Design of dynamic route planning method based on live weather[D].Harbin Engineering University.

[6] Mingfeng Li, Shengzheng Wang, Zongxuan Xie. Multi-variable and multi-objective optimization modeling of ship routes under severe weather conditions[J]. China Navigation. Commun,2020,43(02):14-19+30.
[7] Pengfei Li. Research and simulation of multi-objective ship weather route optimization algorithm[D]. Jilin University.

[8] Lokukaluge P. Perera, C. Guedes Soares. Weather routing and safe ship handling in the future of shipping[J]. Ocean Engineering, 2017, (130): 684-695. https://doi.org/10.1016/j.oceaneng.2016.09.007.

[9] Yunsheng Fan, Yongsheng Zhao, Linlong Shi, Yue Zhang. Global path planning of unmanned surface craft based on electronic chart rasterization[J]. China Navigation, 2017, 40(01): 47-52+113.