The method of comprehensive performance optimization design for trimaran unmanned vehicle

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Abstract. The comprehensive performance optimization design of the trimaran unmanned vehicle can be summarized as a complex optimization design problem with multiple objective functions under multiple constraints. First, this paper uses the towing resistance test data of a certain ship model to establish a ship type and resistance database using the response surface fitting method. Then, a single total objective function is used in the form of power exponential product to normalize the objective functions of the trimaran unmanned craft's speed, maneuverability and seakeeping. Secondly, the constraint conditions are the upper and lower limits of the design variables, the penalty function is composed of multiple equality and inequality constraints involved, the fitness function is established, and a more complete comprehensive optimization mathematical model is constructed. Finally, the overall performance of the trimaran unmanned vehicle is optimized by genetic algorithm, particle swarm algorithm and two improved optimization algorithms. Discussed the pros and cons of each optimization algorithm and the sensitivity of the influence factor under the parallel strategy, compared and analyzed the calculation results of each optimization algorithm, selected the best optimization calculation plan, and obtained the best optimization calculation result, which is trimaran how to ensure the comprehensive and optimal navigation performance during the design of unmanned boats provides a practical way and method.

key words. USV; Performance optimization; GA; PSO; Improved algorithm; Penalty function

1. Introduction
Trimaran unmanned craft is a comprehensive unmanned system platform including motion control, ship design and other technical fields. It must not only achieve precise unmanned control but also have better navigation performance. Due to the many sailing performances of ships, and the interrelated effects between the performances, the optimization design of the comprehensive performance of the trimaran unmanned craft is a multi-objective function solution and optimization problem under multiple constraints [1].

For the processing of multi-constraint problems, the methods currently proposed by scholars at home and abroad include: penalty function method, feasibility rule, random ordering method, hybrid method, multi-objective optimization method, etc [2]. Among them, the penalty function method is simple and efficient, and has been widely used in solving various constraint problems. There are basically two ways to deal with multi-objective function problems: normalization processing and multi-objective optimization algorithms. The advantage of the former is that it can be solved by using mature intelligent evolutionary algorithms. Foreign countries have used intelligent evolutionary algorithms to solve ship optimization problems earlier [3]. For example, professor Rober wolf used a
In order to solve the problem of comprehensive performance optimization of the trimaran unmanned boat, this paper uses the penalty function method to deal with the multi-constraint problem in the optimization, and uses the normalization method to convert the multi-objective function problem into a single-objective problem. Then, the self-adapted optimization software containing a variety of intelligent evolutionary algorithms is used to solve the problem, so as to obtain the unmanned boat type with better comprehensive performance.

2. Mathematical model of comprehensive optimization

2.1. Ship type and resistance database
For the selection of the main hull, the round bilge type, which has better static water resistance than the deep V-type, has become the choice of most high-speed trimarans at present [5]. For the side body, adopt the hull form obtained from the main hull by scaling ratio of 3.5. According to the residual resistance coefficient map and the hydrostatic curve of the mother ship, the residual resistance coefficient, the main scale of the ship form and the ship form coefficient are fitted by using the response surface analysis method and polynomial function. For example, the expression of the square coefficient changing with the relative draft can be obtained by adopting the uncrossed quadratic form, as shown in Equation 1, \(C_B\) represents the square coefficient and \(T_b\) represents the standard draft.

\[
C_B = 0.971910412 - 1.035538995 \times T / T_b + 0.59292006 \times (T / T_b)^2
\]  

(1)

2.2. Total objective function
This paper establishes three optimized sub-objective functions for the speed, maneuverability and seakeeping of the trimaran unmanned craft using double propellers and single rudder. To meet the principle that the sub-objective function requires the direction of the superior and inferior to be consistent with the overall objective, a reasonable correction coefficient is assigned to the value of each sub-objective function, so that the range of each sub-objective function value is between 1-10. The optimization sub-objective function of rapidity is constructed by the navy coefficient as shown in Equation 2.

\[
f_1(x) = \frac{V^3 A'^{2/3}}{P_s} = \frac{V^3 A'^{2/3} \eta_l \eta_h \eta_s}{P_b} = \frac{V^3 A'^{2/3} \eta_l \eta_h \eta_s}{R \times V \times 0.5144 \times 1.35961}
\]  

(2)

The dimensionless rotation index and stability criterion are combined in the form of the product of power exponent as the maneuverability objective function of the trimaran, as shown in Equation 3. \(\phi_1\) and \(\varphi_2\) respectively represent the weight of the ship's rotation and maneuverability.

\[
f_2(x) = K^{\phi_1} \times C^{\phi_2} \times \left[\frac{Y' N' - N' Y'}{Y' N' - N' (Y' - m)}\right]^{\eta_1} \times \left[Y' N' - N' (Y' - m)\right]^{\eta_2}
\]  

(3)

The Behrs ship seakeeping index is used as the objective function of the seakeeping of the trimaran, as shown in Equation 4.

\[
f_3(x) = R = 8.422 + 45.104C_{w1} + 10.078C_{w2} - 378.465(T / L) + 1.273(C / L) - 23.501C_{vpr} - 15.875C_{vp3}
\]  

(4)

The overall objective function is expressed as shown in Equation 5, \(a_1\), \(a_2\) and \(a_3\) respectively represent the weights of rapidity, maneuverability and seakeeping.

\[
U(x) = f_1(x)^{a_1} \times f_2(x)^{a_2} \times f_3(x)^{a_3}
\]  

(5)
2.3. Constraint condition
Static Floating Constraint as shown in Equation 6, \( A_M \) and \( A_S \) represent the displacement of the main hull and the sheet body respectively. Constraint of torque balance and thrust balance constraint as shown in Equation 7, 8.

\[
A = A_M + 2A_S = \rho g C_B (L_MB_M d_M + 2L_SB_S d_S) \tag{6}
\]

\[
\eta_k \eta_p \frac{P_k}{2\pi N} = K_0 \rho N^2 D_p^4 \tag{7}
\]

\[
R_i = 2K_1 \rho N^2 D_p^4 (1-t) \tag{8}
\]

Propeller shall meet cavitation requirements as shown in Equation 9. According to the ship's stability specification, the initial stability of positive flotation should be greater than 0.3 m, as shown in Equation 10.

\[
(1.3 + 0.3Z)T_e \times ((P_0 - P_0^2)D_p^2)^{-1} + K - (A_k / A_h) \leq 0 \tag{9}
\]

\[
GM > 0.3 \tag{10}
\]

2.4. Penalty function establishment
The penalty function, also known as the penalty function, is a function that can play a constraint. The inequality and equality constraint can be transformed into unconstrained problem by using the penalty function, and then the operation can be simplified. Taking the torque balance constraint established in this paper as an example, the torque balance constraint formula is shown in Equation 11. The penalty value of the established penalty function as shown in Equation 12, \( F_i \) is the penalty facto.

\[
\eta_k \eta_p \frac{P_k}{2\pi N} = K_0 \rho N^2 D_p^4 \tag{11}
\]

\[
b_i(x) = e^{-F_i \eta_k \eta_p \frac{P_k}{2\pi N} K_0 \rho N^2 D_p^4} \tag{12}
\]

The value of the total penalty function involved in this paper is shown in Equation 13, \( P_1(x) \) and \( P_2(x) \) respectively represent the total product of the penalty function values of all equality constraints and inequality constraints.

\[
P(x) = P_1(x) \times P_2(x) \tag{13}
\]

2.5. Establishment of fitness function
In order to improve the convergence speed of each optimization algorithm faster, the selection and establishment of fitness function is very important, which often affects whether the optimization algorithm can find the optimal solution. Therefore, in this paper, the total objective function \( U(x) \) is multiplied by the penalty function \( P(x) \) to establish the fitness function, as shown in Equation 14.

\[
A(x) = U(x) \times P(x) \tag{14}
\]

2.6. Design variable
According to the summary, a total of 23 design variables were selected in this paper, including: propeller diameter \( (D_p) \), propeller speed \( (N) \), propeller disk ratio \( (A_k / A_h) \), propeller pitch ratio \( (P_{DP}) \),
rudder area \((A_g)\), lateral spacing of side hull \((b)\), design speed \((V)\), ship design draft \((d)\), trimaran cut-off ratio \((C/L)\), displacement \((\Delta)\), wet area \((S)\), length \((L)\), breadth molded \((B)\) and so on.

3. **Computational analysis**

In this paper, a conventional slender trimaran unmanned vehicle with a displacement of 140 tons is taken as the object of discussion, and the comprehensive optimization calculation and analysis of its sailing performance are made. Before optimization calculation, reasonable upper and lower limits are set for each design variable, and reasonable weights are set according to the pros and cons of each performance: rapidity (2), seakeeping (0.5), maneuverability (1), reversibility (1.6), direct navigation stability (0.625).

3.1. **Optimization calculation of genetic algorithm**

The calculated based on an impact factor, other factors remain unchanged, the best set numerical solution of an impact factor in turn again after calculation, set other impact factors for each group of computing solutions are more than 3 times computation, and only keep the constraint conditions are calculated to reach more than 99% of the effective data. The discussion scope of genetic algebra is set as 2000-7000, and the population size of 200-700 is calculated and analyzed. The calculated results are shown in the figure 1 and 2. Figure 1 and 2 show that both genetic algebra and population size have an increasing relationship with the value of the total objective function. When the genetic algebra is 6000 generation and the population size is 400, the value of the total objective function basically does not change. Therefore, these two values are the best set values for subsequent calculations.

![Figure 1. Genetic algebraic optimization calculation results](image)

![Figure 2. Optimal population size calculation results](image)

The optimal setting values of evolution weight, genetic factor, mutation probability and crossover probability are determined respectively. The calculation results are shown in figure 3, 4, 5 and 6. Figure 3, 4, 5 and 6 show that the optimal setting values of evolutionary weight, genetic factor, mutation probability and crossover probability are respectively 0.7, 0.5, 0.6 and 0.4, which are all irregular except that the genetic factor and the total objective function value are basically increasing.

![Figure 3. Calculated results of different evolutionary weights](image)

![Figure 4. Calculated results of different genetic factors](image)
Under the above set calculation scheme, the program was re-calculated in another computer for 3-5 groups of effective calculation, and the best value was selected. Finally, the optimal calculation results of genetic algorithm were: fitness function values (90), the total objective function value (91.67), penalty function value (0.982).

3.2. Particle swarm optimization algorithm

The discussion range of the number of particle iterations was set as 2000-7000, and other impact factors remained unchanged for calculation. After solving the number of particle iterations, the population size of 200-700 was calculated and analyzed. The calculated results were shown in the figure 7 and 8. Figure 7 and 8 show the number of particle iterations or the population size are in an increasing relationship with the total objective function value. When the former is in 5000 generation and the latter is in 500 generation, the total objective function tends to be stable.

Therefore, these two values can be the best set values in subsequent calculations. Different fixed weights and maximum particle flight velocities are calculated and analyzed, the calculated results are shown in the figure 9 and 10. Figure 9 and 10 show the influence of fixed weight and maximum particle flight speed on the total objective function value is not regular, and the total objective function value reaches its maximum when the two set values are 0.6 and 0.17 respectively.

Same as genetic algorithm, the optimal calculation results of particle swarm optimization algorithm are finally obtained: fitness function values (94.40), the total objective function value (94.91), penalty function value (0.995).
3.3. Parallel strategy optimization calculation

The optimal particle swarm optimization algorithm was selected as the basic algorithm of the parallel algorithm. Before the calculation, the sensitivity analysis of each design variable was needed. After comprehensive consideration, $N$, $V$, and $b$ were selected from all the design variables for sensitivity variable analysis. According to the existing upper and lower limits of these three variables, the minimum, medium and maximum values are respectively taken for optimization calculation, and the calculation results are shown in the Table 1.

| Table 1. Analysis of calculation results of sensitive variables |
|---------------------------------|-----------------|-----------------|
| Variable name                  | The total objective function value | Maximum difference of total objective function values |
| $N$ (550 r/min)                | 93.79            |                 |
| $N$ (750 r/min)                | 78.60            | 47.81           |
| $N$ (950 r/min)                | 45.98            |                 |
| $V$ (12 kn)                    | 95.84            |                 |
| $V$ (15 kn)                    | 80.11            | 45.68           |
| $V$ (18 kn)                    | 50.16            |                 |
| $b$ (4.5 m)                    | 58.52            |                 |
| $b$ (6 m)                      | 71.31            | 34.37           |
| $b$ (7.5 m)                    | 92.89            |                 |

It can be seen from the above table that with the change of each sensitive variable, the value of the total objective function has a significant change. According to the magnitude of its change, the sensitivity relationship of each variable is as follows: $N > V > b$. In order to improve the efficiency of calculation, this paper only selects the first two as sensitive variables for subsequent studies. Parallel optimization calculation was carried out for the two variables of airspeed and rotational speed, and the calculation results were shown in the Table 2.

| Table 2. The results of parallel strategy calculation |
|---------------------------------|-----------------|-----------------|-----------------|
| Parallel manner                 | Fitness function values | The total objective function value | Penalty function value |
| Not parallel                    | 92.31            | 92.78            | 0.995           |
| The parallel one ($N$)          | 93.33            | 93.66            | 0.996           |
| The parallel two ($N$)          | 93.53            | 94.30            | 0.992           |
| The parallel one ($V$)          | 93.43            | 93.66            | 0.997           |
| The parallel two ($V$)          | 94.87            | 95.23            | 0.996           |
| The parallel one ($N + V$)      | 95.13            | 95.39            | 0.997           |
| The parallel two ($N + V$)      | 95.32            | 95.82            | 0.995           |

It can be seen from the above table that the results of non-parallel calculation are significantly lower than those of other groups using parallel strategy algorithm, which proves that the parallel strategy algorithm can improve and enhance the particle swarm optimization algorithm. In addition, it can be seen that with the increase of the number of parallel times or the increase of the number of parallel sensitive variables, the optimization calculation results will be improved.

3.4. Hybrid optimization algorithm optimization calculation

In this paper, the optimal particle swarm optimization algorithm is selected as the basic algorithm of the hybrid optimization algorithm, and the calculation results of multiple groups of hybrid algorithms are discussed in groups. The optimization calculation results of the hybrid optimization algorithm are shown in the Table 3.
Table 3. Calculation results of hybrid optimization algorithm

| Hierarchical way   | Fitness function values | The total objective function value | Penalty function value |
|-------------------|-------------------------|------------------------------------|------------------------|
| PSO               | 93.29                   | 94.07                              | 0.992                  |
| PSO+PSO           | 95.39                   | 95.86                              | 0.995                  |
| PSO+GA            | 94.55                   | 94.76                              | 0.998                  |

It can be seen from the above table that the calculation result of the hybrid optimization algorithm is better than the conventional optimization algorithm, and the hybrid optimization algorithm of particle swarm optimization and particle swarm optimization has the best calculation result. It can be seen that the hybrid optimization algorithm can improve and enhance the particle swarm optimization algorithm.

3.5. Comparison of calculation results of each optimization algorithm

In order to obtain the optimal optimization algorithm and optimal optimization results for the comprehensive performance optimization of the three-maroon unmanned vehicle, the optimal calculation results of each algorithm were summarized and compared, as shown in the Table 4.

Table 4. Comparison of optimal calculation results of each algorithm

| The algorithm name     | Fitness function values | The total objective function value | Penalty function value |
|------------------------|-------------------------|------------------------------------|------------------------|
| GA                     | 90.00                   | 91.67                              | 0.982                  |
| PSO                    | 94.40                   | 94.91                              | 0.995                  |
| Parallel strategy      | 95.32                   | 95.82                              | 0.995                  |
| Hybrid optimization    | 95.13                   | 95.80                              | 0.993                  |

It can be seen from the above table that the optimization result of particle swarm optimization algorithm is the best for the two basic algorithms. For the two improved algorithms, the parallel strategy algorithm is the best. In summary, the best optimization algorithm for this paper is the parallel strategy algorithm.

3.6. Optimum optimization result

According to the optimal calculation result file, some design variables and ship-related design parameters of the three-maroon unmanned vehicle under the optimization of comprehensive performance are obtained. The specific values are as follows: $D_r$ (0.906 m), $\frac{A_e}{A_b}$ (0.506), $P_{top}$ (0.828), $A_b$ (1.432 m$^2$), $b$ (7.499 m), $V$ (12.01 Kn), $d$ (1.489 m), $L$ (43.12 m), $B$ (16.08 m) and so on.

4. Conclusion

Based on the towing resistance test data of a certain ship model, this paper uses response surface fitting to establish the ship type and resistance database. Establishes the sub-objective functions of rapidity, seakeeping and maneuverability, and uses the power exponent product to divide the three sub-objective functions. The objective function is combined into a single total objective function, reasonable constraints are selected, penalty function and fitness function are established, and a relatively complete comprehensive optimization mathematical model is constructed. The optimization calculation software including particle swarm algorithm and genetic algorithm was adapted. Two optimization algorithms and two improved optimization algorithms were calculated and analyzed for a 140-ton conventional slender trimaran unmanned boat. The parallel strategy is determined to be the most suitable optimization algorithm for this paper, and the best optimized calculation result is obtained, which verifies the feasibility of this algorithm, and provides a reasonable and feasible method for solving the multi-constraint and multi-objective problem in ship optimization design.
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