Uncertainty optimisation design of USV based on the Six Sigma Method

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Abstract: In order to improve the sailing performance of unmanned surface vehicles (USVs), maximise the value of their sailing performance function, and minimise disturbances caused by uncertainty factors, this study introduces a 6σ theory of quantitative descriptions of uncertainty levels into the USV sailing performance optimisation model. It uses the Multi-Island Genetic Algorithm to optimise the certainty of the design variables and plot the optimal curve and the Monte Carlo simulation to analyse the sensitivity of the total objective function. The Mean on target and the Minimise variation function are used for the 6σ optimisation. The uncertainty factors are the floating range of the design variables. Results indicate that the design variables affect the value of the total objective function. A comparative analysis of the certainty optimisation results and the results obtained by the 6σ uncertainty optimisation shows that although the value of the latter's total objective function decreases, its reliability is greatly improved. The 6σ optimisation method, therefore, can be applied to improve the sailing performance design of USVs and obtain reasonable and highly reliable results, which can ensure that the constraint condition has a high degree of immunity to the uncertainty of actual situations.

Key words: USV; sailing performance; uncertainty; Monte Carlo; 6σ optimization

1. Introduction

In the design of ship schemes, the conventional method is based on the certainty principle to achieve the optimal performance of the ship. However, in the real travelling process, disturbance of certain parameters is unavoidable, which reflects the uncertainty of environment. Thus, considering only the certainty factors can cause discrepancies in the design results.

Researches in the field of naval architecture and ocean engineering design has focused on this uncertainty: Diez [1] et al. considered operational and environmental factors as uncertainty factors and used robust optimisation methods in the ship design phase to determine the minimum of mean and variance of the transportation cost. Shari et al. [2] introduced uncertainty and its optimization methods in multidiscipline ship design, and proved its fine feasibility. Hou Yuanhang[3] et al. created a hull lines optimisation design to minimise the Energy Efficiency Design Index (EEDI) based on a random and cognitive analysis of the uncertainty optimisation method. Li Dongqin [4] et al., considering ship speed and draught as uncertainty factors, created a multidisciplinary Robust Design Optimisation of offshore supply vessels using a new multidimensional polynomial chaos approach. Wei Xiao [5] applied Robust Design Optimisation and Reliability-Based Design Optimisation to engineering optimisation schemes of bulk cargo ships and found that the failure probability of the optimisation target value is decreased and the ship's robustness is improved. All these studies have proved the effectiveness of the uncertainty method in ship optimisation design. Therefore, design schemes are more reliable when both certainty and uncertainty factors are taken into consideration.

Furthermore, it reveals that many analytical methods in uncertain optimization design are worth further study. Zhuo Siyu [6]et al. constructed a RBF neural network approximation model, and used ASA, MIGA, PSO algorithm to reduce the weight of ultimate strength of the oil tanker, the results indicate that the hull girder failure probability would increase the least under the PSO-RBF algorithm. Parunov [7]et al. proposed a rational statistical model to describe the uncertainty of the extreme vertical wave bending moment for hull reliability analysis. This method was used to assess ultimate longitudinal strength for floating production, storage and offloading ship, a modern double-hull oil tanker and an old single-hull oil tanker. It was shown that reliability of double-hull oil tankers higher than single-hull oil tankers. Tang Yang [8] et al. used small water-plane area twin-hull USV as the research object, select the speedability, manoeuvrability, seakeeping and solar system objective function, determine the design variables and constraints range, create mathematical model optimization and get optimal ship form parameters. Yang Songlin [9] et al. created a mathematical model of single unmanned boat optimization, developed a navigation performance optimization program based on the optimization algorithm, and get the optimal navigation speed and optimal displacement through a large number of calculations. As can be seen, designers need to improve the immunity of the ship to uncertainty factors in the overall design stage, not only considering the reliability of the ship's strength, but also taking account the robustness of the ship's performance, and the uncertainty optimisation method can make the ship design better correspond to real conditions.

Although the aforementioned research has demonstrated the superiority of the uncertainty optimisation method for ship design, it has lacked a quantitative standard for measuring the quality of the scheme. The 6σ quality design method uses σ as the quality criterion with a highly automated solution. It can process continuous and discrete variables at the same time and employ various methods to sample and evaluate the robustness to make the scheme gradually approach a high σ level. Therefore, improving the design variables for the σ level of the constraint can greatly improve the ship's robustness.

The 6σ optimisation method is based on a statistical approach. In the overall design stage, the probability model is introduced to analyse the effect of uncertainty factors on the product, thus improving the robustness of the optimisation result. Cheng Yanxue [10] et al. replaced ANSYS Inc.'s simulation model with the RBF model to design the 6σ quality of the pressurized cylindrical shells of underwater vehicles and reduce the number of iterations in condition of the premise of ensuring accuracy. Peng Shandong [11] et al. proposed an inverse calculation method of correction parameters for machine settings based on the design for 6σ, and established an optimization model. The results show that the tooth contact performance obtained by the 6σ design method make the maximum and minimum values reduced under the condition of meeting the requirement, which proves the reliability and practicability of the method. It can be seen from the above literature that the product can be optimized by the Six Sigma method to reach a high σ level. If this method is used in the preliminary design of ship, the reliability of the scheme can be further improved.

This study combined the 6σ optimisation method with the overall design of an unmanned surface vehicle (USV) to obtain a more reliable, higher-quality level of response optimisation results. USV has a high degree of intelligence and requires high robustness. The 6σ method uses σ as the quality level, fully considering the constraints and the uncertainty of the design variables, and this method can significantly improve the robustness of ship design schemes. A small USV [12] was used as the research object, and a mathematical model was created to perform certainty optimisation. The Monte Carlo method was used for a sensitivity analysis to determine the effect of design variables on the total objective function. A reliability analysis was conducted to determine the reliability and σ level of the constraint conditions. Finally, the 6σ optimisation results were compared with those of certainty optimisation to assess the rationality of each scheme.

2. USV sailing performance framework

Any ship design department naturally aims to design vessels with excellent sailing performance [13]. The main factors measured to determine a ship's performance include stability, buoyancy, rapidity, seakeeping, and manoeuvrability. This study built a mathematical model based on 17 design variables and used the speed and resistance, seakeeping, and manoeuvrability indicators as the main optimisation objects, and buoyancy and stability as the main constraints. Set reasonable upper and lower limits for design variables for certainty optimisation. This study used Monte Carlo Simulation to make a contribution plot, and found out several variables with greater influence on total objective function. Analysis of reliability used to analyse the probability that the constraint condition meets the set threshold value, the constraints that do not reach the required σ level need to be optimised by 6σ method. Fig. 1 shows the proposed sailing performance optimisation framework.

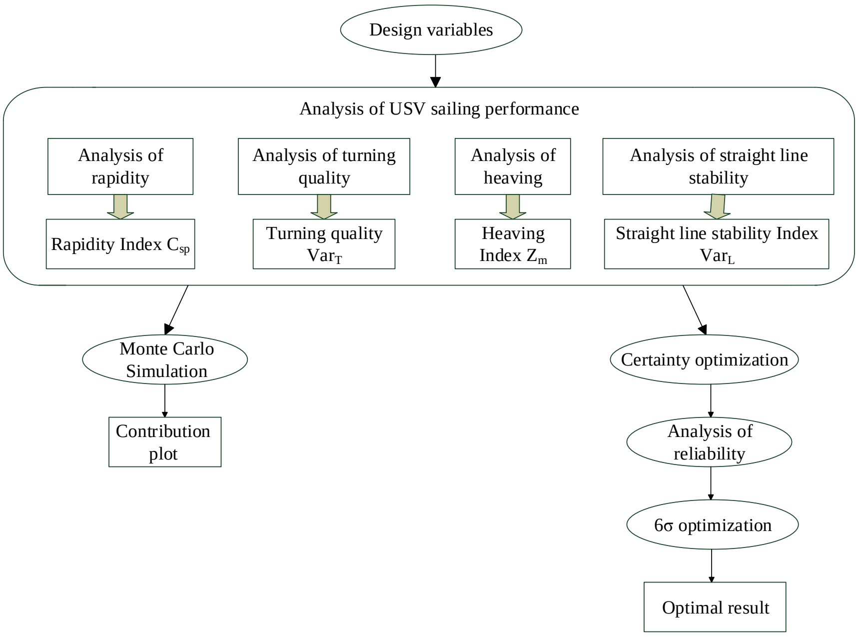

Fig. 1. Framework of USV sailing performance based design

3. Mathematical model of USV sailing performance

3.1. Design variables

The USV sailing performance was assessed mainly taking into consideration three aspects: seakeeping, manoeuvrability, and speed and resistance. A total of 17 design variables of the total objective function were included, and all of them were uncertainty variables.

The vector composed of the 17 design variables is as follows:

$$X = \{L,B,T,C_b,C_m,C_w,I_e,At/Am,Ae/Ao,Z_g,N,D_p,P/D_p,V_s,\alpha,\beta,L_{cb}\} \quad (1)$$

Where: L is the ship's length, B is the ship's width, T is draught, C_b is the block coefficient, C_m is the midship section coefficient, C_w is the design waterline coefficient, I_e is the semi-flooding angle, At/Am is the sectional wetted area, Ae/Ao is the blade area ratio of the screw, Z_g is the height of the centre of gravity from the baseline, N is the propeller's rotation speed, D_p is the propeller's diameter, P/D_p is the pitch ratio, V_s is the ship's speed, α is the trim angle, β is the inclination angle, and L_{cb} is the longitudinal centre of buoyancy.

3.2. Performance target functions

3.2.1. Speedability Index

To comprehensively consider the resistance and propulsion performance, C_{sp} was used as the objective function:

$$Csp = \Delta Vs / \left(R_t / \eta_0 \eta_H \eta_R \eta_S \right) \tag{2}$$

where: Δ is displacement, V_s is the ship's speed, R_t is hull resistance, η_0 is the open water propeller efficiency, η_H is hull efficiency, η_R is the relative rotation efficiency, and η_S is the shafting's transmission efficiency.

The calculation formula of the open water propeller efficiency η_0 is the following:

$$\eta_0 = \frac{K_T}{K_Q} \frac{V_S (1-\omega)}{ND} \tag{3}$$

where: K_T is the propeller thrust coefficient, K_Q is the propeller torque coefficient, V_S is the design speed, ω is the wake fraction, N is the propeller's rotation speed, and D is the propeller's diameter.

The empirical formula used to calculate the hull resistance is the following:

$$R_t = 1/2 * S * \rho * V_S^{\,2} * \left(C_R + C_f + \Delta C_f \right) \tag{4}$$

where: S is the wetted surface, ρ is seawater density, V_s is the design speed of the ship, C_R is the residual resistance coefficient, the formula refers to Jin's regression formula [14], C_f is the frictional resistance coefficient, and ΔC_f is its correction value.

3.2.2. Manoeuvrability index

The straight line stability criterion Var_L and the diameter of relative reversibility Var_T were used to represent the manoeuvrability index.

The calculation formula of Var_L is the following:

$$Var_L = N_v^{'} \left(Y_r^{'} - m' \right) - Y_v^{'} N_r^{'} \tag{5}$$

where: $Y_v^{'}$, $Y_r^{'}$, $N_v^{'}$, $N_r^{'}$ is the ship's dimensionless hydrodynamic and moment coefficient and $m^{'}$ is the dimensionless hull mass, whose formula is:

$$m^{'} = m / \left(\frac{1}{2} \rho L^3 \right) \tag{6}$$

According to the linear derivative regression formula collated by Clarke [15],

$$\begin{aligned}
Y_v^{'} &= -[1 + 0.40 C_b B / T] * \pi \left(T / L \right)^2 \\
Y_r^{'} &= -[-1/2 + 2.2 B / T - 0.080 B / T] * \pi \left(T / L \right)^2 \\
N_v^{'} &= -[1/2 + 2.40 T / L] * \pi \left(T / L \right) \\
N_r^{'} &= -[1/4 + 0.039 B / T - 0.56 B / L] * \pi \left(T / L \right)^2
\end{aligned} \tag{7}$$

The calculation formula of Var_T is the following:

$$Var_T = D / L \tag{8}$$

where: L is the ship's length and D is the constant turning diameter, which can be obtained from the Bus Juning formula:

$$D = L_s^{\,2} d / 10 A_R \tag{9}$$

where: L_s is the length of the waterline, d is draught, and A_R is the rudder's wetted surface area, whose calculation formula is:

$$A_R = \mu L_S d \tag{10}$$

where: μ is the rudder area coefficient.

3.2.3. Seakeeping index

The seakeeping index was based on Fridsma's study, which assessed the performance of prismatic planing boats in irregular waves, and analysed the experimental data to produce a calculation graph. Interpolation based on these graphs to calculate the amplitude of heaving. The estimation formula is as follows:

$$Z_m = 0.25 * F * G * B \tag{11}$$

where: F is the trim angle correction function and G is the inclination angle correction function. After the correction, the heave value can be calculated using the estimation formula.

3.3. Constraints

The study included equality and inequality constraints, which are stated as following.

3.3.1. Equality constraints

(1) In order to ensure the basic floatability, floating constraint is:

$$\Delta - LBTC_B = 0 \tag{12}$$

(2) For the equality of propeller thrust and resistance of the ship on voyage, the constraint formula is as follows:

$$N_P K_T \rho N^2 D_P{}^4 (1-t) - R_t = 0 \tag{13}$$

where: N_P is the number of propeller shafts, K_T is the propeller thrust coefficient, ρ is seawater density, N is the propeller's rotation speed, t is the thrust deduction fraction, and R_t is resistance.

3.3.2. Inequality constraints

(1) The inequality constraint of height of initial stability GM should satisfy is:

$$GM > 0.7 \tag{14}$$

where, GM can be calculated using the formula below:

$$GM = BM + BK - Z_g \tag{15}$$

where: BM is the transverse metacentre radius and BK is the height of the centre of buoyancy. The calculation formula is as follows:

$$BM = \frac{nB^2}{C_B T}$$

$$BK = C_{WP} T / \left(C_{WP} + C_B \right) \tag{16}$$

where: n is the function of the design waterline coefficient [16].

(2) The rolling period T_ϕ should satisfy the constraint below:

$$T_\phi = T_\phi(x) > 2.0s \tag{17}$$

The calculation formula of T_ϕ is as follows:

$$T_\phi(x) = 0.58\sqrt{\frac{B^2 + 4Z_g{}^2}{GM}} \tag{18}$$

3.4. Total objective function

The total objective function of USV comprises four sub-objective functions. Because of their equal importance, equal weight was used. In the project, it can be appropriately weighted as needed. Because of the order of the sub-objective function is different, this paper uses the multiplication of the sub-objective function to compose the total objective function. This can reduce the gap between the sub-objective functions and make the value obtained by the total objective function more reasonable. The product form can be estimated as follows:

$$F(X) = Csp * VarL * VarT * Zm \tag{19}$$

4. Certainty optimisation

4.1. Certainty optimisation of a single target

The usual optimisation method for the overall design of the ship is certainty optimisation. Before optimisation, the upper and lower limits of the design variables and the initial plan are first determined, as shown in Table 1:

Table 1. Ranges of design variables and initial plans

Design variable	Initial value	Lower limit	Upper limit
L (m)	14.15	13.9	14.3
B (m)	3.35	3.2	3.5
T (m)	0.90	0.86	0.93
C_b	0.415	0.40	0.43
L_{cb} (%)	-1.2	-25.0	0.0
D_p (m)	0.575	0.55	0.60
Ae/Ao	0.775	0.65	0.90
P/D_p	0.95	0.70	1.20
C_m	0.875	0.86	0.89
V_s (Kn)	19	18	21
Ie (°)	6	4	12
α (°)	5	3	7
β (°)	20	10	30
C_{wp}	0.625	0.60	0.65
N (r/min)	1325	1300	1400
At/Am	0.09	0.00	0.18
Z_g (m)	0.81	0.56	1.03

The objective function of this paper involves many constraints, and the optimisation problem is complex. So the certainty optimisation algorithm used in this study is the Multi-Island Genetic Algorithm. Multi-island genetic algorithm has strong global search ability and it has good performance in multi-peak search ability, in addition, it requires less calculation time. Inspired by the 'survival of the fittest' from the field of evolutionary biology, imitating the genetic breeding mechanism in the evolution of organisms, the self-individual coding in the solution space of the optimisation problem and then the coded individual genetic populations were performed iteratively to find the optimal solution, setting the subgroup size to 10, the total evolution algebra to 50, and the number of islands to 20. The certainty optimisation results obtained after 10,000 calculations are shown in Table 2.

Table 2. Results of certainty optimisation

Design variables	L	B	T	C_b	C_m	C_w	Ae/Ao	At/Am	α
Optimal value	14.077	3.4969	0.91398	0.41474	0.862	0.62159	0.67142	0.16456	6.9305
Design variables	β	N	V_s	Ie	P/D_p	D_p	L_{cb}	Z_g	
Optimal value	10.062	1308.9	20.526	4.1845	0.70619	0.55023	-0.7541	0.89375	

The optimisation curve of the total objective function was obtained by applying the Multi-Island Genetic Algorithm 10,000 times. As shown in Fig. 2, the optimal result was yielded by the 9,861th calculation, represented by a red rectangle, with a value of 0.05581.

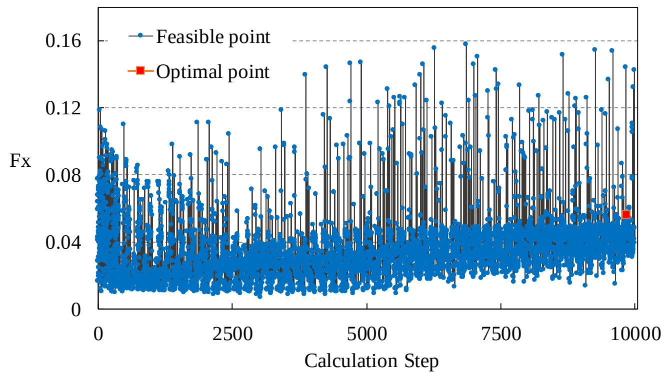

Fig. 2. Optimisation curve of the total objective function

4.2. Sensitivity analysis

The method's first step obtained the optimal solution of the 17 design variables based on the constraints. These results were subsequently imported into the Monte Carlo simulation for a sensitivity analysis. The Monte Carlo simulation is a numerical calculation method guided by probability and statistics theory. This method has been confirmed by numerous experiments, and its results are highly reliable. The probability density function selected for this study is a normal distribution function. The optimal value obtained in the previous step was taken as the mean value of the normal distribution. The Descriptive Sampling method was used to sample 10,000 times to determine the effect of the design variable on the total objective function. The result is shown in Fig. 3.

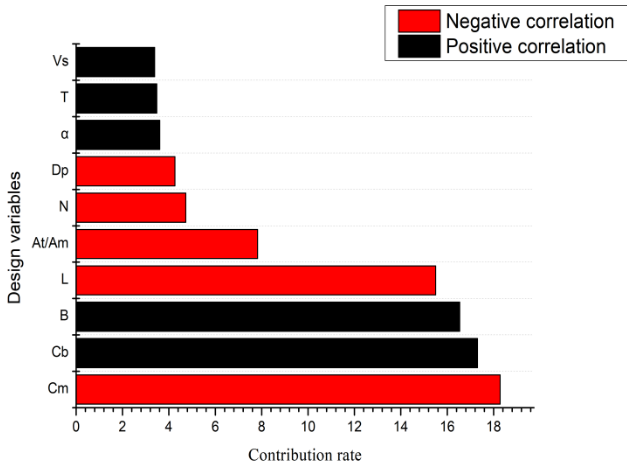

Fig. 3. Sensitivity analysis

The red bars indicate that the design variable in question has a negative correlation with the total objective function, while the black bars indicate a positive correlation. The specific sensitivity values are presented in Table 3.

Table 3. Partial sensitivity value

Design variable	C_m	C_b	B	L	At/Am	N	D_p	α	T
Sensitivity (%)	-18.28	17.31	16.54	-15.50	-7.82	-4.73	-4.26	3.60	3.47

Table 3 shows that the variation of L, B, C_b, and C_m can cause large fluctuations in the value of the total objective function. Consequently, the changes in these variables should be taken into consideration in the ship design process. C_b and C_m mainly affect the change in the value of the residual resistance coefficient, which affects the change of the rapidity index: C_b causes positive changes, while C_m causes negative changes. L and B affect all three indicators: L causes negative changes, and B causes positive changes.

5. 6σ optimisation

5.1. Reliability analysis

The purpose of the reliability analysis was to evaluate the quality level of the scheme. The basic idea is to randomly disturb the design points, generate a set of sample points around its mean value, and then estimate the reliability and σ level of the output response index at a single design point by performing a statistical analysis. In this study, the design variables were the uncertainty factors, the standard deviation was 0.01 times the mean value, and the reliability analysis used the mean value method of one of the representative algorithms. The method uses the failure function $g(X)$ as the average value μ_x of the Taylor series expansion, and P_f represents the failure rate. The reliability index is defined as the shortest distance from the origin of the standard normal space to a point on the failure surface. The specific principle is shown in Fig. 4.

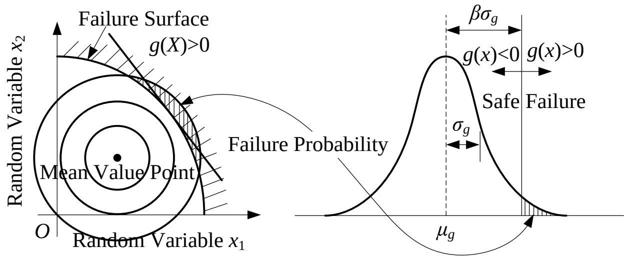

Fig. 4. Schematic diagram of the Mean Value method

In terms of the number of simulation program executions and function calculations, the Mean Value method is the most efficient method, requiring only one failure function and sensitivity evaluation. The first-order and second-order reliability methods are more effective in dealing with nonlinear functions. The second-order reliability method is better than the first-order reliability method in approximating the curvature of the failure surface.

The value of the optimal solution obtained by certainty optimisation of a single target is usually close to the constraint boundary, and the generation of random disturbance may cause it to deviate from the constraint condition, which constitutes a major problem in the actual ship-building process. Therefore, improving the quality level of the design variables and responses can increase the reliability of the USV.

Table 4 shows the results of the reliability analysis. Set the range of equality of thrust and resistance from -2 to 2, lower bound of floating constraint, height of initial stability and rolling period is 0. Results show that the floating constraint reaches the 8σ level, while the other response levels are relatively lower, with values close to the constraint boundary, which is unreasonable. Since the numerical differences of thrust and resistance are very small, the reliability of the thrust and resistance equality is only 78.4%. To improve the σ level and reliability of the response, 6σ optimisation should be introduced, as it can provide a higher degree of immunity to the uncertainty factors under the premise that the scheme is reasonable.

Table 4. Results of the reliability analysis

Output of response	Quality level/σ	Mean value	Standard deviation	Reliability (%)
Equality of thrust and resistance	1.237	0.738	1.428	78.4
Floating constraint	8	0.466	0.009	100
Height of initial stability	2.322	0.076	0.037	97.977
Rolling period	3.717	6.281	1.775	99.98

5.2. 6σ optimisation

The goal of 6σ optimisation is to minimise the response fluctuation caused by uncertainty factors, improve the quality level of the output response, and then improve the reliability of the total objective function. The mathematical model of 6σ optimisation [17] is described as follows:

$$\begin{cases} \&Minimize\ F\left(\mu_y(X),\sigma_y(X)\right) \\ \&subject\ to\ G_j\left(\mu_y(X),\sigma_y(X)\right)\le 0 \\ \&X_{LSL}+\Delta X\le X\le X_{USL}-\Delta X \end{cases} \tag{20}$$

Where: X is the aggregate of random design variables, y is the aggregate of the performance parameters, F is the objective function of DFSS, G is the constraint function of DFSS, which is defined by the mean value μ_y of Y and the standard deviation σ_y, $\pm\Delta X$ is the fluctuation interval of the random variable X, and X_{LSL} and X_{USL} are the upper and lower limit of the design variables, respectively.

The objective function can be divided into two parts; the formula is as follows:

$$F=\sum_{i=1}^{l}\left[\frac{\omega_{1_i}}{S_{1_i}}\left(\mu_{Y_i}-M_i\right)^2+\frac{\omega_{2_i}}{S_{2_i}}\sigma_{Y_i}{}^2\right] \tag{21}$$

where: The first addend inside the brackets indicates that the average performance goal has been reached and the second addend indicates that minimisation of the performance fluctuations has been achieved, i indicates the subscript of each component of *Y*, μ_y indicates the mean value of *Y*, σ_y indicates the standard deviation of *Y*, M indicates the average performance target of expectation reaching, ω_1 and ω_2 are the weight coefficients of the mean value and variance of *Y*, respectively, and S_1 and S_2 are the normalisation coefficients of the mean value and variance of *Y*, respectively.

The 6σ optimisation results were then compared with those of certainty optimisation, as shown in Table 5.

Table 5. Comparison between six sigma and certainty optimisation results

Variables	Initial	Certainty optimisation			6σ optimisation	
		Results		6σ analysis	Results	Quality level
Equation of thrust and resistance	17.8372	μ	0.7393	σ level = 1.237 Reliability = 78.4%	0.1132	σ level = 2.7596 Reliability = 99.42%
		σ	0.0074		1.4451	
Floating constraint	0.4426	μ	0.4665	σ level = 8 Reliability = 100%	0.4405	σ level = 8 Reliability = 100%
		σ	0.0047		0.0088	
Height of initial stability	0.0862	μ	0.0756	σ level = 2.322 Reliability = 97.98%	0.2136	σ level = 6 Reliability = 100%
		σ	0.0008		0.0363	
Rolling period	5.3501	μ	6.2835	σ level = 3.717 Reliability = 99.98%	2.6593	σ level = 7.5 Reliability = 100%
		σ	0.0628		0.3560	
C_{sp}	0.4569	0.2917			0.2266	
Var_T	10	10			10	
Z_m	1.01	1.6344			1.4617	
Var_L	0.0102	0.0117			0.0108	
Total objective function Fx	0.0473	μ	0.0558		0.0358	
		σ	0.0006		0.0042	

The result of 6σ optimisation is expressed as a vector:
X={13.997,3.41,0.89018,0.41474,0.8746,0.62659,5.9445,0.16816,0.77642,0.73375,1323.9,0.53223,0.74612,19.506,6.6105,10.862,-0.8241}

When the other constraints reach the 6σ level, the equality of thrust and resistance still remains at a relatively low σ level due to strict threshold settings, so the upper and lower limits of the constraint are appropriately broadened and reach the 2.8σ level. The design scheme is not subject to the same high σ level as product. A reliability of 99.4% is acceptable for the designer. The main goal of this study was to determine a maximum total objective function value. Table 5 shows that, though the total objective function value obtained by certainty optimisation is larger, the quality level is very low. The objective function value obtained by 6σ optimisation, on the other hand, is lower but more reliable. For designers, high reliability values are more credible, while less reliable ones involve greater risks.

6. Conclusion

This study applied the 6σ optimisation theory to the overall design and navigation performance optimisation of USVs. The Multi-Island Genetic Algorithm was used in certainty optimisation to the obtain the optimal results and draw the optimisation curve. The Monte Carlo simulation was used to analyse the sensitivity of the total objective function. The results were then compared with the 6σ optimisation results. The conclusions drawn are as follows:

(1) The constraint results obtained from certainty optimisation are close to the boundary, and the reliability is relatively low. The interference of uncertainty factors tends to cause the constraints to cross the boundary.

(2) L, C_m, B, and C_b are more sensitive to the total objective function, which designers should consider a priority. L and C_m are negatively correlated, while B and C_b are positively correlated.

(3) A reliability analysis using the Mean Value method shows that only the floating constraint reaches a high σ level, while the σ levels of other constraints remain low. In contrast, after 6σ optimisation, all constraint conditions reach a high σ level.

(4) Regarding the value of the total objective function, the result of 6σ optimisation is 0.02 less than that of certainty optimisation, but the σ level and reliability are high, and the immunity to uncertainty factors is strong.

(5) This study considered design variables as uncertainty factors. Future studies could analyse uncertainty factors obtained from external environmental conditions and change the coefficient of variation of the standard deviation to the mean.

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