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Abstract. The shape of blended-wing-body underwater glider (BWBUG) is an important factor in determining the hydrodynamic efficiency. In order to reduce the needed computation time and efforts during the search of the optimum shape, a new surrogate-based shape optimization framework is proposed to solve the complicated BWBUG shape design optimization problem in this paper. During the search, seven baseline airfoils are used to build the parametric geometric model of the BWBUG, with the planar surface being fixed. Moreover, a newly proposed ensemble of surrogates based global optimization algorithm using a hierarchical design space reduction method (ESGO-HSR) is employed to optimize each baseline airfoil. Then, the optimum shape of the BWBUG can be determined and rebuilt based on all baseline airfoils that are successful optimized. As the optimization target, the maximum lift to drag ratio of the initial design is increased by 13.72% under the given operating conditions. The results demonstrate that the presented surrogate-based shape optimization framework is efficient and capable in identifying the optimum shape of the BWBUG.

1. Introduction

As a specially-designed flying-wing structure underwater glider, the blended-wing-body underwater glider has the superior hydrodynamic performances compared with the classic cylindrical configurations glider. It’s composed of distinct and separate wing structures, and the body is blended and smoothed into the wings [1]. The advantage of this blended-wing-body configuration lies in higher lift to drag ratio and lower wetted area to volume ratio.

The growth of the BWBUG application has increased the significance of optimum shape of the BWBUG. However, it generally involves a larger number of computationally expensive black-box function evaluations to identify the optimal solution compared with the conventional cylindrical AUGs. The hydrodynamic shape optimization is rarely applied in the context of the BWBUG design since the existing optimization methodologies and design tools are not sufficiently fast to be used within a specific optimization target. To relieve the computational burden, surrogate models are regularly used to speed up the search process [2]. Sun et al. use the kriging-based genetic algorithm, called efficient global optimization (EGO) to deal with the hydrodynamic shape optimization of the BWBUG for achieving higher maximum lift to drag ratio [1]. Wang et al. obtain the maximum lift to drag ratio and minimum moment of the BWBUG by using the Gaussian kernel function driven multi-objective optimization method [3]. Sun et al. establish an energy consumption model for a given BWBUG and
optimize its shape with a combined computational fluid dynamics (CFD) and EGO method [4]. Zhang et al. introduce a novel optimization approach to find the optimal layout of landing gears for a BWBUG based on which the comprehensive performance of the underwater landing platform is significantly improved [5].

In the authors’ previous study [6], a novel ensemble of surrogates based global optimization algorithm using a hierarchical design space reduction method is presented to improve the accuracy, efficiency and robustness for dealing with the complicated engineering design optimization problems. The ESGO-HSR algorithm is used to solve the computation-intensive BWBUG shape optimization problem in this work. It’s noted that the 3D BWBUG shape can be considered as a distribution of airfoils across the wing span [1]. That is, the optimum shape of the BWBUG can be obtained through many key section airfoils which are successful optimized. This simplification is beneficial to efficient determination of acceptable approximate solutions as the complex shape of the BWBUG may cause difficulties during optimization. A section parameterization method (SPM) based on the class function/shape function transformation method (CST) is used to parameterize the section airfoils in this study [7, 8]. Then, the ESGO-HSR algorithm is used to optimize the baseline airfoils of the BWBUG according to the optimization target with the maximum lift to drag ratio. Afterwards, the optimum shape of the BWBUG is built based on the optimal baseline airfoils obtained. The open code CFD packages XFOIL is used to simulate the flow around the designed section airfoils of the BWBUG during the search. XFOIL can not only provide the accurate prediction of the flow around the airfoils, but also strike a good balance between computational cost and convergence stability [9, 10]. At last, the hydrodynamic performance of the optimal BWBUG is calculated and analysed to show the accuracy, efficiency and validity of the proposed surrogate-based shape optimization framework.

2. Geometry configuration

The basic design concept of the BWBUG is considered that relates to the development of a hydrodynamics superior vehicle which can be easily launched, operated and recovered underwater without any special handling equipment. An axisymmetric body which is blended and smoothed into the wings is considered in this study, as shown in figure 1.

Figure 1. Initial BWBUG shape.

The BWBUG shape is built by Computer Aided Design (CAD) software Unigraphics NX (UG) based on seven typical and symmetric NACA 00XX series airfoils named XF1 ~ XF7 with the chord lengths of \( c_1 \sim c_7 \). Figure 2 shows an illustration of the parameterization of the hull geometry, including the horizontal distances between seven airfoils and the origin \( l_1 \sim l_7 \), and the vertical distances between the leading edges of seven airfoils and the origin \( d_1 \sim d_7 \). The leading edge of XF1 is selected as the origin in this work. The planar surface of the BWBUG is fixed and determined by fourteen control points, i.e. leading and trailing edges of seven baseline airfoils using UG software. Moreover, the baseline airfoils are also employed to determine the thickness of any section of the airfoil by means of UG. That is, the BWBUG shape can be obtained once the geometry configuration of all baseline airfoils is determined. The BWBUG shape shown in figure 1 is taken as an initial design to compare
with optimal solutions in this paper, which is characterized with a length of \( L = 1 \) m and a width of \( D = 0.35 \) m. Its design parameters are listed in Table 1.

To parameterize the BWBUG, seven control sections i.e., baseline airfoils are used to determine its hydrodynamic shape. A section parameterization method presented is used to parameterize the baseline airfoils [7, 8]. Details of the problem formulation on the BWBUG shape optimization are discussed in the next section.

### Figure 2. Parameterization of the hull geometry.

### Table 1. Parameters of the BWBUG.

| Airfoils | XF₁ | XF₂ | XF₃ | XF₄ | XF₅ | XF₆ | XF₇ |
|----------|-----|-----|-----|-----|-----|-----|-----|
| NACA Series | 0022 | 0017 | 0008 | 0008 | 0008 | 0008 | 0008 |
| Chord length \( c \) (mm) | 350 | 310 | 235 | 165 | 130 | 88 | 30 |
| Horizontal distances \( l \) (mm) | 0 | 50 | 90 | 150 | 190 | 275 | 500 |
| Vertical distances \( d \) (mm) | 0 | 20 | 55 | 95 | 120 | 175 | 320 |

### 3. Problem formulation

The objective is to maximize the lift to drag ratio of each baseline airfoil at the gliding conditions of the velocity \( v = 1 \) m/s, the angle of attack \( AOA = 7° \) with the constraints on the maximum thickness and cross sectional area of the baseline airfoils. For this case, seven baseline airfoils are parameterized using the section parameterization method of 4th-order, resulting in 5 design variables for each symmetric section airfoil and 35 in total.

The formulation of the airfoil shape optimization problem can be defined as

\[
\begin{align*}
\min \quad & f (X) = -C_L / C_D \\
\text{s.t.} \quad & g_1 (X) = t_{ini} - t_{opt} \leq 0 \\
& g_2 (X) = s_{ini} - s_{opt} \leq 0 \\
& x_i^l < x_i < x_i^u, \quad i = 1, 2, ..., 5
\end{align*}
\]

where \( C_L, C_D \) represent the drag coefficient and lift coefficient of the airfoil separately, \( t_{ini}, t_{opt}, s_{ini}, s_{opt} \) indicate the maximum thickness, cross sectional area of the initial airfoil and optimal airfoil respectively, \( x_i^l \) and \( x_i^u \) are the lower and upper bounds of the design variables. Considering larger displacement volume increases the loading capacity, the constraints that the maximum thickness and cross sectional area of the optimal airfoil obtained are larger than that of the initial airfoil need to be strictly met. In other words, these two constraints can well balance the weight between the loading capacity and hydrodynamic performance.

According to the parametric design of the BWBUG, the lower and upper bounds of design variables are shown in Table 2, which are determined by avoiding abnormal shapes. As shown in Figure 1, the empirical design has been completed by using the initial baseline airfoils, i.e. the initial design.
scheme in the optimization process. A new surrogate-based shape optimization framework used to solve the BWBUG shape optimization problem is introduced in the following section.

| Parameters | XF1 | XF2 | XF3 | XF4 | XF5 | XF6 | XF7 |
|------------|-----|-----|-----|-----|-----|-----|-----|
| x1        | -0.0714 | -0.0714 | -0.0286 | -0.0286 | -0.0286 | -0.0286 | -0.0286 |
| x2        | 0.0714 | 0.0714 | 0.0286 | 0.0286 | 0.0286 | 0.0286 | 0.0286 |
| x3        | -0.0627 | -0.0627 | -0.0251 | -0.0251 | -0.0251 | -0.0251 | -0.0251 |
| x4        | 0.0627 | 0.0627 | 0.0251 | 0.0251 | 0.0251 | 0.0251 | 0.0251 |
| x5        | -0.0677 | -0.0677 | -0.0271 | -0.0271 | -0.0271 | -0.0271 | -0.0271 |
| x6        | 0.0677 | 0.0677 | 0.0271 | 0.0271 | 0.0271 | 0.0271 | 0.0271 |
| x7        | -0.0500 | -0.0500 | -0.0200 | -0.0200 | -0.0200 | -0.0200 | -0.0200 |
| x8        | 0.0500 | 0.0500 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 |
| x9        | -0.0702 | -0.0702 | -0.0281 | -0.0281 | -0.0281 | -0.0281 | -0.0281 |
| x10       | 0.0702 | 0.0702 | 0.0281 | 0.0281 | 0.0281 | 0.0281 | 0.0281 |

4. Shape optimization framework
The proposed shape optimization framework searches for the optimum shape through four stages: a) build the baseline airfoils parameterization models using the section parameterization method, b) calculate the hydrodynamic performance of baseline airfoils using the XFOIL software, c) explore the design spaces and obtain the optimal baseline airfoils using ESGO-HSR algorithm, d) rebuild the 3D BWBUG shape using all optimal airfoils. The proposed shape optimization framework is summarized into the following steps, and illustrated by the flowchart in figure 3.

Figure 3. Flowchart of the proposed shape optimization framework.
(1) Set parameter $k = 1$ ($k$ is the index of baseline airfoil).
(2) Choose the $k$th baseline airfoil as the optimization object.
(3) Initialize parameters for ESGO-HSR algorithm [6] and set the operating condition.
(4) Calculate the corresponding design space for the $k$th baseline airfoil.
(5) Generate an initial number of sample points in the obtained design space through sampling method translational propagation and successive local enumeration (TPSLE) [11].
(6) Build the airfoil parameterization models of the new sample points using SPM.
(7) Estimate the hydrodynamic performance for the candidate airfoils using XFOIL software.
(8) Search for the optimal solution using ESGO-HSR algorithm.
(9) If the current best solution satisfies the convergence criterion formulated in equation (2), go to the step 11. Otherwise, go to the next step.

$$|\bar{F}_{i+1} - \bar{F}_i| \leq \varepsilon,$$

$$\bar{F}_i = \sum_{j=1}^{5} f_j$$

(2)

Where $\varepsilon$ is a small value given by the designer, $f_j$ is the $j$th smallest function value.
(10) Obtain the new sample points through ESGO-HSR algorithm, and add them to the sample set. Go to the step 6.
(11) Build the optimum shape for the $k$th baseline airfoil and store the relevant optimal parameters.
(12) Check $k < 7$? If it’s true, $k = k + 1$ and go to the step 2. Otherwise, go to the next step.
(13) Rebuild the 3D BWBUG shape based on seven optimal baseline airfoils using UG software.

The proposed surrogate-based shape optimization framework starts with a set of initial solutions. Such solutions are generated using the variable bounds and fed into the section parameterization module that generates a design for each of these solutions. The optimal solution for each baseline airfoil is found by using the ESGO-HSR algorithm. The optimization process runs till the convergence criterion is satisfied or the assigned number of function evaluations is completed. The 3D BWBUG shape can be rebuilt through UG software based on seven optimal baseline airfoils obtained.

5. Results and discussions

This study aims to achieve the maximum lift to drag ratio using the proposed surrogate-based shape optimization framework. To verify the viability and effectiveness of this framework, the optimal design of the BWBUG has been completed to compare with the empirical design.

5.1. Shape optimization

The maximum lift to drag ratio is used as the optimization target to complete the design of seven baseline airfoils in the shape optimization process. The inlet velocity is set to be equivalent to the glider velocity 1m/s, and an angle of attack 7° is used for each airfoil performance evaluation. The Reynolds number for each baseline airfoil is given in table 3. It is noted that the chord length of each baseline airfoil is normalized for clearly display. This study focuses on optimizing the hydrodynamic performance of the BWBUG.

The optimal results for each baseline airfoils are given in table 4. In addition, the comparison of hydrodynamic performance between initial airfoils and optimal airfoils with the gliding angle of 7° is also presented in table 5. As shown in table 5, the lift to drag ratio for the optimal airfoils are all larger than the initial airfoils. Thus, the optimal 3D BWBUG model can be rebuilt using the optimal airfoils obtained. Figure 4 shows the comparison of shapes between empirical design and optimal design. It can be found that the initial BWBUG has sharper nose and thinner airfoil of the centerline so that it has a larger displacement volume. In actual, the total displacement volume of the optimal BWBUG is 0.0028 m³, which is 6.64% higher than the initial BWBUG. In a word, the optimal baseline airfoils get both superior hydrodynamic performance that keeps the BWBUG high gliding efficiency and large displacement volume that enables the BWBUG to carry more loads.
Table 3. Reynolds number for each baseline airfoil

| No. | XF_1  | XF_2  | XF_3  | XF_4  | XF_5  | XF_6  | XF_7  |
|-----|-------|-------|-------|-------|-------|-------|-------|
| Re  | 3.50E+5 | 3.10E+5 | 2.35E+5 | 1.65E+5 | 1.30E+5 | 0.88E+5 | 0.30E+5 |

Table 4. Optimal results for each baseline airfoil

| No. | XF_1  | XF_2  | XF_3  | XF_4  | XF_5  | XF_6  | XF_7  |
|-----|-------|-------|-------|-------|-------|-------|-------|
| x_1 | -0.0616 | -0.0456 | -0.0456 | 0.0279 | 0.0278 | 0.0274 | 0.0184 |
| x_2 | 0.0615  | 0.0540  | 0.0540  | 0.0213 | 0.0245 | 0.0228 | 0.0244 |
| x_3 | 0.0631  | 0.0407  | 0.0407  | -0.0216 | -0.0186 | 0.0006 | 0.0237 |
| x_4 | 0.0473  | -0.0441 | -0.0441 | 0.0150 | -0.0129 | -0.0102 | 0.0097 |
| x_5 | -0.0630 | 0.0664  | 0.0664  | -0.0265 | -0.0018 | -0.0262 | -0.0166 |

Table 5. Comparison of the L/D for each baseline airfoil with the gliding angle of 7°

| No. | XF_1  | XF_2  | XF_3  | XF_4  | XF_5  | XF_6  | XF_7  |
|-----|-------|-------|-------|-------|-------|-------|-------|
| Initial L/D | 46.58  | 56.09  | 29.26  | 23.81  | 22.07  | 18.18  | 11.18  |
| Optimal L/D  | 54.62  | 63.02  | 38.60  | 33.84  | 30.68  | 25.47  | 14.27  |
| Percent     | 17.25% | 12.36% | 31.92% | 42.13% | 39.01% | 40.10% | 27.68% |

Figure 4. Comparison of shapes between initial design and optimal design.

5.2. Analysis of optimization results

A CFD analysis of the initial shape and optimal shape is also carried out for assessing the performance of the detailed design. As this object is axisymmetric, a half model is used for CFD analysis to reduce the computational costs in this work.

In order to minimize the influence of block caused by the BWBUG, a cuboid domain with a dimension of 25D x 20D x 15D (D is the width of the BWBUG and is equal to 0.35 m) is chosen. The BWBUG is placed in the mid-plane of the domain and 10D to the inlet boundary. Meanwhile, this computational domain is meshed with structured hexahedral grids to obtain more accurate results with smaller number of grids. Here, the non-dimensional y+ is set to be smaller than 5 for all meshes for the compatibility with the SST k-ω turbulence model [3, 12]. Moreover, the inlet velocity at the front and the bottom of the domain is set to be equivalent to the movement speed of the BWBUG, i.e., 1 m/s with various angels of attack from 1° to 9°. The outlet pressure at the back and the top of the domain is set to be 0 Pa. And, smooth wall condition is imposed at the left side surface, where the shear effects are neglected to minimize the influences of the walls [13]. The standard wall condition is allocated to the surface of the BWBUG. Besides, a symmetry plane through the center of the BWBUG is applied for reducing the computational cost.
The hydrodynamic performance of the preliminary and detailed designs with angles of attack from 1° to 9° is reported in Table 6. Significantly, the optimization results show that the maximum lift to drag ratio of detailed design with the gliding angle of 7° is 13.04, which is 13.72% larger than the preliminary design. Furthermore, the hydrodynamic performance of the optimal design is also comparable to that of the initial design with other angles of attack. The comparative results demonstrate that the proposed surrogate-based shape optimization framework can well enhance the hydrodynamic performance and loading capacity of the BWBUG. Furthermore, it can greatly reduce the computational effort compared with the traditional optimization algorithm.

Table 6 Comparison of hydrodynamic performance between initial and optimal BWBUG

| AOA | Initial design | Optimal design | Percent |
|-----|----------------|----------------|---------|
|     | $C_L$ $C_D$ $L/D$ | $C_L$ $C_D$ $L/D$ |         |
| 1°  | 0.0161 0.0036 4.47 | 0.0163 0.0037 4.42 | -1.02% |
| 2°  | 0.0321 0.0038 8.41 | 0.0325 0.0039 8.34 | -0.85% |
| 3°  | 0.0479 0.0042 11.44 | 0.0485 0.0043 11.37 | -0.61% |
| 4°  | 0.0635 0.0047 13.38 | 0.0643 0.0048 13.34 | -0.27% |
| 5°  | 0.0785 0.0056 14.08 | 0.0795 0.0056 14.10 | 0.11% |
| 6°  | 0.0925 0.0068 13.60 | 0.0940 0.0068 13.84 | 1.74% |
| 7°  | 0.1033 0.0090 11.46 | 0.1077 0.0083 13.04 | 13.72% |
| 8°  | 0.1127 0.0119 9.44 | 0.1189 0.0106 11.25 | 19.19% |
| 9°  | 0.1210 0.0152 7.93 | 0.1286 0.0135 9.52 | 19.99% |

6. Conclusions

To handle a complex, black-box engineering design optimization problem, researchers always face the challenge of finding the best tradeoff between the search efficiency and accuracy of optimal solution. In this paper, a surrogate-based shape optimization framework is presented to efficiently solve the computationally expensive BWBUG shape optimization problem. The objective of this work is to further improve the maximum lift to drag ratio of the BWBUG for a given set of user requirements. The primary contributions from the proposed surrogate-based shape optimization framework are summarized as follows.

(1) Introduce a new parametric geometric model for BWBUG. The parameterization model of the BWBUG can be simplistically obtained deriving from the parameterized baseline airfoils and the unaltered planar surface. Meanwhile, the important baseline airfoils are parameterized by using the section parameterization method.

(2) Introduce a novel efficient design optimization approach for the design and optimization of the BWBUG. This approach is developed to greatly reduce the computational time and efforts during optimization. The optimum shape of the BWBUG is completed and the maximum lift to drag ratio of the empirical design has been increased by 13.72%.

The BWBUG has been designed without considering the planar surface. In actual, the planar surface has an effect on the hydrodynamic performance of the BWBUG. The design and optimization of the planar surface will be taken into account in future research.

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References

[1] Sun C, Song B and Wang P 2015 Parametric geometric model and shape optimization of an underwater glider with blended-wing-body International Journal of Naval Architecture and Ocean Engineering 7 995-1006

[2] Ye P and Pan G 2017 Global optimization method using adaptive and parallel ensemble of surrogates for engineering design optimization Optimization 66 1135-1155

[3] Wang Z, Yu J, Zhang A Wang Y and Zhao W 2017 Parametric geometric model and hydrodynamic shape optimization of a flying-wing structure underwater glider China Ocean Engineering 31 709-715

[4] Sun C, Song B, Wang P and Wang X 2017 Shape optimization of blended-wing-body underwater glider by using gliding range as the optimization target International Journal of Naval Architecture and Ocean Engineering 9 693-704

[5] Zhang B, Song B, Mao Z and Li B 2018 Layout optimization of landing gears for an underwater glider based on particle swarm algorithm Applied Ocean Research 70 22-31

[6] Ye P, Pan G and Dong Z 2018 Ensemble of surrogate based global optimization methods using hierarchical design space reduction. Structural and Multidisciplinary Optimization, https://doi.org/10.1007/s00158-018-1906-6

[7] Liu J, Song W, Han Z and Zhang Y 2017 Efficient aerodynamic shape optimization of transonic wings using a parallel infilling strategy and surrogate models Structural and Multidisciplinary Optimization 55 925-943

[8] Shi L, Han Z, Shahbaz M and Song W 2016 Surrogate-based robust airfoil optimization under aleatory flight condition and geometric uncertainties 54th AIAA Aerospace Sciences Meeting, San Diego, 2016.1.4-2016.1.8

[9] Hu W, Choi K, Zhupanska O and Buchholz J 2016 Integrating variable wind load, aerodynamic, and structural analyses towards accurate fatigue life prediction in composite wind turbine blades Structural and Multidisciplinary Optimization 53 375-394

[10] Morgado J, Vizinho R, Silvestre M and Pascoa J 2016 XFOIL vs CFD performance predictions for high lift low Reynolds number airfoils Aerospace Science and Technology 52 207-214

[11] Pan G, Ye P and Wang P 2014 A novel latin hypercube algorithm via translational propagation Scientific World Journal 2014 163949 https://doi.org/10.1155/2014/163949

[12] Lu L, Gao Y, Li Q and Du L 2018 Numerical investigations of tip clearance flow characteristics of a pumpjet propulsor International Journal of Naval Architecture and Ocean Engineering 10 307-317

[13] Tian W, Mao Z, Zhao F and Zhao Z 2017 Layout optimization of two autonomous underwater vehicles for drag reduction with a combined CFD and neural network method Complexity 2017 5769794 https://doi.org/10.1155/2017/5769794