A novel hybrid drone for multi-propose aerial transportation and its conceptual optimization based on surrogate approach

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Abstract. In recent years the Unmanned Aerial Vehicles (UAVs) are increasingly adopted in various applications of the aerial transportation, meanwhile both the two main classifications, the fixed wing and multi-rotors drones, are limited by their own drawbacks in different specialized domains. In order to improve the short duration of multi-rotor drone and the strict conditions for taking-off and landing of the fixed-wing, an innovative hybrid UAV with integral advantages of “delta+canard wing” and vertical lift-fans has been developed. Meanwhile, the parametric optimization with multi-objects are discussed based on surrogate model to determine the conception of the delta wing and canard wing, and only the design speed of cruise model is considered, thus excluding the lift fan. Firstly, several parameters are chosen according to precedent experiences and researches, together with the optimal objects and constraint conditions determined by design conditions which are concluded into the typical multi-objective optimal problem; secondly, with the aid of computational fluid dynamics (CFD) limited design points generated by meta-model will make up the design of experiment (DOE) to create the response surfaces by means of Kriging method; lastly, the adaptation of the multi-objective genetic algorithm (MOGA) integrating in modeFRONTIER helps to reach the heuristic approach optimization for this problem. Therefore, the final conception of the delta wing and canard wing is achieved to perform the cruise model of the hybrid UAV.

1. Introduction
With the development of autonomy technology and deep learning algorithm, the Unmanned Aerial Vehicles[1] (UAVs or drones) are becoming increasingly important and acceptable in many civil domains such as logistics transport, agriculture application, environmental supervising, power transmission line inspection and aerial mapping and meteorology[2]. Inheriting from both advantages of the fixed-wing and multi-rotor drone (see table 1), the hybrid UAV is valued mostly with theirs multi-purposes.
advantages in the aerial transportation, especially with many existing prototypes and commercial products developed by the researchers and companies in recent years, which are classified into four types: fixed-rotor UAV[3], tilt-rotor UAV[4], tail-sitter UAV[5], tube-fan UAV[6]. Despite the disadvantages of complicated mechanical system and additional dead weight, the Tube-fan is viewed as one of the most promising hybrid UAV in the domain of transport application with the benefit of the high payload capacity and excellent aerodynamics during cruise flight, which are practiced and proved by amount of engineer experience [7] [8] [9].

TABLE 1. The comparison of main performances of UAVs

| Performances       | FW | VTOL | Hybrid |
|--------------------|----|------|--------|
| Runway Free        | ×  | √    | √      |
| Hovering           | ×  | √    | √      |
| Cruise Speed       | High | Low  | High  |
| Endurance          | Long | Short | Long  |
| Range Distance     | Long | Short | Long  |
| Payload            | Heavy | Light | Heavy |

2. Hybrid UAV with canard configuration

2.1. Fight models

After lots of researches on the state-of-art and feasibility of hybrid UAV, the team of Dr. Bassir has raised the conception of a new Tube-Fan drone with the excellent performance profiting from its fixed-wing[3][4]. Benefiting from the lift-fan installed in the delta wing and switchable gate to control its tube-flow, the new drone is characterized with three flight models (see figure 1): 1) cruise model, when the main propeller works individually meanwhile the VTOL system, including the lift-fans and the tube gates, stops and remains silent; 2) VTOL model, with the tube gate on the lift fans and propellers function corresponding to the autonomy technology to make the drone take off or land in a stable way; 3) transitional model, which makes the drone transfer between the two models above more safely.

![figure 1](attachment:image1.png)

(a) VTOL  (b) cruise

Figure.1 The status of gate and flow of the VTOL and cruise model

2.2. Function of the canard wing

As the low aspect-ratio delta wing results in the poor aerodynamics performances, the lift capacity would be reduced with limited principal dimensions, which are important to have good portable advantage and easy taking-off and landing space requirement. Furthermore, according to the conventional configuration of the fixed-wing, the tail wing always has to produce negative vertical force to achieve the trimming purpose, which leads to the dilemma that the delta wing must produce additional positive lift to keep balance.

The canard configuration was raised just with the invention of the first modern plane of Wright Brothers in 1903, and it’s still widely preferred in the modern fixed-wing plane, particularly in modern military air vehicles which take advantage of low trim drag and excellent maneuverability at high attack angle[5]. Moreover, it makes the UAV safer by preventing into stall with a larger incident angle of
3. Conceptual optimization of wing shape

Considering with the flight conditions and missions are determined before the design, the preliminary conceptions of the two wings are firstly taken on to realize the aerodynamical performance at the cruise model, in which the tube gates are turned off so all of the VTOL system isn’t concerned. According to the design conditions and application constraints given, there are 9 parameters, which are listed as followings, within those to describe the geometrical conception of the two wings to be picked up to be optimized in this article (see table 2).

The delta wing: 1) the incident angle $\alpha_{in1}$; 2) the chord length $L_{c1}$; 3) the span of delta wing $s_{p1}$; 4) the ratio of tip/chord of the plain wing $\lambda_1$; 5) the ratio of tip/chord of the winglet $\lambda_{sw}$.

The canard wing: 6) the incident angle $\alpha_{in2}$; 7) the chord length $L_{c2}$; 8) the span of the upward part $s_{p2}$; 9) the height of the upper part $h_{up}$ to avoid the structural stabilize.

During the model design process, some parameters are defined directly with recommendation values offering by traditional design manuals or restriction conditions, while the others are picked up to be optimized with respecting the previous researches and design experiences.

3.1. Optimization with the surrogate approach

To satisfy both the accuracy and efficiency of the optimization with the aid of CFD method, the surrogate approach(see figure 2) is preferred in our research to reach the optimal conceptual design of the wings[8][9]. During application, the surrogate modelling approach makes it possible to realize the massive genetic algorithm with limited design points by building the response surfaces, especially considering the time-costly disadvantage of the finite element method. The flowchart of the surrogate approach that is integrated in modeFRONTIER is illustrated as following, which two steps of heuristic approach is adopted to reach the optimal solutions of the multi-objective goals[10][11].

\[ Q_{sd} = F_x \times (S_1 \times L_{c1} + S_2 \times L_{c2}) \]
where \( F_x \) is the total drag of the delta wing and canard wing at cruise speed, \( S_1 \) and \( S_2 \) are respectively the area of the upper surface of the delta wing and canard wing.

Integration with the other constraint conditions given (the maximum of taking-off weight should be larger than 30kg, the length and the span of the drone should be less than 2m), a classical optimal problem in this symmetrical conception of the delta wing and canard wing, that faciliate the simulations based on CFD method, is concluded as followings.

\[
\begin{align*}
\text{Maximization of } & \{F_y\} \\
\text{Minimization of } & \{Q_{sd}\} \\
\text{s.t.} & \begin{cases} 
F_y \geq 150N \\
sp \leq 1m \\
L_t \leq 2m 
\end{cases}
\end{align*}
\]

Where \( F_y \) is the total lift produced by the two individual wings at cruise speed which could support half of the drone weight, \( sp \) is the overall span of one wing, \( L_t \) is the overall length of the drone.

It should be noted the constraint conditions of \( sp \) and \( L_t \) have been taken into account in the candidate values of the 9 parameters to optimize.

3.3. Formation of RSM based on DOE points

With the aid of CFD simulations, the results of points from the Design Of Experiments (DOE) could be obtained in a low-cost and time-consuming way, which its boundary conditions and mesh grid are illustrated as followings (see figure 3). Meanwhile, the SST-k\(\omega\) turbulence model is adopted in the calculations and the grid quantity reaches about 1.5 million after the grid independent verification in the previous researches.

![Boundary conditions](image1.png) ![Mesh grid](image2.png)

Figure 3 Boundary conditions and mesh profile in CFD simulation

To minimize the number of experiments and accelerate the progress of optimizing searching, it’s important and worthy to select a propriate method for the design of experiments. Central Composite Design (CCD) is regarded as one of the most accepted means which could provide a screening set with the overall trends for a better guide the choice of options in parametrial optimization[12]. Central Composite Design, that is also named as Box-Wilson Central Composite Design, has three main advantages which are preferred in this research: 1) Good sequence which could help us understand the relationships of the selected parameters in the future research; 2) Excellent efficiency which would help us save much time with numbers of input values; 3) Flexible application which would meet the variable need in this article.

Benefiting from the Kriging method, the response surfaces between the objectives and those optimizing parameters are established based on DOE points. Besides, the validations of each objectives are verified again by the results of the CFD simulations adopting the verifying points[13].

3.4. Establishment of the Pareto-Front based on MOGA

As there are two objectives to achieve their optimization, the Pareto-Front is proved quite effective and necessary to help recommend the best solution, as well as adopting of the Multi-Objective Genetic Algorithm (MOGA) to obtain the global optimal solution.
Based on the response surfaces concerning the objectives, the MOGA will help to search the optimal results, which would probably have the contradictory between the two objectives, that’s the reason why the Pareto-Front is recommended to evaluate and select the best strategy of optimized conceptual design[14]. Therefore, by optimal searching with MOGA method on the response surfaces based on DOE points[15], the Pareto-Front is established with the respect of constraint conditions (see figure 4) where the black points are the objective values of the DOE points, the rouge points represent those of the MOGA searching points, while the blue points are chosen to form the Pareto-Front.

![Figure 4 Pareto-Front based on MOGA method](image)

### 3.5. Determination of optimal parameters

Considering the actual importance of the objective performances, especially with the fact that this two objective goals reflect an opposite tendency in the optimization process, the final optimal parameters that compose the conceptional design of the delta wing and canard wing (see table 2 and figure 5).

#### TABLE 2. The optimized parameters of the wing

| Variables                     | Candidate Values | Optimal Values |
|-------------------------------|------------------|----------------|
| **Delta wing**                |                  |                |
| Incident angle $\alpha_{in1}$ | 4–6°             | 5.96°          |
| Chord length $L_{c1}$         | 1.3m–1.5m        | 1.38m          |
| Span of wing $s_{p1}$         | 0.8–0.9m         | 0.89m          |
| Ratio of plainwing tip $\lambda_{1}$ | 0.4–0.6   | 0.41           |
| Ratio of winglet tip $\lambda_{sw}$ | 0.2–0.4  | 0.38           |
| **Canard wing**               |                  |                |
| Incident angle $\alpha_{in2}$ | 6–8°             | 6.78°          |
| Chord length $L_{c2}$         | 0.1–0.2m         | 0.17m          |
| Span of wing $s_{p2}$         | 0.5–0.7m         | 0.70m          |
| Height of upper part $h_{up}$ | 0.4–0.6m         | 0.58m          |

![Figure 5 The optimal conceptual design of the delta and canard wings](image)

By verification the values of objective goals by means of CFD method(see table 3), it’s obvious that the errors between those estimated by surrogate method and those verified by CFD simulation are less than 1%, which also indicates the accuracy and robust of the response surface.
TABLE 3. The verification by CFD method

| Optimal Objectives | Estimated by surrogate method | Verified by CFD simulation | Error/% |
|--------------------|-------------------------------|----------------------------|---------|
| Lift/N             | 151.402                       | 151.720                    | 0.21    |
| $Q_{sd}$(N*m^3)    | 59.607                        | 59.908                     | 0.50    |

With the aid of virtual results provided by CFD simulation, the contours and vectors of velocity on the sectional planes around the canard and delta wing respectively (see figure 6). As there isn’t any quite apparent coincident region of vortices/sources in these two images, it’s testified that in the optimal conceptual design in this article, the delta wing is very little affected by canard configuration which assure the lift improvement without large negative interaction, which is particularly vital to decrease the aerodynamical performance in aerial transport application.

![Contours and vectors of velocity](image1)

(a) around canard wing  
(b) around delta wing

Figure 6 Contours and vectors of velocity around canard & delta wing

Meanwhile, the CFD-post results can also provide the detailed and necessary datum for the following researches. For example (see figure 7), the surficial pressure on the wing could be loaded as the boundary conditions in the structural design and optimization, which our team would take on the future researches.

![Surficial pressure](image2)

Figure 7 Contours of surficial pressure on the delta and canard wings

4. Conclusion

Introducing the novel tube-fan hybrid UAV with the adaptation of canard configuration, the conceptual design of the wing shape is taken on in terms of cruise model. To economize the simulation time caused by the CFD method, the surrogate approach is chosen to solve this multi-objective optimization problems with nine parameters and two objective goals and constraint conditions concluded and clarified according to actual condition. Therefore, by means of heuristic searching on the response surface that is established on DOE points, the Pareto-front is obtained to offer us the reasonable optimal solutions to determine the final conceptional design of the two wings. Furthermore, some performances predicted by CFD simulations would be profited in the following research in the tube-fan hybrid UAV.

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References

[1] M. Hassanalian and A. Abdelkefi, “Classifications, applications, and design challenges of drones: A review,” *Progress in Aerospace Sciences*, vol. 91, no. November 2016, pp. 99–131, 2017.
[2] G. Horsman, “Unmanned aerial vehicles: A preliminary analysis of forensic challenges,” *Digital*
[3] D. H. Bassir, “Design & Optimization of Hybrid Drones State of Art and Future Challenges,” in 12th MODERN MATERIALS AND MANUFACTURING, 2019, pp. 1–61.

[4] H. Yue, K. Abouzaid, D. H. Bassir, M. Zhang, and H. Medromi, “Structural Optimization of a Hybrid Drone under Aerodynamic&Dynamic Loading,” in International Conference on Materials Science and Manufacturing Engineering, 2018, pp. 1–8.

[5] X. D. Li Zhonghua, Tian Huijie, “Flight Dynamics Characteristics and Current Situation of Canard Aircraft,” Jiangsu Science & Technology Information, no. 8, pp. 60–61, 2016.

[6] J. Muchowski, M. Szumski, and A. Krzyziak, “Aerodynamic Concept of the UAV in the Gyrodyne Configuration,” Transactions on Aerospace Research, vol. 2018, no. 1, pp. 49–66, 2019.

[7] E. L. Tu, “Numerical Study of Steady and Unsteady Canard-Wing-Body Aerodynamics,” 1996.

[8] D. H. Bassir, S. Guessasma, and L. Boubakar, “Hybrid computational strategy based on ANN and GAPS: Application for identification of a non-linear model of composite material,” Composite Structures, vol. 88, no. 2, pp. 262–270, 2009.

[9] N. Lebaal, “Robust low cost meta-modeling optimization algorithm based on meta-heuristic and knowledge databases approach: Application to polymer extrusion die design,” Finite Elements in Analysis and Design, vol. 162, pp. 51–66, 2019.

[10] N. Lebaal, S. Puissant, F. Schmidt, and D. Schlafli, “An Optimization Method with Experimental Validation for the Design of Extrusion Wire Coating Dies for a Range of Different Materials and Operating Conditions,” Polymer engineering and science, vol. 52, no. 12, pp. 2675–2687, 2012.

[11] N. Lebaal, F. Schmidt, and S. Puissant, “Optimisation of extrusion flat die design and die wall temperature distribution, using Kriging and response surface method,” International Journal of Materials and Product Technology, vol. 38, no. 2–3, pp. 307–322, 2010.

[12] Z. ZHANG, Z. HE, and Z. LIU, “A comparative study of three central composite designs in response surface methodology,” Journal of Shenyang Institute of Aeronautical Engineering, vol. 24, no. 1, pp. 87–91, 2007.

[13] H. Hamdani, B. Radi, and A. El Hami, “Optimization of solder joints in embedded mechatronic systems via Kriging-assisted CMA-ES algorithm,” International Journal for Simulation and Multidisciplinary Design Optimization, vol. 10, 2019.

[14] X. Tang, D. H. Bassir, and W. Zhang, “Shape, sizing optimization and material selection based on mixed variables and genetic algorithm,” Optimization and Engineering, vol. 12, no. 1–2, pp. 111–128, 2011.

[15] F. X. Irisarri, D. H. Bassir, N. Carrere, and J. F. Maire, “Multiobjective stacking sequence optimization for laminated composite structures,” Composites Science and Technology, vol. 69, no. 7–8, pp. 983–990, 2009.