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# A Flying Wing UCAV Design Optimization Using Global Variable Fidelity Modeling

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## 1. Abstract

This paper describes the multidisciplinary design optimization (MDO) process of a flying wing unmanned combat aerial vehicle (UCAV) using global variable fidelity modelling (GVFM) algorithm. A developed flying wing UCAV design framework combines aerodynamics, weight and balance, propulsion, performance, stability and control, and other disciplines. Analysis codes are based on low fidelity analysis and empirical equations. Design problem formulation focuses on features of a flying wing aircraft configuration that is known for its good aerodynamics, and poor stability and control (S&C). GVFM algorithm is implemented to increase prediction accuracy of analysis for important aerodynamic and S&C functions such as, lift-to-drag ratio, parasite drag coefficient, static margin etc. An automated high fidelity aerodynamic analysis (CFD) process is developed and integrated into GVFM model. Design optimization problems with low fidelity analysis and with implementation of GVFM model are successfully solved. The optimum solution obtained with low fidelity analysis shows 18.6% improvement of an objective function, while solution obtained with GVFM model about 15.9%. However CFD analysis of a low fidelity optimum solution indicates only 14.4% improvement, which means that low fidelity analysis underestimates the value of objective function by 4.2%. GVFM model converges to high fidelity value of a function by algorithm definition. The optimum UCAV configuration has longer operational range and improved stability and control characteristics comparing to the baseline.

## 2. Keywords

Unmanned Aerial Vehicle, Multidisciplinary Design Optimization, Variable Fidelity Optimization, Aircraft Conceptual Design, Computational Fluid Dynamics

## 3. Introduction

Unmanned aerial vehicle (UAV) systems are recently in a great interest. These days an application of UAV systems is narrowed down to military and special operations. But civil UAV market is also rapidly growing. Less strict design requirements for internal compartment of UAVs lead to development of unconventional configurations. These days one of the most promising aircraft schemes is a flying wing configuration. A clean flying wing is sometimes treating as theoretically ideal fixed wing aircraft. Lower parasite drag, lower radar cross section makes it fly further without risk to be discovered by radar. But stability issues inherent in this type of configuration were limiting it from being widely used. The current level of knowledge is high enough to efficiently solve stability and control problem by implementation of automatic control and special control devices. A flying wing configuration is becoming more popular nowadays.

Aircraft conceptual design is a complex problem that involves multiple disciplines. Multidisciplinary Design Optimization provides an efficient ways of treating all disciplines together. High accuracy of analysis methods at conceptual design stage narrows down the scope of preliminary and detailed design. Accuracy of analysis can be enhanced by implementation of computationally expensive high fidelity analysis methods. However, direct use of high fidelity analysis for design optimization faces number of problems. The main problem is huge computational time required to perform the analysis. Variable fidelity optimization algorithms tend to combine advantages of low and high fidelity analysis methods. Combination of both high and low fidelity algorithms makes it possible to achieve accuracy close to high fidelity one within lower computational time. This paper focuses on development of a flying wing UCAV conceptual design framework by expansion of existing GVFM algorithm for an MDO problem.

## 4. Integrated Design Framework

An integrated multidisciplinary design framework is developed [1] for a flying wing UAV conceptual design optimization.

Figure 1 shows the structure of the program. The analysis methods are based on textbook methods, empirical equations, and low fidelity aerodynamic analysis codes. Current analysis methods were validated using available information about existing aircraft configurations of current category (Flying wing UCAV). Prediction error of analysis results comparing to existing aircraft data is less than 10%. This level of accuracy is acceptable to be used at conceptual design stage. However analysis accuracy can be increased by implementation of variable fidelity algorithms. Increasing analysis accuracy at conceptual design stage may significantly reduce the scope of preliminary and detailed design stages and reduce the total cost of the development project.

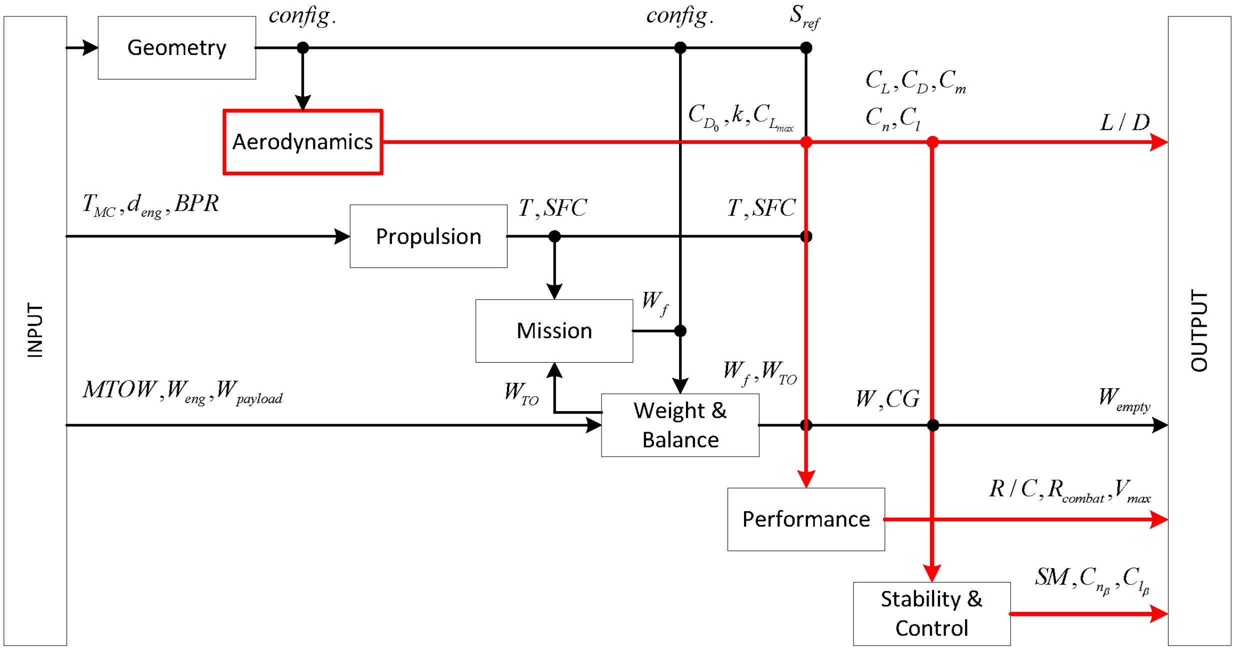

Figure 1: Integrated Design Framework Structure with Variable Fidelity Aerodynamic Module

## 5. Variable Fidelity Optimization Methodology

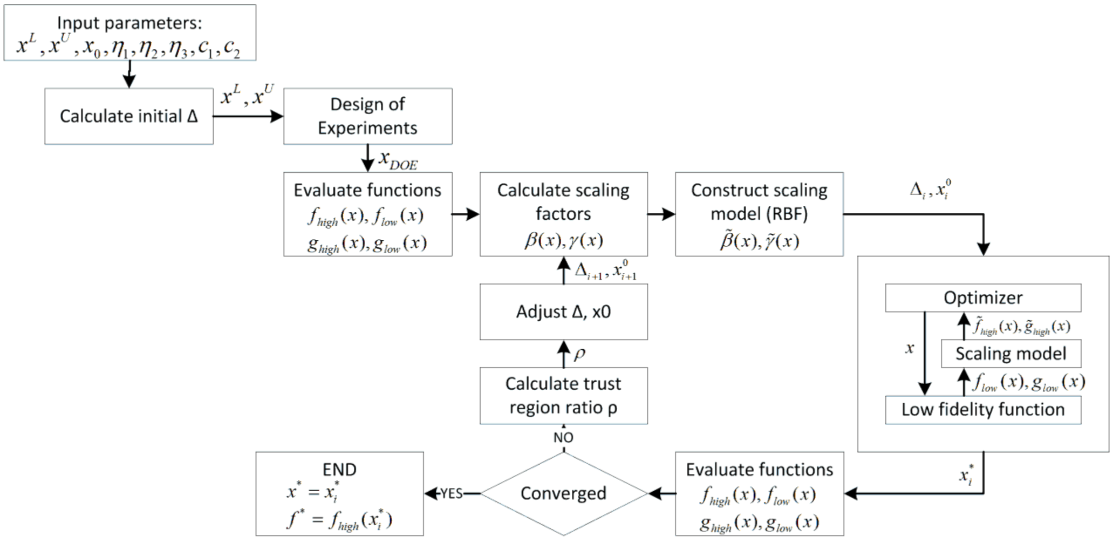

Figure 2: Global Variable Fidelity Modelling Process [2]

A variable fidelity optimization algorithm used in this study is the Global Variable Fidelity Modelling [ref] algorithm. The general idea of GVFM method is the initial sampling of high and low-fidelity functions over the design space and iterative refinement of a scaling model that represents the difference between high and low fidelity functions. The scaling model is a radial basis functions (RBF) network constructed using scaling factors at a given point $x_i$ . Scaling factors are calculated as:

$$\beta(x_i) = f_{high}(x_i) - f_{low}(x_i) \tag{1}$$

And approximation of a high fidelity function can be reconstructed as:

$$\tilde{f}_{high}(x) = f_{low}(x) + \tilde{\beta}(x) \tag{2}$$

Where: $f_{high}(x)$ - High fidelity function
$f_{low}(x)$ - Low fidelity function
$\beta$ - Scaling factor
$\tilde{\beta}(x)$ - Scaling model
$\tilde{f}_{high}(x)$ - Approximation of a high fidelity function

The sample points for scaling model initialization are uniformly distributed using design of experiments (DOE). The scaling model is then iteratively refined using points obtained at optimization. The detailed process of GVFM is presented in
Figure 2.

### 5.1 Variable Fidelity Aerodynamic Analysis Module

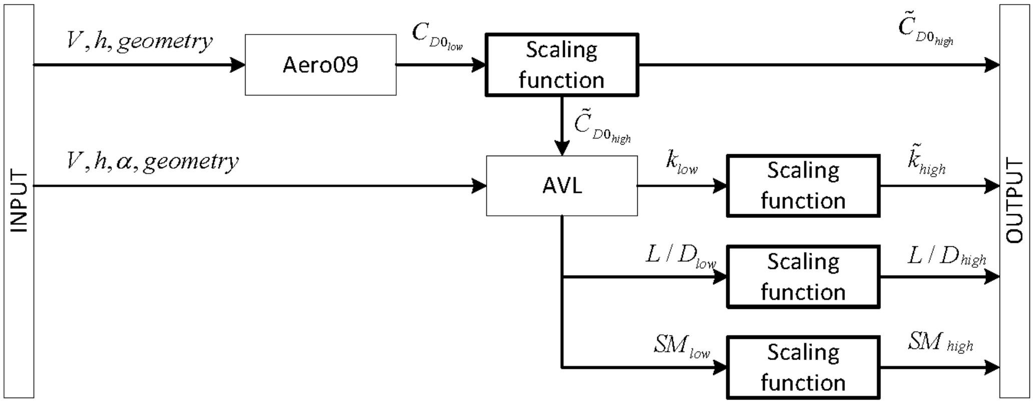

Figure 3: Variable Fidelity Aerodynamic Analysis

Aerodynamics, stability and control disciplines are extremely important for a flying wing aircraft configuration. This discipline supplies data for almost all other analysis disciplines as shown in
Figure 1 and it has a large effect on most characteristics of an aircraft. A high fidelity computational fluid dynamics (CFD) solver is added the aerodynamic analysis module to increase the accuracy of analysis. Automation of a high fidelity analysis process is a complex task. An automated framework for CFD analysis is developed that includes generation of a CAD model, generation of a structured computational grid, and pre and post processing of aerodynamic analysis results.
Figure 3 shows details about variable fidelity aerodynamic analysis module. Analysis estimates approximated values of high fidelity $C_{D_0}, k, L/D,$ $and\ SM$ for given aircraft configuration and flight condition. Module contains four scaling functions that are initialized and iteratively updated according to GVFM algorithm. Parameters such as lift-to-drag ratio and static margin are used directly as objective and constraint functions, while parasite drag coefficient and induced drag factor are supplied to performance analysis module.

## 6. Unmanned Combat Aerial Vehicle Design

### 6.1 Optimization formulation

Design formulation for a flying wing UCAV aircraft is mostly based on Nicolai [3] and Torenbeek [4] textbooks. An objective function of maximizing lift-to-drag ratio is quite common for different aircraft design optimization formulations. Maximizing L/D parameter also leads to an increase of operational range that is constrained to be greater than 750 km for suppression of enemy air defenses (SEAD) [5] mission profile. Longitudinal stability of an aircraft is constrained by a static margin. It is decided to design aircraft with positive static margin between 5 and 15% that is slightly higher than static margin of a conventional fighter aircraft of similar size and weight. Low speed trim condition constraints elevator and wing area authority. Maximum trim angle of attack at landing speed of 65 m/s is set to 8 degrees with trim elevator deflection to be between -20 and 20 degrees. One of the main issues of a flying wing is a directional stability [6] [7] [8] [9]. Level of directional stability similar to that of conventional aircraft is not achievable without implementation of special control devices. It is decided to keep positive directional stability for clean configuration at level of $C_{n_\beta} \geq 0.003$. By summarizing design requirements, optimization formulation can be written as shown in Table 1: UCAV Optimization Formulation.

Two design problems are solved in this study. The first one implements pure low fidelity optimization and the second one with GVFM aerodynamic model in an MDO loop. Table 1 shows that 6 of total 14 functions are affected by variable fidelity aerodynamics.

Table 1: UCAV Optimization Formulation

|  | Variable |  | Value | Function type |
|---|---|---|---|---|
| Maximize: |  |  |  |  |
|  | L/D |  |  | Variable Fidelity |
| Subject to: |  |  |  |  |
|  | SM | ≤ | 0.15 | Variable Fidelity |
|  | SM | ≥ | 0.05 | Variable Fidelity |
|  | $R_{combat}$ | ≥ | 750km | Variable Fidelity |
|  | R/C | ≥ | 125m/s | Variable Fidelity |
|  | $M_{max}$ | ≥ | 0.90 | Variable Fidelity |
|  | $W_{empty}$ | ≤ | 3500kg | Low fidelity |
|  | $C_{n\beta}$ | ≥ | 0.003 | Low fidelity |
|  | $C_{l\beta}$ | ≤ | -0.075 | Low fidelity |
|  | $\alpha_{trim}$ | ≤ | 8deg. | Low fidelity |
|  | $\delta_{e_{trim}}$ | ≤ | 20deg. | Low fidelity |
|  | $\delta_{e_{trim}}$ | ≥ | -20deg. | Low fidelity |
|  | $l_{fuselage}$ | ≥ | 5.5m | Exact |
|  | $\Lambda_{LE1}$ | ≥ | $\Lambda_{LE2}$ | Exact |

### 6.2 Baseline configuration

Boeing X45C UCAV is selected as a baseline configuration. The baseline is a typical low aspect ratio flying wing aircraft. The wing has two segments: central and outer. The central segment serves as a fuselage and stores a power plant, payload, and avionics. The planform shape of the wing can be parameterized with total 9 design variables. An internal space volume is secured by constraints that restrict the intersection of leading and trailing edges of central segment with the payload and engine. Longitudinal and lateral control device is joined and located on the outer segment of the wing. Elevon to chord ratio is 0.9, 0.85, and 0.8 at root, middle and tip chords respectively. The other components are GE F404 turbofan engine, fixed fuel weight of 3000 kg, 300 kg of uninstalled avionics, and 1132 kg of drop payload.

## 7. Results and Discussions

Table 2 shows results of MDO with implementation of low fidelity analysis only, and variable fidelity optimization using GVFM algorithm adopted for MDO use. In addition baseline and low fidelity optimum configurations were analyzed using high fidelity analysis. GVFM optimum is equal to high fidelity by algorithm definition. Figure 4 shows comparison of the baseline with optimum configurations of UCAV.

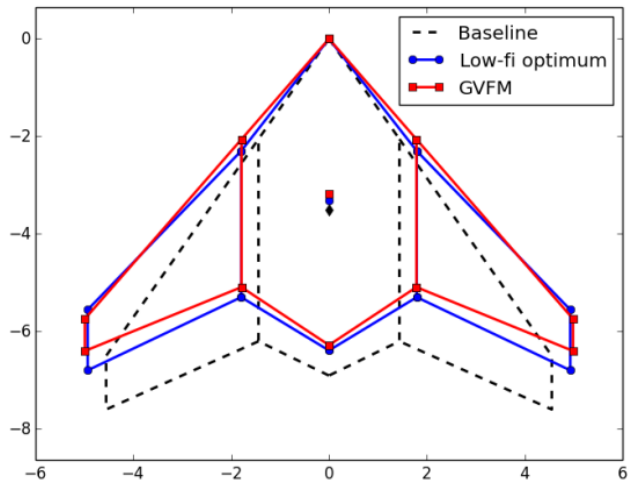

Figure 4: Baseline and Optimum UCAV Configuration

Results in Table 2 show that low fidelity analysis overpredicts the value of the objective function (lift-to-drag ratio at cruise flight condition). Low fidelity optimization shows 18.6% improvement of the objective function, however high-fidelity analysis of the low-fidelity optimum configuration shows only 14.4% improvement. MDO implementation of GVFM algorithm has terminated with the objective function value of 18.83 that is 15.9% higher than that of the baseline. Finally the combat radius of GVFM optimum configuration is 75 km longer than that of low-fidelity optimum. Overprediction of L/D and combat radius by low-fidelity analysis may lead to infeasible solution in case of more strict constraints, while variable fidelity model guarantees convergence to a high-fidelity result.

Table 2: UCAV Optimization Results

| | | LB | UB | Baseline | | Low-fidelity | | GVFM |
|---|---|---|---|---|---|---|---|---|
| | | | | Low-fi | CFD | Low-fi | CFD | |
| | *L/D* | | | 16.84 | 16.25 | 19.27 | 18.6 | 18.83 |
| Constraints | *SM* | 0.05 | 0.15 | 0.1182 | 0.1258 | 0.0501 | 0.0729 | 0.1123 |
| | $C_{n_\beta}$ | 0.003 | | 0.0038 | | 0.0030 | | 0.0030 |
| | $C_{l_\beta}$ | | -0.075 | -0.109 | | -0.09 | | -0.088 |
| | $\alpha_{trim}$ | | 8 | 9.75 | | 8.00 | | 8.00 |
| | $\delta_{e_{trim}}$ | -20 | 20 | -8.81 | | -4.92 | | 4.75 |
| | $W_e$ | | 3500 | 3551 | | 3500 | | 3492 |
| | $R_{combat}$ | 750 | | 688.32 | 629.63 | 869.77 | 809.91 | 886.44 |
| | *R/C* | 125 | | 139 | 138.7 | 143.7 | 142.9 | 146.4 |
| | $M_{max}$ | 0.9 | | 0.9372 | 0.9373 | 0.9439 | 0.9433 | 0.9398 |
| Design Variables | $\Lambda_{LE_1}$ | 40 | 60 | 55 | | 52.05 | | 49.07 |
| | $\Lambda_{LE_2}$ | 40 | 60 | 55 | | 46.08 | | 49.02 |
| | $c_1$ | 6 | 7.5 | 6.91 | | 6.39 | | 6.28 |
| | $c_2$ | 3 | 5.25 | 4.15 | | 3 | | 3.03 |
| | $c_3$ | 0.5 | 1.8 | 1.1 | | 1.24 | | 0.66 |
| | $l_1$ | 1 | 1.8 | 1.44 | | 1.79 | | 1.79 |
| | $l_2$ | 3 | 3.2 | 3.11 | | 3.13 | | 3.20 |
| | $\phi_1$ | -4 | 0 | 0 | | -1.2449 | | -0.87 |
| | $\phi_2$ | -4 | 0 | -2 | | -0.6869 | | -1.08 |

In terms of computational time, GVFM evaluated high fidelity function 31 times including 25 for scaling models initialization and 6 for their refinement. Single run of the high fidelity function takes about 18 hours, and about 1 hour for optimization loop. Total computational time required to get a converged solution is about 23 full days on a desktop computer. This value is quite high comparing to pure low fidelity optimization that converges in a couple of hours but also significantly lower than pure high fidelity optimization.

## 8. Acknowledgements

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