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Design Optimisation of UAVs Systems achieved on a Framework Environment via Evolution and Game Theory

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ABSTRACT

Over recent years, Unmanned Air Vehicles or UAVs have become a powerful tool for reconnaissance and surveillance tasks. These vehicles are now available in a broad size and capability range and are intended to fly in regions where the presence of onboard human pilots is either too risky or unnecessary. This paper describes the formulation and application of a design framework that supports the complex task of multidisciplinary design optimisation of UAVs systems via evolutionary computation. The framework includes a Graphical User Interface (GUI), a robust Evolutionary Algorithm optimiser named HAPEA, several design modules, mesh generators and post-processing capabilities in an integrated platform. These population –based algorithms such as EAs are good for cases problems where the search space can be multi-modal, non-convex or discontinuous, with multiple local minima and with noise, and also problems where we look for multiple solutions via Game Theory, namely a Nash equilibrium point or a Pareto set of non-dominated solutions. The application of the methodology is illustrated on conceptual and detailed multi-criteria and multidisciplinary shape design problems. Results indicate the practicality and robustness of the framework to find optimal shapes and trade—offs between the disciplinary analyses and to produce a set of non dominated solutions of an optimal Pareto front to the designer.

Key Words: Evolutionary Algorithms, Multi-objective Optimisation, Game Theory, Unmanned Aerial Vehicles.

1. INTRODUCTION

The significance of unmanned aircraft research and development is rapidly increasing over the world. The current technology developments, the availability of compact, lightweight, inexpensive motion detecting sensors and Differential Global Positioning Systems (DGPS) and compact lightweight low-cost computing power for autonomous flight control allow the development of fully autonomous operational systems. Nonetheless similar to the manned counterpart challenges in the integration of multiple disciplines whilst accounting for the trade-offs between the different objectives involved are still present.

Design optimisation in aeronautics is a common practice given that a small change in geometry might produce significant gains in aerodynamic and structural performance. The common approach is the use of traditional gradient bases techniques. These techniques are effective when applied to specific problems and within a specified range and efficient in finding optimal global solutions if the objective and constraints are differentiable. The benefit of population based techniques such as EAs [1,2] is now being realized as some of the problems in aeronautics might require its use. EAs are good for cases problems where the search space can be multi-modal, non-convex or discontinuous, with multiple local minima and noise, problems where we look for multiple solutions simultaneously, a Nash equilibrium point or a set of non-dominated solutions.An attractive feature of EAs is that they evaluate multiple populations of points and are capable of finding a number of solutions in a Pareto set.

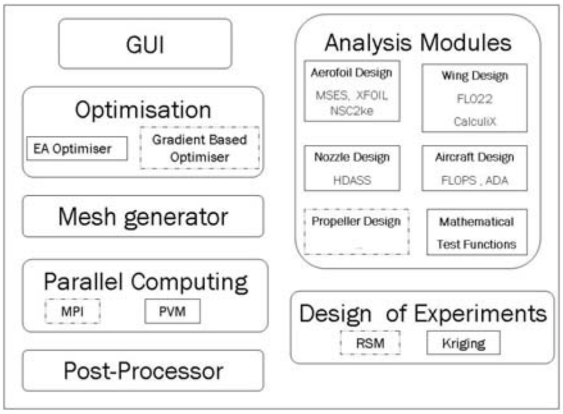
EAs have been successfully applied to different aircraft, wing, aerofoil and rotor blade design and optimization problems [3-8]. One major drawback of EAs is that they are slow in converging, as they require a large number of function evaluations to find optimal solutions and have poor performance with increasing number of variables. Hence the continuing effort has been on developing robust but faster numerical techniques to overcome these challenges and facilitate the complex task of design and optimization in aeronautics. It is also desirable from the engineering point of view to have a design framework that the engineer or team of designers uses to address this complex task of optimisation.

In this direction we developed a framework for the design and optimization of aeronautical systems and which is applicable to UAV systems design. This framework uses a multi-objective parallel evolutionary technique, and several modules or parallel computing, pre- and post-processing capabilities. It can be used for conceptual or detailed studies using combination of fidelity models in search for the optimal or non-dominated solutions.

The full paper will detail the requirements for a robust framework for multi-criteria and multidisciplinary design optimisation; it will also describe the design characteristics of the proposed framework and the application of the method to UAV systems design optimisation.

2. FRAMEWORK

Figure 1 shows a representation of different components. The framework has a GUI, a robust optimization tool, several analysis modules and capabilities for parallel computing, mesh generation, Design of Experiments (DOE) and post-processing.



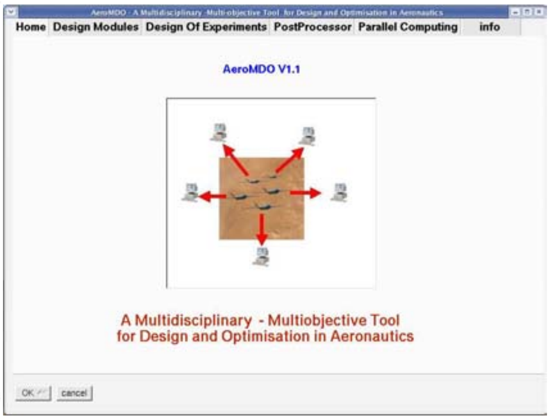


Figure 1. MDO Framework **Figure 2. GUI Sample**

The framework uses a Hierarchical Asynchronous Parallel Evolutionary Algorithm (HAPEA) approach developed by Whitney [4, 5] as the optimisation tool. The foundation of this algorithm lies on traditional evolution strategies and incorporate the concepts of multi-criteria optimisation, hierarchical topology, parallel computing and asynchronous evaluation. Details on the algorithm can be found in Whitney et al [4,5] and Gonzalez et al [6,7]. The approach used to capture solutions of multi objective solution is based on game strategies described in [5,7].

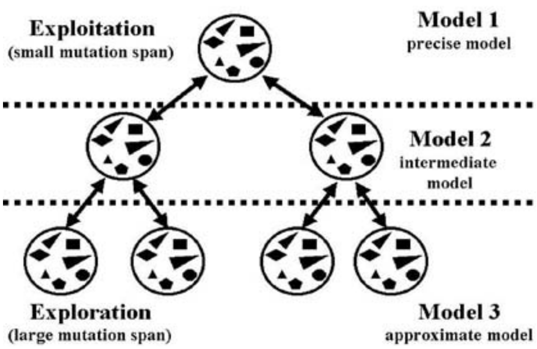


Figure 3. Hierarchical Topology

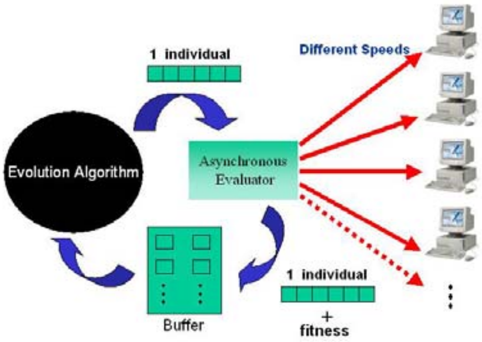


Figure 4. Parallel Computing and Asynchronous Evaluation

3. APPLICATIONS

The framework has been used to evaluate several real world problems including inverse and direct problems for aerofoil, high- lift aircraft system, multidisciplinary and multi-criteria wing and aircraft design and optimization problems [4-7]. In this work we illustrate the application of the method for a conceptual and one detailed cases related to UAV and UCAV aerofoil design.

Conceptual Design: Two Objective UAV Aerofoil Section Design.

This test case focuses on generating a trade-off of aerofoils for a UCAV configuration operating at transonic speeds. There are two transonic speed design points that are considered for optimisation; one for cruise and another for rapid-loitering flight. The two fitness functions to be optimised are defined as minimisation of drag (Cd) at two flight conditions.

$$f_1 = c_{d_1} \quad \rightarrow \mathrm{M}_\infty = 0.77,\ \ \mathrm{Re} = 9.0 \times 10^6,\ C_l = 0.60$$

$$f_2 = c_{d_2} \quad \rightarrow \mathrm{M}_\infty = 0.80,\ \ \mathrm{Re} = 10.0 \times 10^6,\ C_l = 0.30$$

In this test case we use an Euler solver incorporating boundary layer correction (MSES)[9] is used for the analysis. The software is a coupled viscous/inviscid Euler method for the analysis and design of multi-element/single-element airfoils. It is based on a streamline-based Euler discretisation and a two-equation integral boundary layer formulation, which are coupled through the displacement thickness and are solved simultaneously by a full Newton method.

The bounding envelope for aerofoil search is shown in figure 5, the resulting Pareto set is shown in figure 6 while the aerofoils comprising the Pareto set are shown in figure 7. It can be seen that traditional shapes for transonic speeds have been evolved, even considering that the optimisation was started at random and the evolution algorithm had no problem specific knowledge of appropriate solution types. Three aerofoils from the Pareto front of 20 members (numbers 1, 11 and 20) are taken for further evaluation. These aerofoils are compared against traditional transonic aerofoils (RAE5212, RAE5215, SC20714 and Whitcomb. Figure 8 shows the drag polar with increasing lift coefficient. The evolved aerofoils have good performance characteristics.

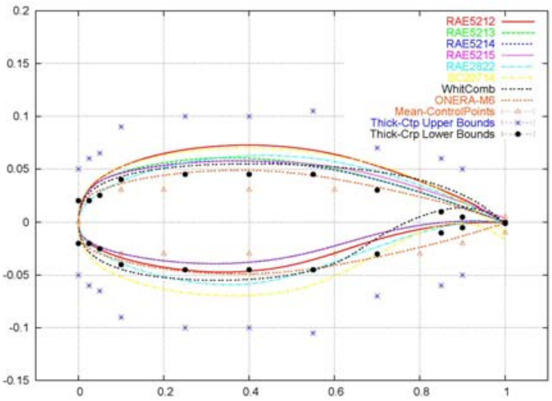


Figure 5. Bounding envelope for aerofoil search

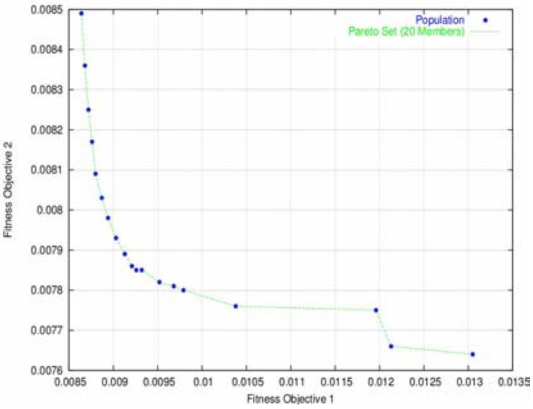


Figure 6. Pareto front – Tradeoffs

Figure 7. The Ensemble of Pareto Aerofoils.

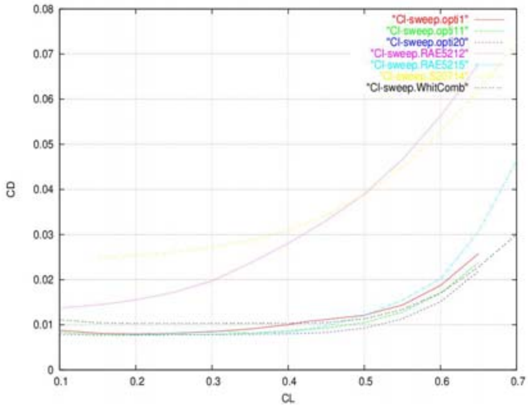


Figure 8. Drag comparison at increasing C_l. [M 0.8, Re 10×10^6]

Detailed Design: UCAV Wing Aerofoil Section/Plan form Design Optimisation

In this case we want to optimise a UCAV similar to Joint Unmanned Combat Air Vehicles (J-UCAVs): Boeing X-45C, Dassault Aviation - Petit Duc and Northrop Grumman X-47A/B. The baseline UCAV is similar to the UCAV design project in Reference 9 and is illustrated in figure 9. The wing plan form shape is assumed as an aero-diamond shape with jagged trailing edge to deflec radar echoes away from the source which is convenient for stealth purposes,. The aircraft maximum gross weight is approximately 5,190 lb and empty weight is 3,249 lbs The leading and trailing edges have identical sweep angles ($\Lambda LE = 55°$) so called plan form alignment. We also assume that this initial design contains two types of aerofoils; NACA 67-1015 for the inboard section and NACA 66-008 for the outboard section. The aerofoils between inboard and outboard sections are interpolated automatically by the flow solver.

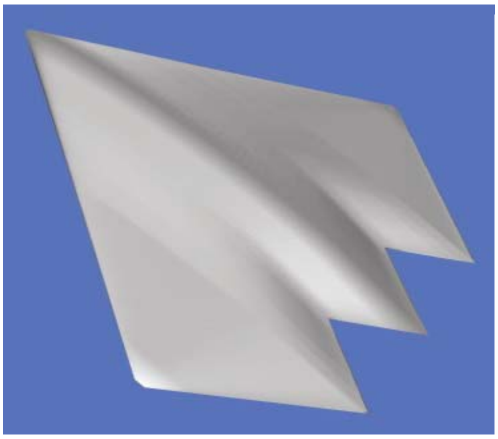
The main objectives are to maximise lift on drag ratio and minimize the bending moment for an UCAV wing at a fixed angle of attack. The fitness functions and flight conditions are as followed:

$$fitness(f_1) = \min\left(1/\left(L/D_1\right)\right) \rightarrow M_\infty = 0.7 \text{ and } \alpha = 5.408°$$

$$fitness(f_2) = \min\left(Cm_{bending}\right) \rightarrow M_\infty = 0.7 \text{ and } \alpha = 5.408°$$

The aerodynamic characteristics of the wing configurations are evaluated using two solvers, a three dimensional full potential wing analysis software (FLO22) written by A. Jameson and D Caughey [11] and the FRICTION program developed by Hendrickson as described in Ref 12 which provides an estimate of laminar and turbulent the skin friction drag.

Figure 10 shows the resulting convex-non-convex Pareto front. Figure 11 shows the Cp distribution at different span wise stations for one of the members of the Pareto front.



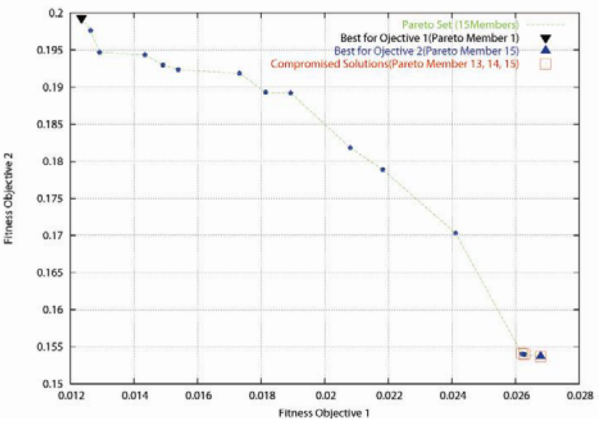


Figure 9. Baseline design for UCAV.

Figure 10. Pareto optimal fronts for UCAV wing aerofoil sections/planform.

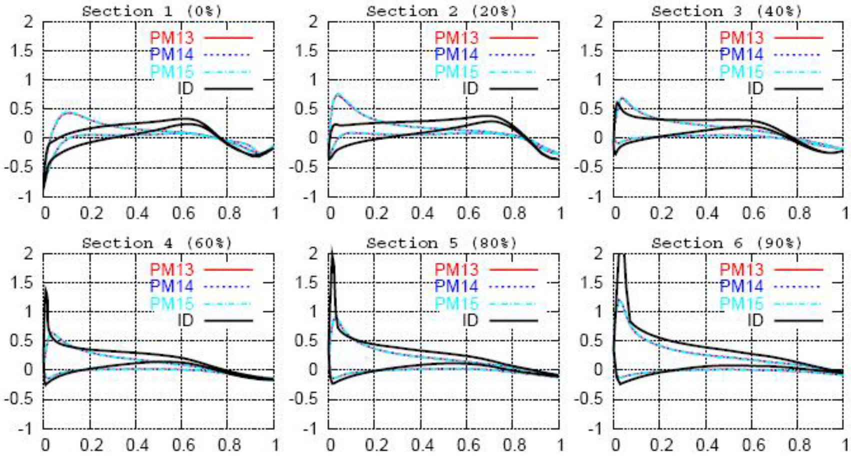


Figure 11. Cp distribution along the span.

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