MULTI-OBJECTIVE AND MULTIDISCIPLINARY DESIGN OPTIMISATION OF UNMANNED AERIAL VEHICLE SYSTEMS USING HIERARCHICAL ASYNCHRONOUS PARALLEL MULTI-OBJECTIVE EVOLUTIONARY ALGORITHMS

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BY

LLOYD HOLLIS DAMP

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To my parents
Thank you Mom and Dad for the countless
sacrifices you made for me and my future

DECLARATION

I, Lloyd Hollis Damp declare that this dissertation, submitted in fulfilment of the requirements of Masters of Engineering (Aeronautical) (Research) represents my own work and has not been previously submitted to the University of Sydney or any other institution for any degree or other qualification.

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NOMENCLATURE

x,y,z = Left hand reference frame attached to wing root. Z+ up, Y+ over span, X+ chord
AR = Aspect ratio
S = Wing wetted area *(m^2)*
C_R = Root chord length *(m)*
b = Semi span length *(m)*
t/c = Thickness to Chord ratio
W = Vehicle Mass *(kg)*
λ_{rc} = Inboard taper ratio
λ_{ct} = Outboard taper ratio
Λ_{rc} = Inboard sweep angle *(deg)*
Λ_{ct} = Outboard sweep angle *(deg)*
Γ_{rc} = Inboard dihedral angle *(deg)*
Γ_{ct} = Outboard dihedral angle *(deg)*
$BP_{Inboard}$ = Inboard break point
$BP_{Outboard}$ = Outboard break point
$SrTr$ = Spar Root Thickness Taper Ratio
$RrTr$ = Rib Root Thickness Taper Ratio
$WstTr$ = Wing Skin Thickness Tip Taper Ratio
$WsTre$ = Wing Skin Thickness Edge Taper Ratio
$WsRt$ = Wing Skin Root Thickness *(m)*
Rrt = Rib Root Thickness *(m)*
Srt = Spar Root Thickness *(m)*
HALE = High Altitude Long Endurance
MALE = Medium Altitude Long Endurance
UAV = Unmanned Aerial Vehicle
EP = Evolutionary Programming
GA = Genetic Algorithm
μ = A population of optimiser solutions

u,v,w = Velocity components in x, y and z
V = Vehicle Velocity *(m/s)*
U_∞ = Freestream velocity magnitude *(m/s)*
M_∞ = Freestream Mach number
Re = Reynolds number
ρ = Air Density (*kg/m^3*)
α = Angle of attack *(deg)*
ψ = Yaw angle *(deg)*
L/D = Lift to drag ratio
C_L = Lift coefficient
C_D = Drag coefficient
C_{D0} = Drag coefficient at zero lift
C_f = Friction coefficient
C_m = Moment Coefficient
ν = Poissons Ratio
τ = Shear Strain
σ = Stress
$crank_l$ = Crank Location
Ns = Number of Spars
Nr = Number of Ribs
Sc = Spar Cap Root Area *(m^2)*
Rc = Rib Cap Root Area *(m^2)*
CFD = Computational Fluid Dynamics
FEA = Finite Element Analysis
MDO = Multiple Disciplinary Optimisation
ES = Evolutionary Strategy
GP = Genetic Programming
EA = Evolutionary Algorithm

SUMMARY

The overall objective of this research was to realise the practical application of Hierarchical Asynchronous Parallel Evolutionary Algorithms for Multi-objective and Multidisciplinary Design Optimisation (MDO) of UAV Systems using high fidelity analysis tools. The research looked at the assumed aerodynamics and structures of two production UAV wings and attempted to optimise these wings in isolation to the rest of the vehicle. The project was sponsored by the Asian Office of the Air Force Office of Scientific Research under contract number AOARD-044078.

The two vehicles wings which were optimised were based upon assumptions made on the Northrop Grumman Global Hawk (GH), a High Altitude Long Endurance (HALE) vehicle, and the General Atomics Altair (Altair), Medium Altitude Long Endurance (MALE) vehicle. The optimisations for both vehicles were performed at cruise altitude with MTOW minus 5% fuel and a 2.5g load case. The GH was assumed to use NASA LRN 1015 aerofoil at the root, crank and tip locations with five spars and ten ribs. The Altair was assumed to use the NACA4415 aerofoil at all three locations with two internal spars and ten ribs. Both models used a parabolic variation of spar, rib and wing skin thickness as a function of span, and in the case of the wing skin thickness, also chord.

The work was carried out by integrating the current University of Sydney designed Evolutionary Optimiser (HAPMOEA) with Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) tools. The variable values computed by HAPMOEA were subjected to structural and aerodynamic analysis. The aerodynamic analysis computed the pressure loads using a Boeing developed Morino class panel method code named PANAIR. These aerodynamic results were coupled to a FEA code, MSC.Nastran® and the strain and displacement of the wings computed. The fitness of each wing was computed from the outputs of each program.

In total, 48 design variables were defined to describe both the structural and aerodynamic properties of the wings subject to several constraints. These variables allowed for the alteration of the three aerofoil sections describing the root, crank and tip sections. They also described the internal structure of the wings allowing for variable flexibility within the wing box structure. These design variables were manipulated by the optimiser such that two fitness functions were minimised. The fitness functions were the overall mass of the simulated wing box structure and the inverse of the lift to drag ratio. Furthermore, six penalty functions were added to further penalise genetically inferior wings and force the optimiser to not pass on their genetic material.

The results indicate that given the initial assumptions made on all the aerodynamic and structural properties of the HALE and MALE wings, a reduction in mass and drag is possible through the use of the HAPMOEA code. The code was terminated after 300 evaluations of each hierarchical level due to plateau effects. These evolutionary optimisation results could be further refined through a gradient based optimiser if required. Even though a reduced number of evaluations were performed, weight and drag reductions of between 10 and 20 percent were easy to achieve and indicate that the wings of both vehicles can be optimised.

1. INTRODUCTION

1.1 MOTIVATION

The global scope of Unmanned Aerial Vehicle (UAV) applications in both military and civilian arenas is increasing rapidly. New vehicles suffer from the pressures of a right-first-time design where all spheres of influence are addressed. This provides many complications as a vehicle may have to fulfil many mission requirements with little to no physical alteration. An example of this is the Predator A vehicle which can perform surveillance missions, and with the addition of hard points, can carry armaments with which the operator can attack spotted enemies. This right-first-time design approach has demanded a new and improved set of numerical tools able to optimise functions where traditional deterministic optimisers have failed.

Aeronautics has always presented the designer with more than one objective to satisfy when designing a vehicle. Furthermore, the fields of interest from which these objectives originate normally require different simulation methods making the solution multi-modal, non-convex and even discontinuous. It is from this requirement that the Multidisciplinary Design Optimisation (MDO) approach was conceived where the different components making up the solution sequence are investigated in a systematic approach. This MDO approach also takes into account the coupling between variables and optimisation objectives. An example of this is wing design where the aerodynamics of the wing strongly influences the structural response.

As modern aircraft approach the limits of current design methodologies, even a small reduction in drag or an increase in the lift generated at take-off can greatly influence the overall performance of the vehicle. The different components contributing to a vehicles performance is shown in Figure 1. The interactions between the components are complex and it is therefore clear that optimisation and MDO are necessity tools when trying to extend a vehicles performance into new territories.

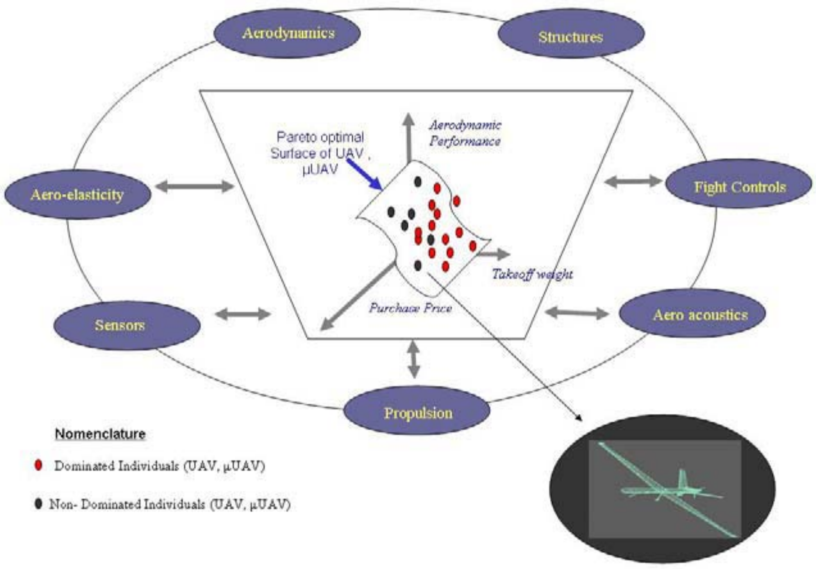

Figure 1: UAV MDO process

A common optimisation objective function found in aerospace engineering is constructed through a weighted sum of the different components. A drawback to this approach is that the weighting needs to be decided *a priori* and can have a large influence on the overall operation of the code and final determined design. A different approach is to rather produce a surface constructed by the optimal values of the different components. This surface is known as a Pareto optimal front and represents the set of non-dominated solutions for the trade-offs between objectives.

When MDO is applied to the external geometry of an aircraft, several analysis tools are required to accurately model the environment and response. The main tools used are Computational Fluid Dynamics (CFD) to model the airflow about the vehicle, Finite Element Analysis (FEA) to model the structural response and the optimisation tool itself. As modern computing power has increased, so the fidelity and user confidence in the different software packages has increased to a point where now these tools can accurately be used in conjunction with MDO such as in the work by Mason [3], Argarwal [4] and Thomas [5]. An industrial fidelity solution still requires too much computational power to effectively be incorporated in an MDO framework. A full three-dimensional Navier-Stokes flow solution about a high performance wing may take numerous hours to solve. If the optimiser were to perform many hundred such solutions, the total time taken to optimise the wing could extend to weeks. Many methods have been proposed to minimise this computational expense such as Design of Experiments (DOE) by Giunta [6] or approximation and variable fidelity models by Coello [7], Deb [8] and Kim [9].

While the field of single objective optimisation has received much interest over the years and the tools have matured, multiple objective MDO tools are mostly in their infancy and suffer robustness issues as noted by Alexandrov [10]. Sobieszczanski-Sobieski [11] and Barholomew [12].

To date, traditional deterministic optimisers have found the widest application when optimising aeronautical vehicles. These deterministic methods are efficient but require that the objective function is differentiable. If the objective function is noisy, non-differentiable or involves approximations, a different robust method is required.

A relatively new optimisation method, Evolutionary Algorithms (EAs), models the Darwinian theory of evolution where populations of candidate solutions evolve in the search space adapting to the environmental constraints placed upon them. In nature, mutation, cross-over and selection are used to evolve one generation from another and it is these same mechanisms which are employed within EAs to evolve candidates over time. EAs have many advantages over traditional deterministic optimisers in that they do not require the calculation of objective function derivatives and are very good at finding global minima in a highly oscillatory environment with many local minima. EAs are easily executed on a parallel computing network and can be made 'black-box' optimisers meaning the optimiser does not require any problem specific knowledge to find a solution. The above advantages coupled with an EAs ability to tackle multi-objective problems directly gives them substantial advantages over traditional deterministic optimisers.

Interest in EAs has grown over the last 15 years though the application of EAs for MDO has been limited. Although EAs have been successfully applied to many aeronautical problems [13-17], when coupled with MDO the number of function evaluations required before the global minima is found has been too large for feasible applications. A continued challenge within evolutionary optimisation has been in increasing the rate at which the global minima is found.

1.2 AIM

The aim of this thesis is to address the issue of High and Medium Altitude Long Endurance (HALE and MALE) UAV wing conceptual design from a multi-objective and MDO standpoint through the optimisation of two vehicle wings. Different fidelity models along with parallel implementation of an evolutionary algorithm and multiple physics models are coupled within the MDO framework to reach a solution.

1.3 OUTLINE

This thesis describes the theory and application of a method for multi-objective multidisciplinary design of UAV wings. The method is based on a unique coupling of a robust evolutionary optimiser to an aero-structural solver.

The evolutionary optimiser makes use of parallel computing, asynchronous evaluation and a hierarchy of different fidelity solvers that reduce the overall computational cost for multi-objective and MDO problems. The evolutionary optimiser method is applicable to single and multi-objective, inverse or direct complex engineering problems that can be multi-modal, involve approximations, are non-differentiable, with convex, non-convex or discontinuous Pareto optimal fronts.

The aero-structural solver makes use of a CFD program, PanAir and a structural program, MSC.Nastran®, to compute the fitness of an optimiser produced candidate wing.

Chapter 2 of this thesis describes the concept of multidisciplinary design optimisation; and the method employed in this thesis. Chapter 3 details the Evolutionary Optimiser; Chapter 4 details and tests the aero-structural solver for two baseline designs. Chapter 5 details the aero-structural optimisation process and Chapter 6 presents the application of the method for two test cases related to aero-structural UAV wing design optimisation. Conclusions are drawn in Chapter 7 and possible further extensions to both the aerodynamics and structural components of the simulation method are detailed in Chapter 8. The appendices are listed after the Bibliography.