

HIGH-DIMENSIONAL BAYESIAN CONTROL CO-DESIGN OPTIMISATION FOR CONSTRAINED AEROELASTIC TAILORING OF FLEXIBLE AIRCRAFT

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ABSTRACT

Modern wing designs have a higher aspect ratio for increased aerodynamic efficiency, but this introduces new challenges in structural flexibility and aeroelastic behaviour. A flexible wing has significant coupling between the control and structural systems. Traditional design approaches follow a sequential or iterative approach and do not account for couplings between the system's inherent dynamics and active control. Control Co-Design Optimisation (CCDO) utilises this bi-directional coupling to create an integrated structural and control design procedure that achieves a globally optimal design. We apply CCDO to the aeroelastic tailoring problem through an optimal Linear Quadratic Regulator (LQR) controller and exploiting the anisotropic nature of Carbon Fibre Reinforced Polymers (CFRP) to tailor the wing's lamination parameters and thicknesses. To address the high dimensionality and non-convexity of the design space, a global optimisation strategy, Autoencoder-Enhanced Joint Dimensionality Reduction for Constrained-Bayesian Optimisation (AERO-BO), is extended to CCDO. The achieved design yields a lighter wing than sequential design approaches. To the author's knowledge, this is the first application of BO-CCDO for aeroelastic tailoring and the joint optimisation of a dynamic control law and structural parameters. The result is a framework to advance aeroelastic co-design for the new generation of high-aspect-ratio flexible wings.

1 Introduction

Aeroelastic tailoring is generally performed in the absence of control, with limited work done in incorporating active control. Robust and LQR-synthesised CCDO for aeroelastic tailoring have been performed, but with low-dimensional structural parameters. Furthermore, all employed local gradient-based optimisers, which can lead to suboptimal convergence due to non-convexity. Binders et al. (2021) [1] provided the best implementation of CCDO for aeroelastic tailoring, combining structural tailoring with idealised feedforward control. However, the structural search space (78 parameters) is smaller than that of a lamination-parameter-based approach, and the controller is non-feedback. To summarise, current CCDO applications for aeroelastic tailoring lack a global optimiser and scalability to high-dimensional problems.

BO is a global optimisation solution used to avoid premature convergence. As a gradient-free algorithm, it can work with non-differentiable simulators and controllers, as well as with discrete and continuous decision variables. It has been applied in the CCDO domain, with a single example of a BO plant-synthesis outer loop with an Optimal Control Problem (OCP) inner loop [2]. This approach used a design-evaluation approach, employing a Nonlinear Model Predictive Controller (NMPC) to evaluate the design with fixed cost matrices, and thus fixed control parameters.

The curse of dimensionality affects all optimisation problems, with increasing dimensionality having an exponential impact on solution tractability. It has been argued that many problems have a smaller intrinsic dimension. Maathuis et al. (2025) [3] developed AERO-BO, a high-

dimensional BO framework for large-scale constraints that uses autoencoders for joint dimensionality reduction, and successfully applied it to passive aeroelastic tailoring, where it outperformed COBYLA. AERO-BO is extended here to CCDO. The active control is performed via a feedback control synthesised via an LQR, as this solves the OCP for a linear-time-invariant system. This work aims to answer the question of how a global optimisation CCDO framework decreases the wing mass compared to traditional design methodologies.

2 Methodology

PROTEUS is an aeroelastic analysis software that performs analyses across multiple load cases to ensure the design meets constraints on lamination feasibility, strength, buckling, flutter, divergence, aileron effectiveness, and stall angle. The CCDO framework is run within PROTEUS to evaluate the design.

Nonlinear static and linear dynamic analyses are conducted to evaluate aeroelastic constraints; these are augmented to include the feedback gain matrix, as shown in Figure 1. A cross-sectional modeller uses ABD matrices derived from lamination parameters and thicknesses to construct a Timoshenko cross-sectional stiffness matrix, which serves as the basis for a non-linear model. The linear dynamic model is obtained by linearising the non-linear model around its static equilibrium. The resulting state spaces synthesise the feedback gain matrix with the optimised cost to enable closed-loop analysis. The optimiser uses AERO-BO to compute the lamination parameters and thicknesses, and the control weighting matrix.

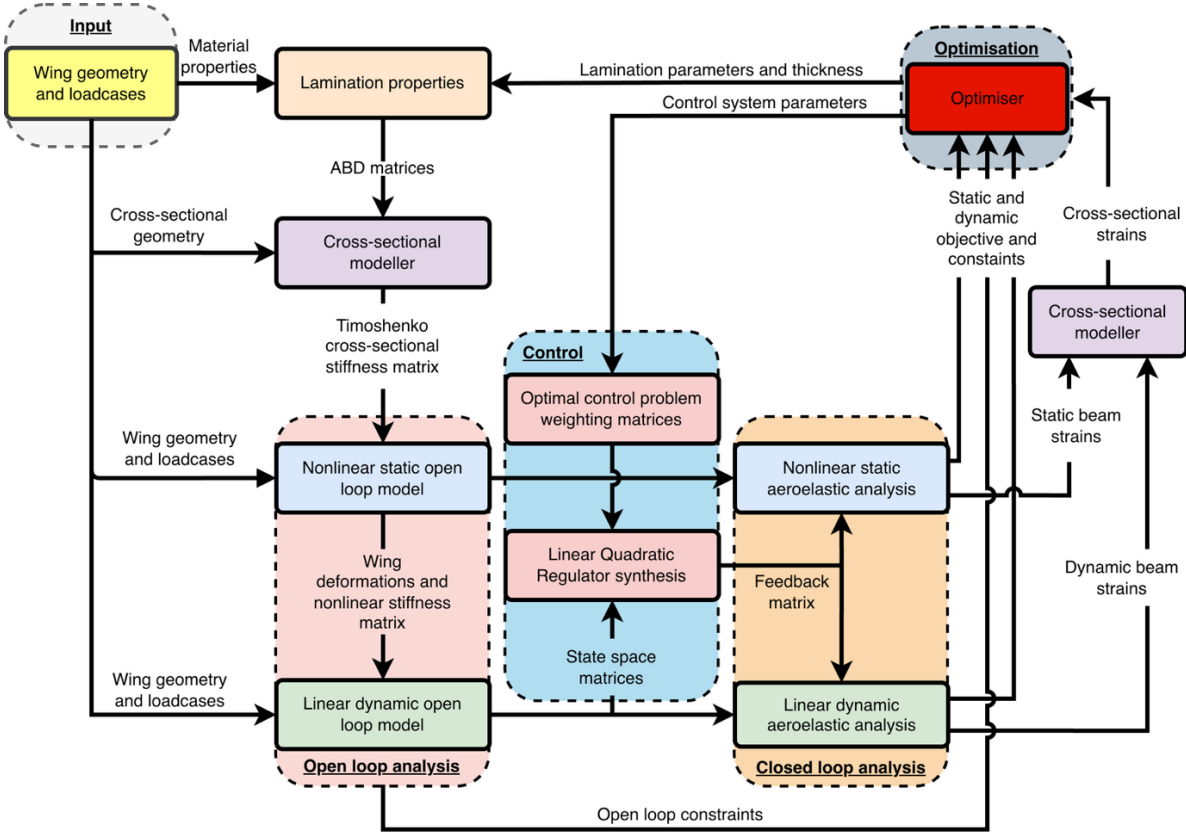


Figure 1. A flow diagram of CCDO implemented in PROTEUS, adapted from [4].

3 Results

The finalised expected results include:

- Line graphs comparing a CCDO and a sequential approach, with the number of

evaluations on the x-axis, and wing weight and constraint satisfaction on the y-axis.

- A table showing the final weight reduction for each structural component.

4 Conclusion

To the best of the author's knowledge, this is the first application of BO-CCDO for aeroelastic tailoring, and the first application of using BO to optimise both a dynamic control law (through the LQR's cost matrices) and structural (plant) parameters. This is motivated by the goal of obtaining a global minimum and by the ability to be applied to non-differentiable models and controllers, unlike local gradient-based methods. AERO-BO is extended to CCDO to enact it in a higher-dimensional space, avoiding CCDO studies. As a result, a framework for a globally optimal CCDO in a high-dimensional input space with large constraints is created. The future goal is to provide a unified approach to CCDO for aeroelastic tailoring by applying more advanced control systems, such as MPC and Incremental Nonlinear Dynamic Inversion (INDI).

5 REFERENCES

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