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Multidisciplinary design, analysis and optimization of fixed-wing airborne wind energy systems

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Abstract. Airborne wind energy (AWE) is the second generation of wind energy systems, an innovative technology which accesses the large untapped wind resource potential at high altitudes. It enables to harvest wind power at lower carbon intensity and, eventually, at lower costs compared to conventional wind technologies. The design of such systems is still uncertain and companies and research institutions are focusing on multiple concepts. To explore the design space, a new multidisciplinary design, analysis and optimization framework for fixed-wing airborne wind energy systems (T-GliDe) is being developed. In this work, the framework of T-GliDe and its problem formulation are introduced.

Introduction

Airborne Wind Energy (AWE) refers to the field of wind energy in which tethered airborne systems are used to harvest wind power at high altitudes. Compared to conventional wind energy, AWE opens new areas for energy from wind, offers increased energy generated per square kilometer, has the potential to provide energy at lower cost and has lower environmental impact [1].

Airborne Wind Energy Systems (AWESs) are typically classified based on their flight operations, which can be crosswind, tether-aligned and rotational as described by Vermillion at al. [2]. Electric power is generated with onboard wind turbines and transferred to the ground through the tether (Fly-Gen) or generated directly on the ground by a moving or fixed ground station (Ground-Gen). This work focuses on crosswind AWESs and the results are applicable to both Ground-Gen and Fly-Gen systems which are characterized by a single fixed wing.

The design of such systems is still uncertain and companies and research institutions are focusing on multiple concepts. To explore the design space and perform a robust design, the usage of MDAO techniques is crucial. This paper aims at introducing the underdevelopment MDAO framework T-GliDe (Tethered Gliding systems Design) [3] and the related problem formulation.

T-GliDe architecture and problem formulation

T-GliDe features an optimization module and an uncertainty quantification module, allowing for a number of algorithm-based design techniques (Fig. 1). The disciplines currently involved are related to the flight dynamics [4], to the optimal control [5], to the structural design, to the aerodynamics [6] and to the economics [7].

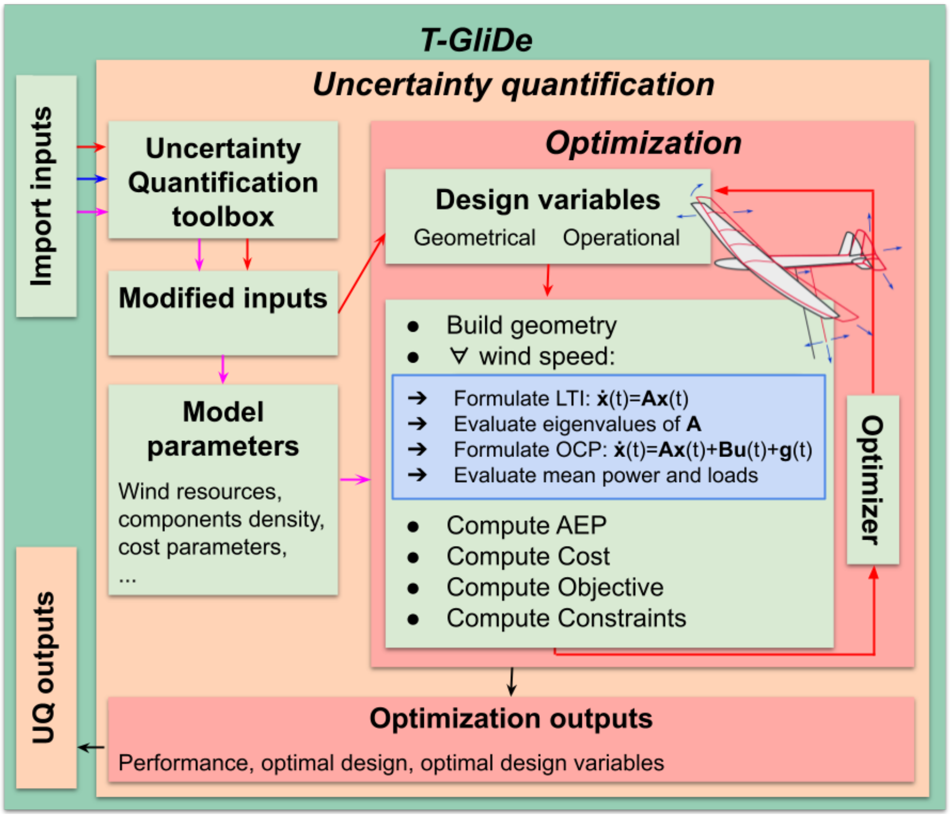

Figure 1: T-GliDe architecture.

The flight dynamics is modelled by linearizing the 6 d.o.f. equations of motion about a fictitious steady state on the circular trajectory where the fluctuating terms $\boldsymbol{g}(t)$ (e.g. gravity) are treated as disturbances. In this way, the dynamics is reduced to a linear time-invariant system

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) \tag{1}$$

and the eigenvalues of $\boldsymbol{A}$ are designed to be stable by the optimizer.

The fluctuating terms and the control inputs $\boldsymbol{u}(t)$ are added to formulate the optimal control problem (OCP)

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{g}(t). \tag{2}$$

Since the OCP is periodic for a steady inflow, it is solved in the frequency domain, reducing the problem size and enhancing the physical understanding of optimal trajectories. Small circular-shaped trajectories, obtained by decreasing the airborne mass, are found to be beneficial for the dynamics, as they decrease the gravitational potential energy exchange over the loop.

Tight trajectories, however, increase the aerodynamic induction and thus decrease the aerodynamic power potential. To model this, an analytical vortex-based aerodynamic model, validated with the lifting line free vortex wake method implemented in QBlade [8], is included. These disciplines are coupled to an underdevelopment economic model based on companies' data.

The optimization problem is being built with a monolithic architecture in a "all-at-once" fashion [9], employing a gradient-based algorithm with algorithm differentiation for the derivative calculation. The uncertainty quantification module allows to study how the optimization problem is influenced globally by uncertainties in the model parameters and in the modelling, to achieve a robust design.

Both Ground-Gen and Fly-Gen Airborne Wind Energy Systems (AWESs), with fixed wing, can be designed with T-GliDe. The optimal designs are expected to perform well in the energy market, while having good dynamic qualities which could enable “soft” trajectories and relieve the control system in presence of turbulence and gusts.

Summary

In this work, the underdevelopment MDAO framework T-GliDe (Tethered Gliding systems Design) and the related problem formulation are introduced. T-GliDe features an optimization module and an uncertainty quantification module, allowing for a number of algorithm-based design techniques. The disciplines currently involved are related to the flight dynamics, to the optimal control, to the structural design, to the aerodynamics and to the economics. T-GliDe will be used to explore the design space and achieve robust conceptual designs of fixed-wing crosswind AWESs.

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