Determination of Optimal Control Laws in Airborne Wind Energy Scenarios With a Self-Consistent Kite Dynamics Model

D. Expósito[1], M. Soler[1] G.Sanchez-Arriaga[1]

[1]Universidad Carlos III de Madrid, Spain

Introduction.

In the reel-in and real out phases of \emph{yo-yo} airborne wind energy generation schemes, appropriate control laws should be imposed to the lengths of the bridle and the main tether of a power kite. The determination of the optimal control laws that maximize the energy production for a given wind conditions is a complex problem that requires a kite flight simulator and robust and efficient optimization algorithms. This work makes use of a recently proposed kite flight simulator based on Lagrangian formulation that explicitly removes the tension force from the equations of motion. Although being a low-order dynamical system with only five degrees of freedom, the simulator captures self-consistently the dynamics of the full system (kite, bridle and tether) and provides a reliable framework with a moderate computation cost. Optimal control laws for the lengths of the three lines of the bridle and the tether are determined by embedding the kite flight simulator in a homemade optimal control library. The continuous-time optimal control problem is transcribed into a nonlinear programming problem using a collocation method and imposing periodic boundary conditions for the trajectories. The optimal open-loop control laws that maximize the generated power were determined by using an interior point solver. Preliminary results are presented in this poster

- Objective (Max. Energy)
- Dynamics
- Eq. & Ineq constraints
- Boundary conditions
- Initial Guess

→

Solution

Optimal Control law: X_C*

Optimal Evolution of States: X_S*

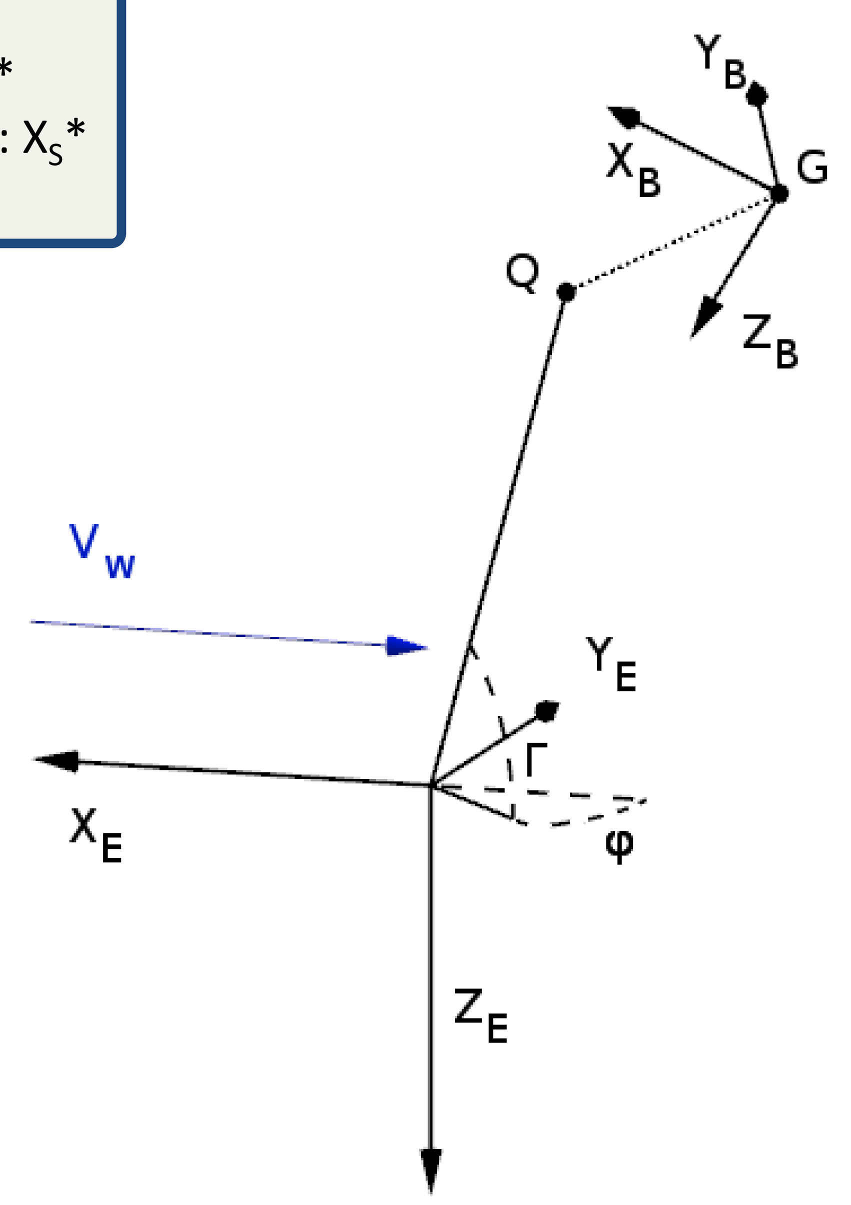
State Vector:

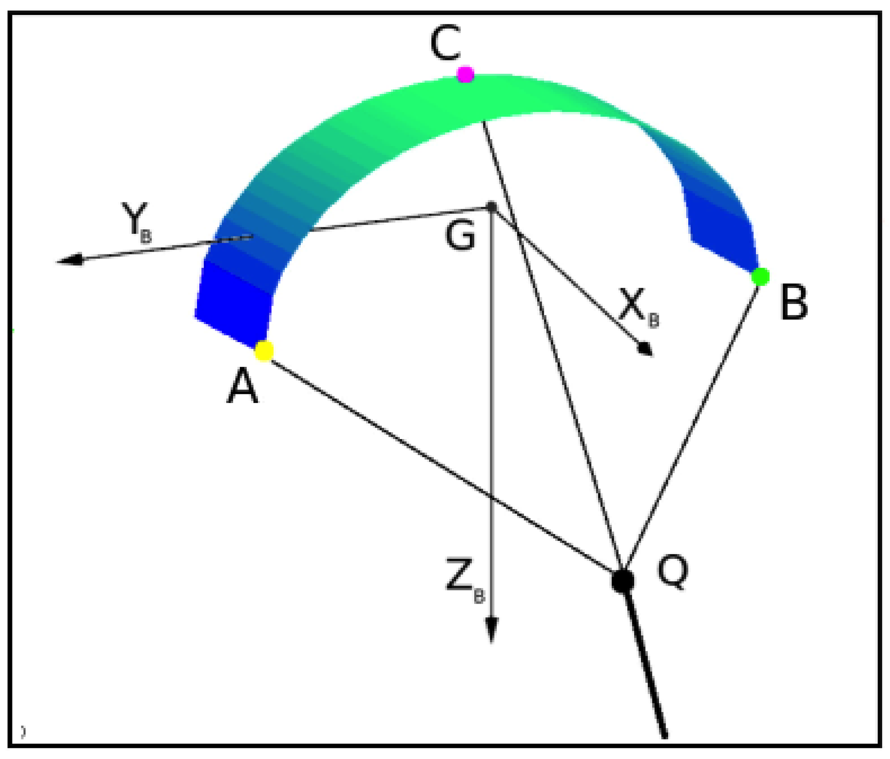
$X_s = [\Gamma, \theta, \Phi, \psi, \phi]$

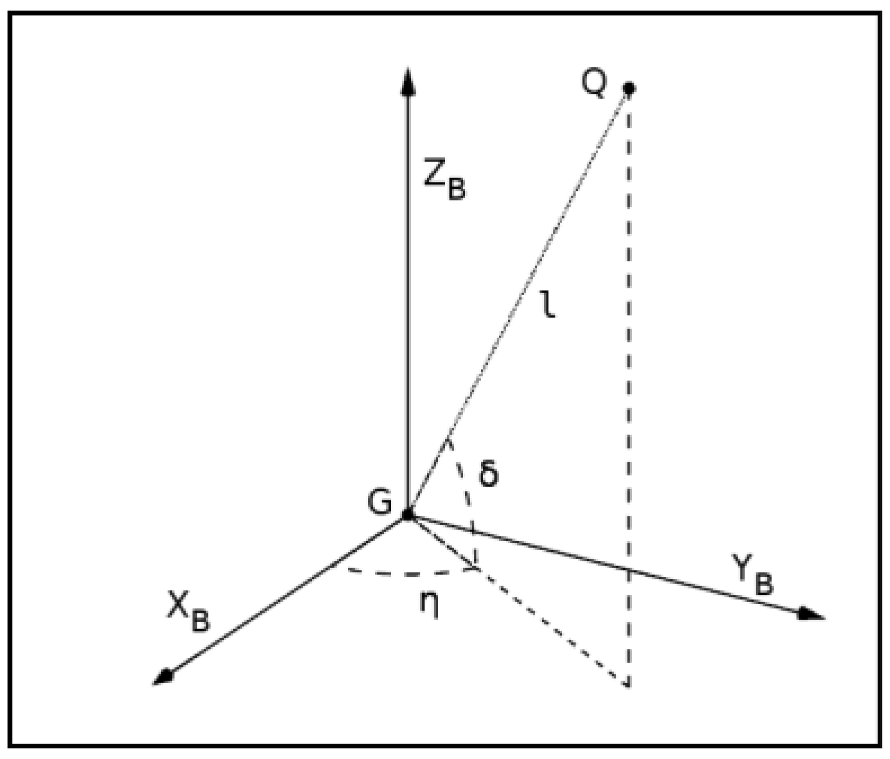
Control Vector:

$X_c = [L, l, \delta, \eta]$

- Language: Python
- Library: Pocapy
  - Open (soon)
  - Developed @ UC3M
  - Direct Collocation
  - Pyomo
  - NLP Solver: IPopt







Case study: For the sake of illustration, the problem has been firstly solved in 2D (the complete 3D problem is on going work). The states are thus Γ and θ (and its first derivatives, being the dynamical system of second order) and the controls L and δ (and its first and second derivatives). The dynamical model of the kite can be consulted in Ref [1]. The control scheme proposed in Ref [1] is used as initial guess for the Optimal Control Problem. Two phases are set: a reel-out (in which winch speed is enforced to be positive) and a reel-in (in which winch speed is enforced to be negative). The initial conditions (except time, which is set to zero) are to be determined by the optimizer, imposing the solution to be periodical, i.e., finale conditions equal to initial ones. Finale time is bounded between 9 and 13.5. The solution is obtained for one hundred discrete points (50 per phase). A second order collocation scheme is used to transcribe the problem into a NLP one.

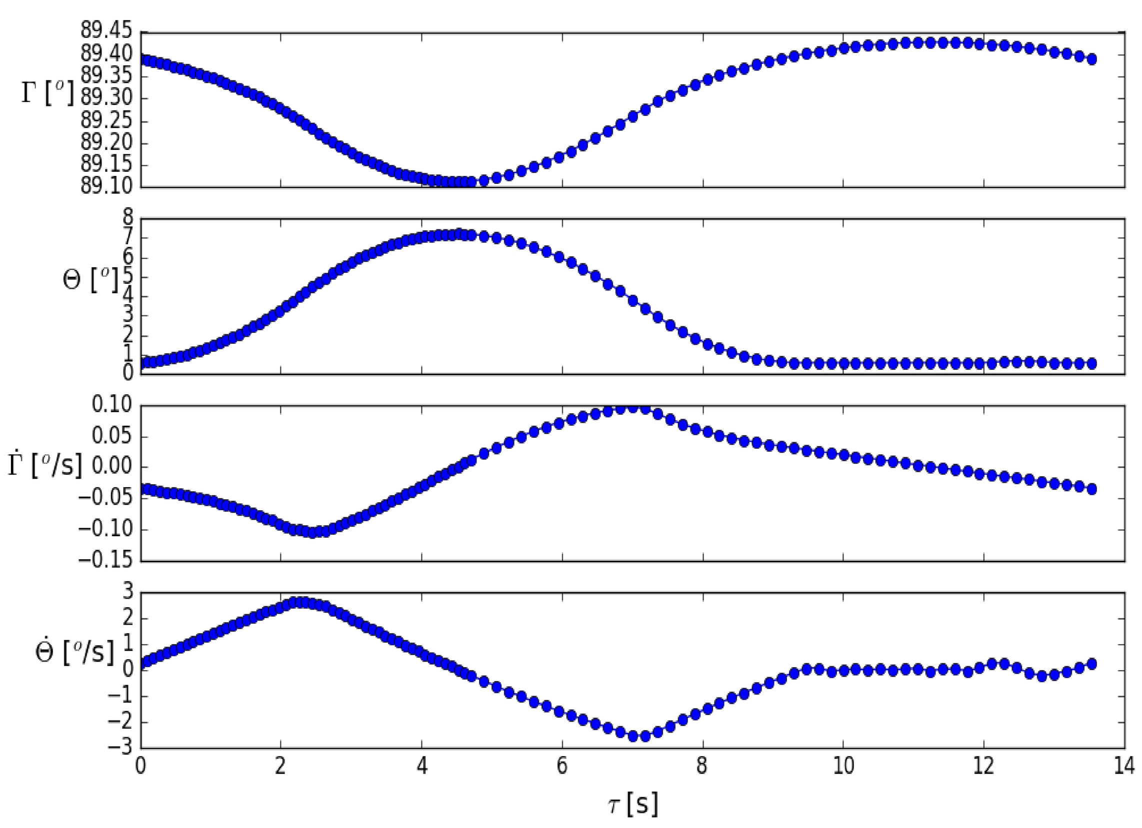


Fig. 1. Evolution of States variables.

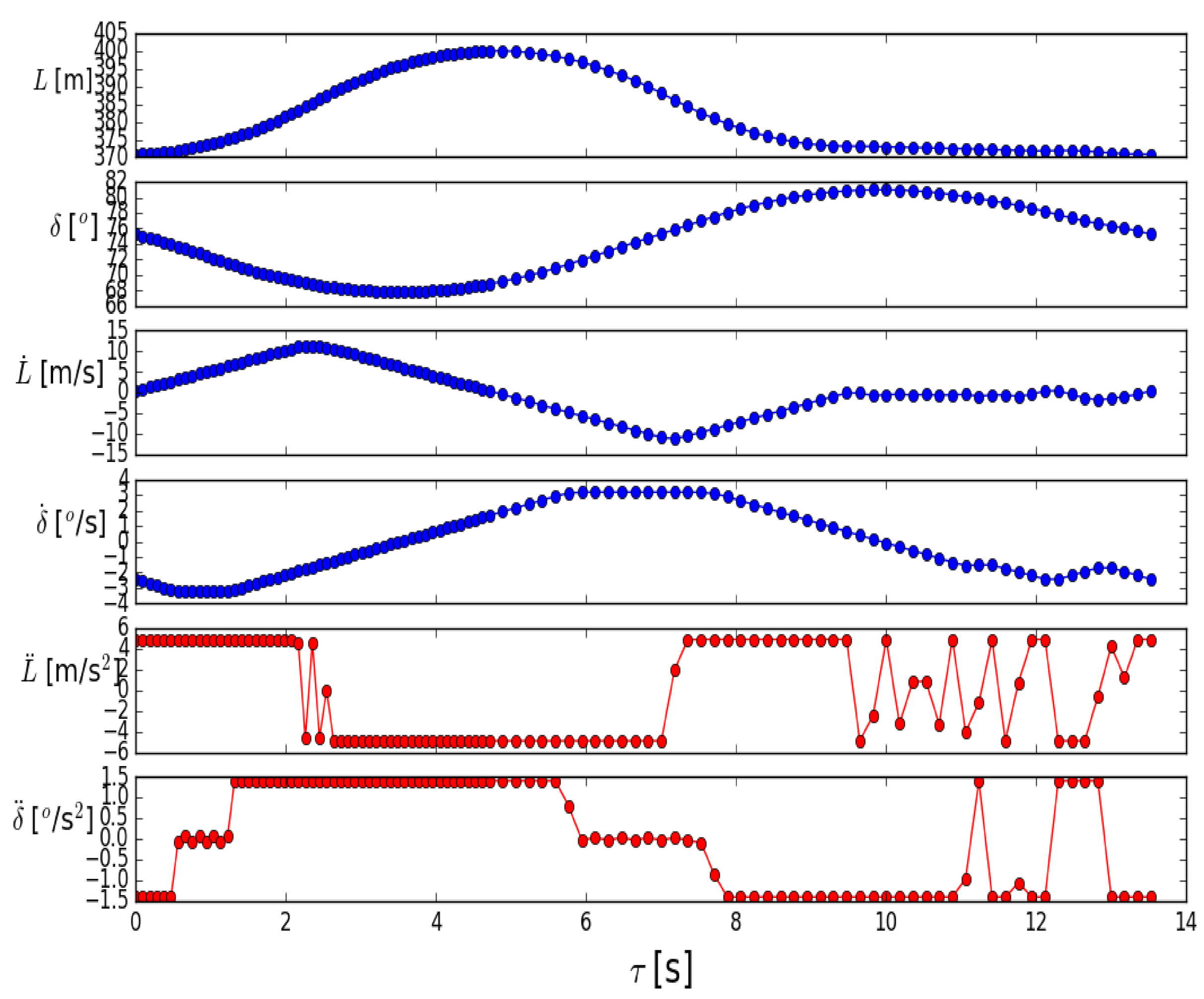


Fig. 2. Evolution of control variables. Notice that it is a second order control system. Only the second derivative acts a real control in the optimal control problem.

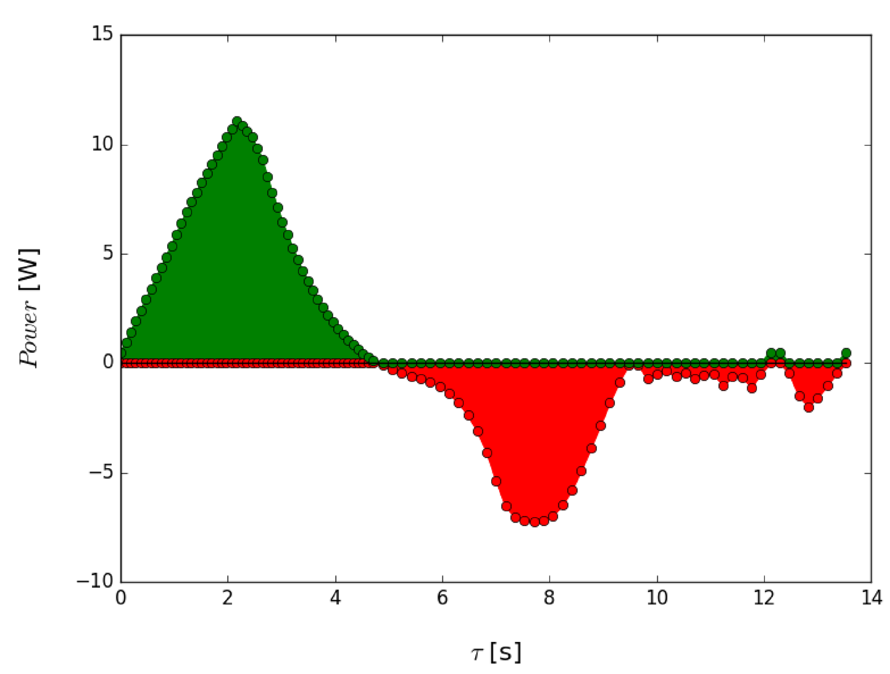


Fig. 1: Power during the cycle. The green area represents the energy (produced) during the reel-out phase, the red area represents the enegy (consumed) during the ree-in phase.

Results: First, notice the reader that the 2D solution is not expected to provide much energy, on the contrary the purpose is to show the different algorithms work. The obtained results show the expected behaviour, with a net energy balance of roughly 6 J. It should be remarked that the last part of the cycle (where the solution wiggles a little bit) is explained by the constraint that enforces the solution to be periodical (finale values equal to the initial ones). This also results in some extra consume of energy. Besides that, the controls behave bang-bang, and the states (notice that L, δ, and its first derivatives act in the problem as auxiliary state variables) behave rather smoothly.

References: [1] *J. Alonso-Pardo and G. Sánchez-Arriaga: Kite Model with Bridle Control for Wind-Power Generation. Journal of Aircraft (3), 917- 923 (2015)*

Acknowledgments: This work was developed with the support of Ministerio de Economía y Competitividad of Spain and the European Regional Development Fund under the project ENE2015-69937-R (MINECO/FEDER, UE). G.S.A was supported by the Ministerio de Economía y Competitividad of Spain (Grant No RYC-2014-15357)