Universidad
Carlos III de Madrid

Simulation and Experimental Research Activities on Airborne Wind Energy Systems at UC3M

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Aero

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Introduction

Short Bio

- **2004**, Minor Thesis (B.S. Aerospace Engineering) on a kite flight simulator based on lagrangian formulation (Journal of Aircraft, 2006).

- **2004-2009** PhD on space tethers and nonlinear waves in plasmas

- **2009-2011** Postdoc on laser/plasma interaction (CEA, Paris)

- **2012-2015** Assistant Professor at UPM: tethers + plasmas + AWE systems.

- **2015 – now** Ramón y Cajal Research Fellow at UC3M.
  - *New group in Space Tethers*: one project funded by the Spanish Goverment. Two failed proposals: StG ERC A-ranked but not funded (1.5M€) and coordinator of a FET-OPEN proposal in the reserve list (3M€).
  - *AWE Systems*: 2015-2016 project funded by Fundación BBVA (40k€).
    2016-2018 project funded by Spanish Goverment (44k€).
  - *Plasmas*: electric propulsion (H2020 project MINOTOR)

Introduction

Framework of the visit

- The visit has been funded by the Ministry of Economy of Spain under the project "Simulation and Flight Testing of Power Kites Applied to Wind Energy Generation". 44k€. 2016-2018.

- The project has three objectives:

  - Develop numerical tools for the simulation of Airborne Wind Energy Systems (AWEs).
  - Give the (very) first steps toward a technology demonstrator -> Flight Testing.
  - Disseminate AWEs in Spain and make networking with consolidated groups.

- Participants: Dr. G. Sánchez-Arriaga (UC3M, PI), Mr. R. Borobia-Moreno (INTA), and Dr. R. Schmehl (TU Delft)

Simulation

2.1 Development of kite simulators

Introduction

- The modellization and dynamic simulation of AWEs are complex tasks because they involve several interlinked bodies, aerodynamic models, optimal control laws determination,….
- The design of AWEs is an iterative process that may involve simulators with different degrees of complexity and accuracy.
- Attention should be paid to the tether because realistic values of the Young's modulus yields to stiff equations.
- There are three approaches
  - Work with the stiff equations (use implicit integrators and solve a heavy problem).
  - Use non-realistic values for the tether stiffness (normally used by lumped-mass-models).
  - Take the infinite stiffness tether limit (bar-models)

2.1 Development of kite simulators

Bar-Based Kite Simulators

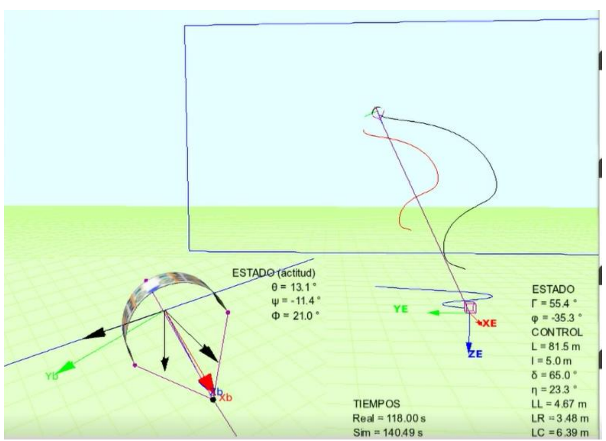
- Advantages:
  - The fast longitudinal oscillations of the tethers are eliminated.
  - The resulting set of equations have a good behavior (non stiff).
  - The results are reliable because real tether stiffness is very high.
- Disadvantages:
  - The implementation is not straightforward (see below).
  - Rigid kites with more than three tethers are hyperstatics (more unknowns than equations).

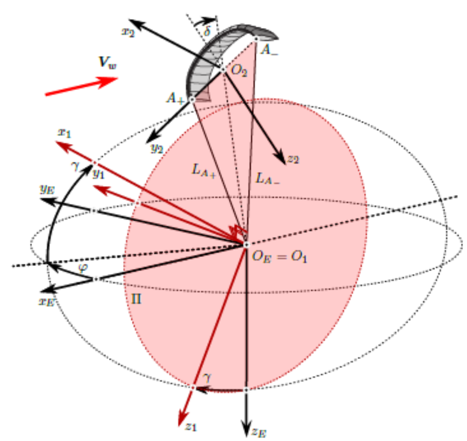
Implementation of Bar-Based Kite Simulator

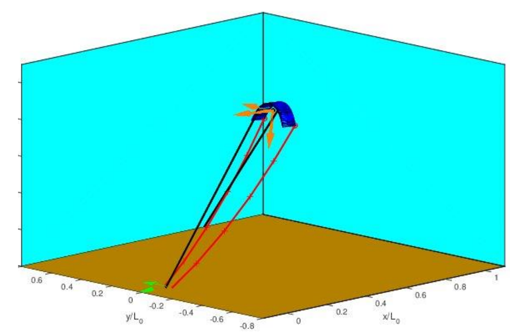
- Classical Mechanics: Newton Law + Constraints
  - Easy implementation but ODEs + Nonlinear Algebraic Equations.
- Analytical Mechanics: Euler-Lagrange or Hamilton Equations
  - Hard implementation but just ODEs.

LAKSA SIMULATION PACKAGE

	KiteFlex	KiteAcrobat	KiteSurf	KiteTrain	KiteElastic
System	Rigid Aircraft 1 flexible tether, bridle, generators	Rigid Aircraft 2 inelastic tethers	Rigid Aircraft 2 rigid + 2 elastic tethers	N Aircraft 2N rigid tethers	Arbitrary number of aircraft and tethers
Language	Matlab,Fortran Paralelizado	Matlab	Matlab	Matlab	Matlab
Application	FlyGen & GroundGen	Traction	UC3M Experimental Setup	FlyGen	Generic Systems

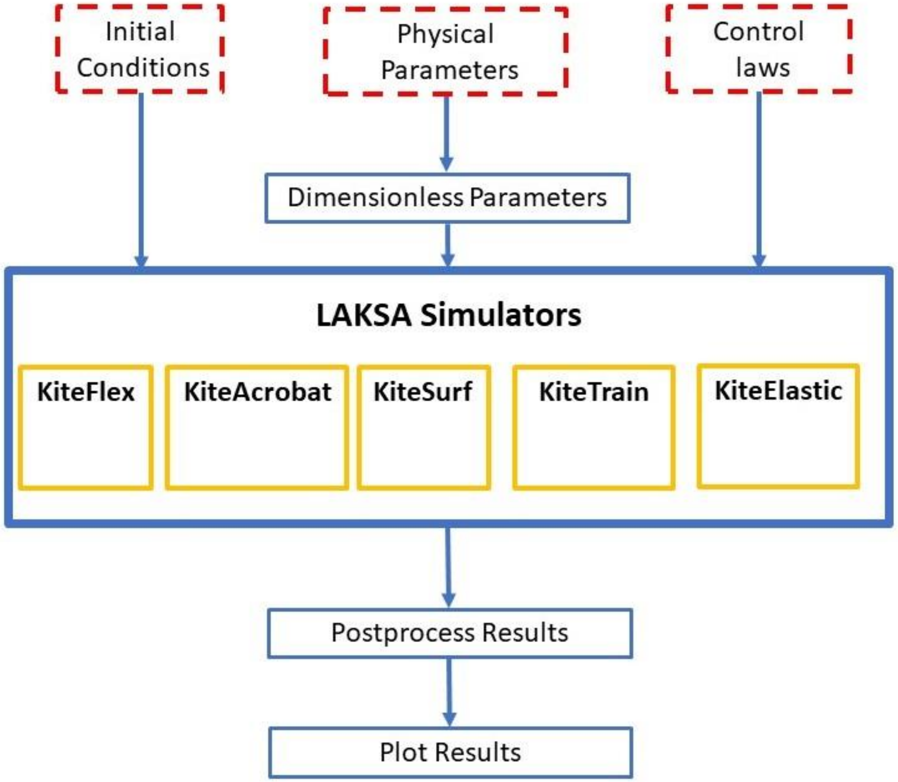






LAKSA is available at https://github.com/apastor3/laksa

LAKSA Architecture



Wish list	LAKSA Solution
Robust	Lagrangian + Minimal coordinate approach (pure system of ODEs)
Non-stiff	Inelastic tethers (fast longitudinal oscillations are removed)
Efficient	The ODEs were found analytically
Reliable	The code passed through several tests

Flight Testing

2.2 Flight Testing

- Short term goals:
  - get real data about the state of the kite and the tethers.
  - get knowledge on experimental activities.
- Medium-term goals:
  - mix real data and simulations to characterize the aerodynamic coefficients of the kite (estimation-before-modeling technique).

2.2 Flight Testing

On-board instruments:

- Inertial navigation unit (GPS, accelerometer, gyroscopes)
- Pitot tube.

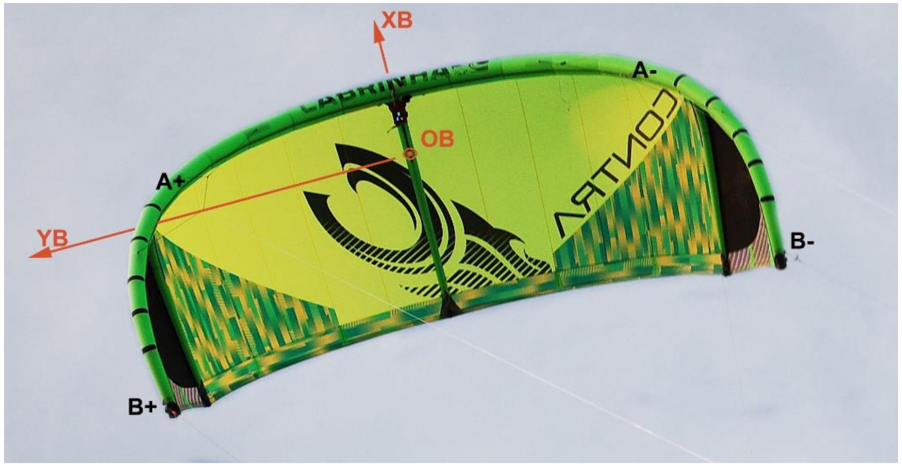
On-ground instruments:

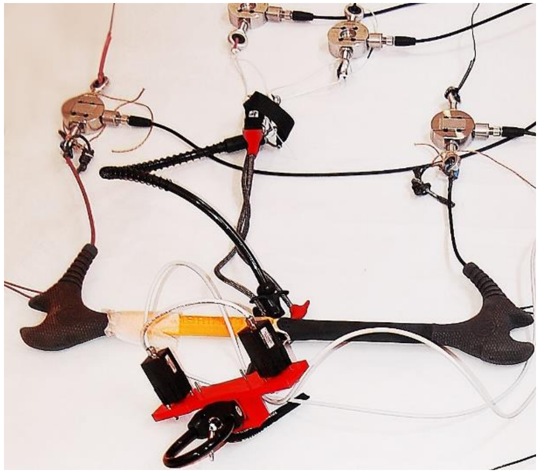
- Load cells
- Position sensors
- Weather station

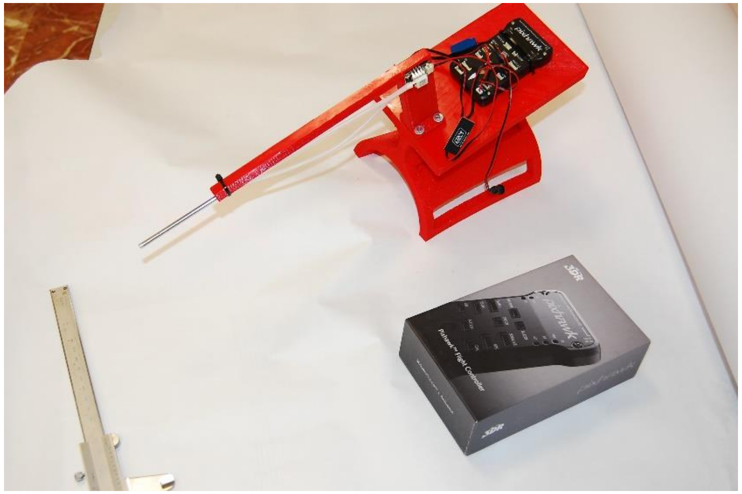
Methodology:

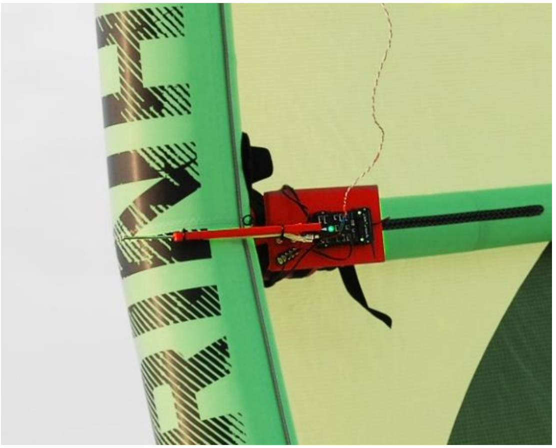
- Iterative process: starting with cheap and low-quality sensors followed by upgrading phases.
- We are now working with the second iteration.

2.2 First iteration

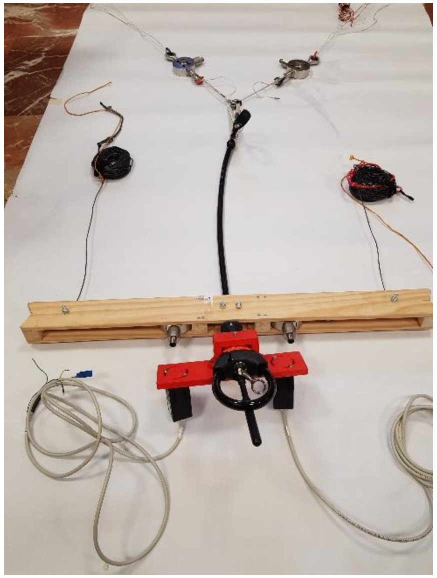




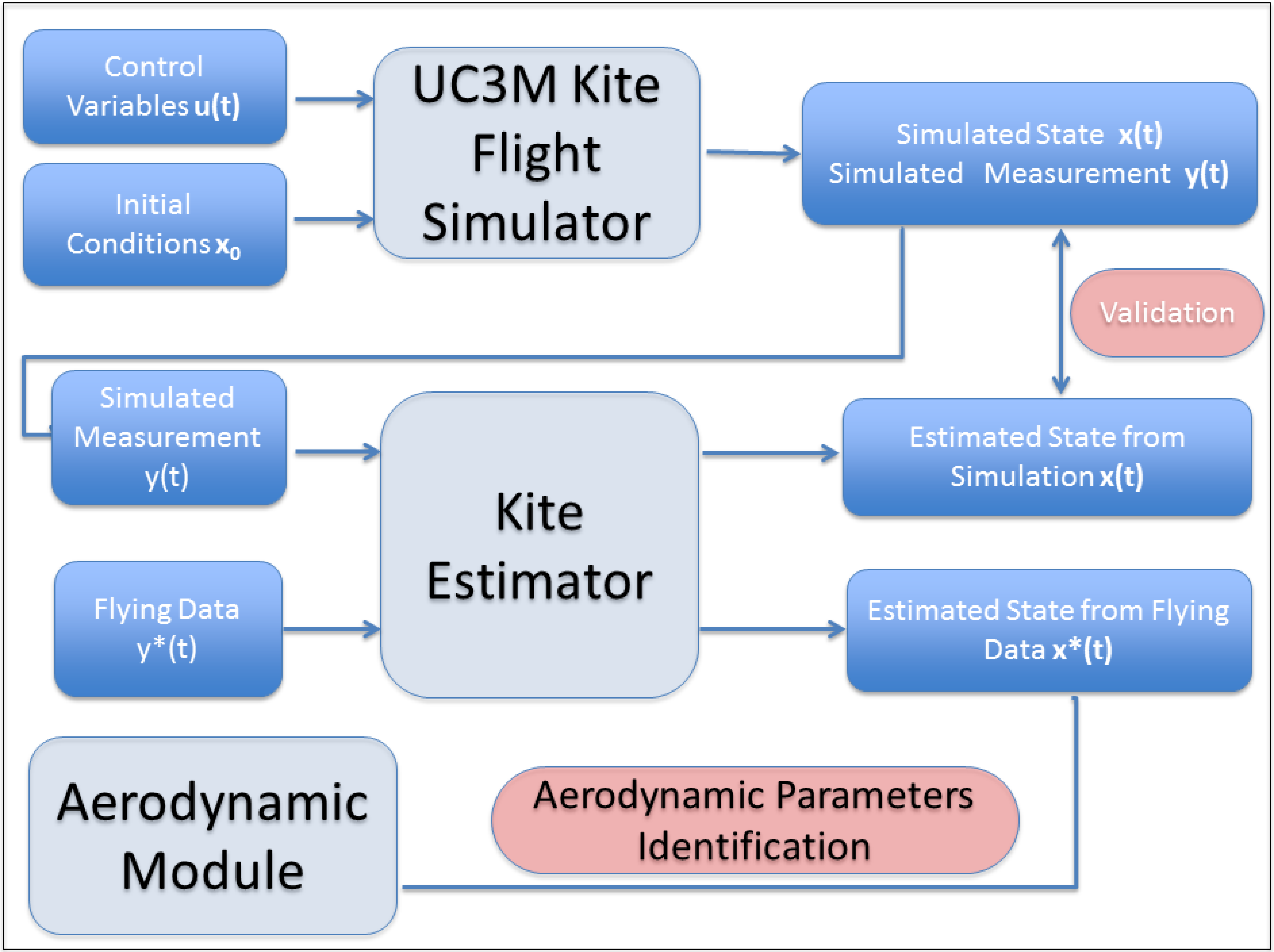




2.2 Second Iteration



2.2 Second Iteration


Control Variables u(t)
Initial Conditions x_0
UC3M Kite Flight Simulator
Simulated State x(t)
Simulated Measurement y(t)
Validation
Simulated Measurement y(t)
Kite Estimator
Estimated State from Simulation x(t)
Flying Data y*(t)
Estimated State from Flying Data x*(t)
Aerodynamic Module
Aerodynamic Parameters Identification

Dissemination

2.3 Dissemination and networking

- Spain has started late the research on AWEs.
- Apparently, UC3M is the only active group on AWEs in Spain.
- One of the goals of the project is to disseminate AWEs technologies among both general public, students, and scientific audience.
- Up to now the project has connected UC3M with several institutions (TU Delft, University of Freiburg, INTA, Politecnico of Torino, and Kyushu University).
- The following actions were carried out:
  - Organization of an exposition at Semana de la Ciencia de Madrid 2016 (also in November 2017).
  - 1 ongoing PhD thesis, 2 Master thesis, and 6 B.S thesis.
  - Mr. Hiroki Endo Kyushu Sangyo University visited us in 2017.
  - Dr. Antonello Cherubini visited us in 2017 and delivered a course.

3. Objectives of the visit and work plan at University of Freiburg

- **Objectives of the visit:**
  - Interact with researchers from University of Freiburg, share information, and look for sinergies.
  - Get your first-hand opinion about our simulators.
  - If you wish, share with you our Matlab codes and give support on how to use them.

- **Work Plan is open but there are already some ideas….**
  - Comparison of LAKSA modules with your code (efficiency, computational cost, robustness, ….)
  - Link LAKSA with close-loop controllers and optimal solvers.

Publications on AWE Systems

1. G. Sánchez-Arriaga. Dynamics and control of singled-line kite. The Aeronautical Journal, 2006.
2. L. Salord and G. Sánchez-Arriaga. Flight dynamics and stability of kites in steady and unsteady wind conditions, J. Aircraft 52, 660-666, 2015
3. J. Alonso Pardo and G. Sánchez-Arriaga. A kite model with bridle control for wind power generation, J. Aircraft 52, 3, 917-923, 2015.
4. A. Pastor-Rodríguez, G. Sánchez-Arriaga, M. Sanjurjo-Rivo, Modeling and Stability Analysis of Tethered Kites at High Altitudes, J. of Guidance, Control, and Dynamics, 40, 8, 1892-1901, 2017.
5. G. Sánchez-Arriaga, M. García-Villalba, and R. Schmehl, Modeling and Dynamics of a Two-Line Kite, Applied Mathematical Modelling 47:473–486, 2017.
6. G. Sánchez-Arriaga, A. Pastor-Rodríguez, R. Borobia-Moreno, and R. Schmehl, A constraint-freeflight simulator package for airborne wind energy systems, Journal of Physics Conf. Series, 062018, 2018.
7. R. Borobia-Moreno, G. Sánchez-Arriaga, A. Serino, and R. Schmehl, Flight Path Reconstruction and Flight Test of Four-line Power Kites, Journal of Guidance, Control and Dynamics, 2018.
8. A Lagrangian Flight Simulator for Airborne Wind Energy System, G. Sánchez-Arriaga, A. Pástor-Rodríguez, M. Sanjurjo-Rivo, and R. Schemehl, submited.

* Find these papers in ResearchGate.