Federal University of Santa Catarina – UFSC
Technological Center – CTC
Department of Automation and Systems – DAS

Master Thesis Proposal

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Design of an electric energy generation system aboard a tethered airfoil

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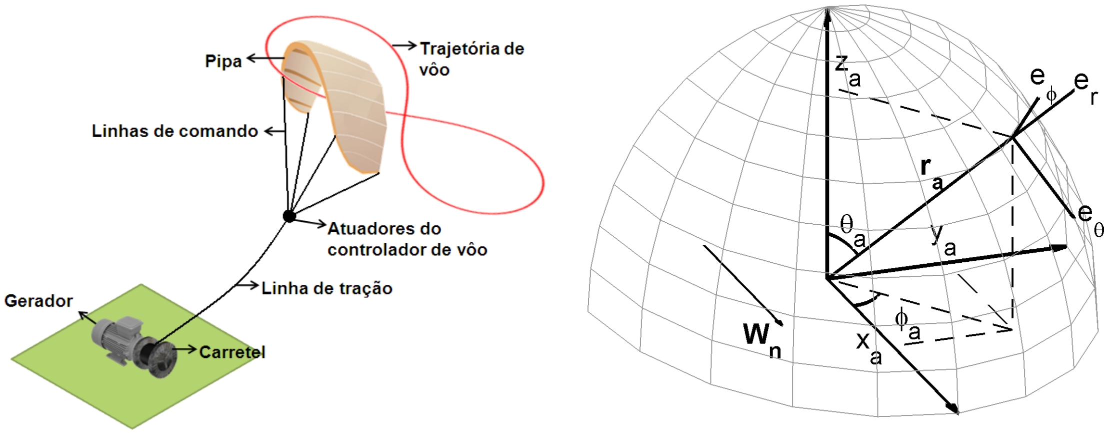
1 Introduction

Tethered airfoils have been investigated in the past decade as a technically feasible means for exploiting the wind energy at a lower cost than conventional horizontal-axis wind turbines. Such new approach is a branch of the so-called Airborne Wind Energy (AWE) technology [9]. Besides the cost advantage, the use of tethered airfoils enables tapping into the wind energy at higher altitudes, where the wind blows stronger and steadier [1]. Among the several mechanical configurations proposed thus far, the Pumping Kite (PK) has been the most investigated one in the literature, probably due to its simple concept, making it easier to experiment with at these early stages of AWE Research & Development.



(a) Airborne and ground-winch parts.

(b) Wind window and coordinate systems.

Figure 1: Pumping Kite (PK) concept.

Principle of operation

The PK consists, essentially, of an airfoil tethered to the ground by means of one or more cables. These are reeled around a drum coupled to either a single, dual Electric Machine[1] (EM) – which shall alternate every minute or so between the generator and the motor mode – or to two dedicated machines on the same shaft. There are several PK variants, specially in terms of location of the actuators (airborne or on the ground), number and functionality of tethers, and types of airfoils (rigid or flexible), each with its advantages and drawbacks. The variant shown in Fig. 1 has one main tether between the ground winch and an airborne control pod, where the pitch and steering actuators as well as the onboard electronics are located. The main tether, whose traction force drives the EM, splits into two

[1] In the sense that it can operate either as a motor or as a generator.

cables connected to the leading edge (front side) of a flexible airfoil (power kite), whereas the two cables connected to the trailing edge (rear side) are used for steering and pitching (control). The instantaneous mechanical power of the PK is obtained through tether reeling as

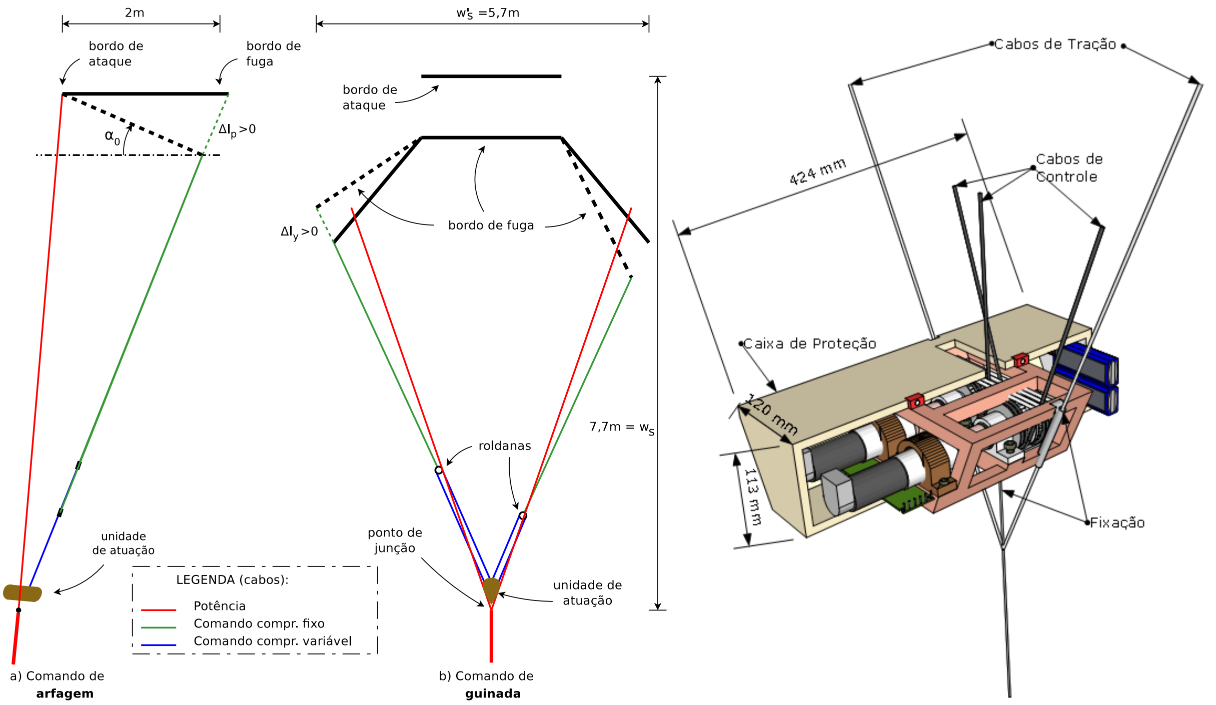
$$P(t) = T(t)\dot{r}_a(t)\,, \tag{1}$$

where T is the tether traction force, and $\dot{r}_a$ is the reeling speed. A PK operation cycle consists of two phases. In the *traction phase* the airfoil flies a "lying-eight" (∞) trajectory [8, 7, 3], which maximizes the traction force while the tether is reeled out at a speed $\dot{r}_a > 0$. When the tether has reached its maximum length the system enters the *passive phase* [10, 11, 6], where the airfoil flies a maneuver ideally at a low angle of attack, minimizing the tether traction force while the tether is reeled back in, i.e. $\dot{r}_a < 0$, until the initial tether length is achieved. In the end of an operation cycle the net mechanical power obtained is an average of the energy produced in the traction phase, and consumed in the passive phase, considering each phase duration, i.e.

$$P_{\text{cyc}} = \frac{\int_0^{t_o} P_{m,o}(t)dt + \int_{t_o}^{t_i} P_{m,i}(t)dt}{\Delta t_o + \Delta t_i}\,. \tag{2}$$

Flight control

In a prototype currently being built at UFSC, the airfoil flight is controlled by means of two actuators (BLDC servomotors) in a control pod. The latter flies close to the airfoil (kite), attached to the traction lines right above the point where they merge into a single line which goes to the ground, as shown in Fig. 2



(a) Steering inputs. (b) Perspective view.

Figure 2: Control pod location and steering inputs.

Each actuator is responsible for one of the following steering inputs, so as to make the airfoil fly a desired trajectory [2]:

a) **Pitch**: the steering tethers with variable length (blue lines in Fig. 2a) on the *inside* of the "V" are reeled around a small drum in the *same* direction. Therefore the torque of both tethers sum up and must be compensated for by the torque of the BLDC motor connected to the drum shaft. By driving this motor so that the length of both tethers is changed by $\Delta l_p \neq 0$ the angle of attack α is changed accordingly;

b) **Yaw**: the steering tethers with variable length (blue lines in Fig. 2a) on the *outside* of the "V" are reeled around a small drum in *opposite* directions. Hence the resulting torque in the respective BLDC motor shaft, connected to the drum, is the subtraction of each tether torque on the drum. By driving this motor so that one tether is released while the other is pulled with the same amount, thus characterizing an anti-symmetrical tether length variation $\Delta l_y \neq 0$, the kite trailing edge is deformed. This creates a non-negative net aerodynamic torque on the airfoil, hence producing a yaw motion.

Dynamic model fundamentals

Many models of the PK have been proposed in the literature, with several levels of detail, and for distinct purposes. Among them is the mass-point model [4, 5], which allows for an analytical approach to the problem, hence being suited for control design and fast computer simulation. One of the key definitions to model the airfoil dynamics is the notion of *effective* wind[2], $\mathbf{W_e}$. It has a strong impact on the aerodynamic forces which, in turn, are preponderant for the kite dynamics. The effective wind results from the interaction of the following speed vectors, all measured relative to the ground: the airfoil speed $\mathbf{W_a}$, the nominal wind speed $\mathbf{W_n}$, and wind turbulence $\mathbf{W_t}$, yielding

$$\mathbf{W_e} := \underbrace{\mathbf{W_n} + \mathbf{W_t}}_{\mathbf{W_l}} - \mathbf{W_a}\,. \tag{3}$$

By considering the two steering inputs discussed above – yawing through a differential, anti-symmetrical steering tether length variation Δl_y, and pitching through a symmetrical tether length variation Δl_p –, the weight of the airfoil and tether $\mathbf{G}$, apparent forces (centrifugal and Coriolis) $\mathbf{P}$, the aerodynamic lift and drag of the airfoil $\mathbf{L}(\Delta l_y, \Delta l_p, \mathbf{W_l})$ and $\mathbf{D_a}(\Delta l_p, \mathbf{W_l})$, respectively, and aerodynamic drag of the tether $\mathbf{D_c}(\mathbf{W_l})$, flight dynamics are governed by the equations of motion

$$\begin{bmatrix} m\, r_a^2 \ddot{\theta}_a \\ m\, r_a^2 \ddot{\phi}_a \sin\theta_a \\ m\, \ddot{r}_a \end{bmatrix} = \mathbf{G} + \mathbf{P} + \mathbf{L}(\Delta l_y, \Delta l_p, \mathbf{W_l}) + \mathbf{D_a}(\Delta l_p, \mathbf{W_l}) + \mathbf{D_c}(\mathbf{W_l}) + \begin{bmatrix} 0 \\ 0 \\ T \end{bmatrix}, \tag{4}$$

where m is the airfoil mass, θ_a is the airfoil complementary elevation angle, ϕ_a is its azimuth angle, and r_a is the tether length. We highlight that, in the whole PK cycle, there must be $T(t) > 0$ in order to ensure that the tethers can be steered to control the airfoil trajectory.

2 Problem statement

The actuators, the embedded processor and the wireless communication boards with the ground station, among other components, are contained in the control pod (see Fig. 2b). Their energy supply comes from batteries. The stronger the steering inputs applied to airfoil are, the greater is the power drawn from the batteries. Moreover, an approximate constant power is required by the embedded computer and peripheral devices. Therefore the operation time of the PK system is limited by the batteries capacity. In order to advance the technology towards time-unlimited operation – which is crucial for a future commercial deployment of the PK – it is necessary to provide time-unlimited electric energy supply to the control pod.

To cope with this issue one possibility is the provision of electric power from the ground through wire(s) inside the traction cable. This approach eliminates the need for an onboard device for electric energy generation. Nevertheless it would imply in additional weight in the traction cable and in the overall airborne parts[3]. Also, there is the technological complexity of making the wire inside the cable withstand the high traction forces and stresses induced by the windings on the drum. Another disadvantage of housing the power supply wires inside the traction cable is the augmentation of the resulting cable diameter, which implies in a greater drag force, hence reducing the effective wind, the cable traction force, and finally affecting negatively the electric power generation on the ground.

[2] also known as *apparent wind*, or airspeed.

[3] The traction and steering cables, control pod and the airfoil.

The onboard generation approach

Another possibility – which is to be investigated in this Master thesis proposal – is the generation of electric energy directly aboard the control pod by means of a small wind turbine driving a generator. This way the problem of increasing the traction cable diameter is avoided, as well as the technological complexity of housing the electric wires appropriately inside the traction cable. The idea is to place the turbine/generator couple *inside* the control pod, along its longitudinal axis.

It is known that the power in the wind flow is given by

$$P_w = \frac{1}{2}\rho A_w \|\mathbf{W_e}\|^3 \,, \tag{5}$$

where $\rho = 1.3\,\text{kg/m}^3$ is the air density, $A_w = \pi d_t^2/4$ is the rotor swept area, and d_t is the rotor diameter. We know that the mechanical power extracted by the turbine is $P_m = \eta_w P_w$, where the turbine maximum efficiency in extracting the kinetic energy from the wind is $\eta_{w,\max} \approx 59\%$, corresponding to the *Betz limit*. Let us also consider a generator efficiency $\eta_g < 100\%$ in converting mechanical to electric energy, so that $P_e = \eta_g P_m$. Then the rotor diameter can be calculated as

$$d_t = \sqrt{\frac{8P_e}{\rho\pi\|\mathbf{W_e}\|^3\eta_w\eta_g}} \,. \tag{6}$$

Assuming an average effective wind speed $\|\mathbf{W_e}\| = 100\,\text{km/h}$, $\eta_w = 40\%$, $\eta_g = 90\%$, and an average power consumption of the control pod $P_e = 60\,\text{W}$, we obtain a rotor diameter $d_t = 12,3\,\text{cm}$. The problem with this design is that the turbine tube occupies a large amount of the control pod volume, leaving only a small space for the components (motors, electronics etc.). Also the turbine and generator would be relatively big, with a considerable weight, which should be minimized.

Improved design

Now let us consider a funneling shape of the air inflow tube leading to the onboard turbine, as shown in Fig. 3.

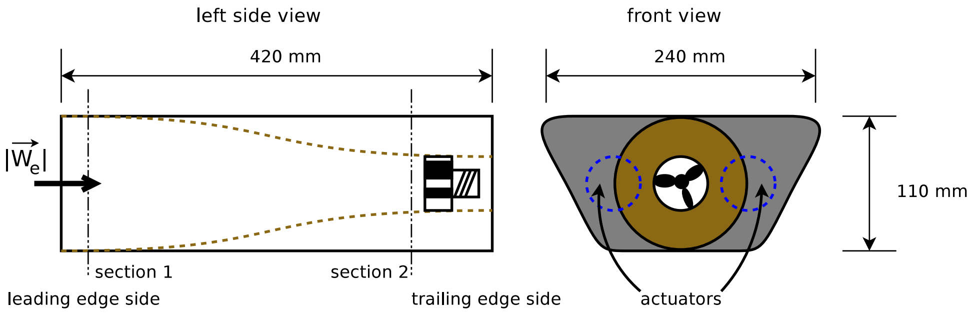


Figure 3: Concept of a new control pod design with energy supply from a funneled onboard turbine.

Considering no leakage (air losses) in the funnel, the mass flow in the air intake (section 1) and right before the turbine (section 2) should be the same. Assuming the air density varies according to the pressure variation – therefore $\rho_1 \neq \rho_2$ – we have

$$Q = \rho_1 v_1 A_1 = \rho_2 v_2 A_2 \quad \Rightarrow \quad v_2 = \frac{\rho_1}{\rho_2}\frac{A_1}{A_2} v_1 \,, \tag{7}$$

where A and v stand for the section area and flow speed, respectively.

Knowing that $R = 287.058\,\text{J/(kg K)}$ is the specific gas constant for dry air, the air density and pressure can be expressed by means of the *ideal gas law*

$$\rho = \frac{p}{RT_e} \quad \Rightarrow \quad RT_e = \frac{p_1}{\rho_1} = \frac{p_2}{\rho_2} \quad \Rightarrow \quad \rho_2 = \frac{p_2}{p_1}\rho_1 \,, \tag{8}$$

where T_e is the air temperature. We need to find p_2 to replace in (8) and find v_2. To this end we use Bernoulli's equation

$$\frac{1}{2}\rho_1 v_1^2 + p_1 + \rho_1 g h_1 = \frac{1}{2}\rho_2 v_2^2 + p_2 + \rho_2 g h_2 = \text{constant}, \tag{9}$$

assuming no pressure losses in the funnel. Considering the same relative height, $h_1 = h_2 = 0$. It can be shown that by replacing (7) and (8) in (9) and solving for p_2 we get two solutions. We discard the one that yields a pressure two orders of magnitude lower, since the resulting v_2 would be too high and violate conservation of energy. Let us consider that the diameter of section 2 is reduced to half compared to section 1. Then $A_1/A_2 = 4$. Assuming the temperature is kept constant at $T_e = 23°C$, we obtain $v_2 = 431.9\,\text{km/h}$ which is more than 4 times the intake speed $v_1 = \|\mathbf{W_e}\| = 100\,\text{km/h}$ that we would get if considered no air density variation in (7). The resulting turbine rotor diameter, replacing $\|\mathbf{W_e}\|$ by v_2 in (6), is $d_{t,2} = 1,43\,\text{cm}$, more than 4 times less than the section 2 diameter.

This conclusion could mislead us to believe that energy is being created since, for generating the same 60 W of electricity, we need to use less area than the funnel output area (section 2). The explanation is that the calculation above does not consider the interaction of the turbine with the funnel. The turbine creates resistance to the air flow, thus slowing down v_2. Had we modeled this interaction, we believe it could be shown that the necessary turbine diameter would be bigger, and that no more than the same 60W could be generated.

In any case, this design approach offers interesting advantages. First, the funneling opens up space (volume) to accommodate the control pod components. Also, the increase in the wind speed driving the turbine allows it and the generator to be smaller, thus reducing weight. Moreover, a faster rotating generator usually has a higher efficiency, which is desired. Finally, by introducing the onboard turbine/generator the air drag on the control pod should at most be kept the same, if not decrease, because now the air can get through, although with some energy dissipation (mechanical input to the turbine). As a consequence the airfoil might be able to reach a higher speed, traction force and, consequently, generate more power on the ground.

Besides the fluid dynamics aspect considered above, the electronics should also be developed/specified in order to allow the system to be implemented. An initial architecture is proposed in the block diagram of Fig. 4.

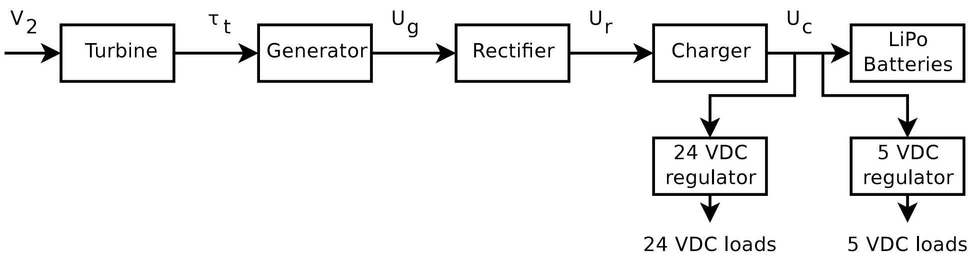


Figure 4: Block diagram of the onboard generation system including the electronics.

The turbine is fed with an incoming wind speed $v_2(t)$ (funnel section 2), and outputs a torque $\tau_t(t)$ to the small generator. This will output an alternate voltage $U_g(t)$ which is rectified, yielding $U_r(t)$, and then input to the LiPo (Lithium-Polimer) battery charger. Because LiPo batteries are known to be very sensitive to charging requirements, special attention must be paid to the charger component. Finally, given that the loads in the control pod operate at different voltage levels, appropriate voltage regulators should be specified/designed.

3 Objectives and expected results

So far no results in the literature were found addressing the design, performance, and impacts of an onboard electric generation system on the overall efficiency of the PK. Therefore, the **general objective** of this Master thesis proposal is the basic design and computer simulation of such onboard system. Specifically, it is expected from the student, at the end of his/her studies:

i) a verification and possible extension of the fluid dynamics analysis presented in Section 2, explaining the operating principles of the funnel and its dimensioning;

ii) a verification and extension of the block diagram proposed in Fig. 4. Are other components needed (e.g. control loops)?

iii) specification of all the mechanical and electric/electronic components involved. This is essential for the formulation of an *engineering basic project*, based on which the system will be implemented in the prototype at UFSC;

iv) if possible, the conception of an algorithm that estimates the remaining operating time of the control pod in face of the current load behavior, battery status and onboard power generation;

v) computer simulation (Matlab and/or Psim suggested) of the system operation;

vi) publication of the results obtained in a scientific paper and Master thesis.

Depending on how the work progresses, it is possible to purchase the specified hardware (turbine, generator, electronics) to realize test bench experiments during the Master studies.

4 Prerequisites of the candidate

The student who will develop this research should comply with the following requirements:

a) Be willing to undertake a full-time Master course at PPGEAS/DAS/UFSC;

b) Be experienced with Matlab and/or Psim, and have substantial knowledge on power electronics, electric machines and linear systems theory. At least basic understanding of fluid dynamics is desired;

c) Attest at least intermediate skills on English, specially in reading and writing;

d) Be proactive and have the interest to work on a relatively new research field at UFSC and Brazil.

Provision of a full-time Master scholarship (CNPq or CAPES) is possible. Candidates are asked to contact the research group on tethered airfoils at UFSC through the e-mails listed below:

- Prof. Alexandre Trofino Neto (Coordinator): alexandre.trofino@ufsc.br ;
- Marcelo De Lellis Costa de Oliveira (PhD student): marcelo.lellis@posgrad.ufsc.br ;
- Ramiro Saraiva da Silva (PhD student): ramiro.saraiva@posgrad.ufsc.br .

References

[1] C. L. Archer and K. Caldeira. Global Assessment of High-Altitude Wind Power. *Energies*, 2:307–319, May 2009.

[2] I. Argatov and R. Silvennoinen. Energy conversion efficiency of the pumping kite wind generator. *Renewable Energy*, 35(5):1052–1060, 2010.

[3] J. H. Baayen and W. Ockels. Tracking control with adaption of kites. *IET Control Theory & Applications*, 6(2):182–191, 2012.

[4] M. M. Diehl. *Real-Time Optimization for Large Scale Nonlinear Processes*. PhD thesis, Ruprecht-Karls-Universität, Heidelberg, Germany, 2001.

[5] L. Fagiano. *Control of Tethered Airfoils for High-Altitude Wind Energy Generation*. PhD thesis, Politecnico di Torino, Torino, Italy, 2009.

[6] U. Fechner and R. Schmehl. Model-Based Efficiency Analysis of Wind Power Conversion by a Pumping Kite Power System. In U. Ahrens, M. Diehl, and R. Schmehl, editors, *Airborne Wind Energy*, chapter 14, pages 249–269. Springer-Verlag, 2014.

[7] C. Jehle and R. Schmehl. Applied Tracking Control for Kite Power Systems. *AIAA Journal of Guidance, Control and Dynamics*, 37(4):1211–1222, Feb. 2014.

[8] M. D. Lellis, R. Saraiva, and A. Trofino. Turning angle control of power kites for wind energy. In *52nd IEEE Conference on Decision and Control*, pages 3493–3498, Firenze, Italy, Dec. 2013. IEEE.

[9] Near Zero. Energy High in the Sky: Expert Perspectives on Airborne Wind Energy Systems, 2012.

[10] R. Saraiva, M. D. Lellis, and A. Trofino. Passive Phase Design of a Pumping Kite Wind Generator. In *19th IFAC World Congress*, pages 6764–6769, Cape Town, South Africa, Aug. 2014.

[11] A. U. Zgraggen, L. Fagiano, and M. Morari. Automatic Retraction Phase of Airborne Wind Energy Systems. In *19th IFAC World Congress*, pages 5826–5831, Cape Town, South Africa, 2014.