CAREER: An Experimentally-Infused Plant and Control Optimization Framework for Airborne Wind Energy Systems

Part I. Research Significance and Objectives

The overarching objective of this research is to lay the foundation for a long-term research program aimed at better understanding the dynamics and optimal control of airborne (tethered) wind energy systems. Airborne wind energy systems (AWEs), which replace conventional towers with tethers, provide the capacity to harness wind at high altitudes, where wind speeds are stronger than at ground-level (as studied in [1] and [2]), using as little as 10 percent of the material required by traditional systems. AWEs have the potential to unlock vast amounts of energy at 20-year levelized costs of \$0.05 to \$0.25 per kW-h, allowing wind energy to penetrate locations where tower-based systems are too costly, including remote, off-grid communities, military forward operating bases, and deep-water offshore locations that are ill-suited to tower installations. The former two locations presently rely on diesel fuel ranging from \$0.40-\$10 per kW-h (see [3], [4]) whereas deep water, offshore sites possess 4000 GW of untapped wind energy (see [5]).

Figure 1 shows three airborne wind energy prototype designs. AWEs can take the form of standard fabric surf kites with ground-based generators (see [6], [7], and [8]), or customized rigid/semi-rigid lifting bodies with airborne generators, as seen in [9], [10], and [11]. Especially in the latter case, the design freedom in both the plant and controller provides the capacity for increased energy generation but also brings forth a host of plant and control design challenges, which represent a present barrier to widespread acceptance.

Figure 1: Recent airborne wind energy systems, including (left to right) the Makani Power (now owned by Google) M30 [11], KITEnergy KE60 [6], and Altaeros Energies Buoyant Airborne Turbine (BAT) [9]. A summary of airborne wind energy technologies can be found in [12].

The research content in this proposal will focus on the creation of a combined plant and controller optimization process for AWEs that fuses lab-scale experiments with numerical optimization; this will be referred to as *experimentally-infused* optimization. Experimental data will be used to identify correction terms and unknown parameters for subsequent iterations of the numerical optimization, and optimal design of experiments will be used to maximize information garnered from experiments. The methods arising from this work will be applied to the design of lifting bodies and flight controllers for two types of airborne wind energy systems. Because the reliance on experimentation for design optimization is not unique to AWEs, the methodologies created through this research are expected to be applicable to other industries as well. Educational activities of the proposed work will include rapid plant and controller prototyping activities at the undergraduate level, design of an energy-rich early college high school science curriculum through the PI's advisory board role, the design of K-12 kite-design camp activities, and participation of select students in the flight testing of an Altaeros Energies AWE prototype.

The methodologies generated in this research will address several key challenges facing AWEs:

Challenge 1: Controller and plant optimization of airborne wind energy systems are coupled.

In formulating a suitable cost function for capturing the performance of AWEs, several factors should be taken into account, including flight performance, net energy generation, ground footprint, and fabrication costs. As a result, the optimal controller is dependent on the plant, and the optimal plant is dependent on the controller. For example, a lighter-than-air platform will occupy minimal ground footprint for high pitch angle setpoints, but achievement of these setpoints with acceptable flight performance requires ballasting configurations and/or tether attachment geometries that drive up fabrication costs.

Challenge 2: Flight dynamics of airborne wind energy systems are complex and not well-understood; therefore, AWE system designers are reliant on experiments to make progress.

Dynamic models for AWEs are in their infancy and often make widely different approximations with regard to tether flexibility and elasticity (ranging from treating tethers as kinematic linkages in [13], [14], [15], [16], [17], [18], [19], [20], and [21], to intricate models that take into consideration tether elasticity and catenary geometry in [22], [23], [24], and [25]) and aeroelasticity (ranging from point-mass models in [13], [14], [15], [16], [17], and [21], to rigid body models in [18], [19], [26], [20], and [25], to multi-body models in [27], [23], [28], and [29]), while typically neglecting unsteady flow effects altogether. While some model-to-model variation is warranted based on the variety of AWEs designs, wide model variability can be seen even across systems that use the same fundamental lifting body. Derivation of low-order models that capture these effects is a long-term research area on its own, but until this understanding is fully realized, AWE system designers will depend on a high level of experimentation in order to make progress.

Challenge 3: Building large-scale prototypes of airborne wind energy systems is expensive.

In AWEs that involve custom lifting bodies, such as composite wings and semi-rigid inflatable structures, the lifting body cost alone for a flight prototype can easily exceed $50,000 (as shown in [30]). Many parameters such as aerodynamic coefficients require a full redesign to fully evaluate. Furthermore, the exploration of stability boundaries on an expensive prototype typically represents an unacceptable risk.

The proposed plant and controller optimization framework, shown in Figure 2, addresses all of the above challenges. Specifically, the research will leverage 3d printing technology to build inexpensive, lab-scale prototype lifting bodies that will be tethered and flown in UNC-Charlotte's 1m x 1m water channel. The use of the water channel provides a platform for replicating important properties of the full-scale system (net buoyancy, added mass, and stability) at 1/100 scale, which would not be possible at such a small scale in a wind tunnel. Using high speed cameras, high performance computers, and DC motors, the PI and his students will perform closed-loop experiments on candidate plant and controller configurations. These experiments will reveal performance implications of unmodeled dynamics and will be used to identify cost function correction terms and/or values of unknown parameters for the subsequent numerical optimization of the combined plant and controller. Following each numerical optimization, optimal design of experiments techniques will be used to produce an information-rich set of new experiments, taking into account the cost and time requirements associated with different plant reconfigurations.

The research plan described herein is aimed at achieving three objectives:

1. Derive a cost function correction/parameter identification framework that leads to guaranteed convergence to optimal plant and control parameters.
2. Propose and validate statistical and model-based designs of experiments that minimize the number of required experimental iterations and/or experimental costs.
3. Demonstrate the effectiveness of the optimization approach for two classes of AWE systems – a lighter-than-air, stationary system, and a high lift/drag crosswind flight system - by contrasting results from the experimentally-infused approach with results from a purely numerical approach.

Through collaborations with Altaeros Energies, the CMS/EPIC Early College High School, and NC State Engineering Summer Camps, the educational plan will accomplish three complementary objectives:

1. Undergraduate and graduate students will participate in the 3d printing and testing of AWE models through coursework and research, and select students will have the opportunity to participate in full-scale flight testing of the Altaeros BAT.
2. The PI, who serves on the advisory board for an early-college high school within Charlotte-Mecklenburg Schools (CMS), will co-design an energy-rich high school science curriculum.
3. The PI will design kite modules for high school camps run by NC State's "Engineering Place."

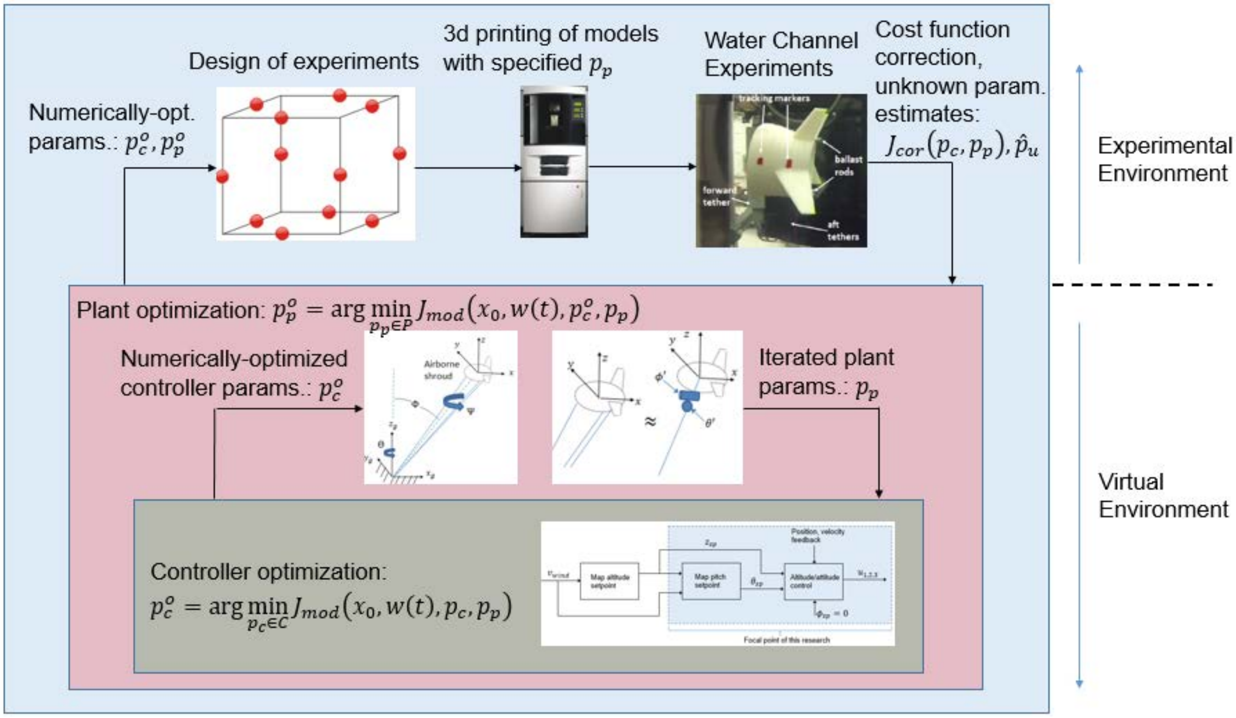

Figure 2: Flowchart of the experimentally-infused optimization framework to be explored in this research, using notation that is introduced throughout the proposal's technical description.

The research and educational content within this proposal will lay the foundation for a long-term program in the dynamics and control of AWEs. The research will engage students at both the Ph.D. and undergraduate levels in one of the most cutting-edge and multidisciplinary problems in mechanical engineering. At the end of the proposed five-year plan, the PI and his students will have created the first-ever lab-scale, closed-loop flight testing framework for AWE lifting bodies, along with tested methodologies for iterating effectively on the plant and control designs. While the focal point of the research is dynamics and control, the research will incorporate other disciplines such as aerodynamics, and additive manufacturing, which will provide students (particularly at the undergraduate, middle, and high school levels) the opportunity to explore a variety of aspects of mechanical engineering under the umbrella of a single application. The PI, having served as a lead engineer for an AWE organization and having flight tested prototype AWEs, is also uniquely qualified to forge long-term relationships with AWE organizations, enabling students to participate in full-scale flight testing and gain exposure to clean-energy startups.

Part II. Intellectual Merit

1. State of the Art

For airborne wind energy systems, the state of the art in combined plant and controller design generally involves adopting anything from phenomenological, point-mass models (see [13], [14], [15], [16], [17], and [21]) to more intricate, but still limited, physics-based models (see [18], [19], [20], [22], [23], [24], [25],

[26], [27], [28], [29], [30], [31], [32], and [33]), then using a model-based design methodology to synthesize an underlying controller and test it in the field. This has resulted in several organizations that have achieved minutes or hours of continuous flight, but no successful long-duration test flights and several failures.

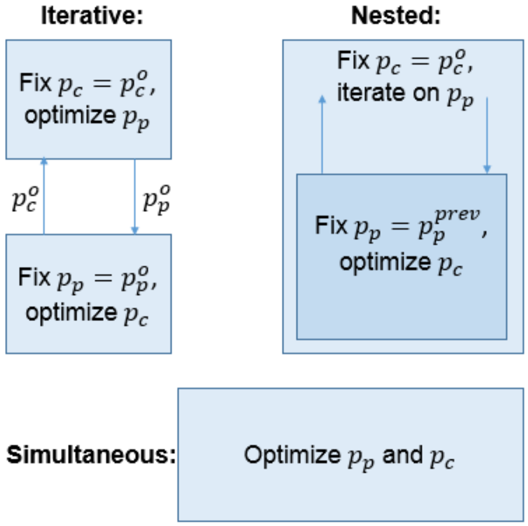

Figure 3: Schematic of iterative, nested, and simultaneous optimizations.

Meanwhile, over the past several decades, a body of literature has emerged surrounding combined controller and plant optimization. Figure 3 depicts three common combined controller and plant optimization methodologies, each of which aims to minimize an overall system cost function that can be described most generically by: $J(x_0, w(t), p_c, p_p) = \int_0^{t_f} h(x(t), w(t), p_c, p_p)dt$, subject to set constraints, $p_c \in P_c, p_p \in P_p$. Here, $x(t)$ represents the system state, $w(t)$ represents the external disturbance (wind speed and directional perturbations in the AWE application), and p_c and p_p represent controller and plant parameter vectors, respectively. The plant is driven by a control input signal, $u(t)$, which is a function of $x(t)$ and p_c. Often in the literature, the cost above is decomposed into control and plant costs, i.e., $J(x_0, w(t), p_c, p_p) = J_c(x_0, w(t), p_c, p_p) + J_p(x_0, w(t), p_p)$, which exposes the coupling between controller and plant optimizations.

The three numerical optimization techniques depicted in Figure 3 can be classified as *iterative*, *nested*, and *simultaneous* (the case of an iterative strategy with one iteration can be referred to as sequential). Iterative optimization toggles between a full plant optimization and full controller optimization until convergence is reached. It is illustrated in [34], [35] and proven in [36], [37] that this strategy does not guarantee convergence to optimal parameters except in special cases where plant-controller coupling is absent. Aside from resorting to a simultaneous optimization (see [38], [39], and [40]), which can become impractical when different teams are responsible for the plant and controller, several approaches have been undertaken in order to achieve guaranteed optimality:

- Incorporation of a controller proxy function (see [41], [42], and [43]) into the plant optimization;
- Pursuing a nested optimization strategy (see [44], [45], [46], [47], and [48]) where a full controller optimization is undertaken at each iteration of the plant optimization;
- Performing decomposition-based design (in [49], [50], [51], [52], [53], [54], [55], [56], and [57]).

Each of these algorithms has been shown under realistic conditions to lead to an optimized design, and several of the approaches have been shown to yield computational benefits.

While the literature has focused largely on algorithms' optimality guarantees and computational efficiency, the benefits promised by these optimality guarantees and computational advantages are diminished when:

- The plant is known to possess a significant degree of modeling uncertainty;
- The design cycle for the engineered system under consideration is far longer than the amount of time required to perform any of the aforementioned optimizations. This is very common, since design cycles are often measured in years, whereas optimization times can be measured in hours.

In the common case when an imperfect model is used for numerical optimization, the inclusion of experiments in controller and plant optimization represents a sensible tactic. This tactic has in fact been pursued in [58], [59], [60], and [61], where experimental results on rapidly prototyped systems are used to identify elements of a Jacobian matrix that captures the sensitivity of important performance considerations (which could include rise time, overshoot, amplitude of oscillations, etc.), which is in turn used to determine the design for the next experimental iteration. Thus, the approach uses the results of one set of experiments to determine designs for the next set, but it does not include the fusion of numerical optimization components and subsequent design of experiments that is considered in the proposed research. The retention of these numerical components and subsequent optimal design of experiments is expected to dramatically reduce the number of required experiments, thereby lowering the cost, in terms of money and time, of completing a design cycle. In fact, the research plan in this proposal is specifically tailored toward achieving these efficiency objectives.

2. Preliminary Results

2.1 Initial Airborne Wind Turbine Modeling and Water Channel Feasibility Study

The PI has derived a series of AWE system dynamic models with varying levels of fidelity (see [25], [26], and [62]). The numerical optimizations in this work will leverage a 6 degree-of-freedom model (in which 3 degrees of freedom are controlled via tether lengths) that is detailed in [62] and derived using an Euler-Lagrange approach, using the following generalized coordinates (Θ, Φ, Φ, θ', and ϕ') that are depicted in Figure 4. Ultimately, the system model can be represented using a 12-state nonlinear state-space model:

$$\dot{x} = f(x, u), \qquad (1)$$

$$y = g(x), \qquad (2)$$

where $y = [\Theta \quad \Phi \quad z \quad \phi \quad \theta \quad \psi]^T$ and u represents the vector of tether release speeds (the control inputs). The variables $z, \phi, \theta,$ and ψ represent the altitude, roll angle, pitch angle, and yaw angles, respectively.

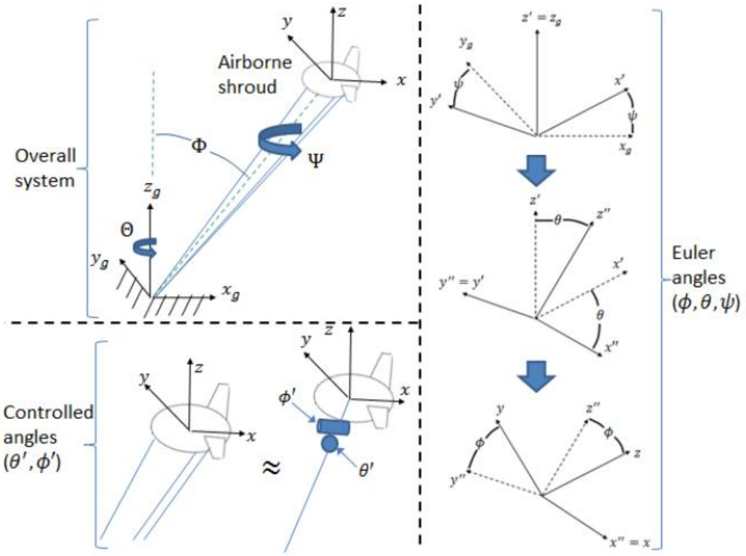

Figure 4: Axis system, including the generalized coordinates (left) and roll, pitch, and yaw angles (right).

During the winter of 2013, an initial water channel test rig was constructed in partnership between the PI and University of Michigan, for the purpose of studying *passive* flight characteristics of AWE lifting bodies. The experimental setup consisted of a test frame to which 1/100-scale 3d printed aerostat models were tethered, as well as side and top view cameras for post-flight motion analysis, but did not include any real-time motion capture or closed-loop control. Models were fitted with a mesh screen to replicate the drag contribution of the spinning rotor.

The PI conducted a scaling analysis to determine the viability of testing with 1/100-scale models. The analysis, which is described in [20] and [62], considered (1) stability, (2) Reynolds number, (3) the ratio of aerodynamic to buoyant force, and (4) the linearized system time constants. Based on this analysis, stability properties were preserved between water channel and full-scale models with the same geometric designs and mass distribution. Furthermore, the flow regime was confirmed to be turbulent at lab-scale and full-scale, even though the Reynolds numbers differed. In order to reconcile differences in time constants and aerodynamic/buoyant force ratio, the dynamic model introduced in Section 2.1 was scaled down to water channel level, and comparisons and improvements were made with respect to the scaled model. The proposed research plan includes a scaling analysis that will use dimensional analysis to more precisely address this dynamic scaling.

Figure 5 contrasts simulated 1/100-scale lateral dynamics with actual observations in the water channel, under different ballasting configurations. Here, the water channel revealed an instability with ballasting configuration A that was unobserved through simulation. Ultimately, the use of the water channel led to design revelations that enabled the Altaeros team to deploy a prototype in 2013 that demonstrated stable operation in 10-15 m/s sustained winds with gusts of up to 21.2 m/s.

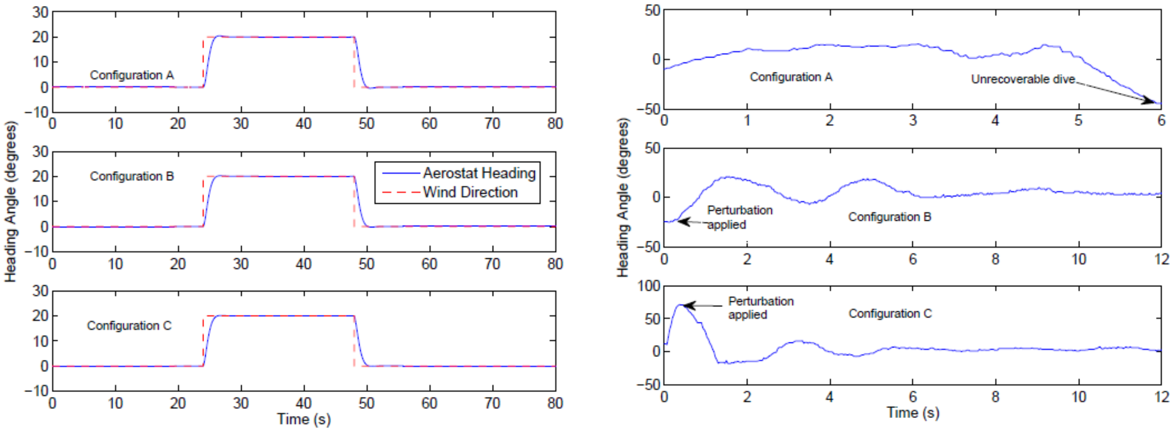

Figure 5: Comparison of simulated lateral system dynamics (scaled down to water channel level - left) with observed behavior in the water channel (right). The use of the water channel was key in identifying a lateral instability that was not revealed via the dynamic model of Section 2.1.

2.2 Experimental Setup of Closed-Loop Water Channel Platform at UNC-Charlotte

Figure 6 shows the experimental setup at the UNC Charlotte water channel, which was completed by the PI and his students in spring, 2014. The water channel's 1m x 1m size (fifth largest in the nation) enables operation at altitudes that are the equivalent to nearly 100m in the full-scale system. The hardware setup for this research includes the following features:

- Three 340 frame/sec camera-link cameras (Basler ACE-series) – a side-view camera, a bottom-view camera, and a slanted side-view camera;
- Three DC motors for positioning geometries with up to 3 tethers;
- A target computer (six core, 64GB memory), which executes real-time image acquisition, processing, and positioning using xPC Target software;
- Input/output PCI Express expansion boards, which support Camera Link frame grabbing and generation of DC voltage outputs to the motors.
- A host computer (basic laptop, running Windows 7), which interacts with the target computer, issuing periodic commands and receiving data.

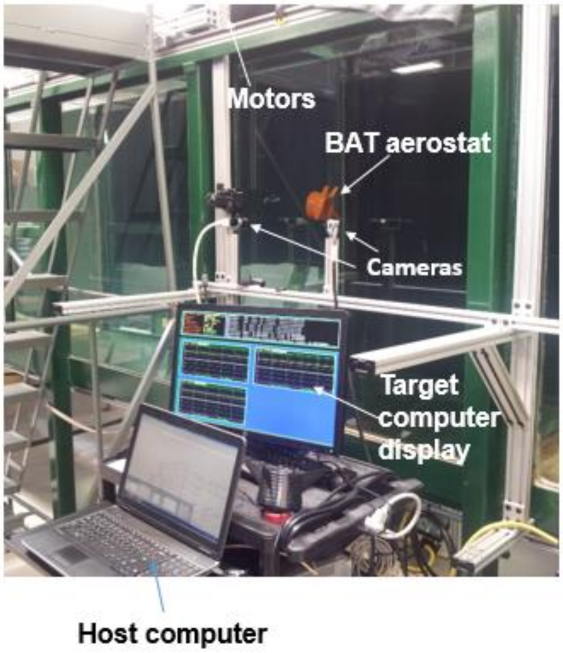

Figure 6: Water channel experimental setup at UNC-Charlotte - The Altaeros BAT aerostat is being flown.

UNC-Charlotte's 3d capabilities enable the generation of new lifting body geometries out of ABS plastic, with a 1-day turnaround. Each model is built with ballasting holes and a number of available tether attachment locations. The DC motors outside the water channel provide precise speed control over the tether spooling rate, and the image processing algorithms running on the target computer provide full position, orientation, velocity, and rate information.

2.3 Initial Test Flights in the UNC-Charlotte Water Channel – A Demonstration of Coupling and Importance of Experimental Tests

During the spring of 2014, two of the PI's students completed a matrix of flight characterization on the Altaeros BAT design, which involved variation in both the pitch angle trim setting (θ_{sp}, which was taken to be a fixed value in each set of experiments) and chord-normalized center of mass position (x_{cm}). The control structure, depicted in Figure 7, is the same as what was used in full-scale flight tests, with parameters adjusted for scale. In order to characterize performance across design configurations, each test run consisted of an initial settling period, followed by a controlled lateral perturbation that consisted of one second of reeling in the aft port tether, followed by one second of reeling out the aft port tether, followed by the resuming of the control strategy in Figure 7. The following simple cost function was evaluated over a period of 60 seconds following the perturbation for each configuration:

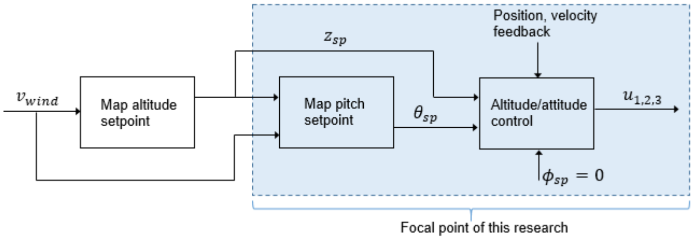

Figure 7: Control configuration for lighter-than-air stationary wind energy system.

$$J(x_0, u(t), w(t), p_p) = \int_0^{t_f} [(k_1 y(t)^2 + k_2(\psi(t))^2 + k_3(x_{cm} - x_{cb})^2 + u(t)^T R u(t)] dt. \qquad (3)$$

This cost function penalizes lateral position, heading deviations, separation of centers of mass and buoyancy (which create a couple that requires the design to incorporate increased buoyancy and/or widely separated tether attachment points, driving up fabrication costs), and energy consumption (via a penalty on the control). Figure 8 shows cost function values for the ranges of x_{cm} and θ_{sp} that were tested, demonstrating that the optimal plant depends on the controller and the optimal controller depends on the plant. This coupling is present regardless of whether a direct penalty on $x_{cm} - x_{cb}$ is considered. The need for experiments, in addition to numerical optimization, is justified by the existence of several phenomena that are difficult to capture in low-order, optimization-oriented models. These include:

- Variations in tether catenary geometry
- Stall
- Unsteady flow/added mass effects

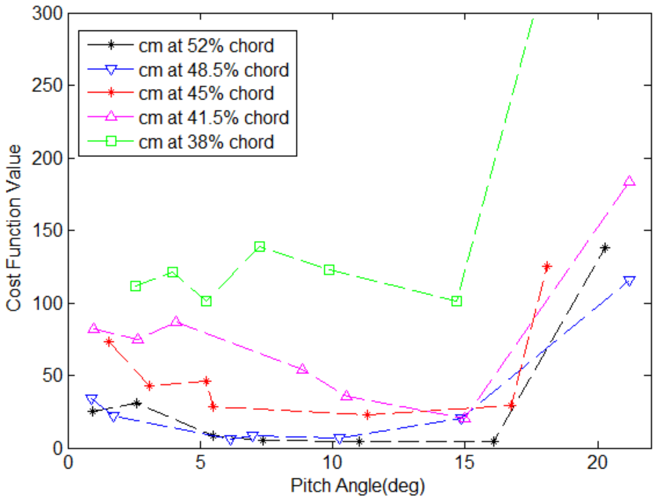

Figure 8: Initial results from closed-loop characterization of Altaeros BAT performance in the UNC-Charlotte water channel, demonstrating controller/plant coupling. $\boldsymbol{k_3 = 0}$ in this case. cm = center of mass.

3. Research Plan

Given the plant/controller coupling demonstrated in preliminary work, along with the strong motivation for the use of lab-scale experiments for AWE plant/controller design, the research plan is centered around establishing mathematical techniques for an experimentally-infused design and demonstrating their effectiveness on AWEs. The research is divided into two core areas, namely:

1. The design and analysis of the components of Figure 2 that set the proposed optimization apart from anything else in the literature;
2. The application of algorithms to the design of lifting bodies and corresponding controllers for two types of airborne wind energy systems.

3.1 Fundamental Mathematical Framework for Experimentally-Infused Optimization

The optimization process of Figure 2 contains two design elements that set it apart from any other combined plant and controller optimization process in the literature, namely:

1. Use of optimal design of experiments techniques: After each numerical optimization, a set of design reconfigurations is proposed that will yield the maximum amount of information about the performance of the system around the numerically-optimized plant and controller parameters.
2. Identification of a cost function correction term and/or values of unknown parameters for the subsequent numerical optimization: Based on the results of experiments, identification of these terms will guide the subsequent numerical optimization to an improved set of plant and controller parameters.

Design Element 1 - Optimal Design of Experiments:

In the absence of a perfect system model, experiments become an essential component to enabling the final system performance to converge to its optimal value, characterized by J^*. Optimal design of experiments, which has been studied in the context of statistical theory (see [63], [64], [65], [66], [67], and [68]) and in the modeling of a diverse range of systems, including biological systems, automotive engines, and batteries (see [69], [70], [71], and [72]). Most design of experiments research focuses heavily on statistical methods for constructing experiments that ensure good coverage of the parameter space to be explored. These techniques are largely predicated on early work by Fisher (see [73], [74], [75], [76], and [77]), where the quality of the experiment may be characterized via the Fisher Information Matrix.

It will be important to account for the relative importance of the parameters and cost, in terms of time and money, associated with varying a parameter. To gain a concrete perspective on relative price of parameter variation, consider the fact that when 3d printing AWE models with holes for ballast, changing the center of mass requires a simple ballasting change, whereas alterations in AWE lifting body shape require a new 3d print. To take relative importance and cost into account, the proposed research will explore a normalization scheme for each parameter, p_i, given by:

$$p_{i,norm} = \frac{1}{Q}\frac{p_i}{\bar{p}_i}\frac{\partial J}{\partial p_i}\bigg|_{p_i^o}, \qquad (4)$$

Here, $\bar{p}_i$ is the range of parameter p_i, p_i^o is that parameter's optimal value, and Q is a measure of the cost (in terms of money and time) of varying parameter p_i. Thus, the parameter space will be "stretched" to bias experiments toward those parameters that are cheapest to vary and for which the overall objective, J, is most sensitive. Statistical design of experiments will be performed within this stretched parameter space.

Design Element 2: Cost Function Correction and/or Identification of Unknown Parameter(s))

Each set of experiments is intended to improve the result obtained by the subsequent numerical optimization. The proposed research will consider two methods for accomplishing this:

1. Direct parameter identification of estimates of unknown plant parameters, $\hat{p}_u$;
2. Identification of a cost function correction term (depicted in Figure 2), $J_{cor}(p_c, p_p)$.

If the model parameters can be partitioned between those that are optimized (i.e., p_c, p_p) and unknown parameters that are not part of the optimization (i.e., p_u), then direct identification of $\hat{p}_u$ represents a sensible tactic. Certain sets of parameters within AWEs exhibit such a portioning. For example, aerodynamic coefficients are functions of geometric parameters, and it is the geometric parameters that are actually specified in the lifting body design (thus, these are part of p_p). The parameters that link the aerodynamics to the geometry represent the p_u. For direct identification of $\hat{p}_u$, standard least squares identification or a constrained optimization-based parameter identification (see [62]) will be used.

In cases where higher-order unmodeled dynamics exist, identification of a few unknown parameters, p_u, is less likely to substantially benefit the underlying optimization. Such unmodeled dynamics can enter AWEs in the form of unsteady flow effects and high-frequency tether dynamics. For cases in which unmodeled dynamics play a significant role, experiments will be used to identify a direct correction to the cost function, $J_{cor}(p_c, p_p)$. As a starting point, linear, gradient-based correction terms will be explored. These are expressed generally by:

$$J_{cor}(p_c, p_p) = k_c \frac{\partial J_{exper}}{\partial p_c}\bigg|_{p_c^o, p_p^o} (p_c - p_c^o) + k_p \frac{\partial J_{exper}}{\partial p_p}\bigg|_{p_c^o, p_p^o} (p_p - p_p^o), \tag{5}$$

where k_c and k_p represent tuning parameters between 0 and 1 that reflect relative trust in the previous experimental data and subsequent numerical optimization.

In addition to the gradient-based correction term described in (5), the proposed research will examine higher-order correction terms and correction mechanisms that blend unknown parameter identification with direct cost function modification. Finally, hybrid approaches will be examined, in which the post-experimental identification includes both an identification of both $\hat{p}_u$ and $J_{cor}(p_c, p_p)$. Because the use of different values of $\hat{p}_u$ will, in general, result in different numerically-optimized solutions and subsequent experimental designs, it is expected that the separate identification of $\hat{p}_u$ and $J_{cor}(p_c, p_p)$ will not, in general, lead to the most efficient optimization (efficiency metrics defined below), simultaneous identification of both $\hat{p}_u$ and $J_{cor}(p_c, p_p)$ will be considered.

Analysis Questions:

In evaluating the proposed design of experiments and cost function correction/parameter identification techniques, two key analysis questions will be considered:

1. Convergence: Under what conditions on the system model, actual engineered system, cost function, and external disturbance profile ($w(t)$), will the final cost value arising from the optimization, J_f, converge to a value sufficiently close to the optimal cost, J^*?
2. Efficiency: What is the minimum number of experiments required to achieve convergence to a cost that is sufficiently close to J^*?

Due to the challenging nature of these questions, the PI and students will consider specific structures such as linear systems with parametric uncertainties and bounded, non-parametric uncertainties, prior to moving to more intricate structures. Furthermore, the analysis will be broken down into several sub questions.

The question of parameter convergence will be broken down into three sub questions:

1. Under what conditions on the modeled system dynamics, actual system dynamics, and external disturbance ($w(t)$) do $J(x_0, p_p, p_c, w(t))$, p_c, and p_p converge to finite values as $t \to \infty$?
2. Under what conditions does $J(x_0, p_p, p_c, w(t)) \to J^*$ as $t \to \infty$?
3. If conditions for (2) cannot be found, does there exist a positive value, δ, such that for every $\varepsilon > \delta$, there exists an iteration k^* such that $k \geq k^* \Rightarrow \left\| J\left(x_0, p_p, p_c, w(t)\right) - J^* \right\| \leq \varepsilon$?

The question of efficiency will be broken down into two sub questions:

1. Supposing that it is possible to achieve $\left\| J\left(x_0, p_p, p_c, w(t)\right) - J^* \right\| \leq \varepsilon$ in a finite number of iterations, what is the minimum *expected* number (or cost) of experimental reconfigurations?
2. Given a limit of n experiments that may be run (or, alternatively, a limit of d dollars that may be spent), what is the minimum achievable *expected* value of $\left\| J\left(x_0, p_p, p_c, w(t)\right) - J^* \right\|$?

3.2 Application of Experimentally-Infused Optimization to Airborne Wind Energy Systems

The second core area of research involves applying the basic technique and theoretical learnings to two different AWE designs, namely:

1. A lighter-than-air geometry intended for stationary power generation, and
2. A high lift-to-drag wing (with on-board turbines) for figure-8 crosswind power generation.

Using 3d printing technology, a state-of-the-art water channel at UNC-Charlotte, and rapid control prototyping technology, the PI and students will realize the optimization algorithm depicted in Figure 2.

Case 1: Stationary system

The PI and students will first consider a lighter-than-air shell with an on-board turbine, which is intended for stationary operation at high altitudes, under a control strategy depicted in Figure 7. A cost function structure similar to that of (3) will be used, with additional terms that penalize zenith angle (accounting for the ground footprint of the system), as well as roll and pitch angle tracking errors. The proposed research will focus on a set of dimensionless plant parameters that have been found, through preliminary investigations, to be most significant in influencing system performance, including:

- Excess buoyancy ratio ($(F_{buoyant} - mg)/mg$);
- Rotor diameter, normalized by chord length;
- Tether attachment coordinates, normalized by chord length;
- Center of mass location, normalized by chord length.

In particular, sufficiently large amounts of excess buoyancy guarantee that tethers will remain in tension at all times, enable wide variation of center of mass, and allow the controller to select its trim pitch angle (θ_{sp}) over a wider range, but buoyancy requires additional helium and material costs. Large rotor diameters result in greater power production but also increase drag (and therefore ground footprint) and cause the shell to act as a bluff body, which shrinks the range of θ_{sp} over which the shell does not stall. Tether attachment locations directly impact the rate at which controlled rotations can be made and how widely separated the centers of mass and buoyancy may lie. And as Figure 8 demonstrates, center of mass location is a major driver of overall system performance, and its optimal location depends on the trim pitch angle, θ_{sp}.

Case 2: High lift/drag, crosswind system

The PI and students will consider a high lift/drag rigid wing with on-board turbines, which is capable of high-speed figure-8 crosswind motion that presents on-board turbines with very high apparent wind speeds. The effectiveness of a crosswind energy system is dependent on the apparent wind speed that is presented to the turbines, which is in turn dependent on the system's lift/drag ratio.

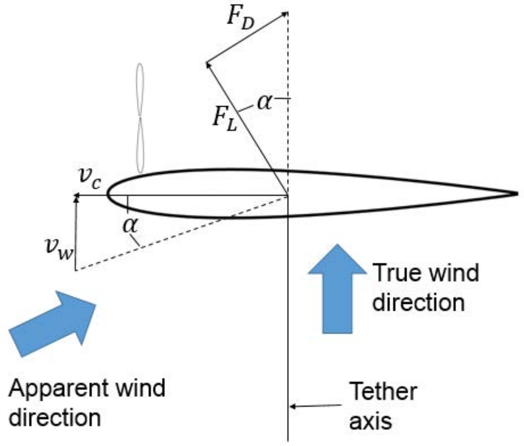

Figure 9: Diagram of the basic forces at play in a quasi-static 2d crosswind analysis.

In a simple quasi-static 2d analysis, which was first conducted in [78], and is illustrated in Figure 9, the wing's crosswind speed, v_c, is given precisely by $v_c = \frac{F_L}{F_D} v_w$, where v_w is the wind speed. Furthermore, the power generated by the on-board turbines is given precisely by:

$$P = \frac{1}{2} C_l \eta^2 \left(1 + \frac{1}{\eta^2}\right)^{3/2}, \qquad (6)$$

where $\eta = \frac{F_L}{F_D} = \frac{C_l}{C_d}$, and C_l and C_d are the lift and drag coefficients, respectively, of the airborne system.

Most crosswind flight control strategies in the literature, including one created by the PI in [79] and depicted in Figure 10 (left), aim to regulate crosswind speed to the optimal value for power production. Plant/controller coupling can be observed even in an idealized, 2d model. Here, although a high lift/drag design will always enable greater power production than a lower lift/drag design for the same turbines, the achievement of high lift/drag typically requires enlarging the lifting body or shrinking the turbine, which impose cost and energy production penalties. In a realistic 3-dimensional setting, the optimal controller and plant designs are even less obvious. As Figure 10 (right) indicates, while the crosswind flight control strategy of [79] outperforms stationary operation, it falls far short of the theoretically optimal energy production based on 2d analysis. The degree to which the control system falls short of this theoretical optimum depends on the extent to which the tethers are effective in controlling both heading and flight path; furthermore, the ability to control flight path effectively depends highly upon aerodynamic moment coefficients.

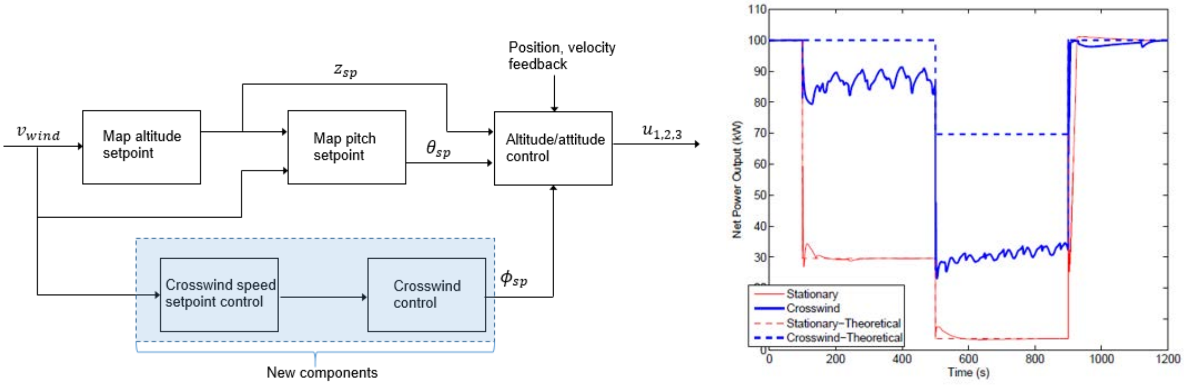

Figure 10: Block diagram of the crosswind flight control structure to be considered in this work (left) and power production results from the crosswind strategy, for a variety of wind speeds, compared against the theoretical steady-state optimum based on 2d analyses (right).

The proposed optimizations will focus on the same plant parameters as were considered by the stationary system optimization (while the system design for crosswind flight is characterized by the same fundamental parameters, their optimal values are expected to be significantly different), along with number of rotors and ratio of rotor diameter to span width. These additional parameters provide sufficient information to characterize the fraction of the wing that is occupied with rotors and the corresponding fraction that is exposed to clean flow; greater rotor area will result in greater maximum available power but will reduce lift/drag ratio, requiring greater true wind speed to obtain that power output. The control structure to be initially considered for crosswind flight is given in the block diagram of Figure 10 (left). Alternative control structures presently under development in conjunction with Dr. Hosam Fathy's group (see attached letter of collaboration) will also be considered. Performance will be evaluated based on a cost function structure that is tailored to crosswind flight objectives, given by:

$$J\big(x_0, u(t), w(t), p_p\big) = \int_0^{t_f} [(k_1 \Phi(\mathrm{t})^2 + k_3 (v_c(t) - v_{rated})^2 + u(t)^T R u(t)] dt, \qquad (7)$$

where v_{rated} is the rated wind speed of the on-board turbines. This cost function penalizes ground footprint, deviation from rated energy production, and control energy expenditure.

For both cases, the PI and students will progress through a series of three tasks in its investigation.

Task 1: Dimensional analysis and non-dimensionalization of variables

While the plant parameters to be optimized are dimensionless, several of the control parameters are not, and the water channel flow speed and altitude setpoint should be chosen to provide as close an equivalency to full-scale conditions as possible. The proposed research will leverage earlier work in [80] and [81], which performs dimensional analysis for a rigid kite. These results use the Buckingham Pi Theorem provide a set of nondimensional variables that can be used to describe the dynamics of a simplified kite dynamic model. The set of variables in the dimensional analysis of [80] and [81] does not include side force or moments about the body-fixed longitudinal or vertical axes (all of which can be shown to be important to tethered system dynamics), nor does the analysis take into account the non-dimensionalization of control parameters (the analysis is restricted to passive flight). Thus, the results of [80] and [81] will be used as a basis for the dimensional analysis in this proposal but will be extended to consider a full set of aerodynamic forces and moments, along with non-dimensionalization of control parameters.

Task 2: Evaluation of the design cycle with a high-fidelity model used as a surrogate for experiments

Prior to embarking on water channel experiments, the PI and students will first evaluate the mathematical optimization machinery using a high-fidelity model as a surrogate for experiments and a lower-fidelity model for the numerical optimization. This will allow the PI and students to fix any bugs in the underlying optimization machinery and identify which techniques for design or experiments, cost function correction, and system identification are most effective, prior to incurring the costs associated with 3d printing models.

<u>Task 3: Complete design cycle using the UNC-Charlotte water channel and 3d printing facilities</u>
Once the process has been validated using a surrogate model for experiments, this surrogate model will be replaced with experiments themselves. Plant redesigns will be performed using SolidWorks CAD software, which is available on all UNC-Charlotte computers and widely known and used across the mechanical engineering community. Altaeros Energies (see attached letter of collaboration) will assist in aerodynamic analysis, in particular providing estimated relationships between geometric parameters and aerodynamic coefficients. UNC-Charlotte's state-of-the art Stratasys 3d printing technology will be used for new models, which will enable 1-day turn around on new designs. The PI has planned for up to 20 new 3d printed models each year, each of which will provide substantial reconfigurabilty, in terms of the adjustment of center of mass and tether attachment geometry. Experimental tests will consist of a sequence of controlled perturbations, via variation in water channel flow speeds and controlled lateral perturbations induced by varying the port and starboard tethers asynchronously.

3.3. Timeline for Research Plan

Figure 11 shows the timeline for research over five years.

Focus Area	Task	Year 1				Year 2				Year 3				Year 4				Year 5			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Fundamental Theoretical Development	Optimal design of experiments	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦										
	Generation of optimal correction surface	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦										
	Convergence analysis											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
	Efficiency analysis											🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Application to Airborne Wind Energy Systems	Dimensional analysis/Non-dimens.	🟦	🟦	🟦																	
	Design cycles with surrogate experiments				🟦	🟦	🟦														
	Design cycle for LTA stationary system							🟦	🟦	🟦	🟦	🟦	🟦								
	Design cycle for high L/D crosswind system													🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Figure 11: Proposed research timeline

3.4 Research Success Metrics

Three metrics will be used to evaluate the success of the research elements:

1. Does the research demonstrate, for specific but practically meaningful system structures, that the experimentally-infused approach leads to successful parameter convergence (quantitatively defined in analysis question 1) when a purely numerical approach does not?
2. Does the research show, for specific but practically meaningful system structures, that the experimentally-infused approach leads to substantially increased efficiency (quantitatively defined in analysis question 2) vs. a purely numerical approach?
3. Does the research show, for both AWE configurations, that the experimentally-infused approach leads to a substantially improved design, based on the resulting cost function value?

Part III. Broader Impacts

4. Educational Plan

The educational plan for this proposal consists of four major components, namely:

1. Building multidisciplinary undergraduate labs that give students hands-on exposure to flight dynamics and control design;
2. Co-designing an energy-rich high school science curriculum for the Charlotte-Mecklenburg EPIC Early College High School;
3. Designing kite design activities for K-12 summer camps sponsored by NC State University;
4. Inclusion of graduate and undergraduate students in full-scale flight testing of the Altaeros Energies Buoyant Airborne Turbine (BAT).

4.1 Build Multidisciplinary Undergraduate Labs

The experimental water channel setup from this work will be used toward building multidisciplinary labs for undergraduate classes, including:

- Dynamics II (MEGR 3122), where students will analyze the time and frequency responses of kite systems within the water channel environment and based on models;
- Introduction to Control Systems (MEGR 3090), where students will design real-time control algorithms to stabilize kites under varying flow conditions;

4.2 Co-Develop Energy-Rich High School Science Curriculum for Charlotte Mecklenburg Energy Production and Infrastructure Center Early College High School

The PI currently sits on the advisory board for a new Early College High School opening adjacent to the UNC Charlotte campus, with the first freshman class of 100 students entering in the fall of 2014. The school is particularly targeted toward preparing non-traditional high school students, including a large percentage of minority students, for an engineering education. This is accomplished through two key means:

1. Integration of a fifth year of high school;
2. Integration of first-year UNC Charlotte introductory engineering classes for college credit.

Based on the overall mission and approach of the school, the PI will work with the other members of the advisory board to build the five-year science and math curriculum, including both the course progression and the course content. The PI will integrate energy content into undergraduate courses and include senior and 13th grade technical electives in energy systems (see attached letter of collaboration). Because students at the EPIC high school will be required to take two years of physics, ample opportunity will exist for integrating energy content. And because the first class is entering in fall of 2014, the activities proposed here will integrate ideally with the first graduating classes. The proposed activities will complement work proposed within the PI's recently awarded NSF proposal, "Altitude Control for Optimal Performance of Tethered Wind Energy Systems," where the PI has proposed 1-day design activities that will integrate neatly into the syllabi and curriculum that are developed within the present proposal.

4.3 Build K-12 Modules in Physics of Kites

Fun and educational K-12 summer camp activities will be designed to teach students basic principles of flight dynamics through the design of kites. The PI has secured a collaboration with NC State University's "Engineering Place" (see attached letter of collaboration), wherein he will design a camp activities where middle and high school students compete in teams to iteratively design kites, using approved equipment, which will be scored based on flight time, flight altitude via altimeter measurement, and qualitative assessment of flight stability. The Engineering Place serves as the premier K-12 outreach program for UNC-Charlotte's sister university, NC State. The Engineering Place has indicated that the proposed kite design camps will fill an important aeronautical engineering gap in current camp activities.

4.4 Organize Student Participation in Full-Scale Flight Testing

Students at either the undergraduate or graduate level will have the opportunity to partake in eight person-weeks of on-site experience with Altaeros per year (see attached letter of collaboration). Depending on the state of Altaeros' prototyping at the time, each on-site experience will consist of either:

- Experience at Altaeros' headquarters in Boston, which is part of the eastern United States' largest clean-tech incubator, Greentown Labs, home to over 30 clean-tech companies, or

- Experience at Altaeros' test site.

It is expected that Altaeros will conduct at least two rounds of flight testing during the period of performance of this proposed work. During each summer experience period, the students will be provided with a stipend for housing and living expenses, either in Boston or on site. These activities will complement proposed educational activities in the PI's recently awarded proposal, "Altitude Control for Optimal Performance of Tethered Wind Energy Systems," which provides two weeks of annual flight testing support but does not provide a student with an extended on-site exposure to Altaeros.

4.5. Timeline for Educational Plan

Figure 12 shows the timeline for educational activities over five years.

Focus Area	Task	Year 1				Year 2				Year 3				Year 4				Year 5			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Multidisciplinary undergraduate courses	MEGR 3090 (control)	🟦	🟦			🟦	🟦			🟦	🟦			🟦	🟦			🟦	🟦		
	MEGR 3122 (dynamics)			🟦	🟦			🟦	🟦			🟦	🟦			🟦	🟦			🟦	🟦
EPIC high school curriculum development	Physics course development	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦												
	Technicical elective development									🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
K-12 camp modules	Initial kite module design	🟦	🟦	🟦	🟦	🟦	🟦														
	Iterative improvements							🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦

Figure 12: Timeline for educational activities

4.6 Educational Success Metrics

Four metrics will be used to evaluate the successfulness of the educational component of this proposal:

1. For the courses that integrate water channel-based AWE experiments (MEGR 3122 and MEGR 3090), does the experimental work result in improved class performance vs. previous semesters?
2. Does the high school science curriculum co-developed by the PI result in substantially higher science proficiency test scores and increased interest in energy systems engineering, versus other North Carolina early college high schools?
3. Do the kite design modules developed by the PI for The Engineering Place increase subsequent interest (as indicated by surveys) among K-12 camp students in aeronautical systems?
4. Do students who participate in full-scale flight testing and on-site experience at Altaeros subsequently report greater interest in renewable energy systems and clean energy start-ups?

5. Societal Impact: Accelerated Acceptance of Airborne Wind Energy Systems

AWEs eliminate as much as 90% of the material required for towered systems and provide access to high-altitude winds, which have been shown to often contain more than 5 times the wind power density of winds at traditional hub height, as discussed in [1], [2]. AWEs provide the capability of wind energy to penetrate locations where tower-based systems are too costly compared with conventional fossil fuels, including remote, off-grid communities, military forward operating bases, and deep-water offshore locations.

Most AWEs nominally promise levelized costs of energy between $0.05 and $0.25 per kW/h, making their installation an economically-attractive solution for several locations:

- Remote, off-grid communities, many of which presently rely on diesel fuel at a cost of $0.40-$1.20 per kW-h, as discussed in [3].
- Military forward operating bases, which presently pay $1.00 - $10 per kW/h for diesel fuel [4].
- Deep-water offshore locations, which are ill-suited to tower-mounted systems due to tower installation costs. The untapped deep-water potential in the U.S. alone has been estimated at over 4000 GW, more than half of which is in waters more than 60m deep [5].

These tethered systems are not being adopted readily, however, because the designs have not reached a level of robustness where they can be deployed for weeks, months, or years at a time. Given the expense associated with de-risking AWEs to the point of industrial acceptance, along with the complexity of these systems, the road to long-duration flights has been a long one. The optimization approaches pursued in this work, particularly with the rapid prototyping capabilities afforded by 3d printing technology and the unique water channel test bed, have the capacity to dramatically accelerate the progress of AWE designs.

6. Relationship to the PI's Long-Term Research and Educational Program

The proposed research and teaching activities will establish the underpinnings of a long-term research program aimed at understanding the dynamics of airborne wind energy system and optimizing their control. In initiating his research, the PI has brought on board two Ph.D. students, one M.S. student, and one undergraduate student. The funding provided by this proposal will provide the PI with the ability to bring on an additional Ph.D. student and maintain at least one undergraduate and/or M.S. student for the duration of the project. Through a vibrant research lab, it is anticipated that the PI and his students will regularly publish scholarly work in high-profile journals such as *Automatica*, *IEEE Transactions on Control Systems Technology, Control Engineering Practice, and AIAA Journal on Guidance, Control, and Dynamics*, in addition to competitive conferences organized by IEEE, ASME, and AIAA.

At the end of this project, the PI and his students will have created the first-in-world lab-scale, closed-loop system for characterizing and improving the flight dynamics and control of AWEs. This will act as a springboard for the PI's research group at UNC-Charlotte to serve as a leader in the long-term research of tethered systems. Because the research conducted under the umbrella of this proposal touches upon a diverse range of topics, such as aerodynamics and additive manufacturing, it is expected to attract significant department-wide and college-wide attention and provide UNC-Charlotte with significant positive exposure. Furthermore, through the connection between the PI's research program and full-scale design activities being undertaken at Altaeros Energies, the PI's research lab will remain on top of the trends in real-world AWE development.

Equally important to the long-term scholarly potential of the proposed research work are the long-term relationships that will be established through the outreach elements of this proposal. The PI's role on the design team for the EPIC early college high school is expected to continue through his career, enabling the PI to positively impact the science curriculum for thousands of high school students, a large fraction of whom come from disadvantaged backgrounds. Furthermore, through collaboration with Altaeros Energies (which is a member company of Greentown Labs, the largest clean energy technology incubator in the eastern United States), the PI will maintain ties between academia and entrepreneurship, giving students first-hand insight into the life of early-stage startup companies, particularly in the clean-tech environment. This relationship is expected to be solidified by and continue well beyond the duration of this proposal.

7. Results from Prior NSF Support

Dr. Chris Vermillion has been awarded NSF support under CMMI-1437296, entitled "Altitude Control for Optimal Performance of Tethered Wind Energy Systems" ($286,819, September 1, 2014 – August 31, 2017).

Intellectual merit: The proposed research will fuse extremum seeking and information maximization approaches to create an altitude optimization framework for AWEs that simultaneously optimizes altitude while mapping the wind shear profile. Because the start date is pending, there are no results to report.

Broader impacts: If successful, the proposed research will significantly increase the capacity factors of AWEs in locations with complex wind shear profiles. Educational elements of the proposal will impact high school students through several one-day renewable energy activities in an early college high school. Because the start date is pending, there are no results to report.

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