Control of an Airborne Tethered Kite for Energy Production

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Abstract

Airborne wind energy is rapidly becoming an area of intense research. Wind turbines are the dominant form of wind power today, despite having serious shortcomings in terms of cost, infrastructure requirements, and having reached a plateau of technological development. Wind can also be harvested by airborne systems such as kites, which have greater technical challenges (control) but may also overcome the limitations of traditional technology. We propose a low altitude ($\approx$ 100 metres or less) airborne energy harvesting method, such that energy harvesting does not use the well-established pumping cycle, but rather the cyclic lateral motion of a kite. This method is designed for use on a small scale, portable system that can use mass produced kite-surfing kites. The existing FreeKiteSim project is used to simulate the system dynamics of a kite power system, and a kite trajectory controller developed that can initialise a power harvesting trajectory and maintain stable flight. A layered controller design results in a simple PD controller correcting kite heading towards the desired trajectory. We discuss concepts for the production of power in the low altitude regime. Simulation results show that the controller is successful for sustained flight along an energy harvesting trajectory.

1 Introduction

Energy production is a major industry in Australia, contributing 7% to GDP in 2013-14. [Dep, 2015] In that same period, Australian electricity generation was 61% coal, 22% gas, 15% renewables with 2% coming from other sources. Generation from coal decreased by 5% over that year, with gas increasing marginally, and renewables increasing by 12%. Growth in the renewables sector was mostly in wind and solar energy; wind generation grew by 29%, and solar generation by 27%. The general trend of decline in coal and growth in renewables has been true for about a decade. Wind generation features most strongly in South Australia, where it accounts for 31% of electricity generation. [Ene, 2015] These trends are expected to continue for the foreseeable future; many countries, including Australia, have set renewable energy and carbon reduction targets to combat climate change. Intentional measures to reduce carbon intensive energy production and increase use of renewables means this sector is likely to continue to grow for many years to come.

The technology underpinning the impressive growth seen in wind based electricity generation is the ground-based, conventional wind turbine. Wind turbines are the dominant form of wind power today, and the technology is well developed. But traditional wind turbine technology has several drawbacks when compared to the potential of the relatively unexplored option of harvesting airborne wind energy (AWE). Wind turbines suffer from a negative image among some of the public and policy makers due to alleged negative health effects and aesthetics. They can be very large but can still only access wind close to the ground where it is not as strong and more turbulent than high altitude winds [Archer and Caldeira, 2009]. Turbines have to be fixed and are not mobile, requiring permanent and costly infrastructure, particularly the towers upon which turbines are mounted. Energy generation systems based on airborne devices, in particular kite power systems (KPSs), have greater technical challenges (control) but also great potential to overcome many of the limitations of current technology.

While relatively unexplored compared to other more established forms of renewable energy such as solar and wind turbine technology, AWE systems have seen growing interest in recent years. In fact, there have been six international airborne wind energy conferences since 2009, most recently in 2015 [Schmehl, 2015]. A burgeoning industry is growing around AWE, with various concepts in development, and ongoing research into modelling, simulation, control and optimisation of these systems. Very little work appears to have been done in Australia however, despite the obvious potential for wind power in this country. AWE technology is generally designed to harvest energy from winds up to between 1000 and 1500 metres above ground [Fagiano and Milanese, 2012]. However, low altitude systems remain relatively unexplored, and may still present advantages in terms of required infrastructure, cost, and mobility.

AWE technologies can be categorised into various kinds, but here we focus on kite based systems that operate on the principal of aerodynamic lift and have ground-level generators (GLGs). These systems consist of a flying kite controlled by one or more control line tether(s) attached to a GLG. Investigations into such systems thus far have largely focussed on a two stage “pumping” cycle [Fagiano *et al.*, 2010][Ahmed *et al.*, 2012][Jehle, 2012][Canale *et al.*, 2010][Erhard and Strauch, 2015][Canale *et al.*, 2009][Canale *et al.*, 2007]. In the first phase, called the power or traction phase, the kite is manoeuvred to maximise the aerodynamic lift force so that it reels out a drum driving an electric generator. In the return phase, the kite is manoeuvred to minimise the aerodynamic lift force and the tether is reeled in [Ahmed *et al.*, 2012]. Systems are designed to spend a minimum amount of energy recovering the kite for the next traction phase, and maximise the energy generated during the traction phase [Ahrens *et al.*, 2013][Fagiano and Milanese, 2012]. With optimal controller design, this method leaves a considerable net amount of generated energy [Fagiano *et al.*, 2010][Erhard and Strauch, 2015]. This type of energy generation method is favoured for high altitude systems, where the reel distance can be considerable, and the tension applied by the kite on the tether can be used directly to generate energy. Figure 1 shows an example of the pumping cycle employed by most KPSs today.

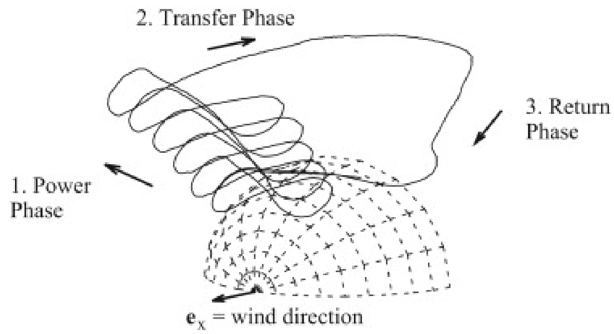

Figure 1: Diagram of the phases of the pumping method of energy generation with a kite power system. The transfer phase is simply the transition from the traction phase to the return phase. Figure adapted from [Erhard and Strauch, 2015].

Modelling and simulation has been recognised as an important tool in the study of kite dynamics and controller design [Fechner *et al.*, 2015][Jehle, 2012][Li *et al.*, 2015][Canale *et al.*, 2009]. Simulation is a low cost and low risk alternative to designing, building and testing a physical system since it allows changing of parameters and testing of control algorithms without the trouble of modifying a physical system. A brief overview of previous kite modelling attempts is presented in [Fechner *et al.*, 2015]. Modelling of KPSs has progressed significantly in recent years, but most methods and models fall short of our requirements. The most common issues are that models are incomplete, not described in enough detail to use or replicate, too simple/lacking accuracy, or too computationally expensive. The model presented in [Fechner *et al.*, 2015] and published as the FreeKiteSim project [Fechner, 2015] is a complete dynamic model of all system components of a KPS and has almost identical requirements to this project, and has been validated by experimental data.

KPS control is a non-trivial problem. A successful controller must maintain stable flight, be robust to variable wind conditions and respond to perturbations (turbulence). It needs to maximise energy production with a high safety level by maintaining a minimal distance from the ground. Various control methods have been employed for KPSs, although they are almost exclusively model-based [Fagiano and Milanese, 2012]. Control has been considered from a direct-inverse approach, which allows computation of a controller directly from data, thus avoiding the need to derive a model of the system [Novara *et al.*, 2011b][Novara *et al.*, 2011a]. An adaptive predictive functional controller has also been developed for automatic control of power kites [Sun and Wang, 2012]. However, these methods were only shown in numerical simulation results. Nonlinear model predictive control methods have been commonly employed and tested on real KPSs with good success and agreement between simulation and experiment [Canale *et al.*, 2010] [Canale *et al.*, 2007]. Adaptive control and machine learning techniques have also been investigated [Yongyu and Qu, 2015]. The main issue for all model based control methods is the requirement for accurate but also fast and simple dynamical models of the airborne physical system (kite).

Here, we investigate the feasibility of a different approach for a KPS: a smaller, simpler, portable, more cost effective device designed to operate at altitudes within the limits of the Civil Aviation Safety Regulations [Standards, 2009] in Australia. This approach is optimised for use with interchangeable mass produced kite-surfing kites and to be easily packed up, moved, and set up again. Limitations on kite mass, visibility and notifying the Civil Aviation Safety Authority mean that operating above the altitude limit (400 ft./120 m above ground level) is not a viable option for a device with the requirement for easy relocation [Standards, 2009]. Therefore, we discuss a novel energy generation method for a KPS that does not use pumping cycles which could not be used at these altitudes. Our method is easier to deploy and a small scale alternative to the large industrial scale energy generating mechanisms currently under development. The system described here may be of particular use in developing regions and small and/or isolated communities, where AWE could provide a cheap and easy energy generation method, particularly those with trade winds or other predictable and strong wind patterns.

The energy harvesting method proposed here would continuously generate energy by careful control of the flight path, using the lateral motion of the kite as it completes sideways figure of eights. Methods for harvesting the kinetic energy of this motion are discussed. Pumping cycles use much of the flight time reeling the kite back in and losing energy. Though the overall efficiency of a pumping cycle comparing energy generated to energy lost reeling in can be quite efficient, it is not applicable in the limited altitude regime and our approach allows for continuous, uninterrupted energy generation.

This research lays the groundwork for a project to build a physical prototype system to use as proof of concept for the controller and energy generation method. Real data about the design and performance of physical systems of noteworthy similarity to the aims stated here is sparse in the literature. However, the ground based controller by Fagiano et al. [Fagiano and Milanese, 2012] [Fagiano and Marks, 2015] and an airborne control system with a ground based energy harvesting mechanism [Fechner and Schmehl, 2012] did provide significant inspiration. Realising an experimental setup for a KPS is a difficult task, involving various facets that currently have no established design guidelines. An investigation into making airborne wind energy accessible to a larger number of researchers is presented in [Fagiano and Marks, 2015]. This paper provides guidelines for a small prototype KPS without energy generation, but with all other capabilities commonly required to test a KPS. It provides full design details and costs of an actual experimental setup that was successfully used to develop and test sensor fusion and automatic control solutions. This research is invaluable for those planning on building a KPS.

This work is based on the previously mentioned FreeKiteSim project [Fechner *et al.*, 2015]. We use this framework to develop a controller for the trajectory of the kite. The controller is designed such that it could be physically implemented to operate the tethers just like a human operator would. The implication of this kind of control system is that it should be modular and interchangeable with many different kites, including commercially available mass produced power kites, such as those used for recreational kite-surfing. We define a successful controller at minimum capable of two states: maintaining stationary stable flight, and initiating and maintaining a horizontal figure of eight flight path. This includes keeping the crossover point of the flight path at a constant azimuthal angle, and maintaining kite altitude.

2 Modelling Framework

The FreeKiteSim project is a full system simulator for describing the dynamic behaviour of all the interconnected systems of a kite power system. It incorporates an atmospheric model, tether model, kite models including wing and bridle, and a winch model for reeling in and out. It is designed to be adaptable, is (soft-) real time capable, written in Python, and the source code is released under the LGPL license, all reasons why it was chosen over alternatives.

It is important to clarify the reference frames and coordinate systems for the various parts of the model that the controller operates on. The system used here is introduced in [Fechner and Schmehl, 2012]. Figure 2 illustrates the *small Earth* reference frame; the key parameter for control is ψ_{SE}. This is the same as the heading of the kite, ψ, assuming a straight tether and that the heading is perpendicular to the tether. ψ_{SE} is defined as the angle between the x axis in small Earth reference frame and the x axis in the kite reference frame. ψ_{SE} will be zero when the kite heading is towards the zenith along x_{SE}, positive when heading towards the north ($+y_w$), and negative when heading towards the south ($-y_w$). $\psi_{SE} = \pm 90\,\text{deg}$ would maintain constant altitude. The small earth reference frame allows the system to effectively be reduced to a single input single output control problem on the heading variable. The control objective of the kite trajectory controller is to control this angle. The reeling in or out of the tether of the kite which moves the kite in the z_k direction is irrelevant to the kite trajectory controller.

The mathematical framework is broadly represented as a particle system using spring-damper elements to describe their mechanical properties and connectedness. There are many assumptions and simplifications in this model that reduce complexity significantly and increase simulation speed. These are justified by the fact that this simulation has been tested and verified against real data to be a reasonable model of the real behaviour of a kite.

The kite model used here is the four point model proposed by [Fechner *et al.*, 2015]: it is the simplest model that includes rotational inertia on all axes, and many of the kite parameters are very easy to determine simply from measurement. Steering sensitivity parameters need to be identified as these are defined by the flexibility of the kite which is not modelled explicitly. Figures 3 and 4 show how the four point kite and the tether system is modelled.

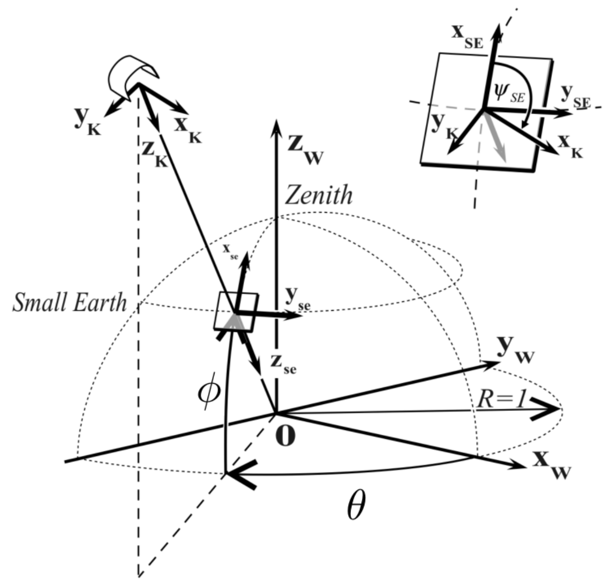

Figure 2: Small Earth reference frame. The frame labelled w is the *wind reference frame*, centred on the ground station of the system with the x axis pointing in the direction of the wind. FreeKiteSim defines the wind direction as from west to east, so the wind frame does not rotate relative to the ground. The *small Earth reference frame* is then introduced as a way to define the heading of the kite. The z axis in the kite reference frame is from the ground station to the kite. The kite's position is projected along this axis onto a unit sphere surrounding the origin of the wind reference frame, and then the position of the kite on this unit sphere can be described with two angles, the azimuthal angle θ and the elevation angle ϕ. This describes the position of the kite in the small Earth reference frame. Figure adapted from [Fechner and Schmehl, 2012]

3 Controller Design

Trajectory design and optimisation has been studied extensively elsewhere [Fagiano and Milanese, 2012]. The most common is the horizontal figure of eight trajectory, which has become the standard choice for KPSs for several reasons. This flight path pre-

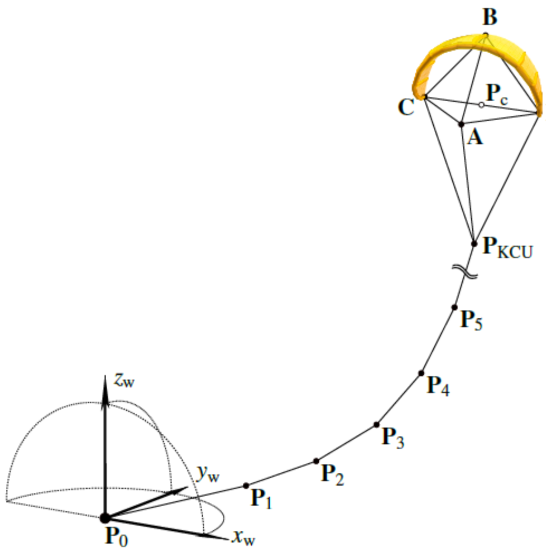

Figure 3: Modelling framework for the tether and kite. The system is made up of discrete point mass particles. Figure adapted from [Fechner *et al.*, 2015]

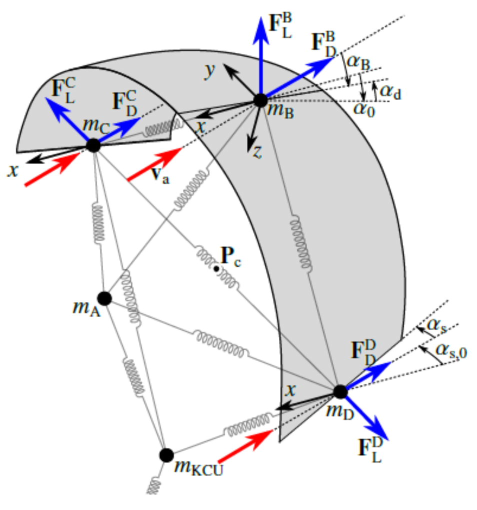

Figure 4: Illustration of the four point mass particle model. α is the angle of attack, v_a the apparent air velocity, α and α_0 depower angles, and α_s steering angle. Figure adapted from [Fechner *et al.*, 2015].

vents tether lines from twisting or winding around each other, which is a problem for other periodic trajectories, while allowing for a high crosswind speed, which maximises traction power and is desirable for the power generation method offered here [Roland Schmehl, 2013]. The figure of eight is also able to achieve a wide azimuthal range while maintaining a relatively consistent and safe elevation, and can be performed from a stationary base station. Given a predefined figure of eight trajectory, the control problem is actually very similar to contour following control, as used for machining operations [Li, 1999].

The control architecture developed here is a layered design. The first layer is the target trajectory; a parametrisation of the figure of eight is developed, and the nearest location on this planned trajectory to the position of the kite (θ, ϕ) is found at every time step. This layer outputs the Euclidean distance between the kite and this nearest point in the small earth reference frame, and the heading vector tangent to this point on the planned trajectory. The second layer is the heading correction term, which takes the distance and tangent heading angle from the first layer, and applies a correction to the tangent heading angle towards the target trajectory based on the magnitude of the distance. The third layer is a simple PD controller, which uses the corrected heading vector as the reference and outputs a control signal to the kite based on the error between the kite's current heading and this reference signal. The final stage is to provide this control signal to the FreeKiteSim steering controller which applies the steering signal to the kite.

The pose of the kite is described in the small earth reference frame, a 3-vector of azimuthal angle, elevation angle, and heading: (θ, ϕ, ψ). Initial experimentation was performed with a simple sinusoidal parametrisation of the figure of eight, defined by Equation 1. The sideways figure of eight shape completes two cycles in elevation for every cycle in azimuthal angle. At low elevations there is more turbulence and lower wind speeds, but at higher elevations the kite does not operate in the optimal crosswind regime any more, so there is less lift force generated by the kite. An elevation at about 30 degrees was experimentally found to produce desirable flight characteristics. The kite needs to be sufficiently clear of the ground that the controller can recover from perturbation without hitting the ground. The turning curve also needs to be realistic to the physical limitations of the kite, which limits how small the elevation range can be. The limits of the trajectory were defined as $\theta \in [-30, 30]$ and $\phi \in [30, 50]$, the elevation frequency as 2 and the azimuthal frequency as 1 over the period $[0, 2\pi)$. This defines the target trajectory.

$$\theta_T(x) = 30\,\sin(x), \quad x \in [0, 2\pi)$$
$$\phi_T(x) = 10\,\sin(2x) + 40, \quad x \in [0, 2\pi) \qquad (1)$$

Equation 1 also defines the heading angle at any point along the target trajectory - it is tangent to the curve, heading downwards at the intersection point. Equation 1 is discretised in x for use in computer simulation, and the heading angle at any point along the trajectory defined by the angle formed by that point and its predecessor, as in Equation 2. The value of Δx must be chosen so that the resolution of the trajectory is sufficient without causing excessive computation.

$$\psi_T = \text{atan}\left(\frac{\Delta\theta}{\Delta\phi}\right)$$
$$\psi_T(x) = \text{atan}\left(\frac{\theta_T(x) - \theta_T(x - \Delta x)}{\phi_T(x) - \phi_T(x - \Delta x)}\right) \qquad (2)$$

The target trajectory positions and headings are now defined; the controller will have the kite move towards these target states. From any arbitrary position, the closest trajectory point can be found by iterating over the discretised target trajectory points, and finding the minimum euclidean distance δ in degrees between the kite position and the trajectory locations. When the closest trajectory point is found, the target heading angle ψ_T is calculated at that point.

This is not enough to have the kite accurately track the desired trajectory however - with the above described algorithm the best the kite could do is track parallel to the nearest trajectory point. The heading angle must be adjusted to bring the kite towards the target trajectory. An extra term is added to the trajectory heading angle ψ_T to act as a potential field attracting the kite towards the desired trajectory. The attraction should be greater the further away from the desired trajectory and vanish when the kite is tracking accurately. The arctangent function has the desired properties, with a result of zero at zero input, steep onset, vanishing gradient after unitary input, and maximum value of 90 degrees.

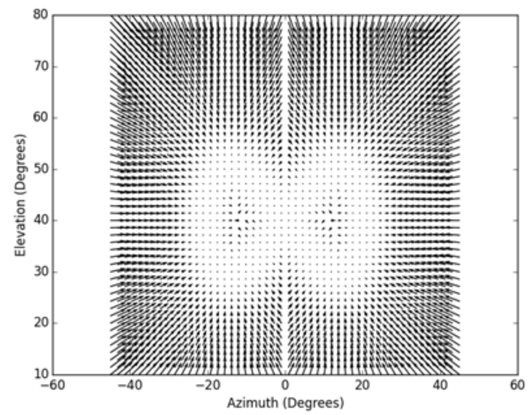

Figure 5: This vector field points in the direction of the closest trajectory point and the magnitude of the arrows is the correction term ψ_C as calculated by the arctangent of the distance ratio.

Using this function and a relative distance δ_0, the correction angle is determined by Equation 3. The effect of this correction can be adjusted by changing the relative distance.

$$\psi_C = \text{atan}\frac{\delta}{\delta_0} \qquad (3)$$

Figure 5 shows the potential field developed by the trajectory point selection algorithm. The arrows point to the closest point, and the increasing magnitude with distance shows the behaviour of the correction term.

Figure 6 shows how the trajectory heading and the correction angle are combined to determine a command angle. This command angle defined in Equation 4 still points in the general direction of the trajectory heading but also back towards the desired trajectory in the event that the kite moves away from this flight path.

$$\psi_{cmd} = \psi_T + \psi_C \qquad (4)$$

Preliminary results indicated a failure of this algorithm to apply the correction term in the right direction. The correction angle needed to be applied towards the target trajectory, but this depends on the relative location of the kite to the trajectory. The arctangent function is always positive for a positive input, but analysing the situation presented in Figure 7 shows that there are eight distinct pose regions

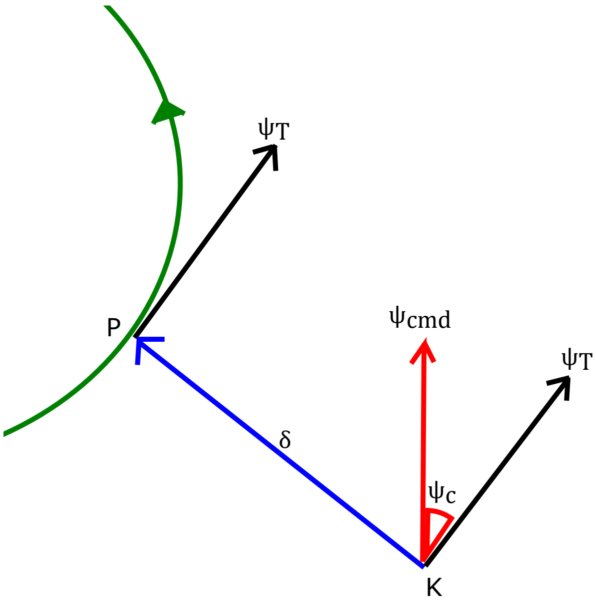

Figure 6: When the kite position does not fall on the target trajectory, the command angle ψ_{cmd} is adjusted by the correction angle ψ_c. Note: ψ_T and ψ_{cmd} are angles from the vertical axis, as defined in the small Earth reference frame.

the kite could occupy, half of which require the correction angle to be negative. These are summarised in Table 1.

This makes clear that by simply multiplying the sign of the azimuth value (negative or positive) by the condition of whether the point is within (+) or outside (-) the trajectory, we obtain the required turn direction. This fixed the correction angle. With correction the kite can turn towards the desired trajectory and follow it despite perturbation.

The corrected command angle is used as the reference signal in a simple PD controller. The gains are tuned via experimentation to produce good tracking behaviour. For a constantly moving reference signal (the constantly updating command angle) an integral controller is not as useful and omitted. The PD controller has the general form of Equation 5.

$$u(t) = K_p e(t) + K_d \dot{e}(t) \tag{5}$$

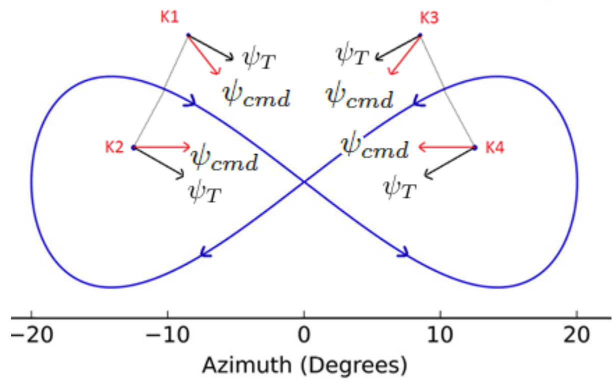

Figure 7: Required turning direction of the correction term.

Where:

$$\begin{aligned} e(t) &= \psi_{cmd} - \psi \\ \dot{e}(t) &= e(t) - e(t - T_s) \\ t &\text{ is the current simulation time} \\ T_s &\text{ is the time step} \end{aligned}$$

This result is provided as input to the steering controller implemented in simulation which provides the steering control mechanism for the kite. This system was already implemented as part of FreeKiteSim.

4 Energy production

This controller has been designed with a real system in mind. Assuming the kite does not stall (it is always powered) and that there is negligible slack on the tether means simple sensors could be built based at the ground station to measure elevation and azimuth from the tethers. This is a reasonable assumption for low elevation and relatively short tether lengths; for a high altitude system with tether lengths of several hundred metres or more this would not be valid.

The control problem is simplified in the case of a continuous energy production method, because the controller does not need to reel the kite in and out or deal with de-powering or powering the kite as in a pumping cycle. We propose a system where the kite is flown in a crosswind figure of eight as above, at constant tether length and traction settings, and power is generated through a mechanism at the tether anchoring points. Two possible concepts have been developed: the first anchors the

Table 1: Poses requiring correction

Point	Azimuth Region (+ or -)	Outside or Inside Trajectory	Required Turn Direction (left or right)
K1	-	Outside (-)	Right (+)
K2	-	Inside (+)	Left (-)
K3	+	Outside (-)	Left (-)
K4	+	Inside(+)	Right (+)

tethers to a lever, and the second anchors the tethers to a rail system or another linear to rotational motion converting mechanism. Both concepts harvest energy through the lateral motion of the kite, as explained in Figure 8. The power generated by a kite with this kind of configuration depends on the crosswind speed of the kite, rather than the reel-out speed as with the pumping cycle regime. One disadvantage compared to the pumping cycle method is that the force used to generate power is not the full tension force on the tether, but some fraction of that depending on the angle between the tether and the anchor point. It is clear by inspection of figure 8 that if the force required to move the anchor point is large, that is, there is large resistance to motion in the generator mechanism, then α will have to be small to produce the required force and much of the motion of the kite will be wasted in changing azimuthal direction in the figure of eight trajectory. Therefore, a generating device with low resistance to mechanical motion is desired. It is clear also that a trajectory with minimal change in elevation and maximum change in azimuth is desired. A vertically thin and horizontally wide figure of eight trajectory fulfils this criteria.

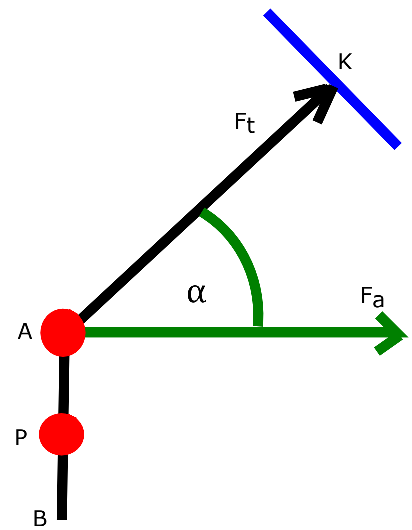

Figure 8: Concepts for power generation using a low altitude KPS. The first is to anchor the tethers to the end of a linkage at A which is able to rotate about P. The lateral motion of the kite applies a force to A and the linkage acts as a lever, applying a mechanical force to B which is used to generate power. In this case, the tether applies a force F_t to A which is reduced through the angle α to an applied force F_a perpendicular to the line AB. This develops a torque about P. Because the anchor point rotates with the kite, F_a and α remain relatively constant from the moment the linkage starts moving until the kite changes direction. The rail concept works by having the tethers anchored to the power generating mechanism directly rather than through a lever, and the kite simply drags the anchor point along a horizontal rail. The angle α decreases and the applied force F_a increases the further the kite gets from the crossover point of the figure of eight. Power is generated through any number of linear to rotational motion converting mechanisms, or for a very small system by induction.

5 Results and Analysis

Initial testing demonstrated the effectiveness of the controller developed above, but also made clear the importance of properly tuning the parameters of relative distance and controller gains. With the controller working correctly, the effect of the relative distance δ_0 on the ability of the kite to trace the target trajectory was first evaluated. Small δ_0 makes the correction angle too large and the kite turn too sharply towards the target trajectory, building up inertia which it struggles to compensate for. Large values cause the correction term to be too small and the flight path of the kite only loosely follows the target trajectory, eventually becoming unstable and deteriorating. A value of around 25 degrees was found to be optimal, causing the correction term to gently steer the kite towards the target trajectory without building up to much rotational inertia.

The effect of controller gains was also investigated. The proportional gain had far less influence on performance than the derivative gain (as long as the proportional gain was high enough for the controller to function). We found that a derivative gain of approximately 100 produced good results. Lower gain values appear to make the kite more prone to over steering, similar to the effect of a small relative distance. When it starts heading down with the assistance of gravity it gains inertia and struggles to turn around again. Large values maintain the figure of eight but the flight path traced by the kite is less consistent, and produce a much tighter figure of eight than intended.

Figure 9 shows the flight path of the simulated kite when the parameters have been well tuned. It is largely successful in tracing the target trajectory, except in the higher elevation ranges. It does not trace out the same path every time but this is expected in what is clearly an under-actuated and open-loop unstable system. Testing was performed in simulation with a variety of wind conditions and starting positions. In all cases, well tuned relative distance and controller gains maintained stable flight as well as acceptable trajectory tracking performance. In all simulation experiments the kite traced the bottom half of the target trajectory well, but the top half poorly; this matches expectations since peak flight performance in the crosswind regime was found to be at approximately 30 degrees. The loss of performance is due to a loss of traction at high elevation angles and an unoptimised target trajectory that does not reflect the capabilities of the system.

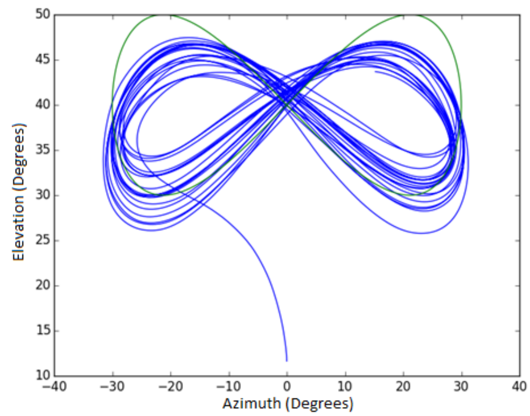

Figure 9: Figure of eight target trajectory, superimposed with flight path of the kite over 4 minutes of simulation. This demonstrates the stability and tracking performance of the controller. The maximum azimuthal range of this trajectory is a little higher than the region where the kite has good traction and therefore could be improved, but the controller succeeds in responding to perturbations and keeping the kite on the target trajectory.

6 Conclusions

The controller developed here is successful at fulfilling the primary goal of stable crosswind flight following an energy generating target trajectory in simulation. With a simple controller that does not rely on a system model or large computation requirements, and concepts for energy production at low altitudes developed, we will be able to build and test a small prototype system based on this work. That system will be able to overcome the limitations of wind turbine infrastructure, and the Civil Aviation Safety Regulations which limit the use of high altitude systems. In the future, we will concentrate on developing an optimised target trajectory. The simulated kite was able to track the target trajectory quite well, but could be improved, perhaps through optimisation techniques as applied elsewhere. The controller also needs further testing; as it stands it is quite simple, with some assumptions about implementation that can only really be tested on a physical prototype. Parameters affecting performance could also be tuned much more finely. Comparison with other control techniques will also be of interest. Further controller refinement and analysis, including a more thorough analysis of long term stability, and more thorough theoretical analysis of parameters including relative distance and gain will be carried out. The simulator could also be further adapted to more closely reflect the kind of system we would like to build, as some modelling components remain the same as the original FreeKiteSim project. The source code for this project is available upon request.

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