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Angular elevation control of robotic kite systems

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Abstract— **The kite mechanics including some basic aerodynamics is reviewed in order to set up a framework for the development of robotic kite systems. Some historical background is provided together with a brief review of kite applications, which have been numerous and diverse. Robotizing the kite is expected to enhance its capabilities and revive scientific kiting. Towards that direction a methodology for controlling the angular elevation (and the altitude) of a single–line kite by actively adjusting the length of its bridle strings is proposed together with the required implementation hardware. Preliminary simulations and proof–of–concept field testing using a box kite were carried out.**

Index Terms— **Kite, robotic kite, kite angular elevation control, scientific kiting.**

I. INTRODUCTION

Kites belong to the class of unmanned, heavier than air, tethered, and non–power driven flying devices. There exist many different types of kites: *delta*, *box*, *Cody sled*, *diamond*, etc. [1], [2]. Most of the existing kite designs were developed for recreational purposes (e.g., hobby or kite fighting) and fewer of them for a functional purpose (e.g., atmospheric probing). Among the latter is the box kite and its variations, which historically has been a workhorse for meteorology. Box kites have the shape of a hexahedron defined by four parallel rods and a diagonal arrangement of crossed struts as shown in Figure 1. The sail is stretched around the framed structure and it is divided into an upper and a lower part. In general, a box kite is characterized by a big area of exposure, steady flight and good payload lifting capacity. Box kites have been used extensively as part of our investigations.

In general, many of the conventional kite designs consist of the following parts: (i) A lightweight *framed structure* with a *covering* (sail) stretched over it, designed to gain lift from the wind flowing around it. (ii) The *control line* (*tether*) used to restrain the kite against the wind. It is attached to the kite through the bridle (see below) or directly at a point on the frame. (iii) The *bridle* consists of two or more lines (*bridle strings*) appropriately attached to the kite and also connected to each other at the *bridle point*. The bridle point acts as a fulcrum around which the kite rotates. (iv) The *tail* includes a string with strips of paper, fabric or other material tied to it at intervals and is suspended at the lower part of the kite. For some kite designs the tail is necessary for the stability of flight but others do not require a tail, as for example the box kite.

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Applications of kites have been numerous and diverse and exploited the lifting capabilities of kites (lifting meteorological instruments, man–lifting for military applications, etc.), as well as the towing capabilities of kites (traction of sea vessels, performing various "extreme sports" including *kite buggying* and *kite surfing*, etc.). Kites have contributed to various fields of science with meteorology being the epicenter. However, after the development of other flying means the interest in scientific kiting gradually declined and today is fairly limited. Another contributing factor to the abandonment of kites is that kite technology always remained low–tech and today kiting is considered more art than science. A possibility which remains largely unexplored is robotization of the kite system through the integration of modern sensing, communication and control technologies, which is expected to renew the interest in scientific kiting. Relevant hardware has become lightweight and miniaturized and therefore, well suited to scientific kiting applications.

A. Motivation

A kite may provide a low–cost, low–tech alternative to other flying means, providing a stable platform often capable of staying aloft continuously for days without requiring any power sources other than aeolic energy. Kites are environmental friendly flying means with good lifting capacity. Unlike airplanes or helicopters kites are not intrusive devices in the sense that they do not create significant disturbances to their surrounding environment that may interfere with the application (e.g., kites were used for insect collection for entomological studies [3]). Kites are easy to transport and do not require any special sites for launching. They can operate at heights up to many kilometers above the ground and can be particularly useful in applications requiring continuous profiling of the atmosphere, as for example in meteorology where kites used to be a major tool. The use of kites in meteorological studies gradually gave its place to balloons. However, balloons leashed they cannot be controlled during strong winds (typically blown towards the ground) and unleashed they drift away, with their payload (e.g., meteorological instruments package) rarely recovered.

On the other hand, kites also have their limitations. Kites are not all–weather systems (e.g., cannot fly during a storm) and require favorable winds. Unfortunately, the kite flier does not have the powers of Aeolos, the god of winds from the Greek mythology, who was keeping the winds captured in a bag and would release them at will. Moreover, one needs to consider the fact that kite flights can be dangerous in the vicinity of power lines. Also, kite lines may become dangerous obstructions to other aerial vehicles. According

Fig. 1. Box kite with standard bridling (dimensions: $102 \times 50 \times 50\ cm$).

to the International Civil Aviation Organization (ICAO) kites are considered to be aircrafts and their use is regulated. Regulations prohibit kites to be flown near airports, gliding centers, over congested areas of cities, towns or settlements, or an open–air assembly of persons not associated with the operation. Moreover, for high–altitude flights early notifications and details need to be provided to the air traffic control authorities.

B. Applications

Through history kites had an important contribution in various scientific fields. Benjamin Franklin is among the most famous kite fliers that in 1752 performed his famous experiments on electricity using kites flown during a thunderstorm. In 1901, Guglielmo Marconi used a kite to help transmit the first transatlantic wireless telegraph message by raising the receiving aerial using a lifting kite. The Wright brothers were also known to have performed extensive kite–flying experiments to expand their aerodynamics knowledge that finally let to the invention of the airplane.

During the end of the nineteenth century and beginning of twentieth century kites became a major tool in meteorology, until finally replaced by meteorological balloons. Kiting for atmospheric probing purposes is currently limited and rather sporadic (e.g., [4], [5], [6], [7], [8], [9], [10]). Among the recent developments one may highlight a device called the “WindTRAM” developed by Balsley et al. [11]. This wind–powered device can climb along the tether under radio control and carry meteorological instruments.

Payload lifting applications for kites include kite aerial photography (KAP), which involves suspending a camera rig from a kite to serve as an “eye in the sky” [12]. Proposed applications of KAP include crop scouting, agronomic management, and management of natural resources, as for example in [13]. Among the recent developments in KAP is a teleoperated camera rig suspended from a kite [14].

II. Aerodynamics of kites

The aerodynamics of a kite is in many respects analogous to that of an airplane from where kite literature borrows much of its terminology. Even though the specifics of the relevant aerodynamics phenomena are quite complex some basic mechanics is often adequate for understanding the flight of a kite [15].

A. Forces acting on a kite

The forces acting on a kite and its control line [16] are shown in Figure 2: (i) Total aerodynamic force acting on the kite (R) at the center of pressure (COP). (ii) Total gravitational force acting on the kite (W) at the center of gravity (COG). (iii) The restraining tension of the line (T) acting on the kite at the bridle point. (iv) The gravity force acting on the control line (distributed). (v) The wind force acting on the control line (distributed). (vi) The force at the ground reel point (T_{reel}). For a straight control line $T_{reel} = T$. (vii) The resultant of the aerodynamic and gravity force due to the tail (B), if there is one. For stronger winds this force assumes a more horizontal direction.

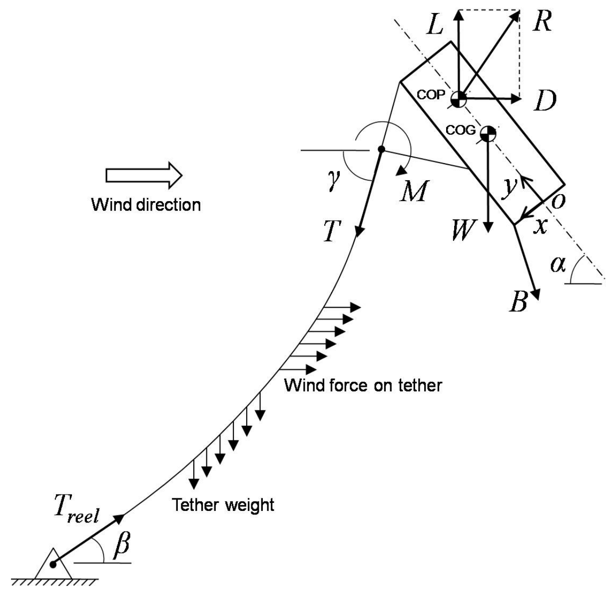

Fig. 2. Two–dimensional model of a kite with forces acting on the system.

B. Aerodynamic forces

The kite will be considered to have a fixed shape even though it is in fact a deformable structure. The aerodynamic force acting on the kite is produced by the uneven flow of air around the kite. Given that the kite is designed to position itself at an angle with respect to the wind direction, the air above the kite moves at a higher velocity compared to the air traveling below the kite. Consequently, the pressure above the kite is lower than the pressure below and the aerodynamic force (R) is generated, as shown in Figure 2. In fact, this is a distributed force for which the overall point of application is called the *center of pressure* (COP). The total aerodynamic force acting on the kite can be resolved into two components, the *lift* (L - vertical component) and the *drag* (D - horizontal component) calculated as follows:

$$L = C_l A \rho \frac{V^2}{2}, \quad D = C_d A \rho \frac{V^2}{2}, \qquad (1)$$

with C_l the lift coefficient, C_d the drag coefficient, A the total frontal projected area, ρ the density of atmospheric air, and V the wind velocity (relative velocity between kite and wind). Both the lift and drag coefficients depend on the geometry of the kite and the *angle of attack* (α - also called *angle of incidence*), which is the angle between the wind direction and the kite as shown in Figure 2. The values for the two coefficients can be measured experimentally through wind tunnel testing but for simple geometries like thin flat plates their values can be found in aerodynamics textbooks. The lift depends proportionally on the density of the air, which implies that in order to sustain flight at altitudes well above the boundary layer it requires stronger winds due to decreased air density. Vertical forces equilibrium requires that the lift should be greater (or at least equal) to the total weight (including the weight of the tail if there is one as well as the weight of the control line) in order for the kite to stay aloft.

Borrowing terms from aircraft aerodynamics, the *span*, s, of a kite is defined as the distance from side to side. Also, the *aspect ratio*, AR, is defined as: $AR = s^2/A$. When calculations are performed attention is required to ensure that the definition of the area is used consistently (total surface area, and frontal projection are often used). The calculated values for the lift and drag coefficient often need to be adjusted for an aerodynamics phenomenon called *downwash*. This phenomenon involves flow spills at the edges of the kite from the bottom to the top side due to the pressure difference. Given the small aspect ratio that characterizes a kite this effect becomes considerable. Calculations of the lift and drag coefficients may follow the relationships found in NASA's webpages on kites [15], which collect a wealth of information regarding kites, with C_{lo} and C_{do} being the corresponding values before the correction for the downwash (with α in radians for the calculations):

$$
\begin{aligned}
C_{lo} &= 2\,\pi\alpha, \\
C_{do} &= 1.28\,sin(\alpha), \\
C_l &= \frac{C_{lo}}{1 + C_{lo}/(\pi\,AR)}, \\
C_d &= C_{do} + \frac{C_l^2}{0.7\,\pi\,AR}.
\end{aligned}
\tag{2}
$$

Regarding the overall drag force there exist another contribution resulting from the friction of the wind while passing over the surfaces of the kite. This force depends on the smoothness of the kite surfaces but will not be included in our model. Another significant force contribution may be due to pockets of rising air called *updrafts*. Updrafts may originate from wind directed upwards due to the topography of the landscape. Also, rising currents are created by daytime heating of the ground which causes surface air to become much warmer than the air at upper layers and start rising (known as *thermal updrafts* or *thermals*).

C. Static two–dimensional model

An accurate dynamics model describing the flight of a kite can be rather complex. A simplified two–dimensional static model of the kite may not provide precise predictions but is often adequate for capturing the overall behavior of the system [15], and will be explained with reference to Figure 2. The *lift–to–drag ratio* ($L/D = C_l/C_d$) primarily depends on the angle of attack. Small angles of attack correspond to high values for the lift–to–drag ratio. However, a very small angle of attack results to little drag but at the same time little lift as well, unable to sustain flight. At the other extreme, very high values for the angle of attack result to very high drag and extremely small lift force causing the kite to stall and fell to the ground. While the lift–to–drag ratio changes, the relative magnitude of the vertical and horizontal components of the line tension are also readjusted accordingly by changing the angular elevation of the kite, i.e., angles β and γ (as defined in Figure 2) change.

The kite can move along a plane, constrained by the ground reel point and the currently released tether. The rotational motion of the body takes place about the bridle point, which is the point where the tether is attached to the bridle string. During flight the kite maintains an angular elevation and orientation associated with the equilibrium of the applied forces (the overall force due to aerodynamics and gravity is equal and opposite to the control line pull):

$$
\begin{aligned}
T_y &= Tsin\gamma = L - W, \\
T_x &= Tcos\gamma = D
\end{aligned}
\tag{3}
$$

and the equilibrium of applied torques (about the bridle point):

$$
\begin{aligned}
M = -Lcos\alpha(y_b - y_p) - Lsin\alpha(x_b - x_p) + \\
Dcos\alpha(x_b - x_p) - Dsin\alpha(y_b - y_p) + \\
Wcos\alpha(y_b - y_g) + Wsin\alpha(x_b - x_g) = 0
\end{aligned}
\tag{4}
$$

with (x_b, y_b), (x_g, y_g), and (x_p, y_p) the coordinates of the bridle point, the COG, and the COP, respectively, expressed in the kite–fixed frame centered at point O, as shown in Figure 2. The kite is considered tailless ($B = 0$). Obviously, angle γ at the equilibrium depends on the lift–to–drag ratio, or equivalently, the angle at which the overall aerodynamic force is acting on the kite. At equilibrium the bridle point lies somewhere along the direction of the resultant of the aerodynamic force and the weight. The equilibrium of the torques about the bridle point yields the orientation of the kite (i.e., the angle of attack).

When the kite assumes a new equilibrium position due to changing wind conditions, with an increased angle of incidence, the overall aerodynamic force becomes more perpendicular to the longitudinal axis of the kite, and its point of application is displaced [16]. In general, for a higher angle of incidence the COP moves away from the forward end of the kite and gets closer to the COG. An approximation that will be embraced in our simulation studies is that for a kite resembling a symmetric thin flat airfoil the location of the COP is fixed at $1/4$ of the chord length (distance from the leading edge to the trailing edge) back from the leading edge [15]. It will also be assumed that the wind velocity is constant and the flow is horizontal, parallel to the ground. In the case of upwards directed winds the kite will noticeably settle with an exceptionally high angular elevation [17].

D. Stable kites

During flight, a kite rotates about the bridle point and the rotation is due to the applied torques created by the aerodynamic and gravity forces. The kite is said to be in (rotational) *equilibrium* (or *balance*) when the net torque about the bridle point is zero. During flight the angle of attack may vary because of turbulence in the air as well as changing wind conditions. If a small change in the angle of attack causes a considerable increase of the net torque then the kite starts to rotate uncontrollably and the system is said to be *unstable*. If on the other hand the change in the angle of attack results to a restoring torque that tends to bring the system back to an equilibrium condition, the system is *stable* [15], [16].

E. Shape of the tether and forces acting on it

The tether extends from the reel point (ground) to the bridle point on the kite. In fact, it does not form a straight line but rather a smooth curve due to its own weight and the wind drag, which are distributed forces along its length. The shape of a hanging cable is known as a *catenary* [16], [17] for which the mathematical solution exists. Through the catenary equation and some in–flight measurements the altitude of the kite can be estimated. However, for low altitude flights a reasonable approximation is to consider the tether as being straight. This is more valid for lightweight and thin strings available nowadays, which will not curve considerably. In that case, the kite altitude can be approximated trigonometrically using the angle and the length of the released control line. The weight of the tether becomes considerable for high–altitude flights. This is taken up by the lift force of the kite and therefore it consumes some of the payload lifting capacity of the system. In general, it is also desirable that the tether is slim in order to reduce the aerodynamic drag forces acting on it. The drag force on the control line due to the wind is counteracted by a corresponding reaction force at the reel. This force becomes considerable when lengthy line is released and this fact explains why for high–altitude flights line breaks are often experienced closer to the reel point.

III. Adjustable bridling and angular elevation control

Typically, the bridle point is located well in front of the kite surfaces at the upper part of the kite. For a torque balance to be possible, the bridle point position should be such that opposite directed torque components may exist. Bridling plays an important role in the stability and the flight behavior of the kite [17]. Typically, a short bridle (the bridle point is close to the frontal surface of the kite) yields greater angular changes for the kite when the wind velocity varies.

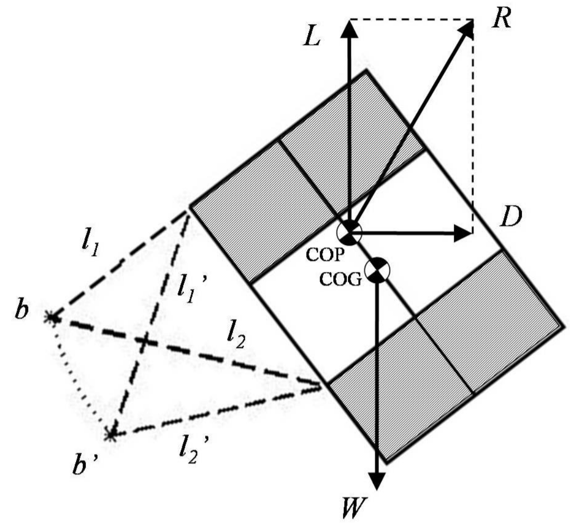

Fig. 3. Two–dimensional representation of a box kite with adjustable bridle. Two bridling configurations are shown (dashed lines) together with the locus of bridle points (dotted line) for the intermediate configurations (fixed bridle length $l = l_1 + l_2 = l_1' + l_2'$).

This effect becomes more evident in the case of kite types that the bridle can be totally discarded and the distance of the point of attachment to the frontal surfaces becomes minimal. On the other extreme, with a very long bridle it may even become impossible for the kite to reach an equilibrium. In general, the kite assumes smaller angles of incidence when the bridle point is shifted towards the forward end of the kite. Similarly, by moving the bridle point away from the forward end of the kite the angles of incidence increase.

A standard bridling arrangement for a box kite is shown in Figure 1 and consists of two strings joined together at the bridle point. The position of the bridle point is determined by the length of the two, normally fixed–length, bridle strings. Therefore, if one can control the position of the bridle point by actively adjusting the length of each bridle string will also modify the equilibrium of the kite and effectively regulate within some limits the positioning of the kite. This is the angular elevation control approach proposed and examined as part of this work. Regarding the usefulness and applicability of this technique it is indicative the fact that experienced kite fliers often adjust the relative size of the bridles prior to the kite launch to account for the existing wind conditions. By controlling the angular elevation together with the amount of the released tether we can effectively control the positioning of the kite (altitude and horizontal distance from the reel point).

The proposed implementation of in–flight bridle adjustments is such that the overall length of the two bridle strings of a kite remains constant ($l_1 + l_2 = l$), i.e., the bridle point effectively slides along the length of the bridle line. Consistent with this assumption, Figure 3 shows the sketch of a box kite together with two different bridling configurations as well as the bridle point locus for the intermediate positions (kite's height: 102 cm, overall bridle length: 146 cm, bridle's footprint on frame: 71 cm). For this example the two extreme bridle point positions shown as asterisks correspond to $l_1/l_2 = 56/90$ and $l_1'/l_2' = 76/70$. The translation of the bridle point also varies its perpendicular distance from the gravity and total aerodynamic forces (indicative vectors of which were drawn on the sketch) disturbing the torque equilibrium. Given the slope of the bridle point locus (its frontal part) relevant to the above two forces, while lowering the bridle point position the system will be driven towards a new equilibrium corresponding to a higher angle of incidence and a lower angular elevation. The proposed flight control methodology exploits this fact for angular elevation adjustments and was preliminarily investigated through simulations as well as field testing.

IV. SIMULATION STUDIES

The model explained in Section II is used here. Gravity and aerodynamic forces on the control line were not considered and the control line is assumed to be a straight line ($\beta = \gamma$). The frontal surface of the kite was taken $A = 100 \times 160$ cm^2 and the overall weight 0.2 kg. The bridle line is attached to the upper and lower edge of the surface and its overall length $l = 200$ cm. The length of the control line is taken 100 m. The wind velocity is set to 4 m/s and the air density 1.229 kg/m^3. The kite is considered to be a thin plate airfoil and the calculation of lift and drag coefficients is done according to Eqs. (2).

Figure 4 shows simulation results with the equilibrium of the kite for various l_1/l ratios. In the list of results d is the horizontal distance of the kite from the reel point and h its altitude. While the bridle point moves away from the forward end of the kite the lift–to–drag ratio decreases, the angle of incidence is increased and the kite settles at a lower altitude position. Among the issues that require further investigation are the bounds within which the l_1/l ratio should remain. Too high values for the angle of attack will eventually result to stall. Also, while the kite is tilted forward a slack bridle segment condition may be experienced.

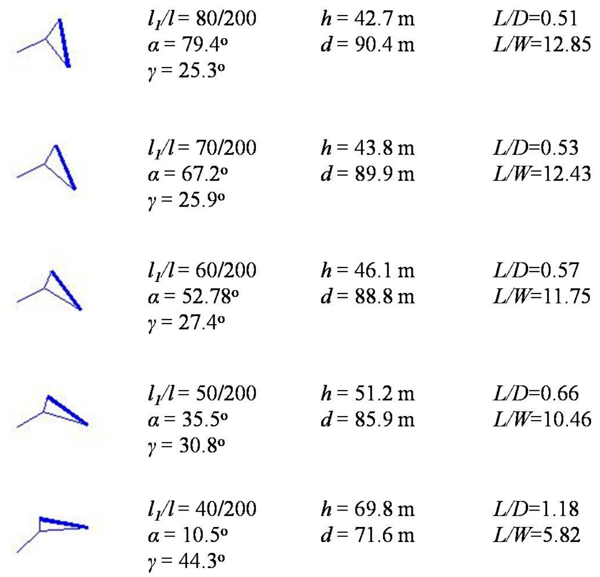

Fig. 4. Simulation results based on the 2–dimensional kite model for different bridling configurations and constant wind velocity.

V. THE EXPERIMENTAL KITE SYSTEM AND FIELD TESTING

The proposed actuation (bridle adjustment) unit, shown in Figure 5, includes a small DC motor driving a worm gear system, followed by a two–stage spur gears reduction which finally turns a 5 mm in diameter drum. The use of the worm drive effectively acts as a break when the device is not activated, given that it cannot be back–driven. Around the drum it is winded the bridle line, each side of which at a different direction. Therefore, while the drum rotates the line is released from one side while equal amount of line is reeled–in on the other side. This allows adjustment of the bridle point position by effectively changing the relative size of the two bridle lines while the overall length l remains constant. The bridle point can slowly travel along the overall length of the bridle. The actuation unit was statically balanced so that it maintains an upright position. An alternative to the proposed bridle point adjustment mechanism would be to individually vary the length of each bridle string but this would require a considerable amount of force difficult to be supplied by a kite–borne, lightweight actuator. The dimensions of the box kite used for the testing were $102 \times 50 \times 50$ cm and the bridle size as described in Section III.

The device is controlled by the kite handler using a hand–held remote control unit and a kite–borne receiver. The receiver is enclosed in a lightweight casing made of balsa wood and is suspended from the kite's framed structure, as shown in Figure 6, at the lower part of the kite. This choice effectively lowers the overall center of mass and contributes to a stabilizing torque, without significantly upsetting the system aerodynamics. Within the box is also included the battery for the actuator. The remote control receiver is connected to the actuation unit through a hanging cable.

Extensive field testing of the robotic kite took place on a field with rather level topography and limited vegetation or other nearby obstructions to avoid particularly irregular wind flow conditions. The wind conditions were fairly constant. Figure 7 shows an example with the kite reaching and settling to two different elevations following the operator's bridle adjustment commands. The photos were taken from a fixed camera position while a constant amount of string was reeled out. When the bridle point is driven upwards the system responds with a corresponding increase of the kite's angular elevation as well as altitude and vice versa. Experiments also confirmed that adjustment should remain within an upper and a lower limit to ensure sufficient amount of lift and allow for an equilibrium condition to be reached, as already discussed. The system's response to the dynamic bridle adjustments was smooth and stability problems were not encountered.

Fig. 5. The proposed bridle adjustment actuation unit.

Fig. 6. The wireless control receiver suspended on one of the lower struts.

VI. Conclusions

Kites served well in the past as tools for various scientific applications. Even though their use has been largely abandoned, opportunities exist for their robotization and redeployment with enhanced capabilities. Robotic kites is an area whose potential remains largely unexplored and it is believed that they do have their own niche in aerial robotics. Control options include altitude control as well as autonomous flight using specially developed launch platforms, which is part of our current research in the field. A method for controlling the angular elevation (and altitude) of a single–line kite has been proposed based on in–flight bridle adjustments. A remotely controlled actuation device was developed and used for the relevant experimental testing providing a proof–of–concept. The system was found to respond smoothly to manual feedback (human–in–the–loop) control and automatic control is seen as the next feasible option. The methodology provides an option for position control but also a means of improving the overall flight performance while the system is subject to wind variations.

Fig. 7. Kite field experiments on angular elevation control.

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