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Utilization of wind shear for powering unmanned aerial vehicles in surveillance application: A numerical optimization study

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Abstract

Dynamic soaring is the rationale behind the prolonged flights of a seabird Albatross. It involves utilization of energy from the wind shear present near the earth surface. Small unmanned aerial vehicles (UAVs) can be kept loitering without any external power input by dynamic soaring. In this work, dynamic soaring is used to power UAVs for the surveillance application. A set of 6-DoF point mass equations governing the aircraft motion is used in the optimal control problem formulation. Appropriate constraints considering the material properties of a UAV, and the loiter pattern of dynamic soaring, are imposed on state variables and control parameters. Trajectories are optimized by using GPOPS-II, MATLAB based optimal control software. The problem is optimized for the efficacy of area under surveillance. Variation in the surveillance area is analyzed with the change in the view angle of camera, wind strength, and nature of wind shear profile. Surveillance by dynamic soaring becomes effective with the increase of wind strength and also with the change of wind shear profile towards the logarithmic variation. The minimum requirement of wind strength to perform dynamic soaring has been identified by considering various wind shear profiles. Finally it is concluded that small UAVs (comparable with the size of Albatross) can be constantly kept on surveying using wind energy as the sole power source, as long as free stream wind velocity is greater than the minimum requirement for dynamic soaring.

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Keywords: Wind energy; Dynamic soaring; Optimal control algorithm; Trajectory optimization for surveillance

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1. Introduction

Wind shear near the earth surface is effectively used by seabirds to fly thousands of kilometres without flapping of wings. It can be very useful for the UAVs meant for prolonged surveillance. Mission capabilities of UAVs are mainly limited by their inability of carrying sufficient fuel. Although improvements of battery technology can enhance their capabilities, immediate performance gains can be obtained by energy utilization from the atmosphere. There are several ways to extract energy from atmosphere and dynamic soaring is one such a technique. Energy extraction from the wind shear present near the earth surface is referred as dynamic soaring. The primary objective of this paper is to demonstrate the propulsion of small UAVs by dynamic soaring through simulations, considering surveillance application.

Constant surveillance is required for many applications such as patrolling, monitoring shipping lanes, commercial fisheries etc. In many potential civilian and military UAV missions, the power requirements reduce their range and endurance, diminishing their utility. As a consequence, UAVs have become primarily limited to short range observation missions. There is a plenty of energy available in the atmosphere where UAVs fly. This energy can be useful to increase their range and endurance. If an aircraft is able to extract kinetic or potential energy from soaring flight, the consumable energy carried on board in the form of batteries or fuel would last considerably for prolonged period, thereby increasing their range or endurance. Capabilities of small UAVs can be increased significantly by utilizing the wind energy present in surrounding ambience in the form of wind shear.

Rayleigh [1] is known to be the first person to propose that energy extraction is possible in a horizontal but non-uniform wind field. After him, many scientists, specifically Turcker and Parrott [2], Weimerskirch et al [3] worked on this subject. Gradually theory of dynamic soaring was evolved. In early 2000s to 2010s, computational algorithms on optimal control were developed rapidly. Sachs [4] found the optimal trajectory for minimum wind

Nomenclature

A	wind shear parameter
AR	aspect ratio (= b^2/S), m
CD_0	parasite drag coefficient
C_L	coefficient of lift
C_D	coefficient of drag
β	average slope of wind shear over [0, h_{tr}], s^{-1}
μ	banking angle, clockwise from backside of glider, degree
ψ	heading angle, measured clockwise from north, degree
ρ	density of air, kg/m^3
γ	flight path angle relative to air, degree
V	velocity of glider, m/s
K	induced drag factor
S	wing area of glider, m^2
m	mass of glider, kg
g	acceleration due to gravity, m/s^2
n	load factor of glider
x, y	east and north position of glider, m
z	altitude of glider, m
W_z	wind velocity variation with altitude, m/s
W_{max}	maximum wind velocity, m/s
h_{tr}	boundary layer thickness, m
L	lift force, N
D	drag force, N
θ	view angle of camera mounted on UAV

requirement to perform dynamic soaring by using a software ALTOS. Zhao [5] solved problem of dynamic soaring by using the collocation method in combination with software NPSOL. In this sequence of development, optimization of trajectories with respect to the surveillance application was not focused and explored. Current work is devoted to accomplish the optimization of trajectories utilizing wind shear for surveillance purpose.

In the first part, methodology behind the formulation of an optimal control problem is given. Governing equations of dynamic soaring, and an equation to capture the variation of wind profile with altitude are specified. Constraints are obtained considering the material properties of a UAV and the loiter pattern of dynamic soaring. Later, objective functions are defined for the two purposes: to find the minimum requirement of wind strength, and to improve the surveillance area by reducing the abandoned portion inside the trajectory. Numerical optimization procedure of GPOPS-II is explained in brief. Finally, the variation in the surveillance area is discussed by varying the governing parameters.

2. Methodology:

2.1. Mathematical modeling

A point mass model is used for the representation of UAV flying in the spatially varying winds. Inertial North, East and Down (NED) reference frame is selected, where the x, y, and z axes are in the direction of North, East, and Down respectively. Wind field is assumed to be varying with space, and constant with time. Line of action of forces and the angles are as shown in the Fig. 1. The orientation of the aerodynamic forces on the aircraft are defined by a set of three successive angular rotations, heading angle (ψ), air relative flight path angle (γ), and bank angle (μ). Thrust force is neglected in the governing equations, since UAV is not generating any propulsive force by itself. Dynamic soaring is used for the propulsion of a UAV.

The flight dynamics model includes six states variables (which are function of a time period *'t'*): horizontal positions [$x(t)$, $y(t)$], altitude $z(t)$, airspeed $V(t)$, flight path angle $\gamma(t)$, and azimuth angle $\psi(t)$. Control parameters are coefficient of lift $C_L(t)$, and bank angle $\mu(t)$. Lift and Drag forces on the aircraft structure are expressed as,

$$L = \frac{1}{2}\rho\, S\, C_L\, V^2 \tag{1}$$
$$D = \frac{1}{2}\rho\, S\, C_D\, V^2 \tag{2}$$

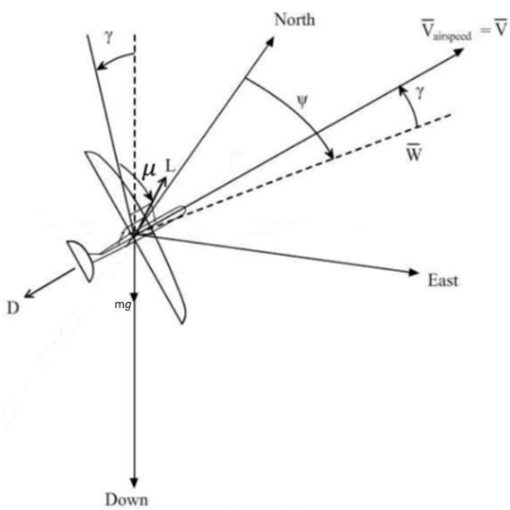


Fig. 1: Forces in the point mass model of a UAV

The governing equations of dynamic soaring [10] are given as follows. These are first order non-linear differential equations, which have six states and two control parameters. Equation 3-5 can be derived by applying Newton's second law in North, East and Down directions in Fig.1. Equation 6-8 are the kinematic equations.

$$m\,\dot{V} = -D - mg\sin(\gamma) - m\,\dot{W}_z\cos(\gamma)\sin(\psi) \tag{3}$$

$$m\,V\cos(\gamma)\,\dot{\psi} = L\sin(\mu) - m\,\dot{W}_z\cos(\psi) \tag{4}$$

$$m\,V\dot{\gamma} = L\cos(\mu) - mg\cos(\gamma) + m\,\dot{W}_z\sin(\gamma)\sin(\mu) \tag{5}$$

$$\dot{z} = V\sin(\gamma) \tag{6}$$

$$\dot{x} = V\cos(\gamma)\sin(\psi) + W_z \tag{7}$$

$$\dot{y} = V\cos(\gamma)\cos(\psi) \tag{8}$$

Results of the trajectory optimization are obtained for numerous wind shear profiles. In the wind shear model, horizontal wind speed is assumed to be zero at the ground level, which increases gradually over the altitude. To capture the variation in the wind velocity, Equation 9 is used. For simplicity, the curvature effect of earth, and variation of density with altitude are neglected. Mathematical model of the wind gradient profile (Equation 9) is used in the studies of soaring flights.

$$W_z = \beta\left[A\,(z) + \frac{(1-A)\times(z)^2}{h_{tr}}\right];\ \beta = \frac{W_{max}}{h_{tr}} \tag{9}$$

Where 'β' is the average slope of the wind shear (0, h_{tr}). In this problem, terrain is assumed to be the water surface. Boundary layer thickness over this terrain is assumed to be 213 meters [9]. Depending on the values of 'A', different wind profiles can be obtained from Equation 2 (shown in Fig. 2). It is required to have $0<A<2$ in order to ensure the wind component is between (0, W_{max}). For $0<A<1$, wind profile is similar to the exponential curve and for $1<A<2$ it looks like logarithmic profile.

2.2. Constraints

Trajectory optimization problem is formed with the goal of finding the state and control time histories, that minimize the selected cost function while satisfying the governing 6-DoF point mass equations. There are mainly two patterns of dynamic soaring: travelling and loiter pattern. In this study, loiter pattern is considered for the surveillance application. Common constraint for the loiter pattern is the periodicity of states and control parameters.

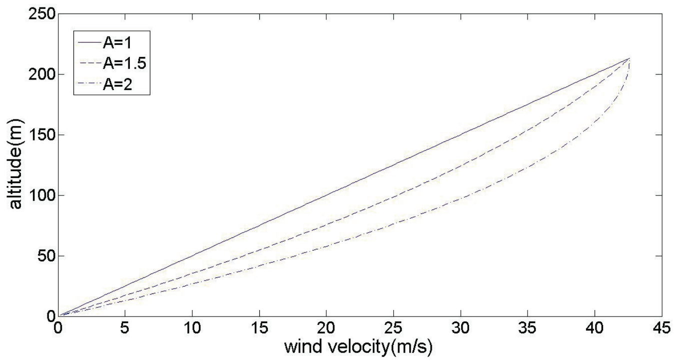


Fig. 2: Wind profile for β = 0.2

For the loiter pattern, periodic boundary conditions are imposed on all six state variables. Also, limits on the manoeuvres of UAV to avoid the excessive loading of a structure are imposed by introducing the load factor (n)

$$\text{Load factor } (n) = \frac{\frac{1}{2}\rho\, S\, C_L V^2}{mg} \tag{10}$$

In addition to satisfying the governing equations of motion, the solution must satisfy additional equality and inequality constraints. Table 1 lists all the constraints that are used throughout the problem.

Table 1. List of trajectory optimization constraints

Constraints	State variables	= or ≤
Equations of motion	All	=
State bounds	x, y, z, V, γ, ψ	≤
Control bounds	C_L, μ	≤
Load factor	V, C_L	≤
Initial condition	All	=
Periodicity condition	All	=

From the governing equations of dynamic soaring (Equation 3-8), the primary characteristics of an unpowered flight by using dynamic soaring are well explained. In general, during the motion of an aircraft, there should be turning of aircraft from upwind to downwind in the portion of maximum wind speed region. On the other hand, at the lowest wind speed region, it should turn into upwind from the downwind. Additionally, there should be an increasing headwind while climbing, and while diving down it should go through a decreasing tailwind. Along with satisfying the constraints imposed for a particular problem, the optimal trajectories are expected to have these general characteristics.

Dimensions of UAV used in simulations are taken similar in shape and size to albatross (see Table 2). It is equipped with a camera, which always remains horizontal irrespective of rolling or pitching motions of aircraft. Gliding is an essential phase while performing dynamic soaring. For smooth gliding, lightweight UAV with high aspect ratio is selected. In subsequent analysis the vehicle makes use of the assumption that it has a quadratic drag polar of the form: $C_D = C_{D0} + K\, C_L^{\,2}$

Table 2. Specifications of a UAV (similar in dimensions to albatross)

Parameter	Value	Unit	Explanation
AR	16		Aspect Ratio
b	3	m	Wing span
C_{D0}	0.00873		Parasite drag coefficient
C_{Lmax}	1.5		Maximum coefficient of lift
C_{Lmin}	−1		Minimum coefficient of lift
K	0.045		Induced drag factor
m	10	kg	Mass of UAV
S	1	m^2	Wing area

2.3. Development of objective function

First objective is to calculate the minimum required wind strength for dynamic soaring to take place. By knowing the wind strength requirement, possibility of dynamic soaring in the present wind condition can be predicted. While surveying, the UAV traces a periodic orbit (which implements dynamic soaring) and uses a camera to capture the image on the ground. In this process, some area on the ground may not be captured. This area is termed here as a grey area, as shown in Fig. 3(a). Our second objective is to minimize this grey area. In order to achieve this, appropriate objective function is defined. As stated earlier, the camera mounted on a glider always remains horizontal, and it captures images in the plane parallel to earth surface, irrespective of the pitching or rolling motions of an aircraft. Assuming the images captured are circular in cross section. In Fig. 3(b), 'z' is the altitude of the glider and 'θ' is the view angle of camera.

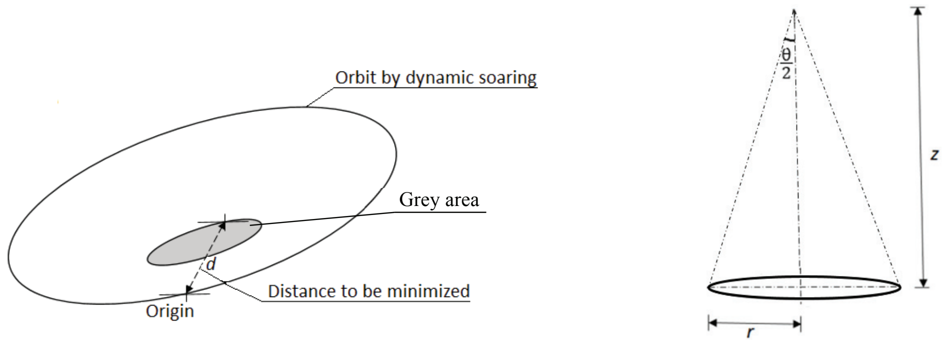


Fig. 3: (a) Grey area; (b) area captured by camera

Radius (r) of the image captured in Fig. 3(b) is given as, $r = z \times \tan(\theta/2)$.

To minimize the grey area, distance 'd' in Fig. 3(a) has to be minimized. Objective function for this purpose is formulated as:

$$d = \sqrt{x^2 + y^2} - z \times \tan(\theta/2) \tag{11}$$

2.4. Construction of codes

Solution of an optimal control problem requires the mathematical approximation for the integration of cost function, for differential equation of control system, and for the state-control constraints. An ideal approximation method should be efficient for all the three approximation tasks. In this work, codes for optimization are constructed in a MATLAB based optimal control software, GPOPS-II [7, 8], which employs Legendre Gauss Radau quadrature orthogonal collocation method. In this method, continuous time optimal control problem is transcribed to a large sparse nonlinear programming problem. In pseudo-spectral method, the continuous functions are approximated to a set of carefully selected quadrature nodes. The quadrature nodes are determined by the corresponding orthogonal polynomial basis. In Pseudo-spectral optimal control method, Legendre and Chebyshev polynomials are commonly used. Mathematically, quadrature nodes are able to achieve the high accuracy with a small number of points.

3. Results and discussion:

In this section, the optimized trajectories are presented. At first, the trajectories are optimized for the objective of minimizing the required free stream wind speed. In the following section, trajectories optimized for the objective of minimizing the inner grey portion are presented. In this process, both the linear and logarithmic wind shear profiles are considered separately.

3.1. Minimum wind strength requirement

Linear wind shear is modelled by Equation 9. Various wind shear profiles can be obtained just by varying the value of a parameter 'A'. Variation of states and controls for minimum wind speed is shown in Fig. 4. For linear wind shear profile, requirement of minimum wind shear coefficient (β) is 0.0879. Correspondingly minimum required wind speed is 10.81 m/s.

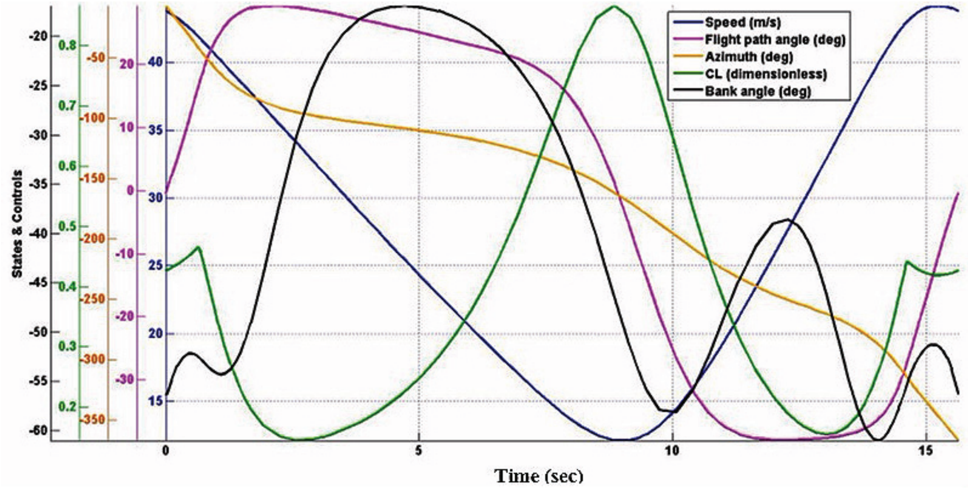


Fig. 4: variation of states and control for calculation of minimum required wind shear for linear variation of wind shear profile (A = 1.9)

In Fig. 4, all state varibles and control parameters are varying periodically. On Y-axis, state and control parameter scales are represented. X-axis shows the time variation. All the parameters are plotted for the time period of one cycle. Next, the value of minimum required wind shear (β) is found for the logarithmic variation of wind shear profile. For logarithmic variation, put A = 1.9 in Equation 9.

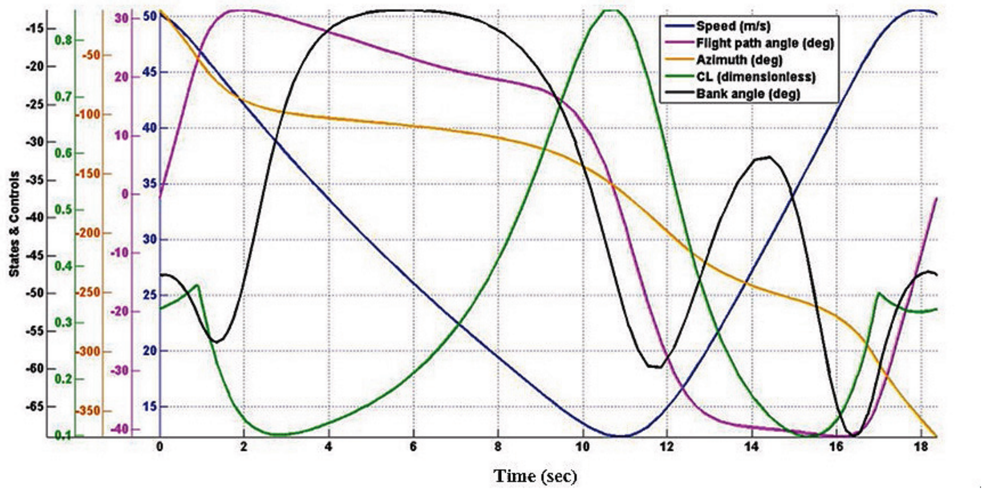


Fig. 5: Variation of States and controls for logarithmic wind shear profile (A = 1.9)

In Fig. 5, maximum attained air speed of UAV in logarithmic profile is less than that of linear wind shear profile in Fig. 4. Likewise the range for other state variables and control parameters of logarithmic wind shear profile (Fig. 5) is less than that of linear wind shear profile (Fig. 4). Peroidicity requirement of the loiter pattern of dynamic soaring is satisfied; all the state variables and control paramters are periodic in nature (shown in Fig. 4 and Fig. 5). For different wind shear profiles, required values of wind shear coefficient and free stream wind velocity are shown in Table 3.

Table 3. Comparison of minimum wind speed requirement for different wind profiles

Nature of the wind shear profile: Governed by 'A'	Minimum wind shear coefficient 'β' (Sec $^{-1}$)	Minimum required wind speed (m/s)
1.0	0.08786	10.81015
1.3	0.07571	9.17826
1.5	0.06885	8.6375
1.7	0.06297	8.27792
1.9	0.05794	8.02221

From Table 3, we can say that, as the wind shear profile tends towards the logarithmic variation, the requirement of minimum wind speed decreases. For the first entry in Table 3, the profile is linear and as we go down, profile gradually tends towards logarithmic. Correspondingly, the values of minimum required wind shear coefficient 'β' and 'minimum required wind speed' decrease. Information in Table 3 can be useful to predict the terrain type for implementation of dynamic soaring to power UAVs. If there is a steep change in the slope of wind shear profile ($A \rightarrow 2$), it becomes easier to perform dynamic soaring. In practice, steep changes in slope ($A \rightarrow 2$) are observed at the edge of sharp ridge. For surveillance in the hilly terrain, dynamic soaring can be implemented in order to power UAVs, since there is formation of shear layers at many places in the terrain due to sharp ridges.

3.2. Area under surveillance:

The second objective is to optimize for the reduction of the grey portion present inside the surveillance area. Objective function in Equation 11 is used for optimization. Simulations are run in GPOPS-II for the selected glider's model (Table. 1). In the first case, wind shear is assumed to be varying linearly with altitude, with wind shear coefficient β = 0.2. The view angle of camera (θ) is taken as 25 deg.

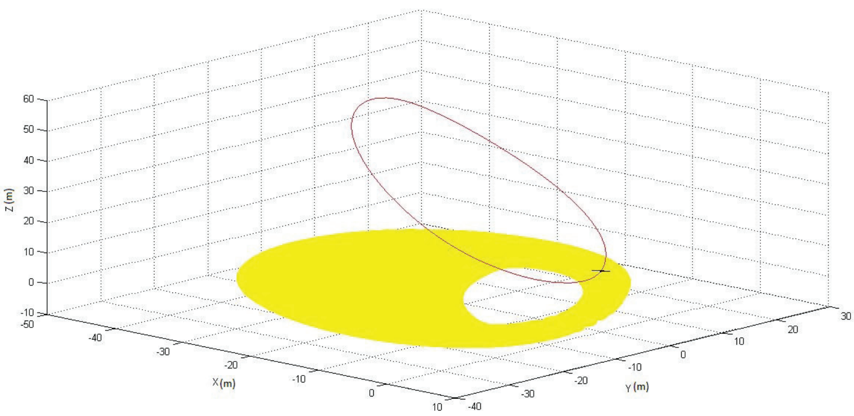


Fig. 6: Area under surveillance for β = 0.2, A = 1.0, θ = 25^0

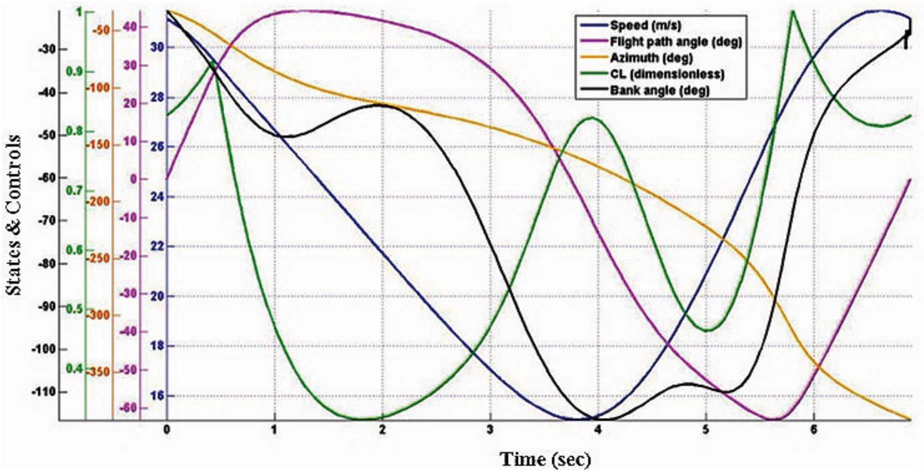


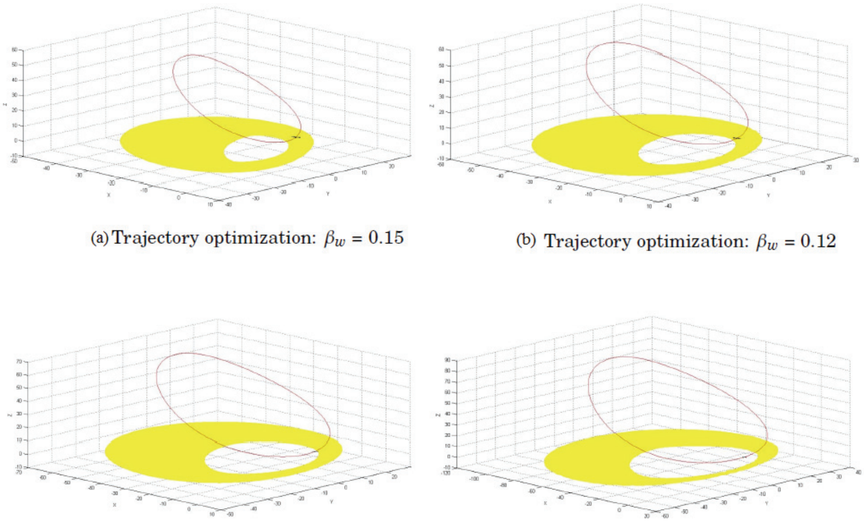
Fig. 7: States and control parameters for $\beta = 0.2$, $A = 1.0$, $\theta = 25^0$

In Fig. 6, inside white portion is the grey area which is to be minimized. Yellow portion is the area under surveillance. For the optimized trajectory in Fig. 6, variation of states and controls is shown in Fig. 7. For this case also, as per the requirement of loiter pattern, variation of all the state variables and control parameters is periodic.

Variation in the surveillance area, state variables and control parameters are studied by varying different parameters in optimal control problem formulation. For now, variation in just the two parameters is considered here:

- Wind shear coefficient 'β'
- Nature of wind profile governed by the parameter 'A'

In Fig. 8, trajectories are obtained for different wind strength (β) keeping wind shear profile constant (logarithmic: $A = 1.5$). As the wind strength increases, trajectories contract inwards and there is significant reduction in the grey portion.



(a) Trajectory optimization: $\beta_w = 0.15$

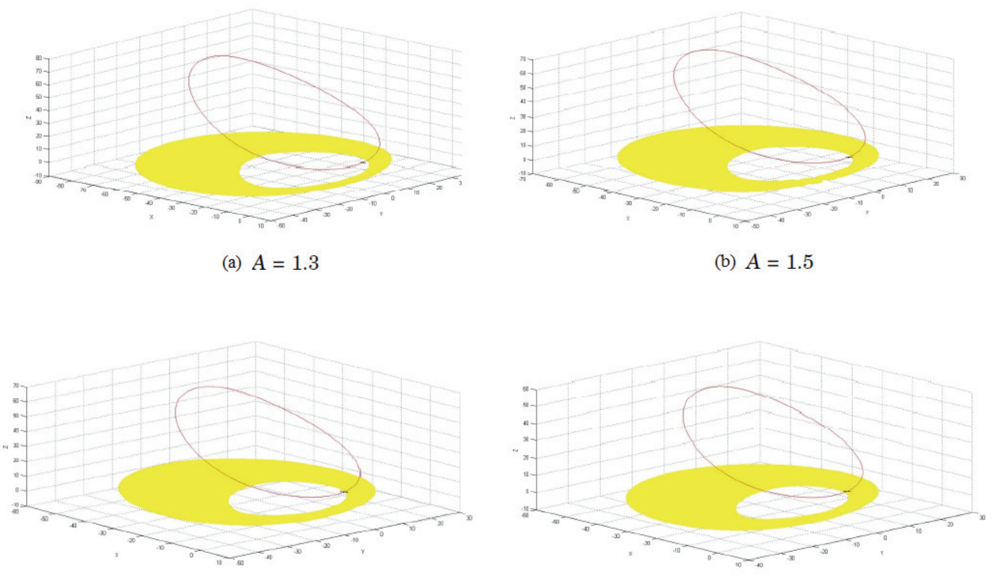
(b) Trajectory optimization: $\beta_w = 0.12$

(c) Trajectory optimization: $\beta_w = 0.1$

(d) Trajectory optimization: $\beta_w = 0.08$

Fig. 8: Variation in the area under surveillance for different strengths of the wind considering wind profile as logarithmic ($A = 1.5$)

From Fig. 9, it can be seen that, with the change of wind shear profile from linear to logarithmic ($A \rightarrow 2$ in Equation 9) and keeping the wind strength constant ($\beta = 0.5$), the grey portion inside the surveillance area reduces. In other words, when there is steep change in the slope of wind shear profile, it is beneficial to perform surveillance by dynamic soaring. In hilly terrains there is always formation of shear layers due to sharp ridges, which is a promising condition for the surveillance using dynamic soaring.



(a) $A = 1.3$ (b) $A = 1.5$

(c) $A = 1.7$ (d) $A = 1.9$

Fig. 9: Variation in the area under surveillance for different wind shear profiles considering wind strength as constant ($\beta = 0.2\ S^{-1}$)

4. Summary and conclusion:

In the past, study of dynamic soaring was mainly focused on understanding the performance of seabirds like albatross who use dynamic soaring for propulsion. Recently researchers have started checking the possibility of dynamic soaring as an alternative energy source for small UAVs (comparable to the size of albatross). This paper extends those studies by considering dynamic soaring as the energy source for the propulsion of a small UAV in surveillance application. In this work, effects of wind gradient slopes and non-linear profile variations on the loiter pattern of dynamic soaring are studied. In the analysis, a set of 6-DoF point-mass equations of motion is used. The state variables include airspeed of UAV, heading angle, flight path angle, altitude, east and north locations in horizontal plane; and the control variables are coefficient of lift and bank angle. Dynamic soaring flights are formulated as the non-linear optimal control problems with two objective functions. First one finds out the minimum requirement of wind shear for dynamic soaring and the second one reduces the abandoned grey portion inside trajectory for the efficient surveillance. All the formulations are subject to glider equations of motion, initial conditions, path constraints on states and controls, and appropriate terminal constraints. Terminal constraints enforce the periodic dynamic soaring flights for loiter pattern. These optimal control problems are converted into parameter optimization via a collocation approach and solved numerically with software GPOPS-II.

The value of minimum required wind shear to perform dynamic soaring decreases as the wind shear profile approaches towards logarithmic variation. In other words, steep change in the slope of wind profile causes efficient dynamic soaring. This is the reason why seabirds fly near the sea surface where there is a steep change in the wind shear profile. As long as the wind shear is greater than the minimum requirement, UAVs can sustain flight using energy present in wind shear as the sole power source.

Abandoned grey portion inside the area under surveillance reduces with the increasing wind shear coefficient (free stream wind speed) which eventually makes the surveillance efficient. Similarly, the inside grey portion increases with the decrease of wind shear coefficient, which affects the area under surveillance badly. Surveillance becomes efficient with the increase in free stream wind speed. Grey portion present inside the surveillance area decreases when wind shear profile approaches from linear to logarithmic. In hilly terrain, steep changes in slope of wind shear can be found easily due to sharp ridges and hence there is huge deployment of UAVs tuned for dynamic soaring.

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