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Optimization of dynamic soaring maneuvers to enhance endurance of a versatile UAV

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Abstract. Dynamic soaring is a process of acquiring energy available in atmospheric wind shears and is commonly exhibited by soaring birds to perform long distance flights. This paper aims to demonstrate a viable algorithm which can be implemented in near real time environment to formulate optimal trajectories for dynamic soaring maneuvers for a small scale Unmanned Aerial Vehicle (UAV). The objective is to harness maximum energy from atmosphere wind shear to improve loiter time for Intelligence, Surveillance and Reconnaissance (ISR) missions. Three-dimensional point-mass UAV equations of motion and linear wind gradient profile are used to model flight dynamics. Utilizing UAV states, controls, operational constraints, initial and terminal conditions that enforce a periodic flight, dynamic soaring problem is formulated as an optimal control problem. Optimized trajectories of the maneuver are subsequently generated employing pseudo spectral techniques against distant UAV performance parameters. The discussion also encompasses the requirement for generation of optimal trajectories for dynamic soaring in real time environment and the ability of the proposed algorithm for speedy solution generation. Coupled with the fact that dynamic soaring is all about immediately utilizing the available energy from the wind shear encountered, the proposed algorithm promises its viability for practical on board implementations requiring computation of trajectories in near real time.

1. Introduction

In-spite of being efficient platform, Small Unmanned Aerial Vehicles (SUAVs) are severely limited in their endurance due to on-board energy storage limitations. Without human on board, endurance in SUAVs is mainly dictated by the amount of fuel UAV can carry, which in turn is governed by UAV size and weight constraints. Besides, the smaller size comes with reduced aerodynamic efficiency by flying at lower Reynolds number and the scaling effect does not play in favor of long endurance. It is therefore highly desirable to improve the range, endurance and speed of such small platforms to give them performance parameters matching to that of a platform several times larger. Of recently, great emphasis is being made in using dynamic soaring [1, 2] as means to acquire energy from atmosphere vertical wind gradients for sustained powerless flight. To optimize the energy gain from the atmospheric wind shear, numerical methods are subsequently employed to formulate optimum trajectories for dynamic soaring. Majority of the research work done in formulating optimal trajectories for dynamic soaring involves techniques which are iterative in nature and therefore require

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substantial time for trajectory optimization. In this research, dynamic soaring optimal trajectories are computed in near real time environment utilizing pseudo spectral technique [3], which is a particular class of direct collocation methods. Pseudo spectral methods which are global in nature have distant advantages over other methods, the most important of which is its fast spectral rate of convergence. This makes such methods the predominant choices in applications that require implementation in near real time environment. In these methods, the original optimal control problem is directly discretized to formulate a nonlinear programming problem (NLP), which is then solved numerically using a sparse nonlinear programming solver to find approximate local optimal solutions. The optimal trajectories formulated in this research are subsequently analyzed to validate different aspects of dynamic soaring and its suitability for real time applications.

2. Problem setup & description

2.1. UAV dynamics

UAV dynamics is represented by a three dimensional point mass model in this work. The dynamic modeling is aligned with other studies [4] for describing system dynamics while formulating dynamic soaring trajectories. The highly coupled non-linear equations of motion utilized in this study are elaborated in equation (1).

$$\begin{aligned}
&\dot{V}_t = \frac{1}{m}[T - D - mg\sin\gamma - m\dot{V}_{W_x}\cos\gamma\sin\psi] \\
&\dot{\psi} = \frac{1}{mV_t\cos\gamma}[L\sin\varphi - m\dot{V}_{W_x}\cos\psi] \\
&\dot{\gamma} = \frac{1}{mV_t}[L\cos\varphi - mg\cos\gamma + m\dot{V}_{W_x}\sin\psi\sin\gamma] \\
&\dot{h} = V\sin\gamma, \dot{N} = V\cos\gamma\cos\psi, \dot{E} = V\cos\gamma\sin\psi + V_W
\end{aligned} \tag{1}$$

where V_∞ is true velocity, γ , ψ and ϕ are flight path, heading and roll angles, V_W is the wind velocity as a function of altitude, T and D are thrust and drag, N and E are the distances along north and east directions and h is the altitude. The geometrical parameters for the baseline UAV utilized in this study are taken from Gao et al [5]. Utilizing the parametric values, prototype UAV was subsequently developed in Solid Works environment. In line with the work done by Mir et al [6], optimal dynamic soaring trajectories for the developed model were than subsequently implemented using rigorously optimized flight parameters.

2.2. Wind shear modeling

Dynamic soaring acquires energy from atmospheric wind shear and is therefore necessary to accurately determine the wind shear conditions. In order to ascertain the estimates for wind shear, two approaches are conventionally followed (a) approximating the wind shear with some known model once the wind conditions are known (b) online estimation of wind shear in unknown wind conditions. Reasonably stable atmospheric conditions exist close to the sea surface with the wind velocity nearly zero at the surface and increasing gradually with altitude. Therefore, the mean velocity profile of actual wind gradients can be approximated using exponential,logarithmic or linear wind models. In this research, linear wind shear model (refer equation (2)), is used to optimize the loiter trajectory.

$$V_W = \frac{\partial V}{\partial h}h = \beta h \tag{2}$$

where β is the linear wind shear parameter

2.3. Optimal control problem formulation

In order to formulate optimal trajectories for dynamic soaring, different type of numerical solvers developed for solving optimal control problems are utilized. Some of the software / algorithm developed are NPSOL [4], ICLOCS [7], GPOPS [5], IDVD [8], PSOPT[9] , PROPT[10], SOCS[11],

AMPL[12] and so on. In this research work, optimal control software GPOPS is utilized to solve the dynamic soaring optimal control problem. GPOPS is a general purpose software developed in Matlab® environment for solving optimal control problems utilizing pseudo spectral techniques. Pseudo spectral methods belong to the class of direct methods and more specifically direct collocation methods. In pseudo spectral methods, the optimal control problem is transcribed to a nonlinear programming problem (NLP) by parameterizing the state and control using global polynomials (basis function are Chebyshev or Lagrange polynomials) and collocating the differential-algebraic equations using nodes obtained from a Gaussian quadrature.

Utilizing three degree of freedom point mass model for UAV dynamics (refer equation (1) and linear wind profile (refer equation (2)), dynamic soaring trajectory optimization problem is configured as an optimal control problem with state and control vectors defined in equation (3) & equation (4) and performance measure in equation (5).

$$\text{State Vector} = [V_t, \psi, \gamma, x, y, h] \quad (3)$$

$$\text{Control Vector} = [C_L, \phi, T] \quad (4)$$

$$J = \min(\text{wind shear parameter, p}) \quad (5)$$

Different modes of dynamic soaring (basic, loiter and forward flight) are implemented through terminal constraints. Boundary conditions for implementing loiter mode of dynamic soaring is depicted at equation (6).

$$V(t_f) = V(t_0);\ \psi(t_f) = \psi(t_o);\ \gamma(t_f) = \gamma(t_o);\ h(t_f) = h(t_0) + \Delta h; x(t_f) = x(t_0); y(t_f) = y(t_0) \quad (6)$$

Total air relative normalized energy is given in equation (7)

$$E_{norm} = gh + 0.5 * v^2 \quad (7)$$

Initial state condition and path constraints for state/ control are depicted in Table 1. In this problem, initial airspeed, flight path angle and heading angle are left unconstrained, so as to permit the optimization process to determine their optimal values for sustainable soaring flights.

Table 1. Initial and path constraints.

S No	Parameter	*Value*	S No	Parameter	*Value*
1	East distance (x) ranges	[-500, 500] m	7	Lift coefficient range [C_{Lmin}, C_{Lmax}]	[0, 1.5]
2	North distance (y) range [y_{min} , y_{max}]	[-500, 500] m	8	Bank angle range [ϕ_{min} ,ϕ_{max}]	[-70 °;70 °]
3	Altitude (z) range [z_{min} , z_{max}]	[0, 1000] m	9	Initial State [x_0,y_0,z_0, γ_0,ψ_0,v_0]	[0,0,0, $\gamma_{min} \leftrightarrow \gamma_{max}$, $\psi_{min} \leftrightarrow \psi_{max}$, $v_{min} \leftrightarrow v_{max}$]
4	Velocity range [V_{min} , V_{max}]	[3, 100] m/s	10	State Path Constraints	[$x_{min} \leftrightarrow x_{max}$, $Y_{min} \leftrightarrow Y_{max}$, $\psi_{min} \leftrightarrow \psi_{max}$, $v_{min} \leftrightarrow v_{max}$]
5	Flight path angle range [ψ_{min} ,ψ_{max}]	[-60 °, 60 °]	11	Control Path Constraint	[$C_{Lmin} \leftrightarrow C_{Lmax}$, $\phi_{min} \leftrightarrow \phi_{max}$]
6	Heading angle range [γ_{min}, γ_{max}]	[-360 °, 90 °]	12	Terminal Constraints [x_f ,y_f, z_f γ_f, ψ_f, v_f]	[$x_f = x_o$,,$y_f = y_o$, $\gamma_f = \gamma_o$,$z_f = z_o$, $\psi_f = \psi_o$,$v_f = v_o$]

3. Results & discussion

3.1. Simulation results

Dynamic soaring optimal control problem formulated in GPOPS environment was subjected to extended simulations under different operating conditions to formulate optimal trajectory for loiter mode. The results achieved greatly qualified the optimization criteria and showed promising results. Figure 1 depicts the graphical 3 dimensional view of the optimal trajectory for the loiter mode of dynamic soaring with a cycle time of 24 sec. The normalized energies (total, potential and kinetic energies) are shown in Figure 2, in which the kinetic energy is exchanged for the potential energy as the UAV gains height. After reaching maximum altitude, the UAV takes the high altitude turn and start its downwind flight where the potential energy is traded for the kinetic energy.

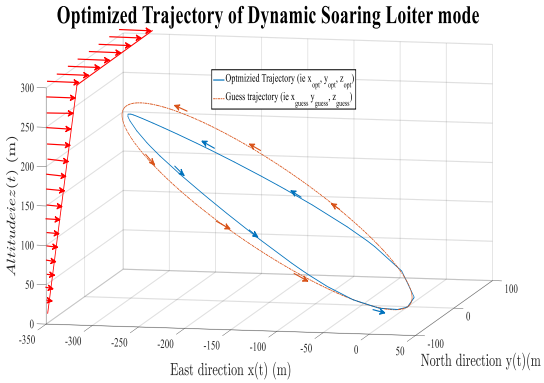


Figure 1. 3D Optimized trajectory.

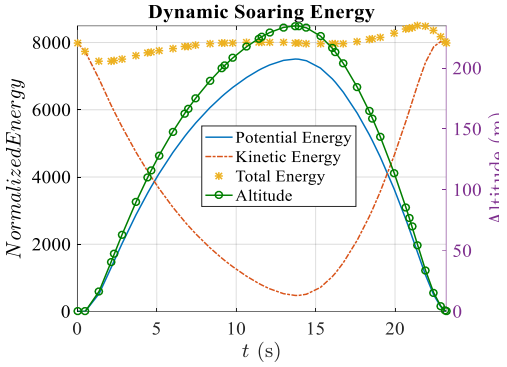


Figure 2. Variation in UAV energy.

Figure 3 reflects UAV attitude showing the flight path, roll and heading angles during various phases of the maneuver. The angles are optimized to implement the desired trajectory.

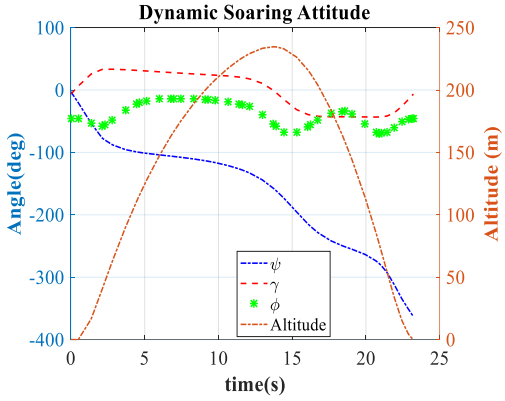


Figure 3. Dynamic soaring attitude.

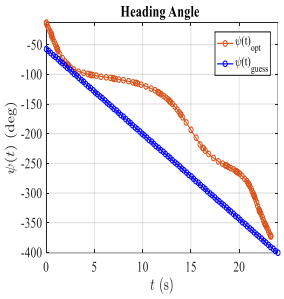


Figure 4. Heading angle.

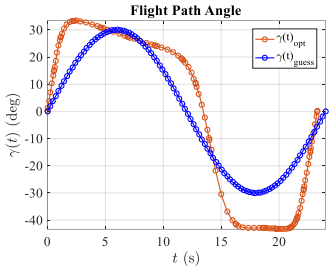


Figure 5. Flight path angle.

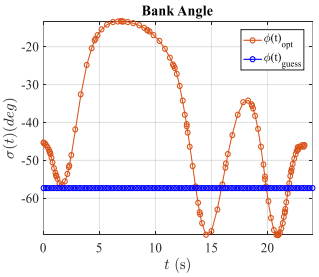


Figure 6. Bank angle.

Optimized trajectory along with guess trajectories for individual UAV states and control variables are depicted from Figure 4 to Figure 6.

It can be seen from Figure 7 that the lift coefficient begin to increase during the windward climb phase and gets to maximum at the highest point (high altitude turn phase) where the flight direction changes from windward climb to downwind decent. Lift coefficient then decreases along the downwind descent phase, goes to the minimum at the lowest point of the maneuver (low altitude turn phase) and then the cycle repeats. Similarly UAV velocity decreases during the wind ward climb phase, reaches to the minimum at the highest point of the maneuver and then increases during the downwind descent phase. Similar trend is also encountered in the bank angle and other states during dynamic soaring cycle. UAV in the start moves away from the shear wind and loses altitude to achieve higher wind shears available near the surface. Subsequently, it then takes a low altitude turn, faces the head wind and gains altitude and comprises kinetic energy from the gained kinetic energy. This smooth shifting between the speed gained while descending and altitude gained during the climb phase is shown in Figure 8**.**

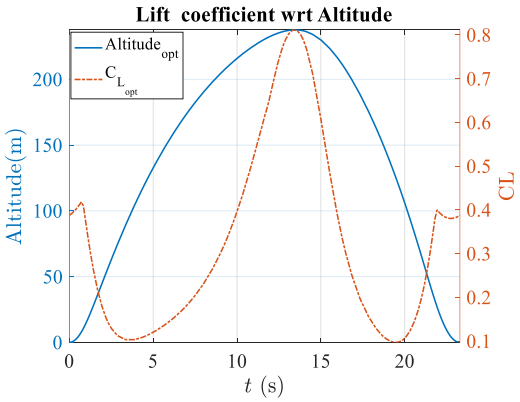


Figure 7. Lift coefficient variation.

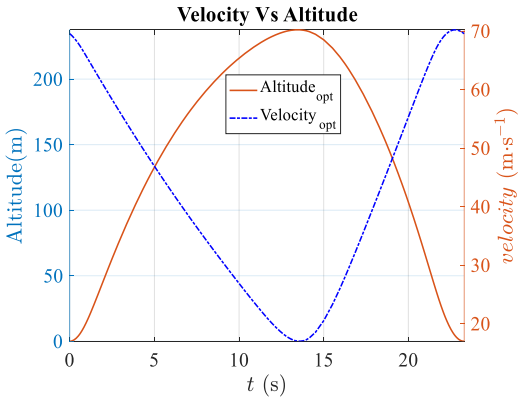


Figure 8. Velocity variation.

3.2. Qualitative comparison with other techniques

The problem of generating optimal dynamic soaring trajectories for UAV in near real time was an area not worked upon by many researchers. In past, majority of the technical studies used off-line numerical optimization techniques such as ALTOS and GESOP [13-15], NPSOL [4, 16] and so on for wind shear calculation and trajectory optimization. Such trajectory optimization software's have a typical computation time of about 100 to 1000sec depending on performance measure. Reinforcement learning technique to acquire speedy results was utilized for such problems due to the inherent goal of balancing exploration and exploitation, but it suffered from the problem of state space complexity and slow learning rates [17, 18]. Akhtar et al. [19] developed trajectory tracking algorithm for powered sailplane that could be implemented in near real time. The technique was based on the "Direct method of Taranenko" [20] could produce optimized trajectories in near real time environment with optimization time of about eight sec. In another study, Akhtar [8, 21] formulated energy-saving trajectories for powered sailplane in near real time by utilizing another method called "IDVD" (Inverse dynamics in the virtual domain). IDVD is a non-linear constrained optimization method, where reference polynomials are determined by the boundary conditions. This method again resulted in considerably rapid solution generation in about eight sec. Similarly , Gao [5] utilizing GPM of GPOPS ([3, 22]) developed dynamic soaring trajectories in real world environment with a computational time of about 15 sec. In this research work, which is a combination of optimization software implemented in GPOPS environment with NLP solver IPOPT, rigorously optimized parameters and guess trajectories, a computational time of below 5 sec is achieved. Generation of optimized trajectories for dynamic soaring within a time frame of less than 5 sec from a nominal core

I-7 platform depicts the effectiveness of the proposed strategy and its viability for practical on board implementations.

4. Conclusion

This paper aims to demonstrate a viable algorithm which can be implemented in near real time environment to formulate optimal trajectories for dynamic soaring maneuvers. The algorithm based upon state of the art optimal control solver and diverse knowledge of dynamic soaring heuristics produces optimal trajectories in a short time of under 5 sec. This optimization time is much lesser than the times achieved earlier. The advantage lies in its characteristics of simplicity as well as rapid trajectory length and parameter computation. Coupled with the fact that dynamic soaring is all about immediately utilizing the available energy from the wind shear encountered, the proposed algorithm promises its viability for practical on board implementations requiring computation of trajectories in near real time.

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