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Dynamics of sideslip perching maneuver under dynamic stall influence

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ABSTRACT

This paper presents the optimization framework and aerodynamic modeling of a sideslip perching trajectory under dynamic stall influence. Based on the optimal trajectory solutions, an impact study of dynamic stall on the spatial and state trajectories of the three-dimensional (3D) perching maneuver is also discussed. At high angles of attack, the behavioral effects of the dynamic separation point on the transient post-stall region are distinguishable with rapid changes of angles of attack and aircraft's turn rates. Introduction of three internal variables thus becomes mandatory for addressing variations in flow state influenced by the swift changes in longitudinal and lateral flight angles. These variables are then integrated into a static nonlinear aerodynamic model, developed using empirical and analytical methods, and into the simulative framework as state variables. In the absence of dynamic stall effects, there is a significant discrepancy in trajectories as opposed to counterpart trajectories inclusive of this phenomenon. The consideration of dynamic stall in longitudinal frame is found to have heightened impact on perching trajectory in response to optimized control inputs as compared to that in lateral frame. With the inclusion of dynamic stall deemed necessary, a comparative study between 2D and 3D perching models is also presented to discuss the distinct drag mechanisms involved. The 3D accommodated perch utilizes the additive combination of longitudinal and lateral drag to dispense its reliance on the gravitational force. Measured against performance parameters which include metrics of spatial cost such as perching distance, longitudinal/lateral deviations and time, the study reveals the 3D mode is an improvement over the 2D mode as the latter model's intransigent characteristic of the undershoot becomes obsolete in the 3D version.

1. Introduction

Perching is an aesthetic technique executed by birds to arrive at their point of landing subtly. Analogous to birds, fixed-wing aircrafts can employ similar high separation drag mechanisms to actualize a comparable form of perching as a landing alternative. The possibilities of a UAV capable of perching ranges from operating in urban environments to surreptitious landings for exploiting the quality of surveillance. One of the bio-inspired maneuver characteristics is the accompanying rapid deceleration which in turn offers greater degree of versatility for the vehicle to perform its swift maneuvers. The most typical form of perching maneuver is the one that is undertaken on a two-dimensional (2D) longitudinal plane. An undershoot that can be represented as the height of an inverted apex on a trajectory is a result of the dive–climb phase sequence during perching. The trajectory of the undershoot is critical for the continuity of UAV's momentum to sustain the successive climb phase. It is not uncommon for the UAV to surpass its stall point for the duration of momentary climb phase. High angles of attack that often exceed over 90 degrees cease the acceleration caused by the dive phase due to resulting drag from flow separation. Loss of kinetic energy due to gravity coupled with rapid deceleration brings about UAV's cessation at its final landing point. The precision landing occurs at a higher altitude with low touchdown velocity which completes the 2D perching motion.

Wickenheiser and Garcia provided illustrative literature on the longitudinal control and dynamics of a perching vehicle with an ingenious morphing mechanism for utilizing separation drag [1,2]. The objectives are to minimize the horizontal perching distance and undershoot in which the latter was deemed as a higher priority and became the underlying motivation in the formulation of double phase optimization procedure. According to Cory and Tedrake [3], there is further vindication of accomplishing a longitudinal perching maneuver by allowing the conventional fixed-wing

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Nomenclature

A_b	body base area
A_p	planform area
b	span
C_D, C_L, C_F	drag, lift and force coefficients
C_{dn}	crossflow drag coefficient
C_N, C_M	yaw and pitch moment
C_X, C_Y, C_Z	force coefficients in body axes
c	chord length
g	gravitational constant
I_{xx}, I_{yy}, I_{zz}	mass moments of inertia about body axis
I_{xz}	cross products of inertia
K	induced drag factor
l_f	fuselage length
m	mass
p, q, r	roll, pitch and yaw rates
S	wing area
t	time
u, v, w	velocities in the body axes
V	total velocity
V_f	fuselage volume
$\bar{x}$	separation internal variable
x_c	axial distance from body nose to centroid of body planform area
x_{cg}	axial distance from body nose to center of gravity of aircraft
α	angle of attack
β	angle of slide slip
β_a	angle of analytical slide slip
η	correction factor for influence of fineness ratio on C_{dn}
δ_e, δ_a, δ_r	deflections of aileron, elevator and rudder
ϕ, θ, ψ	angles of roll, pitch and yaw
τ_1, τ_2	time constants

Subscripts

att	attached flow regime
sep	separated flow regime
b	body axes
e	inertial axes
t	tail
v	vertical tail
w	wing

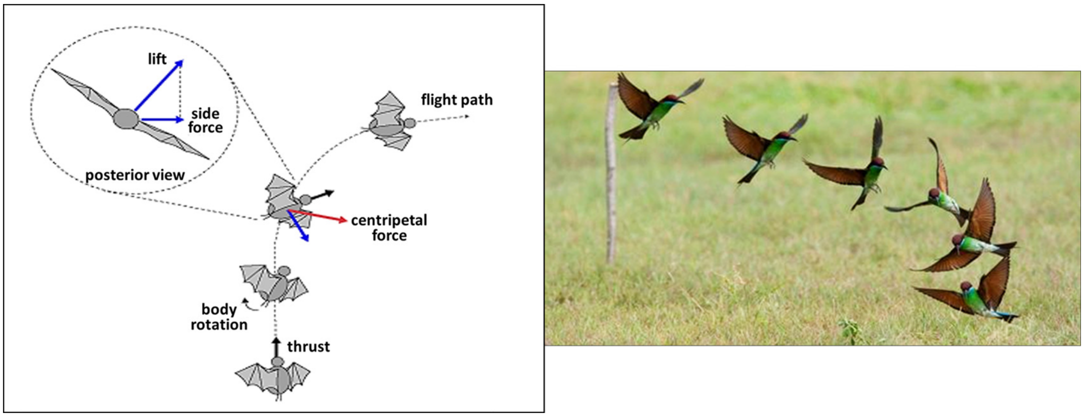

Fig. 1. Fruit bats' crabbed turn (left) [8] and a spiral-like avian perch-landing [9] (right).

glider to glide through an aggressive high angle-of-attack maneuver. Innovative demonstrations of perching have also been proven on smaller scale in indoor experiments such as by Cory R. and Paranjape et al. [4], the latter who successfully guided the perching of an unpowered tailless UAV on a human hand. This vehicle utilized the synchronous operation of flexible articulated wings and elevator for maximum exploitation of the aircraft's post-stall regime to decelerate the aircraft in a firmly controlled and stable manner in an attempt to idealize the perching maneuver. Robertson and Riech have designed perching experiments in which a PID controller was employed to perch a bio-mimetic remote controlled aircraft based on a reference 2D trajectory [5]. Stability issues pertaining to fixed-wing aircraft with birdlike planform designs have also been addressed. Several factors to increase perching success in experiments have been identified that includes velocity drainage mechanics based on trajectory shapes. Thus, inferences drawn from the research of 2D perching maneuver highlight the application of separation drag and weight as the primary forces employed in an aircraft's braking mechanism during perching. Use of breakaway design features, such as morphing wing and variable dihedral wing to conform to class 'Aves' species' naturalistic perching capabilities, have been experimentally justified for producing marked improvement in the vehicle's capability to perch and minimizing undershoot. The latter subject has enthused Rao and Go into investigation of factors such as aerodynamic and thrust vectoring for suppression of undershoot in a generic 2D perching maneuver [6,7]. The undershoot is generally viewed as an undesirable characteristic that is intrusive to the 2D perching optimization procedures. Circumventing the undershoot may even become obligatory in scenarios where there is not any allowance for vertical displacement. Besides this, the undershoot characteristic represents a severe drawback to UAV's versatility and therefore deemed a hindrance for high-risk stealth and reconnaissance missions where the perching criterion might be more restrictive.

From the limited demonstrations of perching so far, its performance potential is yet to be scrutinized for trajectories other than on a longitudinal plane. The typical 2D form of perching as described before which lies on this longitudinal plane is not the most efficient of its maneuvering concepts. Inclusion of the third spatial dimension to accommodate a 3D perching maneuver provides breakthrough to a wide range of quixotic trajectories previously improbable with the 2D version of perching. Inspiration for such 3D mode of perching can be drawn from the fruit bats' crabbed turn and a spiral-like avian perch landing (as depicted in Fig. 1). This extreme mode of perching executed adeptly by class 'Aves' species introduces new challenges when it comes to emulation