Perched Landing and Takeoff for Fixed Wing UAVs

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Abstract

The perched landing manoeuver enables a conventional fixed wing flight vehicle to be delivered to a point space with nominal zero vertical and horizontal velocity. This provides a novel means of retrieving UAVs in environments where obstructions or adverse terrain preclude the use of a conventional landing approach. The use of an elevated landing site enables subsequent re-launch after indefinite loiter.

This paper describes the development of a simulation model for perched landing and takeoff, presents and discusses simulation results and describes the use of a genetic algorithm to optimise the landing manoeuver. It was found that the dynamics of the landing manoeuver could be greatly simplified if an active braking force, e.g. due to wing flapping, was available. The takeoff manoeuver is relatively simple compared to landing.

Nomenclature

C_D	drag coefficient
C_L	lift coefficient
m	aircraft mass, kg
S	wing area, m^2
u	horizontal velocity component, m/s
V	speed, m/s
w	vertical velocity component, m/s positive upwards
W	aircraft weight, N
x	aircraft horizontal coordinate, m
z	aircraft vertical coordinate, m, positive upwards
α	aircraft angle of attack, degrees
ρ	air density, kg/m^3
η	elevator angle, degrees, trailing edge down positive
$\delta\eta$	Magnitude of elevator step input, degrees
$t_{\delta\eta}$	Length of elevator step input, s
θ	aircraft attitude relative to horizontal, degrees, nose-up positive

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1 Introduction

Smaller UAV systems are being increasing deployed in environments where there is no access to conventional runways such as from the back of ships, within urban areas or in the field. Whilst rotary wing or directed thrust vehicles are able to operate without the use runways, there are significant cost and performance implications compared to the use of fixed wing craft. In light of this, a number of different systems for launching and retrieving fixed wing UAVs have been developed. The most widespread type of field launch systems for UAVs are based around the catapult principle in which stored energy from a spring is converted into kinetic energy of the vehicle. Approaches to vehicle retrieval are more varied, including use of a deep stall approach (e.g. Pointer hand launched UAV), the use of a catching net (e.g. for ship borne recovery), a wing mounted hook that grabs a cable[1], guided parachutes[2,3] and unguided parachutes (e.g. British Army Phoenix UAV) and capture by a second flying vehicle (mid air recovery). This paper develops a further method of retrieving fixed wing UAVs based on the perched landing approach used by many birds and other flying animals[4].

An important advantage of perched landing is that re-launch can be achieved using the stored potential energy of the vehicle. In contrast, with other landing methods, once the vehicle has come to rest, it can only be re-launched by transferring it to a dedicated launch system. The use of perched landing has advantages for surveillance missions where a small unmanned vehicle may be flown to an area of interest and landed on an existing urban or natural structure where it can gather information or wait for further commands. When required, the vehicle can then re-launch itself to continue its mission elsewhere.

When landing a flight vehicle on a conventional runway, the goal is to deliver the vehicle at point just above the runway surface with nominally zero vertical velocity, but with finite horizontal velocity. Once the aircraft touches the ground, the mismatch in velocity between the vehicle and the ground reference is taken up by the wheels, which also support the weight of the aircraft as it decelerates horizontally and loses wing lift. In contrast, a perched landing requires delivery of flight vehicle to a point in space with nominally zero vertical velocity *and zero forward velocity*. The additional requirement of nominally zero forward speed can be met by extending the flare manoeuver used for conventional runway landing to what has been called a perched landing manoeuver.

A typical perched landing trajectory is shown in figure 1. There are three phases to the landing manoeuver. Firstly a relatively steep, conventional approach. Secondly, an extended flare leading to a fully stalled flight condition, and thirdly a post stall capture phase in which the aircraft is manoeuvered on to some form of platform or ‘perch’.

The proposed perched landing manoeuver is based on the inherent dynamic behaviour of a fixed wing aircraft following an elevator step input. This is important because it greatly simplifies the design of an appropriate guidance and control system for automated landing[5].

The proposed perched landing manoeuver is similar to that used by gliding animals such as flying squirrels that are unable to generate aerodynamic lift by flapping. There are also some bird species like woodpeckers that choose to

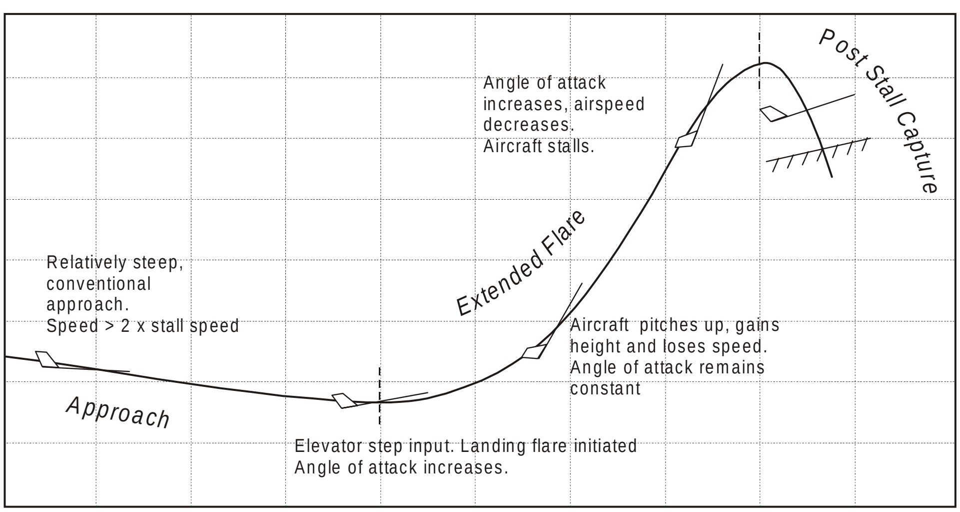

Figure 1 *Aerodynamic characteristics of the perched landing manoeuver*

use this type of manoeuver when flying from tree trunk to tree trunk, presumably because it involves least energy expenditure. Most birds, however, adopt a modified version of the perched landing manoeuver when landing on a perch. The main difference would appear to be the use of wing flapping to generate an additional aerodynamic braking force at low speed during the final part of the landing sequence and hence increase horizontal deceleration. For given horizontal velocity landing constraints, this allows landing to be achieved using a manoeuver with less pronounced flare and thus reduced vertical clearance.

The aim of the work presented in this paper is to validate the feasibility of perched landing/re-launch capability for UAVs. Section 2 describes the simulation used for the present investigation and results are presented and discussed in section 3. Section 4 discusses the use of a genetic algorithm to optimise landing trajectories and conclusions are drawn in section 5.

2 Perched Landing: Description of present simulation study

A longitudinal flight vehicle simulation model was developed that captured the essential aerodynamics of the perched landing manoeuver. The simulation represents an unpowered fixed wing flight vehicle of conventional layout. The aerodynamics are based on an unswept wing with an aspect ratio of seven and a C_{Lmax} of 2.0 and an all moving tailplane. Elevator angle corresponds to the angle of the tailplane relative to the zero lift line of the wing. Wing and tailplane aerodynamic models are valid for +/- 180 degrees angle of attack. Beyond stall, lift is modelled as $C_L=\sin 2\alpha$ and drag as $C_D=\mathrm{abs}(\sin\alpha)$. Fuselage aerodynamics are not explicitly modelled.

For the purposes of the present a study, the criteria for a successful landing were set as follows
a) the horizontal velocity component should be less than 3m/s and greater than zero m/s
b) the vertical velocity component should be greater than -3m/s and less than 0m/s
the vehicle attitude should be greater than zero degrees and less than 60 degrees

3 Presentation and discussion of simulation results

3.1 Aerodynamic characteristics of the landing manoeuver (non-optimised results)

Simulated landing trajectories and time histories of horizontal velocity, vertical velocity, angle of attack and attitude for elevator step inputs of increasing length are shown in figure 2.

The zero elevator input case in figure 2a approximates a steep conventional landing approach. A vertical velocity of less than 3m/s achieved at t=3s. However, airspeed (figure 2d) and horizontal velocity (figure 2e) remain at approximately 20m/s throughout.

With increasing elevator step input length, the flare trajectory becomes increasingly steep and a greater maximum height is reached. This leads to an increasing amount of the vehicle's kinetic energy being converted to potential energy and a corresponding reduction in vehicle speed (figure 2d).

The horizontal and vertical components of the vehicle speed during the flare manoeuver are shown in figures 2e and 2f. Note that the imposed vertical velocity landing criterion of $-3<w<0$m/s can be met at a number of different points on all the flare trajectories. The challenging aspect of a successful perched landing is in achieving a horizontal velocity $0<u<3$m/s at the same time. From figure 2e it is evident that the horizontal velocity landing condition is only met for the most steeply peaked landing trajectories ($t_{\delta\eta}>0.8$s). For the results shown, a landing within the imposed velocity limits could be achieved with $t_{\delta\eta}=1$s. The nominal landing would occur at x=33m, z=8m, t=3.3s

The attitude of the aircraft fuselage relative to the horizontal ground reference during the flare manoeuver is shown in figure 2c. Note that the vehicle attitude is a variable independent of both the angle of attack and the gradient of the flight trajectory. The initial attitude angle on the glide slope is -7^o (-10^o glide slope plus 3^o angle of attack). The elevator step input provides a pitching moment that accelerates the vehicle in a nose up sense. The pitch rate is set by the magnitude of the elevator step input and the maximum attitude angle reached determined by the length of the step input. For the $t_{\delta\eta}=1$s case, $\theta_{max}=90^o$, i.e. the aircraft is standing on its tail. Once the elevator step is removed, the aircraft pitches nose down, typically regaining a nose down flying attitude for t>3.5s. Note however, that for the fully stalled trajectory ($t_{\delta\eta}=1$s) the aircraft remains at a high attitude angle for an extended time. This is because at this condition the aerodynamic restoring forces are small compared to the inertia of vehicle.

At the nominal landing condition based on velocity requirements ($t_{\delta\eta}$=1s, t=3.3), the vehicle attitude is approximately 70^o, just outside the target of 60^o.

3.2 Aerodynamic characteristics of the perched take off

A perched take off was simulated by releasing the aircraft with a nose down attitude at zero airspeed with fixed elevator input. The effect of varying elevator input, i.e. varying steady state trimmed C_L , for a purely gravity-assisted take off is shown in figure 3. Of interest is the achievement of steady level flight with the minimum loss of altitude. From figure 3a it can be seen that increasing trimmed C_L reduces the vertical clearance required. However, as C_{Lmax} (C_L =2) is approached the associated increase in drag becomes significant and the aircraft stalls soon after launch.

The provision of conventional axial thrust in a forward direction enables flight speed to be attained more quickly and reduces the vertical clearance required. Note that for thrust less than the weight of the aircraft, minimum vertical clearance is always achieved by launching with a nose down attitude.

Investigation of the use of vectored thrust during take off showed that for thrust to weight ratios of less than one, there is little benefit in varying the thrust direction from axial.

4 Optimisation of landing trajectories

Problem
For given aircraft parameters and wind speed, what are:

- the optimal starting conditions for the manoeuver (i.e. approach flight condition), and
- the optimal control inputs during the manoeuver,

Adopted solution

- Introduce appropriate adjustable parameters in the simulation
- Optimise parameters using a genetic algorithm

Genetic algorithms provide a robust and relatively simple means of finding optimal solutions in a large solution space. A flow diagram describing the operation of a genetic algorithm is shown in figure 4. The approach has been previously demonstrated in various other aerospace-related trajectory optimisation studies[6,7,8,9].

As an initial study, it was decided to take the adjustable parameters as the glide slope conditions immediately preceding the flare (attitude, angle of attack and speed), the length of the elevator step input during the flare and the time delay between start of the flare and application of reverse thrust. The wind speed is taken as zero. Each of the five free parameters were encoded as a four bit chromosome, giving 20 possible values for the parameter. The chromosomes were then concatenated to give a sixteen bit gene.

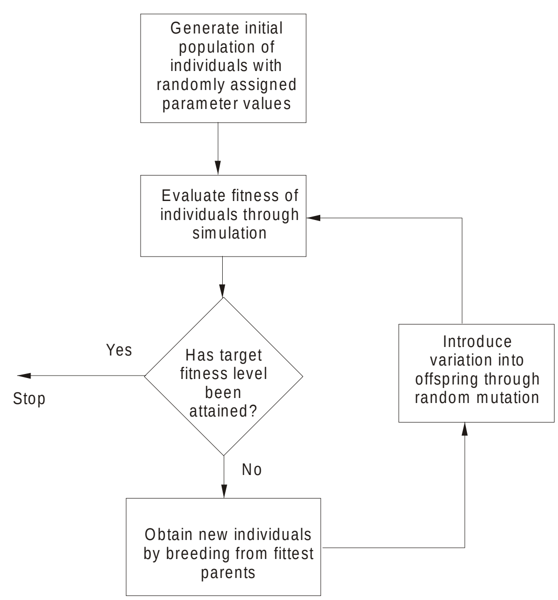

Figure 4 *Genetic algorithm flow diagram*

The target landing conditions for the optimisation algorithm were w = 0 m/s, u = 2 m/s and θ = 30^o. The fitness of an individual gene (i.e. a given set of parameters) was assessed by running a simulation using the parameters and by finding the minimum value of an error function e for that trajectory:

$$e = (u-2)^2 + (w)^2 + 0.05(\theta - 30)^2$$

An initial population of 10 genes was initialised with random numbers. The fitness of each of these genes was then obtained through simulation. Following this, a new set of genes was obtained by combining the most successful genes from the population using crossover with probabilistic random mutation. This process was continued until the gene pool converged on an optimal solution.

For a 20 bit gene there are $2^{20} \approx 1 \times 10^6$ possible parameter combinations thus an exhaustive search would require 1×10^6 simulation runs. Using a genetic algorithm approach, convergence was typically achieved using the order of 100 simulation runs.

Simulation results for parameters optimised using a genetic algorithm are shown in figure 5. For the zero thrust case, the optimal touchdown point occurs 2.4s after the flare initiation. At this point, $u \approx 3$m/s, $w \approx 0$ and $\theta \approx 30^0$. The vertical clearance required is approximately 11m. Note that the results obtained from the GA optimisation are improved over the original 'best guess' results shown in figure 2. The main difference is that the GA has identified a slower approach at higher C_L as advantageous.

With the availability of reverse thrust at 20N, the optimal touchdown point occurs 1.8s after flare initiation and the required vertical clearance is reduced to approximately 5m. The result shown in figure 5 that the provision of an active braking force, e.g. due to wing flapping, is beneficial for perched landing in that the required manoeuver dynamics are simplified and the vertical clearance reduced.

5 Conclusions

- Perched landing and takeoff offers operational advantages for fixed wing UAVs operating without access to runways
- Perched landing of a fixed wing unpowered aircraft can be achieved using a simple pitch-up manoeuver
- The use of vectored thrust as active braking during landing simplifies the manoeuver dynamics
- Takeoff from a perched position is straight forward compared to landing
- The main challenge with perched landing is the increased complexity of guidance and control required

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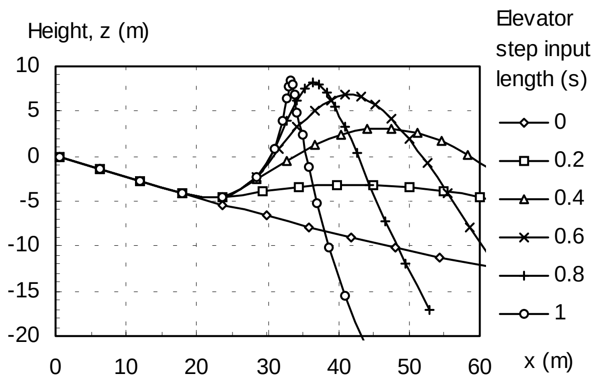
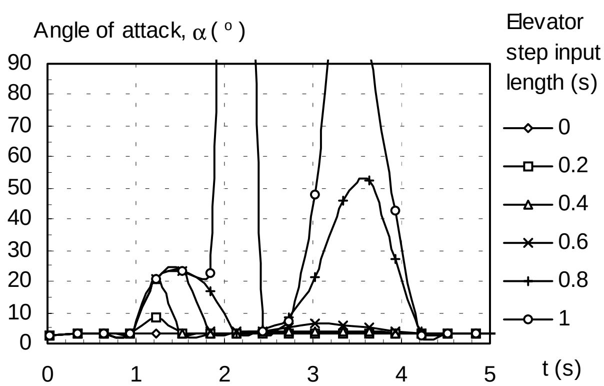
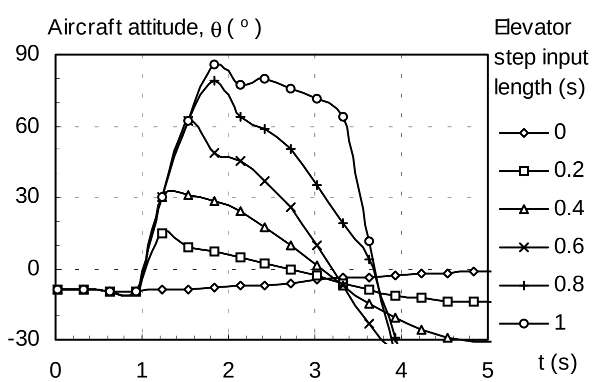


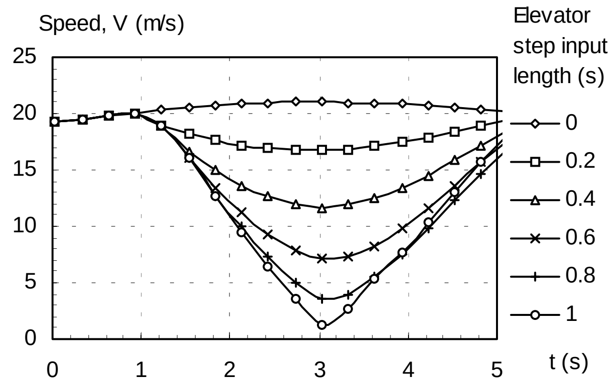
a) *x-z flare trajectories*



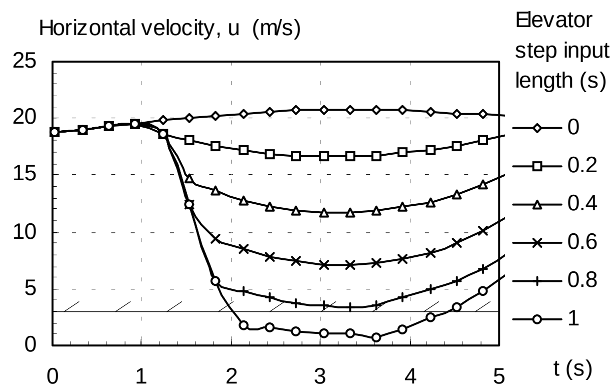
b) *Angle of attack time history*



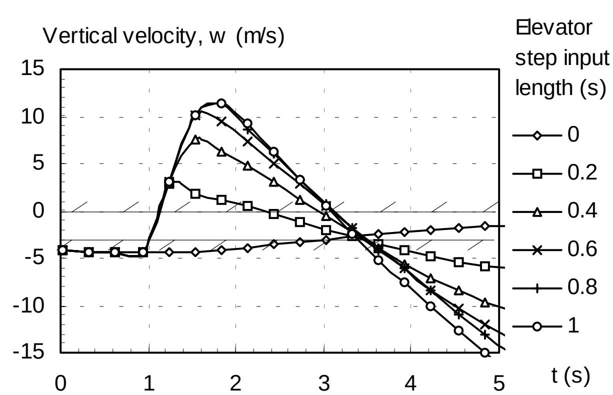
c) *Aircraft attitude time history*



d) *Speed time history*

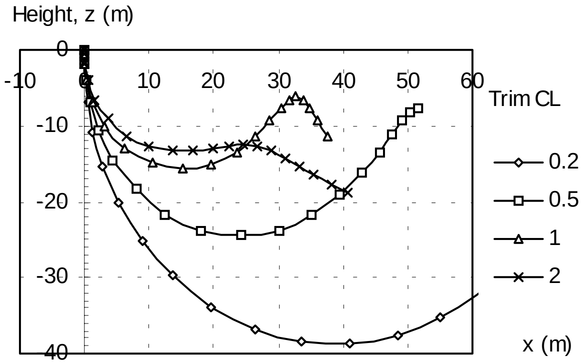


e) *Horizontal velocity time history*

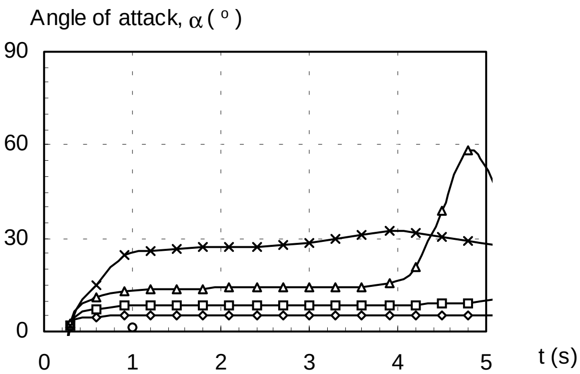


f) *Vertical velocity time history*

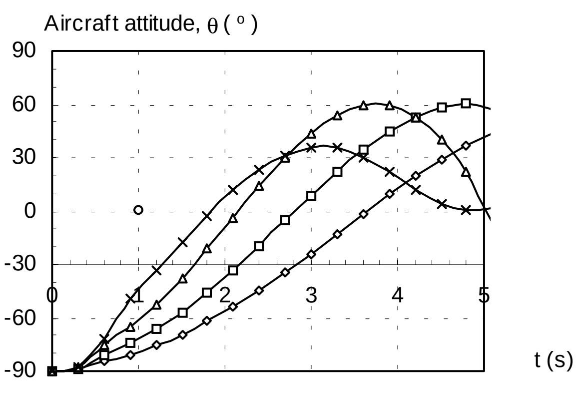
Figure 2 *Extended flare manoeuvres following an elevator step input of increasing length.*
Elevator step magnitude -10 degrees, wing loading 70N/m², mass 3kg, time step between displayed points 0.3s.



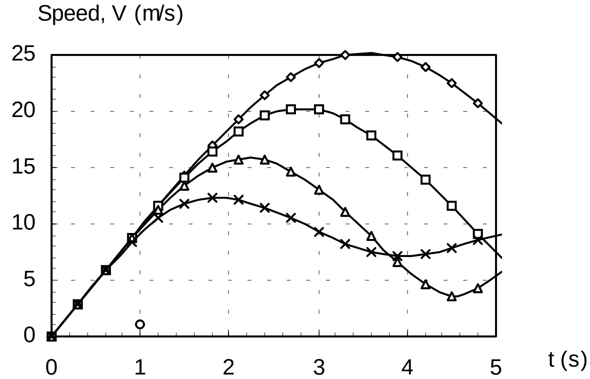
a) *x-z flare trajectories*



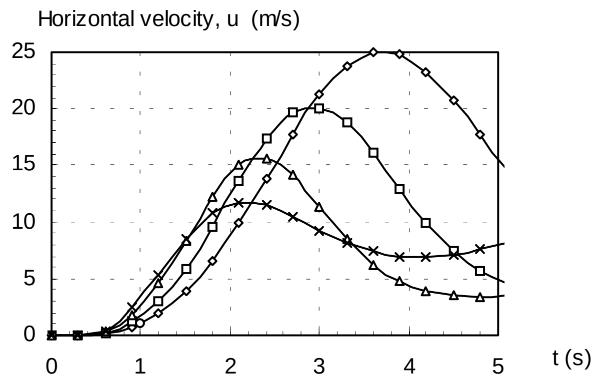
b) *Angle of attack time history*



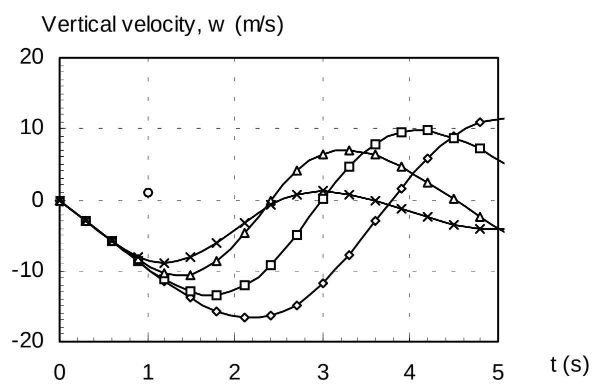
c) *Aircraft attitude time history*



d) *Speed time history*

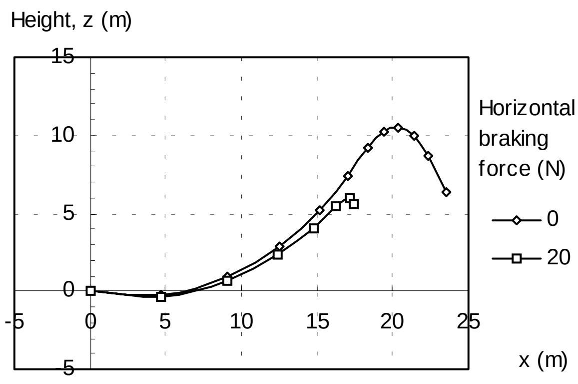


e) *Horizontal velocity time history*

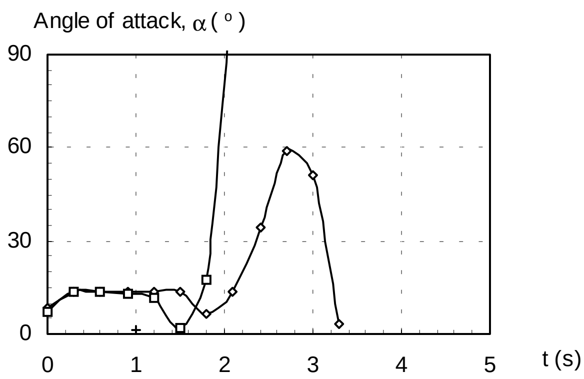


f) *Vertical velocity time history*

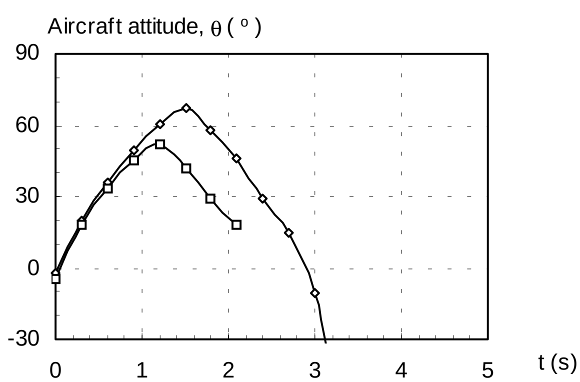
Figure 3 *Gravity assisted take off from perched starting conditions*



a) *x-z flare trajectories*



b) *Angle of attack time history*



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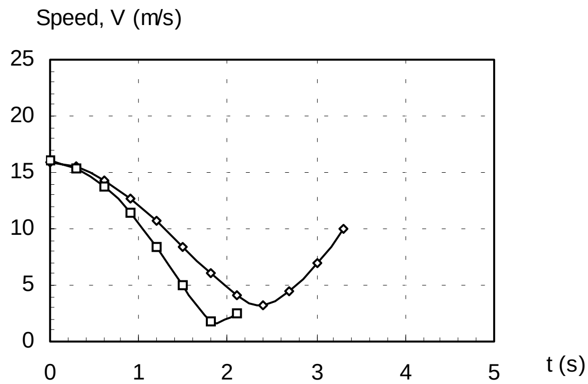

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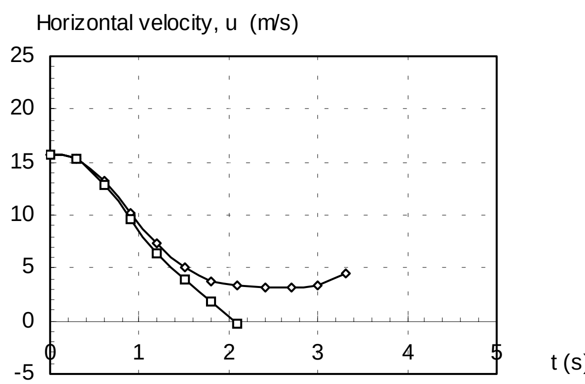
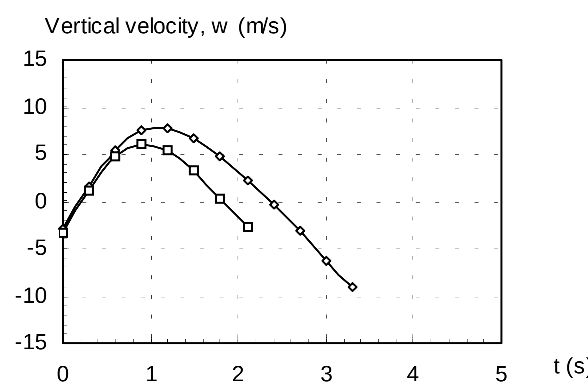


e) *Horizontal velocity time history*



f) *Vertical velocity time history*

Figure 5 *Perched landing manoeuvers optimised using a genetic algorithm*

Paper No : 19

Given by *:* W.J.Crowther

Question posed by: Ozcan Ertem (TAI Turkey)

Perched landing for fixed wing UAVs appears to be a single trial (one shot) landing. How will missed approach techniques be employed, if any?

Answer

Like conventional landing, a perched landing will have a predefined approach 'corridor' defined in terms of physical and parameter space. If the aircraft goes outside this corridor, e.g. following encounter with a gust, then the landing manoeuvre must be aborted. The corridor for perched landing is much more highly constrained than for conventional landing. The type of about manoeuvre adopted will depend on where in the landing sequence the aircraft is. If the aircraft is some distance from the landing site and forward airspeed is sufficient then a conventional turn to the left or right is appropriate. Otherwise power should be applied to enable the aircraft to climb over the landing site. A further possibility is extension of the flare followed by a 'hammer head' turn manoeuvre.

Question posed by: V De Brederode (Teca. Univ. Lisbon*)*

You mentioned 'easy perched take-off' with no forward speed, in a fully separated regime and no control whatsoever?

Answer:

A stable fixed wing aircraft dropped with a nose down attitude from rest will naturally achieve accelerated gliding flight with no control input. Once control speed has been attained, the aircraft may then be manoeuvred accordingly. It should be noted that the initial part of the take off will be adversely affected by gusts.

Question posed by: *V De Brederode (Teca. Univ. Lisbon*)

I didn't grasp the difference between deep stall and perched landing.

Answer:

In a deep stall approach, the goal is to stall the aircraft such that it descends at high angle of attack with wings and fuselage approximately horizontal. In a perched landing as described in the paper, horizontal velocity is reduced primarily using lift. In a deep stall landing, horizontal velocity is reduced primarily using additional drag. The descent speed for deep stall landing is always finite downwards and is determined by the wing loading. With a perched landing it is theoretically possible to achieve touch down with zero horizontal and zero vertical speed.

Question posed by*:* *V De Brederode (Teca. Univ. Lisbon*)

How did you model the fully separated aerofoil performance in the final descending phase before touchdown?

Answer:

Aerofoil force and moment coefficient data was based on static wind tunnel tests from 0 to 90^0 angle of attack. It should be noted however that the aerodynamic forces at this point of the manoeuvre are small compared to the inertial forces acting on the aircraft.

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