

Post Stall Landing for Field Retrieval of UAVs

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Abstract

The post stall landing manoeuvre 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 reviews current retrieval methods for UAVs, describes the development of a simulation model for post stall landing, presents and discusses simulation results and discusses guidance and control requirements for successful implementation.

The primary aerodynamic scaling factor affecting the space required to achieve a post stall landing is the vehicle wing loading. For a C_{Lmax} of 1.8, a vehicle with a wing loading of $100N/m^2$ requires 20m of vertical clearance. The presence of a head wind is beneficial in that it reduces the steepness of the extended flare required for successful post stall landing. It is proposed that a vehicle guidance algorithm should be based on a look up table of pre-simulated trajectories. Precise control of the landing manoeuvre is challenging because the time constant of the manoeuvre is of the same order as the time constant of the elevator response.

Biography

Bill Crowther has an undergraduate degree in Aeronautical Engineering (1990) and a PhD in High Angle of Attack Aerodynamics from the University of Bath (1994). He was at the Fluid Power department of the University of Bath from 1995 to 1997 working on the application of neural networks to fault diagnosis of hydraulic systems. He was then appointed as a lecturer at School of Engineering, University of Manchester where his research interests are the application of intelligent technologies to the control of nonlinear flight vehicles.

Konstantinos Prassas graduated from the University of Manchester in 1998 with a degree in Aerospace Engineering. He is currently studying for an MPhil.

Nomenclature

C_D	drag coefficient
C_L	lift coefficient
m	aircraft mass, kg
S	wing area, m^2
T	engine thrust, N
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
<i>DGPS</i>	Differential Global Positioning System
<i>GPS</i>	Global Positioning System
<i>HTOL</i>	Horizontal Take-Off and Landing
<i>ILS</i>	Instrumental Landing System
<i>MARS</i>	Mid-Air Recovery System
<i>RPV</i>	Remotely Piloted Vehicle
<i>UAV</i>	Unmanned Aerial Vehicle
<i>VOR</i>	Very high frequency Omni-directional Range
<i>VTOL</i>	Vertical Take-Off and Landing

1 Introduction

Landing is the process by which a flight vehicle moving through a body of air is brought to rest relative to some frame of reference, which is usually fixed relative to the Earth's surface. In a conventional runway landing of a conventional fixed wing aircraft, the goal is to deliver the flight 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. The conventional landing manoeuvre is an extremely effective and safe way of retrieving flight vehicles. However, it is constrained by the need for an expanse of relatively flat land, clear from obstacles such as trees and rocks.

Post stall landing is a means by which a fixed wing flight vehicle is delivered to a point in space with nominally zero vertical velocity *and zero forward velocity* relative to a ground-based reference. A typical post stall landing trajectory is shown in figure 1. There are three phases to the landing manoeuvre. 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 manoeuvred on the landing mast. The proposed post stall landing manoeuvre 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.

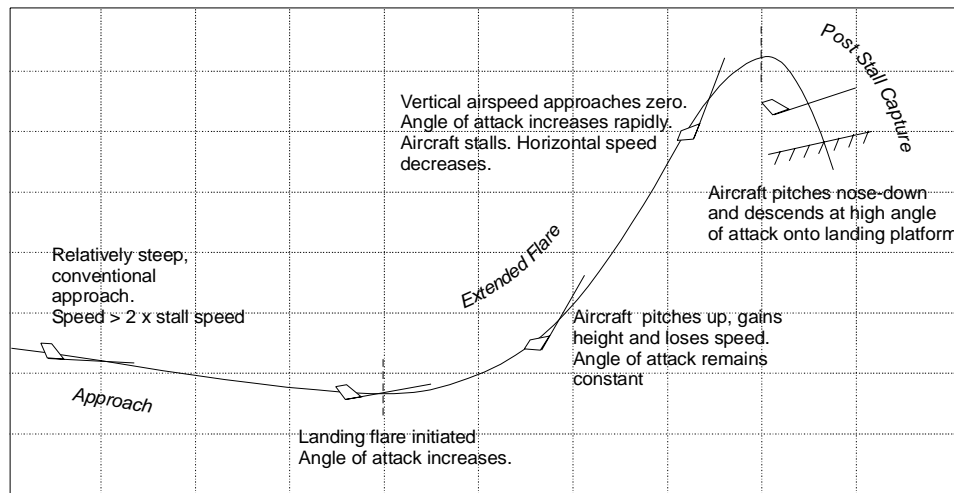


Figure 1 Aerodynamic characteristics of the post stall landing manoeuvre

Using a post stall landing manoeuvre, a fixed wing flight vehicle may be set down in rugged or cluttered terrain that precludes the use of a conventional landing. As a further advantage, the use of an elevated landing site allows the vehicle to be re-launched using its stored potential energy.

The most immediate potential application of post stall landing would be the field retrieval of small reconnaissance UAVs using a purpose built landing mast. Looking further to the future, it is anticipated that autonomous vehicles with sufficiently developed vision and control systems could identify and make use of landing sites in urban or natural environments. This would greatly extend the potential loiter time of these vehicles, which could land then re-launch themselves when conditions were appropriate

Note that the post stall landing manoeuvre, as it has been called here, is the basis of the landing strategy used most commonly by birds since it allows landing on tree branches or other fixed natural structures. However, compared to conventional fixed wing aircraft, birds have the advantage of being able to generate wing lift at zero forward speed by flapping, which makes the final manoeuvring in what has been termed the 'post stall capture' much easier. This said, it has been observed that some birds such as wood peckers do not flap their wing at all when landing and follow a trajectory not dissimilar to that shown in figure 1.

The primary motivation behind this paper is the investigation of the aerodynamic feasibility of post stall landing of conventional fixed wing aircraft. Section 2 examines other retrieval methods currently used for UAVs. Section 3 describes the simulation used for the present investigation and results are presented and discussed in section 4. Section 5 discusses the guidance and control requirements for successful implementation of an autonomous landing system and conclusion are drawn in section 6.

2 Review of current retrieval techniques

2.1 Overview of UAV roles

In the last decade, the primary roles of UAVs/RPVs and Aerial Targets have taken many forms both in the civil and military sector. As a result, these roles have a direct effect on the operation of the aerial vehicles. In the civil sector, many UAVs are produced for meteorological, surveillance, and atmospheric measurement purposes. On the other hand, military

UAVs and Aerial Targets have been extensively used for surveillance, electronic warfare, and pilot training¹. In both cases, the flexibility on choosing a suitable site for launch and recovery becomes very important specially in the latter case. The traditional methods for retrieving UAVs are currently limited in parachute deployment, horizontal or vertical landing on skids or landing gear, the use of catching nets and other methods combining the above. In this section, a review on these methods is presented concerning only conventional fixed wing vehicles.

The successful completion of UAV missions in the Gulf and Bosnian War, together with successful civil operations, increased the demand on UAVs by governments and companies². The introduction of the Global Positioning System (GPS) allowed autonomous navigation in short, medium, and long range missions. In addition, the use of the Differential Global Positioning System (DGPS) allowed for a better position accuracy which in turn improved the total efficiency of the vehicles³.

The rapid improvement of flight systems in the last years, following the increased needs for more sophisticated UAV roles, had a direct impact on the development of the respective landing systems⁴. Following this development, although the recovery methods have remained the same, the number of UAVs using different retrieval techniques has increased or decreased depending on the vehicle's configuration and mission. Figure 2a shows this development for the existing recovery methods while figure 2b shows the current trends. A description of these methods follows.

2.2 Horizontal Take-Off and Landing (HTOL)

Although this term is mainly used for UAVs launched and landed horizontally, it is also used for UAVs launched from a conventional launching rig in any way but landed horizontally. Figure 3a shows the development of the individual recovery methods used in horizontal landing in the last ten years.

Skid Landing has always been a favorite retrieval method due to its simplicity, specially with Aerial Targets or UAVs without any sensitive external parts. Skid Landing requires either radio control or a relatively sophisticated autonomous landing system, which is able of decreasing the touchdown impact. The main advantage with this method is the flexibility in choosing a landing site as long as this is flat and preferably soft. However, it is not suitable for vehicles carrying any sensitive equipment under the fuselage.

Wheel Landing is used more in HTOL vehicles in the last years. The main reason for this is the general preference in using landing gear (tricycle in most cases) which allows operations from runways or aircraft carriers, fitting antennas and other sensitive parts under the fuselage, and reduced landing accelerations. Also, the recent appearance of large and heavy vehicles (*Global Hawk*⁵, *Theseus*⁶, etc.) requires the use of runways. Runway landings are beneficial because landing systems used by manned aircraft, such as ILS or VOR approach may be used by UAVs, so a further development in UAV landing systems is not required. The use of GPS has played an important role in *Wheel Landing* as well, specially in autonomous UAV landing systems, which are being increasingly employed (figure 3b).

2.3 Vertical Take-Off and Landing (VTOL)

Vertical Take-Off and Landing UAVs seem a very attractive solution especially in recovery. However, the conventional aircraft shape of the UAVs considered in this survey requires the installation of a complicated mechanism to allow for VTOL capabilities which in turn increases the total weight and has a direct effect on the operation of the vehicle⁷. As a result VTOL is mainly used in drones with an unconventional shape, except in special cases like the Scorpion UAV⁸.

2.4 Parachute

The main advantage of this method is that the UAV may be retrieved at any time anywhere (although an accurate point landing is difficult). In addition, if a parachute is used as the primary recovery method, it may also be used as the emergency recovery method saving additional cost and weight. Figure 4 shows the relative development of Parachute Landing in the last ten years. The difference between *Emergency Autonomous* and *Autonomous* as used in the legend of figure 4, is that the former indicates an autonomous parachute deployment in case of an emergency, whereas the latter indicates an autonomous parachute deployment system being the primary recovery method. Autonomous Emergency systems are responsible for deploying the parachute in case of a critical failure (lost of radio control signal, electrical or engine failure). Usually, the UAV flies autonomously to a pre-selected site and the parachute is deployed ensuring safe recovery.

Most parachutes are parafoil or cruciform shaped, stored in the fuselage⁹. In cases where external sensitive equipment is under the fuselage, the parachute is deployed from the belly and the vehicle is

inverted so that the parts under the fuselage are protected from the impact. A more complicated system for protecting the vehicle structure or any sensitive parts is the combination of a parachute (deployed normally on top of the fuselage) and an airbag which is inflated under the fuselage a few seconds before touchdown. The airbag may also be used to keep the UAV afloat when landed on water.

The main problem in parachute recovery is the transition from horizontal to vertical motion of the vehicle, which starts as soon as the parachute is deployed. Then, although parachute steering is possible, the oscillatory movements of the vehicle present problems in recovery such as inaccurate point landing or touching down at different angles which may damage the vehicle structure¹⁰.

2.5 Catching Net

This method is more favorable in ship operations where a large net is positioned at the back of the ship, and the UAV flies into the net. This is either done autonomously, using GPS or a signal from the ship, or manually where the approach is radio controlled. In both cases, if a propeller is situated in front of the fuselage, it shuts down and the rotor halts just before the net impact. Figure 5 shows the relative development of this method in the last ten years and apparently the autonomous capabilities are increasing specially after the introduction of the GPS where accurate approach was made possible. Net retrieval is also performed on the ground where special trucks (usually carrying the launching rig) deploy a vertical net for retrieval. This method is also common in jet aerial targets where the approach speed is high and their size does not allow the fitting of a parachute or landing gear. The main disadvantage of this method is the large rate of change of momentum during the impact with the net, and as a result any equipment or the whole structure of the vehicle may be damaged.

2.6 Mid Air Recovery System (MARS)

This system allows mid-air recovery from a helicopter, which flies close to a flying vehicle. Then, the latter attaches on the helicopter under special bays. This system is still under development and its main advantage is the retrieval of UAVs over regions where the ground texture is not suitable for any other retrieval methods.

3 Post Stall Landing: Description of present simulation study

A flight vehicle simulation model was developed that captured the essential aerodynamics of the post stall

landing manoeuvre. The simulation represents an unpowered fixed wing flight vehicle of conventional layout (tail plane aft). The aerodynamics are based on an unswept wing with an aspect ratio of seven and a $C_{L_{max}}$ of 1.8 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 $C_D = \text{abs}(\sin \alpha)$. Fuselage aerodynamics are not explicitly modelled.

Newton's Second Law is used to express horizontal and vertical acceleration of aircraft centre of gravity and angular acceleration of pitch inertia. Resulting differential equations integrated using Euler's method with a time step of 0.003 seconds.

The simulation was developed using Visual Basic. The user can vary model parameters interactively and observe the vehicle motion and parameter histories in real time.

For the purposes of the present a study, the criteria for a successful landing were set as follows

- the horizontal velocity component should be less than 3m/s and greater than zero m/s
- 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

4 Presentation and discussion of simulation results

4.1 Fundamental aerodynamic characteristics of the landing manoeuvre

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 6.

The zero elevator input case in figure 6a approximates a steep conventional landing approach. A vertical velocity of less than 3m/s achieved at $t=3s$. However, airspeed (figure 6d) and horizontal velocity (figure 6e) 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 6d).

This transfer of energy from kinetic to potential is the basis by which a point landing at nominally zero horizontal and zero vertical velocity is possible.

The elevator step input at beginning of the flare manoeuvre ($t=1s$) increases the angle of attack of the aircraft, figure 6b. Increasing length of elevator step input increases the max angle of attack achieved, up to approximately 20° where the wing is stalled. For the more gentle flare trajectories (length of elevator step less than 1s), the angle of attack returns to the trim value of 3° when the elevator input is removed. However, for the steeply peaked flare trajectory, the angle of attack continues to increase after the elevator input is removed, leading to a deep stall condition ($t=2s$). Note that the stall speed for the vehicle in level flight is approximately 8m/s ($C_{L_{max}}=1.8$, $\alpha=17^\circ$). However, during the extended flare manoeuvre it is possible for the angle of attack to be transiently unstalled even with the airspeed close to zero.

The horizontal and vertical components of the vehicle speed during the flare manoeuvre are shown in figures 6e and 6f. 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 post stall landing is in achieving a horizontal velocity $0 < u < 3$ m/s at the same time. From figure 6e it is evident that the horizontal velocity landing condition is only met for the most steeply peaked landing trajectories ($t_{\delta\eta} > 0.8s$). For the results shown, a landing within the imposed velocity limits could be achieved with $t_{\delta\eta}=1s$. 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 manoeuvre is shown in figure 6c. 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° (-10° glide slope plus 3° 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 $t_{\delta\eta}=1s$ case, $\theta_{max}=90^\circ$, 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 ($t_{\delta\eta}=1s$) 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° , just outside the target of 60° .

4.2 Effect of increased drag

Landing trajectories for an elevator step input length of 1s but vary step magnitude $\delta\eta$ are shown in figure 7. Increasing $\delta\eta$ from -8° at first reduces the radius of the initial flare and increases the peakedness of the overall trajectory. However, for $\delta\eta > -12^\circ$ the trajectories become increasingly flat. This is because the main wing of the aircraft now stalls during the initial pitch up manoeuvre, leading to reduced lift and marked increase in drag.

It was anticipated that the increased drag during a fully stalled flare would be a useful means of reducing the vehicle's overall kinetic energy and the horizontal component of velocity in particular. However, the simulation results show that increased drag is not useful in trying to achieve a post stall landing. In the worst case, with $\delta\eta > 30^\circ$, the drag is sufficiently high that the aircraft fails to climb at all after the control input is applied and enters a steep descent at an attitude of around 30° and an angle of attack of around 60° . This manoeuvre meets the horizontal velocity landing requirement ($0 < u < 3m/s$) but has excessive vertical velocity component.

4.3 Manoeuvre scaling parameters

Of key importance in the practical implementation of a post stall landing system is the height clearance required between the ground and the top of the landing mast. The main parameter affecting this variable is the aircraft wing loading, as shown in figure 8. Note that the aircraft mass is constant in each case with the wing loading changed by changing the wing area. Increasing the wing loading increases the level flight stall speed. Since the approach speed is set at 2.5 times the stall speed, increased wing loading is associated with increasing approach speed. Furthermore, for a given C_{Lmax} , increased wing loading increases the minimum attainable flare radius. The net result is that wing loading strongly affects the spatial clearance required for post stall landing.

The approximate relationship between wing loading and height clearance required for post stall landing is illustrated in figure 9. In terms of implementing a post stall landing system, the maximum height of the retrieval mast height will be around 20m, requiring a

wing loading of no more than $100N/m^2$. For reference, the wing loading scale in figure 9 is identified with various different flight vehicles. Many smaller UAVs currently flying are within the $100N/m^2$ wing loading limit.

The effect of changing vehicle mass for constant wing loading is shown in figure 10. For increased mass, the wing loading is kept constant by increasing the wing area and hence the linear length scale of the aircraft. Thus increasing mass also increases the pitch inertia, which is the primary driver behind the spread of results shown in figure 10.

4.4 Landing in the presence of wind

Preceding results have all been for the zero head wind case. Figure 11 illustrates how increasing head wind affects the landing trajectory. Note that increasing head wind does not just linearly compress the trajectory in the x direction. Rather, the greatest distortion occurs at the points in the trajectory where the horizontal speed is lowest, i.e. at the top of the landing flare. Note also that head wind does *not* affect the time histories of the aircraft motion (apart from u), i.e. the α , θ , V, w histories are the same as those shown in figure 6 for the $t_{\delta\eta}=0.8s$ case. The horizontal velocity u time history is simply modified by a uniform decrement equal to the head wind speed.

Increasing headwind speed effectively offsets the horizontal landing velocity requirement. For example, if the head wind is 5m/s then the new landing requirement is $5 < u < 8m/s$. Since achieving sufficiently low horizontal velocities is the most challenging aspect of the post stall landing manoeuvre, it can be seen that landing in to a headwind is a distinct advantage in terms of reducing the severity of the manoeuvre required.

5 Discussion of guidance and control requirements for post stall landing

Section 4 outlined the inherent dynamic response of a conventional flight vehicle and showed that it was possible to generate a flight trajectory suitable for post stall landing using a simple elevator step input. This section considers the guidance and control requirements for implementation of a post stall landing system on a real flight vehicle.

A general schematic of the proposed guidance and control strategy is shown in figure 12. It is assumed that x, z location of vehicle and its velocity

components u , w relative to the landing platform will be determined using differential global position data, and that airspeed, angle of attack and attitude are obtained from airdata and inertial sensors on board the aircraft. Furthermore, the instantaneous wind speed at the landing platform is measured and transmitted to the vehicle. The control system will have two outputs: elevator angle and engine throttle setting. The addition of thrust control enables a small degree of manoeuvring capability in the post stall capture mode where elevator control effectiveness is very limited. Landing will be directly into wind and lateral control of the aircraft will not be considered.

The role of the guidance algorithm is, given the vehicle dynamic characteristics, current vehicle parameter values, e.g. wing loading, the wind speed at the target landing point and the relative position of the landing point, determine a suitable landing profile in terms of trajectory, position, speed, attitude and angle of attack. This can not be done explicitly; rather, a data base of possible profiles must be generated in advance (using a simulation model) and the most appropriate selected therefrom. With a perfect vehicle model, no external disturbances, e.g. wind gusts, and a fully effective control system, the guidance algorithm need calculate only a single landing profile which can be followed all the way. However, under normal conditions, the guidance algorithm will continually recalculate the most appropriate landing profile as the manoeuvre progresses. The algorithm will also have the authority to abort if conditions are reached where a landing is no longer possible, or unsafe.

The primary controlled variables are different for each of the three landing phases:

Approach: Speed V and height z

Extended flare: speed V and angle of attack α .

Post stall capture: attitude θ , horizontal velocity u , vertical velocity w .

Note that it is practical to control height directly during the approach phase. However, once into the flare manoeuvre, the system time constants associated with height (and horizontal position) are too long for practical control of these variables. Instead, position must be controlled indirectly via speed and angle of attack. Once into the post stall capture phase, and assuming the tailplane is in the slipstream of the power plant, the vehicle attitude may be controlled to some extent by elevator inputs. Furthermore, given sufficient thrust to weight ratio and short engine thrust/throttle time constant, some degree of control of u and w should be possible during the final descent phase.

A possibly useful addition to the control suite would be fast acting spoilers. These would give direct control over the vehicle drag, and provide a means for quickly dumping lift.

6 Conclusions

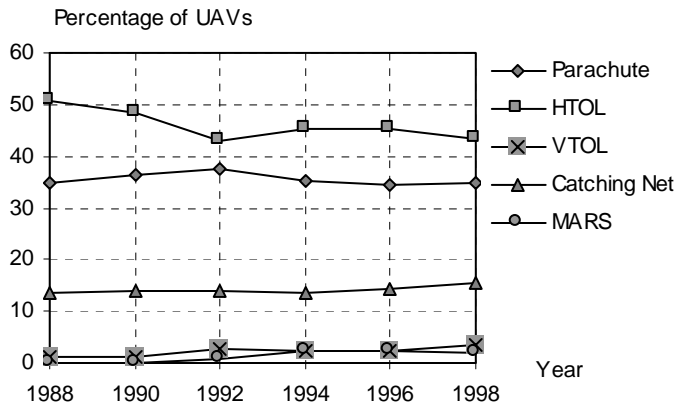
1. Post stall landing is a means by which a flight vehicle may be delivered to a point in space with nominally zero horizontal and vertical velocity
2. A numerical simulation of a conventional, unpowered flight vehicle has been developed to investigate the aerodynamic feasibility of post stall landing manoeuvres
3. Simple elevator step inputs were used to generate a range of extended flare manoeuvres suitable for post stall landing. Flight trajectories and time histories of α , θ , V , u and w were presented and discussed
4. The most challenging aspect of achieving a post stall landing is reducing the vehicle's horizontal speed whilst still maintaining control over vertical speed and attitude.
5. The presence of head wind is advantageous in that it reduces the severity of the extended flare manoeuvre required for post stall landing
6. The primary design parameter affecting the required vertical clearance between the landing platform and the ground is the vehicle wing loading. Post stall landing is ideally suited to aircraft with wing loadings below 100N/m^2 , which is lower than typical of most current UAVs.
7. A guidance and control scheme has been outlined for practical implementation of a post stall landing system
8. Guidance will be provided via a lookup table of pre-simulated landing profiles
9. Vehicle position can not be directly controlled in the flare and post stall capture flight modes since the associated control time constants are longer than the duration of the manoeuvre itself. Instead, position control will be affected indirectly via control of T , α and θ .

References

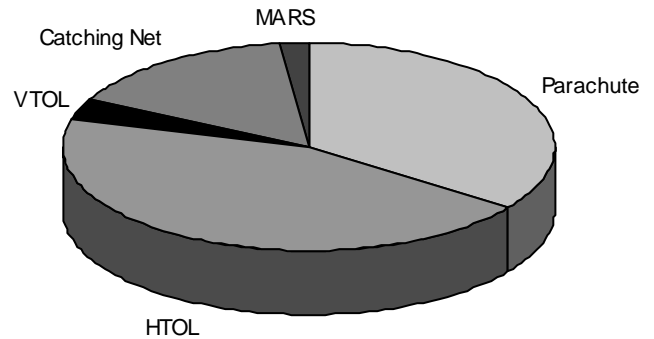
1. Harari, D, *UAV Current Technologies and Future Trends*, The 33rd Israel Annual Conference on Aviation and Astronautics, pp 83-88, 1993.
2. CBO Paper, *Options for enhancing the Department of Defence's Unmanned Aerial Vehicle Programs*, Congressional Budget Office, Washington, 1998.
3. Wahnnon Elias, Ruddell Steven, Rubinstein Aharon, "Automatic Recovery System for UAV's using Differential GPS". Proceedings of the 37th Israel Annual Conference on Aerospace Sciences, Feb 26-27, 1997.
4. George, F, "Autonomous Aircraft Landing Systems", *Journal of Business and Commercial Aviation*, Vol. 76, No.2, 1995, pp 46-48.
5. *Global Hawk*, Teledyne Ryan Aeronautical Update Sept. 1998, San Diego.
6. *Theseus, Theseus B* by Aurora Flight Sciences Corp., Manassas, VA, 1998.
7. Stoney, Robert B., "Design, Fabrication and Test of a Vertical Attitude Takeoff and Landing Unmanned Aerial Vehicle", MS Thesis, Naval Postgraduate School, Monterey, California, 1993.
8. *Scorpion*, *Scorpion 60-25* by Freewing Aerial Robotics Corp., Maryland, 1998.
9. Wyllie Tim, Downs Peter, "Precision Parafoil Recovery – Providing flexibility for Battlefield UAV Systems", AIAA Paper 97-1497, 1997.
10. Bauer, Jeffrey E. and Edward Teets, *An Impact Location Estimation Algorithm for Subsonic Uninhabited Aircraft*, NASA TM-97-206299, Nov. 1997.
11. *JANE's All The World's Aircraft*, Jane's Publishing Company Ltd., London, 1998.
12. *JANE's Unmanned Aerial Vehicles and Targets Updates 1,2,3*, Jane's Publishing Company Ltd., London, 1998.
13. Tennekes, Henk, "The Simple Science of Flight – From Insects to Jumbo Jets", MIT Press, Cambridge, MA, 1997.

Notes on figures 2-5

1. All results were obtained from references 11 and 12.
2. Many vehicles may be using more than just one retrieval method (described in the legend).
3. The "Percentage of UAVs" axis includes all the vehicles and aerial targets operating at a given year.

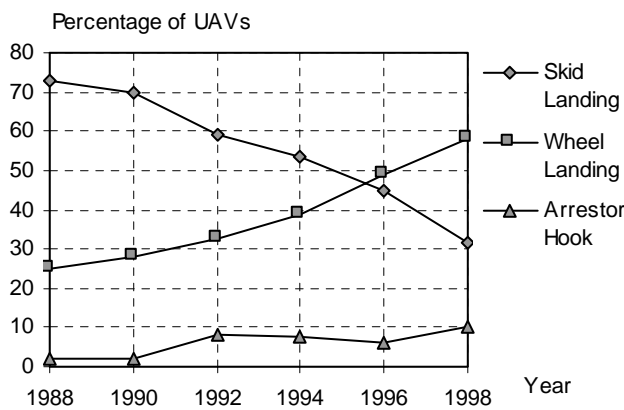


a) Development of UAV recovery methods in the last ten years.

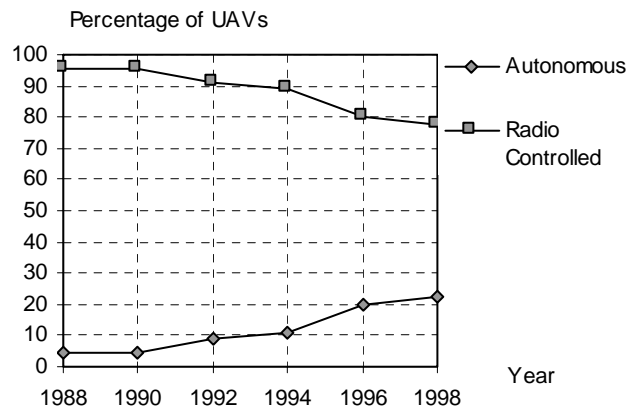


b) Current methods in UAV retrieval.

Figure 2 Development of UAV recovery methods



a) Development of HTOL UAV landing methods.



b) Development of HTOL autonomous methods.

Figure 3 Development of HTOL UAV landing methods in the last ten years.

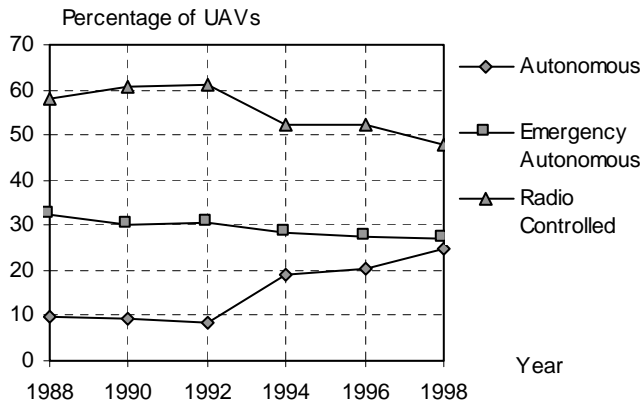


Figure 4 Development of UAV parachute landing methods in the last ten years.

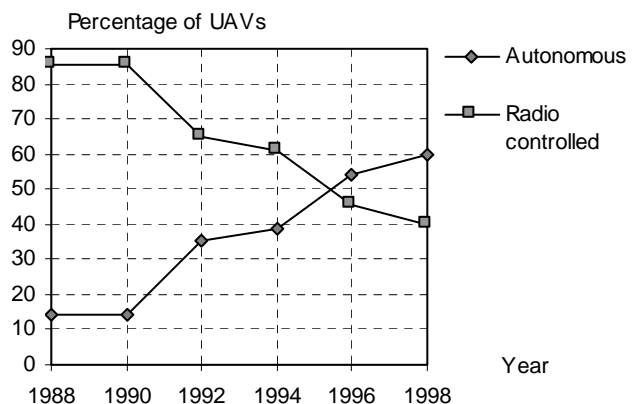
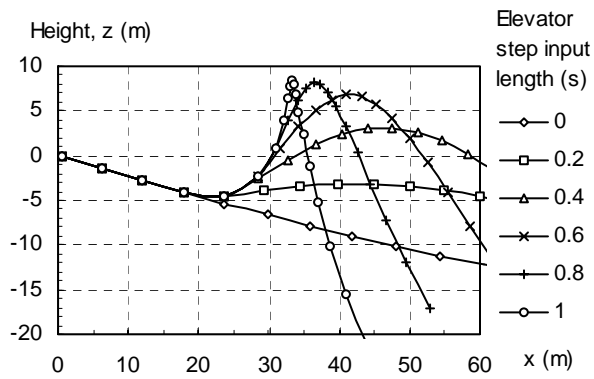
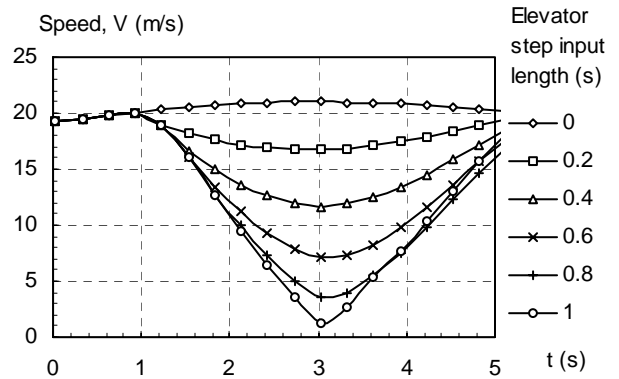


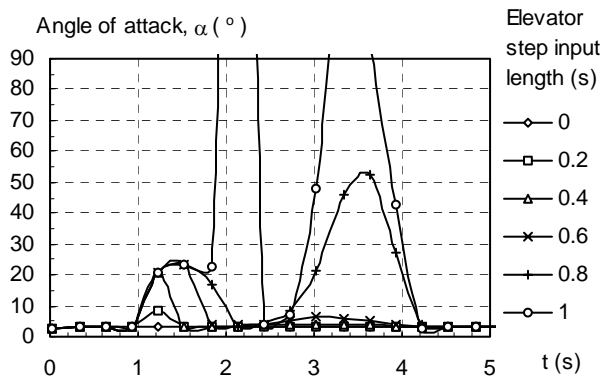
Figure 5 Development of UAV catching net landing methods in the last ten years.



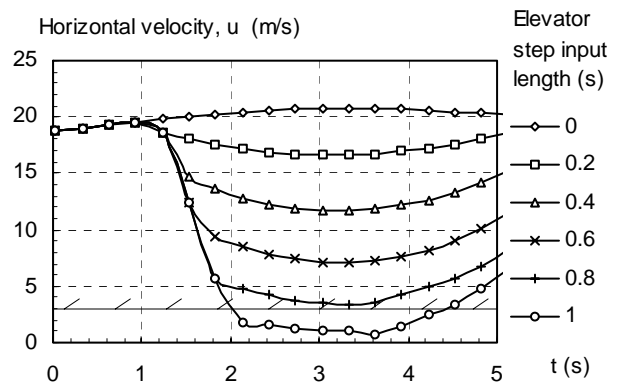
a) *x-z flare trajectories*



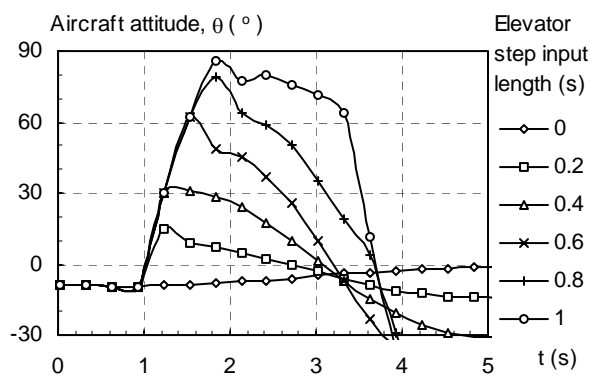
d) *Speed time history*



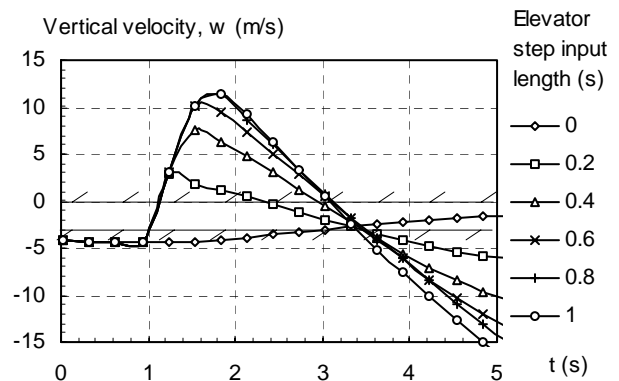
b) *Angle of attack time history*



e) *Horizontal velocity time history*



c) *Aircraft attitude time history*



f) *Vertical velocity time history*

Figure 6 *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.*

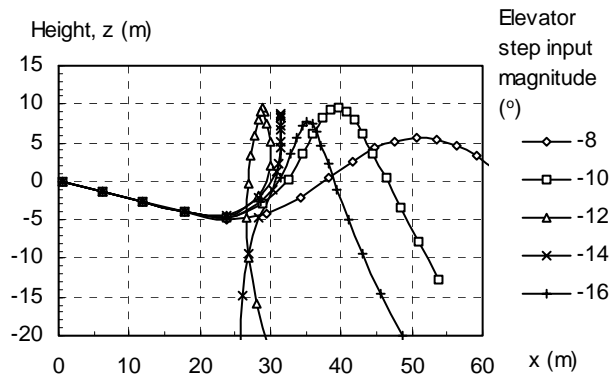


Figure 7 Post stall landing trajectories for increasing elevator step input magnitude. Step input length 1s. Wing loading 70kg/m^2 , mass 3kg

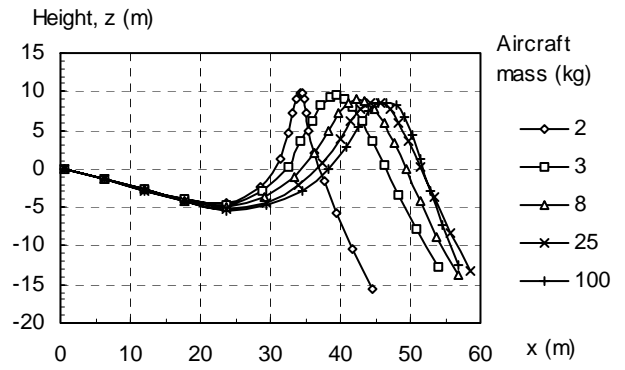


Figure 10 Post stall landing trajectories for increasing wing loading. Elevator step input length 1s, magnitude -10° , mass 3kg

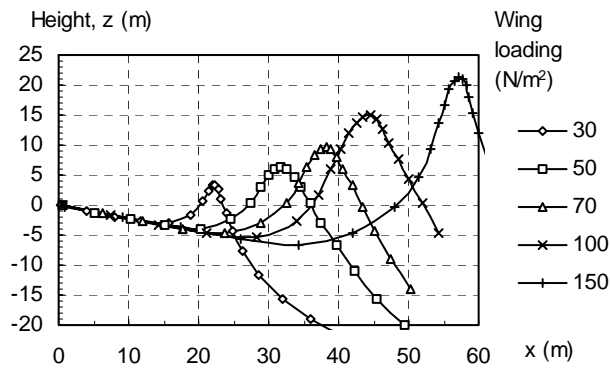


Figure 8 Post stall landing trajectories for increasing aircraft mass. Elevator Step input length 1s, magnitude -10° . Wing loading 70kg/m^2

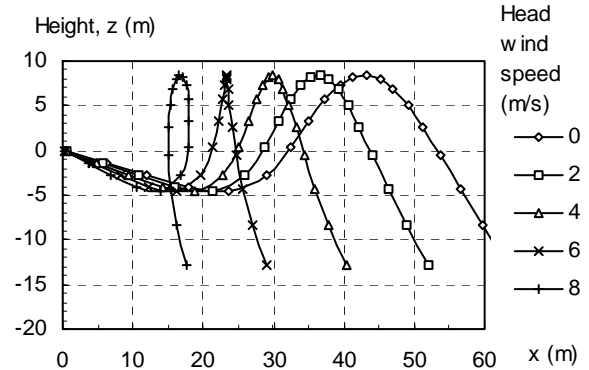


Figure 11 Post stall landing trajectories for increasing head wind. Elevator Step input length 0.8s, magnitude -10° . Wing loading 70kg/m^2 , mass 3kg (approach speed 20m/s)

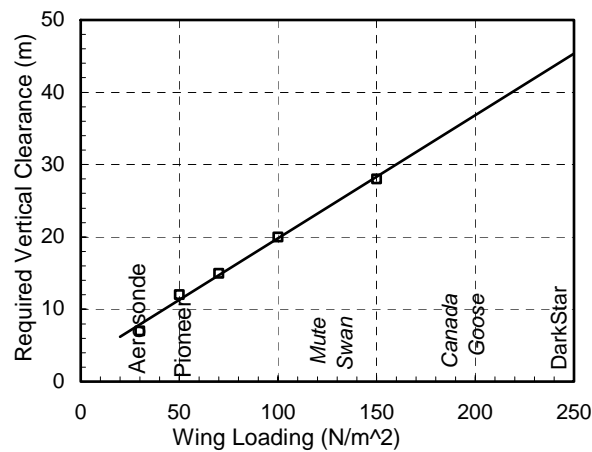


Figure 9 Required vertical clearance for post stall landing as a function of flight vehicle wing loading. (Based on data in figure 8 and Ref. 13)

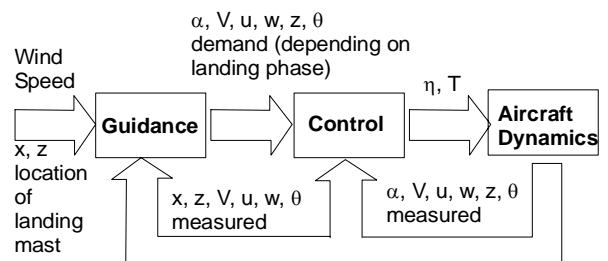


Figure 12 Guidance and Control schematic for Post Stall Landing