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Parachute recovery for UAV systems

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Contributed paper

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Abstract

Parachute recovery systems are described from a systems perspective. Parachute recovery is particularly suited to tactical fixed wing UAV systems that require a high degree of mobility by allowing air vehicle recovery onto unprepared terrain. The descent environment is described, and the impact of wind on recovery is considered. The relative merits of cruciform, round and parafoil canopies are assessed, taking three real-world systems as design examples. Throughout, design considerations are approached from a systems perspective, with a view to producing safe, autonomous and accurate recovery systems.

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Introduction

When considering recovery systems for fixed wing UAVs there are several options open to the designer. The final choice will be influenced by the role and mission requirements of the UAV system as a whole. A number of possible mandatory and desirable characteristics of any UAV recovery system are listed below:

- *Safety*. As with all UAV operations, safety of operation is a mandatory requirement during the recovery phase of flight.
- *Protection*. The recovery system must protect the air vehicle from damage on landing. Additionally, some sensitive on-board systems may have strict load limitations, and thus require a low-g landing.
- *Accuracy*. The recovery system must return the air vehicle to a pre-determined point with a high degree of accuracy, to minimise turn-around times and landing damage.
- *Automation*. A high degree of automation may be desirable, to reduce operator workload, or reduce the number of tasks requiring highly specialist skill in air vehicle operations.
- *Mobility*. The requirement for a system to recover within the area of responsibility of the tactical unit that it is supporting.
- *Reliability*. Any recovery system must be highly reliable and predictable in its operation – without this, unsafe operation and air vehicle loss will result.
- *Repeatability*. The recovery procedure is an operation that will be undertaken many times in the life of an air vehicle. It must therefore be undertaken in a way that is repeatable.

It may be seen that within these requirements there is some degree of conflict. For example, a wheeled recovery system will offer an accurate recovery and a high degree of protection to the air vehicle, with low loading on landing, but at the expense of system mobility, as it relies on a minimum level of strip preparation on which to land. A

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parachute recovery system on the other hand will allow mobility, with its ability to land on unprepared ground, but it will be subject to inaccuracies due to wind, and will largely dictate the structural design of the airframe due to the higher landing loads that result. This being the case, parachute recovery tends to be favoured by smaller systems as tactical mobility is more important for these systems and there is a smaller structural efficiency price to be paid for rugged design than with larger, longer endurance and more efficient air vehicles. This is borne out by Figure 1, where UAV systems are classified by recovery system, and endurance (as a first-level indicator of aerodynamic efficiency) is plotted against air vehicle mass.

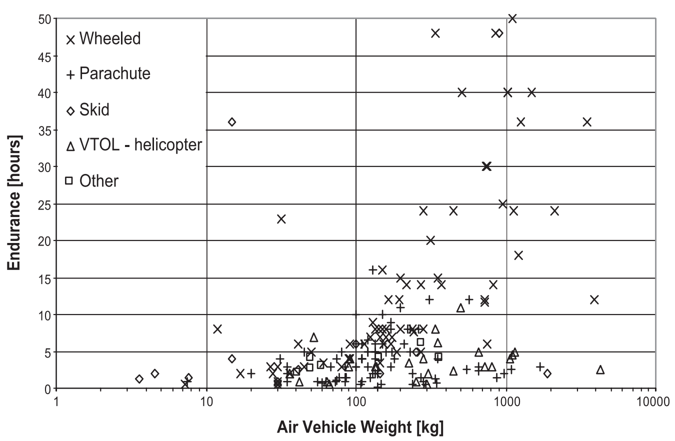
This paper seeks to present a review of parachute systems technology as applied to UAV recovery systems, exploring some of the basic design considerations and illustrating these with some real-world system examples.

Design drivers for parachute recovery

When considering a UAV parachute recovery system, the major design considerations are as follows:

- *System mass*. Air vehicle fly-away mass is of critical importance, especially with smaller UAVs. The mass fraction of the installed parachute system may be of the order of 5-10 per cent of air vehicle launch mass, although this proportion decreases as the vehicle gets larger.
- *Available pack volume and position*. In addition to system mass, there may be restrictions on the volume available for the packed recovery system. Parachute system volume requirements and the deployment path of the pack must be considered from the start in air vehicle design, or deployment problems may result.
- *Maximum system loading*. System deceleration loads on impact are likely to be specified by avionics component limits. With the primary goal of the recovery system being to return the air vehicle to the ground in such a manner as to minimise system damage and turn-around, this is maybe the biggest single constraint governing recovery system performance.
- *Accuracy*. It is important to be able to recover the air vehicle to a chosen position on the ground with a reasonable degree of confidence. For non-gliding parachutes, there is no direct control available to steer the system after parachute deployment, and so the final ground impact position is largely dependent on system dynamics and local wind conditions. As parachute deployment height above ground increases, the effect of wind will become increasingly dominant. It thus makes good sense to include some form of wind estimation in the air vehicle, and this is mentioned in more detail later.
- *Ground impact aspect/stability*. Although it may not be possible to control the air vehicle and parachute system after deployment, different parachute types have differing oscillation characteristics. For landing a UAV, it is desirable to have as great a chance as possible of impacting the ground with the air vehicle flat, rather than (for example) wing on, during a pendulous swing of the system. Air vehicle design and impact attenuator design must take into account the possibility of ground impact heading in any direction.

Figure 1 Air vehicle recovery system choice



Having considered some of the design drivers from the system perspective, it is also important to understand the environment that the recovery system will be functioning in, and how this affects system performance.

The descent environment

A parachute and air vehicle system descending through the lower atmosphere will

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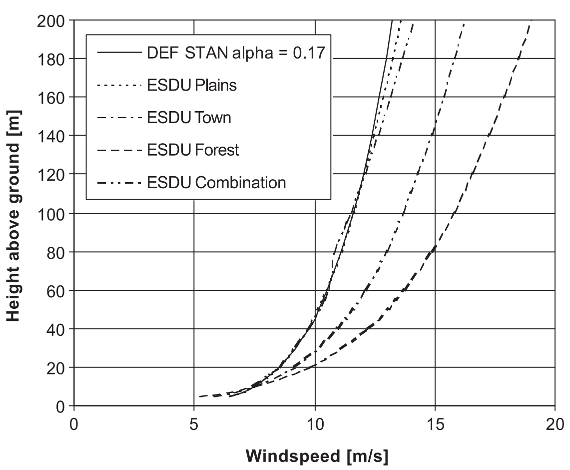
be subject to winds. The presence of wind significantly complicates the process of air vehicle recovery in that as well as determining the position of impact with the ground, wind will also give the air vehicle a horizontal component of velocity relative to the ground on impact. With a typical descent rate for a UAV parachute recovery system of 5m/s, it is likely that the horizontal component of velocity on impact will actually be greater than the vertical component. This fact has considerable implications for impact shock attenuator design, as described later.

Although average wind speeds, directions and long term trends are fairly predictable, it is more difficult to predict the sort of short term wind characteristics that will have significant effect on a parachute descent from say 100 or 150m above ground level. On this scale, local terrain will exert significant influence, and short-term fluctuations or gusting will be particularly important.

In the first 600m or so of the atmosphere above the Earth, surface friction is the dominant effect on windspeed. Mean windspeed generally increases with height in this region, without being significantly modified by other factors such as jet streams. There are several methods for determining the windspeed at a given height having prior knowledge of windspeed at a single point, such as those given in DEF-STAN 00-35 (part 4) Chapter 5, and ESDU 82026. These are compared in Figure 2, for a 7.5m/s steady wind measured at 10m above ground level. Values are given for an equilibrium atmosphere, i.e. one that has not been subject to a change in surface roughness for at least 100km. The "combination" profile plotted is for a non-equilibrium atmosphere, at a point within a 100m diameter clearing in a forest that extends for 5km, the surrounding area being plains. The DEF-STAN uses a straightforward power law to translate the windspeed at 10m above ground, V_{10} to windspeed V_H at any other height H as follows.

The factor α takes account of terrain, varying from about 0.1 to 0.4, with a general value of 0.17 often adopted, corresponding to undulating country with few trees or other obstructions. The ESDU wind engineering series takes a slightly more detailed approach, allowing for terrain changes upwind, i.e. changes in local surface friction, which result in a non-equilibrium atmosphere at the point of interest. There is good general agreement between the two methods (assuming that the factor alpha is varied accordingly), and for most scenarios, the formula given above is entirely adequate. For the purposes of parachute recovery, the DEF-STAN guidelines will be considered sufficient, although consideration should be taken of the applicability of the factor α. A guide for applicability of α is given in Table I.

Figure 2 Comparison of wind velocity profiles



Recovery system elements

The parachute canopy is only one element of the recovery system; to improve recovery performance, the following should be considered together in the system design process:

- wind estimation;
- parachute system;
- impact attenuation;
- parachute discard system.

These elements are now covered in more detail.

Wind estimation

Estimation of the local wind conditions is essential in producing an accurate and

Table I Guide to applicability of factor α with 15kts wind, measured at 10m a.g.l.

Type of terrain	Value of α
Summer farmland with few trees	0.19
Suburbs, small towns	0.26
Forests	0.32

autonomous parachute recovery system. Although the descent environment is subject to unpredictable gusting, it is important to determine the prevailing trend in windspeed and direction. For a system deploying a parachute at 150m, with a descent rate of 5m/s, a wind estimation error of 2m/s will result in a position difference of approximately 50m on the ground. It is important that any wind estimate is made available to the navigation system and used in calculating the optimum position for parachute deployment.

Wind may be estimated onboard the air vehicle in a variety of ways. In simple terms, the windspeed vector may be determined by subtracting airspeed from air vehicle groundspeed. Assuming co-ordinated flight, this may be determined using air vehicle airspeed, heading and GPS-derived ground track information. This information is often averaged to obtain a more representative estimate of steady windspeed and direction. To be completely rigorous, it is necessary to transform the two velocity measurements so that they are in the same axis system. More advanced estimation and filtering methods are often used as part of an integrated navigation system, with Kalman filter methods in particular having been used to great effect.

The final positional accuracy of a drag-only parachute system will be dependent on descent environment variation from the estimated state, variation from one deployment to the next, and the navigational accuracy of the system. As the air vehicle/canopy system may not be controlled after canopy deployment has started, positional accuracy may be improved by good quality estimation of the local descent environment. This allows calculation of the required parachute deployment position with some confidence, which must then be followed by accurate navigation to that deployment position, and by ensuring that the parachute deployment process is reliable and repeatable.

Parachute technologies

The basis of parachute operation is to deploy a high-drag device into the free airstream, thus producing a retarding force to gravitational acceleration. When this force and acceleration due to gravity balance, the system is in steady state descent. The drag force is defined conventionally:

$$D = \frac{1}{2}\rho V^2 S C_D$$

(Equal to mg in steady state descent.)

With S representing parachute canopy area, and C_D the canopy drag coefficient.

Three classes of parachute canopy design are considered; cruciform, or cross-type canopies, "round" canopies, and parafoils. The first two types represent the most used canopy types for UAV recovery, and are drag-only devices and uncontrollable in descent, in contrast to the parafoil, which produces lift and is controllable. The basic characteristics of each canopy type will be noted here, before considering some of the system implementation issues in more detail later as we look at recovery system case studies. Performance comparison will be made based on three parameters, as given in Knacke (1992):

(1) C_D the drag coefficient;
(2) C_X the opening force coefficient;
(3) ϕ the mean angle of oscillation.

Figure 3 shows primary parachute system elements, arranged as for a controlled, or "lines-first" deployment. In such a deployment process, the pilot chute pulls the canopy (still in its sleeve or bag) out of the stowage compartment in the air vehicle and ensures that the lines and riser are also deployed before the canopy is extracted from its bag. This helps to control parachute inflation.

Cruciform canopies

Cruciform canopies (see Figure 4) were developed first at the US Naval Ordnance Laboratory in the late 1940s. They are of simple construction, consisting of two strips of cloth overlaid, and sewn together. The arm length ratio (L/W) and canopy fabric porosity are important in determining the stability

Figure 3 Parachute system components

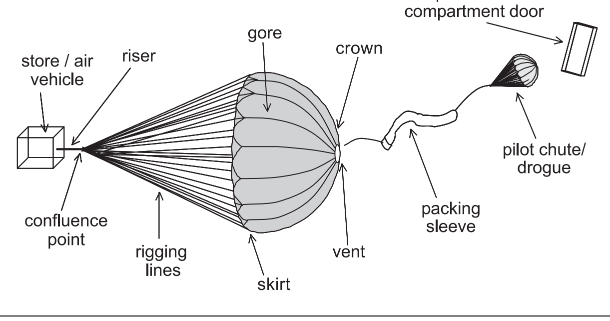
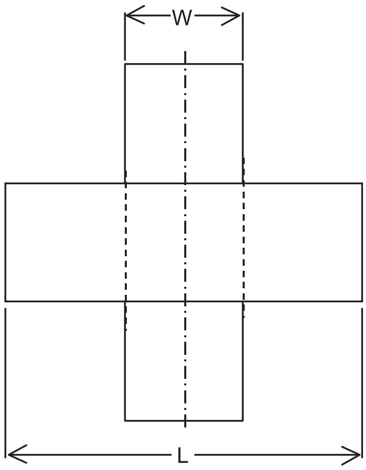


Figure 4 Cruciform canopy configuration



characteristics of the resulting canopy. Increasing the canopy arm ratio or the fabric porosity will produce an increase in canopy static and dynamic stability (Shen and Cockrell, 1988). These effects are related as increasing the arm length ratio effectively increases the amount of "gap" in the inflated canopy, and thus its overall porosity. This is sometimes referred to as geometric porosity to distinguish it from fabric porosity.

Inspection of Table II shows that cruciform canopies have lower drag and opening force coefficients than round canopies, and tend to oscillate less. The low oscillation is the major reason that they are the most popular type of canopy for UAV recovery. This will reduce the chance of air vehicle damage on ground impact, as less oscillation will mean that the air vehicle is approaching the ground more levelly. Although a low opening force coefficient will mean that canopy inflation is relatively gentle, it will also increase the variation and height loss possible in this phase, and thus the uncertainty in final positional accuracy. Cruciform canopies do have a tendency to rotate, although this rarely causes problems in practice.

Round canopies

For the recovery of subsonic UAVs, we will limit our discussion to solid fabric canopies, as slotted, ribbon type canopies are primarily designed for supersonic use. The traditional flat and hemispherical round canopies are now obsolete, and have been replaced by conical and polyconical designs that offer improved drag characteristics. These canopies have high-drag and opening force coefficients when compared to cruciform types, and thus will provide less variability on opening, and require less surface area to achieve a given rate of descent for a set store. They are more likely to oscillate, however, although removing one or more panels around the skirt to provide a "drive-slot" may reduce this tendency. As with cruciform canopies, they are easy to pack, manufacture and maintain.

Table II Parachute canopy performance comparison

Canopy type	C_{Do}	C_x	ϕ
Cruciform	0.6 - 0.85	~1.2	0° - ±3°
Conical	0.75 - 0.9	~1.8	±10° - ±20°

Parafoil canopies

Parafoil canopies are considered here as the most common type of gliding canopy currently in use. They were initially developed from a kite design at the University of Notre Dame in 1964, and been used increasingly since then, especially as sports canopies. They are essentially twin-skin, ram air inflated devices that form an aerofoil section when inflated, and may be controlled by deforming the trailing edge symmetrically or asymmetrically, using pull-down "brake lines". Application of symmetric control can produce a dynamic flare manoeuvre, significantly decreasing canopy forward speed and sink rate for a limited time. Asymmetric control input results in turn rates that may be of the order of 60°/s or more. Turning flight is drag and yaw dominated, with the rolling moment resulting from canopy sideslip. Glide ratios in excess of 3:1 are common, with this value being influenced by canopy aspect ratio and wing loading. Further details of parafoil dynamics and performance may be found in Lingard (1981).

As a parafoil must remain inflated to operate as intended, it will be manufactured from low or zero-porosity fabric. Because of this, they will tend to experience higher opening shock loads than many other canopy types. In order to reduce these loads, and control canopy cell inflation, some form of reefing is often used, especially for larger canopies. Reefing systems may be as straightforward as a slider that retards canopy opening through aerodynamic force, or much more complex, using multi-stage pyrotechnic cutters to control inflation. Deployment is further complicated by the need to protect the control-line servos from the opening loads that the canopy experiences. However this is

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done, there is likely to be significant time and height loss in deployment before a system becomes controllable.

Ground impact attenuation

With air vehicle avionic components and sensors often limited to impact loadings of the order of 10-20g, it is vital that a parachute recovery system includes some form of impact attenuation to cushion the air vehicle as it hits the ground. The basic laws of dynamics govern the operation of impact attenuators, with kinetic energy being absorbed over a set stroke length. The required stroke length s to limit ground impact to ng is readily deduced, and is given by Knacke (1992) as:

$$s = \frac{V^2}{2g(n\eta - 1)}$$

where:

V = rate of descent of system (m/s)
g = acceleration due to gravity (m/s^2)
n = allowable impact deceleration (multiples of g)
η = impact attenuator efficiency

Two types of impact attenuator are commonly used on UAV systems, crushable devices and airbags. Crushable impact attenuators are often made from foam, or paper and/or aluminium honeycomb. They are best used in applications that require cushioning primarily in the vertical plane, as they are less effective in the horizontal plane and can often be "wiped off" air vehicle attachment points by a horizontal velocity component on impact. Impact attenuator depth will need to be greater than the required stroke length, due to the residual thickness of the absorbing material once it is crushed. Paper honeycomb bottoms out at approximately 30 per cent of its original height, while plastic foams may bottom out at around 50 per cent.

Airbags have a major advantage over crushable shock absorbers in being deployable. They thus incur no additional drag penalty on the air vehicle throughout its mission. Airbag impact attenuators are typically inflated with fan-blown air or stored gas systems, depending on required inflation pressure, mass constraints etc. Careful design can both confer stability to the air vehicle on impact and ensure that the airframe is protected in impacts with high horizontal velocity components. They have a typical efficiency of 0.65.

Parachute discard mechanism

It is vital that once an air vehicle has landed under a parachute that it is able to discard the canopy to prevent dragging and damage to the airframe in high winds. Parachute discard mechanisms may be either passive or active, and are placed inline somewhere between the canopy and its attachment point on the air vehicle. Passive devices are often armed mechanically by the loading of the parachute canopy as it inflates, and then discard when this load relaxes as the air vehicle lands. Unfortunately, this type of mechanism sometimes fails to operate in high wind conditions, as the loading on the canopy does not reduce sufficiently, and the air vehicle is dragged in the very situation that the discard mechanism should be protecting against. Active systems may use a servo, solenoid or other actuator to effect the parachute discard. They must first sense the appropriate moment to discard, often achieved by a ground impact detector, accelerometers, or a pressure switch in an airbag. Care must be taken to ensure that the discard mechanism is fail-safe, and that the sensing system allied to it is sufficiently reliable in its operation. Several systems have had problems with this in the past, and it is often in the off-design cases that failure occurs and damage ensues.

Recovery system implementation

The following sections briefly describe some of the implementation issues with parachute recovery systems, taking real systems as examples.

Cruciform use – Phoenix

The Phoenix UAV system now in service with the British army uses a cruciform canopy and airbag to recover the air vehicle. As may be seen from Plate 1, Phoenix has a large pod slung underneath the air vehicle, containing a cooled thermal imaging sensor and fore and aft antennas for the directional datalink. This pod is stabilised in roll, and must be protected from impact damage due to the expensive equipment contained within.

The parachute is installed within a module in the tail-cone of the air vehicle, streaming underneath the horizontal tailplane. To protect the pod on landing, the air vehicle inverts during the recovery process, so that it lands "on its back". The air vehicle initially

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Plate 1 Phoenix air vehicle in flight

stabilises in a nose-down attitude under the canopy. A latch then releases the parachute attachment strops from a holding position, and the air vehicle turns over. In order to give sufficient time for the turnover process, it is necessary to deploy the parachute from a greater height than would otherwise be necessary. Positional accuracy on recovery is maintained by employing a Kalman filter based wind estimator, compensating for the longer descent time.

While the air vehicle is descending in a nose-down attitude under the canopy, the airbag inflation begins. A hatch opens on the upper surface of the air vehicle, hinged so that it opens forward and latches, forming a solid base over the nose of the air vehicle. The airbag is contained within the compartment exposed by the hatch, and makes use of the hatch to increase its attachment footprint on the air vehicle. The airbag is fan-inflated, with a control system ensuring that pressure is maintained within the bag until ground impact. On impact, bag deflation and thus landing loads are controlled as patches are blown-out of the bag. Frangible tail fins help to absorb impact energy; otherwise, the complete recovery system is re-usable and modularised for ease of replacement.

"Round" canopy use – Observer

The Observer UAV system demonstrator has been developed by the DERA Farnborough and Cranfield Aerospace UAV systems team (Dyer *et al.*, 2000; Wyllie, 2000). One of the primary drivers of the system design has been to reduce the level of operator skill and training necessary to use the system effectively. As part of this, work has been undertaken to automate the parachute recovery process. The general approach taken with recovery has been to deploy a fast-opening round canopy at relatively low level, thus minimising wind effects on system accuracy. Impact attenuation is with a fan inflated airbag system.

A 4.25m diameter aeroconical canopy is installed in the starboard wing root of the delta winged air vehicle. This canopy is modified from escape systems use and offers good repeatability in its opening characteristics. A drive slot has been added to improve stability. The canopy is packed in a sleeve, which folds into the parachute bay. It is extracted using a drogue chute with an internal spring, which ejects the canopy bay door, before pulling the canopy sleeve out.

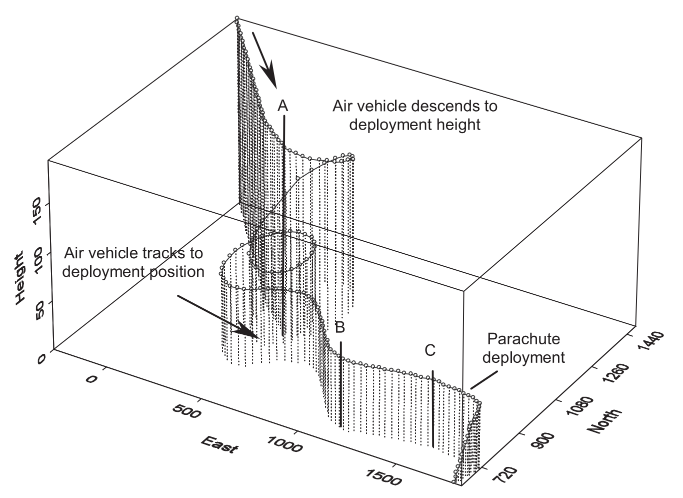
Parachute deployments have been made from 200m initially, decreasing height steadily to 65m, as confidence in canopy performance grew. Steady state rate of descent is highly repeatable from one deployment to another, at approximately 4.5m/s. Plate 2 shows the system descending under parachute with the airbag inflated, prior to ground impact.

Successful navigation to the deployment position has been proved, with a new flight control mode having been developed that takes in a number of recovery waypoints and a desired recovery height. On reaching the initial waypoint (A in Figure 5), the air vehicle descends until it attains the commanded height and speed. It then tracks through the remaining waypoints, descending further if required, before deploying the parachute canopy at a point calculated onboard to return the air vehicle to the desired recovery position on the ground.

A semi-empirical model of system dynamics from engine cut was constructed, allowing the physical processes involved in recovery to be matched with observed flight test data. This model includes wind gradient effects, and has formed the basis of the automatic deployment point calculation. The model is tested against

Plate 2 Observer air vehicle recovery system

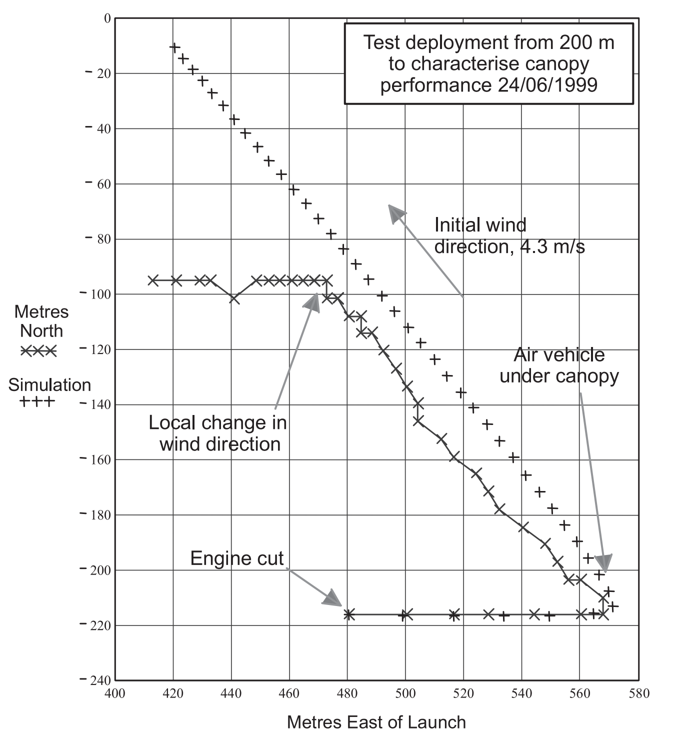
Figure 5 Typical Observer recovery trajectory



real data, with input conditions set up to correspond to those on the day. Figure 6 shows such a test, from the first system deployment. This illustrates the accuracy problems that may result in prolonged descents, with the system drifting significantly in a change of wind direction to that initially measured.

Initial results of the automatic parachute deployment point calculation have been promising, returning the air vehicle to within 15m of the desired landing position on the ground.

Figure 6 Comparison of descent dynamics model with real data



The place for parafoils in UAV recovery

Few UAVs worldwide use a parafoil recovery system. The Skyeye and Eyeview air vehicles have both had parafoil options, but other than this, they have not seen widespread use. In an effort to understand the issues involved with autonomous parafoil recovery, DERA Farnborough ran an experimental programme in 1996/1997 (Wyllie, 1997). Working with Meggitt Defence Systems, the 80kg Banshee aerial target air vehicle was used as a platform, with uprated avionics installed, and mated to an off-the-shelf $13.7m^2$ parafoil (see Plate 3). The resulting experimental programme lasted for 15 months, and involved 30 test flights. Flights were initially conducted with a ground pilot in the loop, to provide control demands to the canopy when deployed, before moving to an automated system.

The Banshee was chosen as a platform as it represented a rugged, well characterised air vehicle, with sufficient volume and power available to cope with the addition of the parafoil canopy. There were disadvantages in using an existing airframe, however, and integration of the canopy with the air vehicle was not straightforward. The chosen canopy was installed along with a box containing winch servos to control the canopy trailing edge brakes within the existing Banshee parachute compartment. In order to make the attachment of the canopy to the air vehicle as stiff as possible, to ensure that the air vehicle and canopy tracked together, it was necessary to spread the canopy attachment points as widely as possible. A four-point attachment was used, with two in the canopy bay, and two near the wing trailing edge.

Plate 3 Banshee air vehicle under parafoil canopy

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Unfortunately, it was deemed that these points would not be strong enough to take the higher deployment loads of the parafoil canopy, and so an intermediate strong point had to be found to protect the airframe from excessive loading as the canopy inflated. A suitable position was found just in front of the vertical fin, and a solenoid release was placed there, allowing the canopy to inflate while held at this single strong point. After some initial difficulties with deployment and canopy rigging, this arrangement was found to work quite well.

During deployment, there was some tendency for the canopy sleeve to twist as it passed the vertical fin. This resulted in risers being twisted, and the canopy sometimes being significantly misaligned with the air vehicle on initial inflation. Allowing time for twists like this to untwist means allowing height, and as sensible control is not possible in this condition, the system may be some distance from the intended point when control becomes possible. Thus a staged deployment process causes problems for the system later. Even with no twisting in the extraction process, it would take 15.5 seconds and roughly 80 metres height loss from cutting the engine to achieving controllable flight.

Because of the variation possible in the deployment process, it was important to try to optimise the deployment point, to minimise the work that the system had to do to get back on track to its desired touchdown position. Less variation tended to be seen in downwind deployments.

The flare manoeuvre was shown to be successful, with achievable touchdown airspeed and sink rates of 5 and 1.5m/s respectively, compared with 15 and 3.5m/s in normal flight. For this manoeuvre to be truly effective, an absolute height sensor such as an acoustic, laser, or radar altimeter must initiate it. Furthermore, account should be taken of the significant lag times associated with winch servos commonly used for such tasks.

The conclusion from this work was that parafoil canopies are not, in the main, particularly suited to small UAV systems. They add complexity and mass with more rigging lines, and canopy control actuators, as well as complicating the deployment process. One of the greatest challenges to be overcome is to package the canopy system in such a way that clean deployment is ensured, and canopy packing is made easier. Packing the canopy for the Banshee test programme took time, and required high levels of skill to ensure that the lines and risers were arranged correctly.

Parafoil recovery systems should not be dismissed easily for all applications though. NASA has recently undertaken drop testing of its international space station emergency crew return vehicle, the X-38 (Machin *et al.*, 1999). This air vehicle is a lifting-body configuration, designed to allow a high degree of flexibility in landing site having made a rapid departure from the space station. Its landing speed would be of the order of 250 knots, demanding significant skill to land manually, or a highly complex automatic system. This problem has been reduced by opting for a parafoil recovery system, which significantly reduces the approach speed, and thus simplifies the automation of landing. There are also benefits in terms of air vehicle all-up mass, due to the reduced loading requirement on the undercarriage. Canopy deployment is a carefully staged process, and takes place at around 15,000 feet. This allows sufficient time for the system to regain control, and steer itself towards its desired landing point, with a laser altimeter initiating the flare manoeuvre just before touchdown.

Conclusions

Parachute recovery is particularly suited to tactical UAVs that require a high degree of system mobility. System components and parachute technologies have been described, and implementation issues discussed. Drag-only canopy types, such as cruciform and aeroconical designs are favoured over parafoil canopies as they are less complex. As these types are uncontrollable in descent, it is important to integrate their operation with good wind estimation and accurate navigation techniques, to accurately calculate and achieve the optimal deployment position. Deploying the parachute canopy at low level minimises the unpredictable disturbance caused by atmospheric gusting. With integrated system design, it is possible to produce a fully automated system that returns the air vehicle to ground safely, accurately and without damage.

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