How to Select and Qualify a Parachute Recovery System for *<u>Your</u>* UAV

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ABSTRACT

This paper presents substantial and detailed information regarding the common issues affecting the design, testing and qualification of a parachute recovery system for all categories of UAVs (reconnaissance, air target, weapon, etc). [1] We assume that our primary audience will be UAV manufacturers and operators. Therefore, in order to familiarize the reader with the basic process of designing and qualifying a recovery system for a UAV, we have provided a simple but detailed exercise in recovery system design and, a review of the program management thereof.

Introduction

The authors assume that you and the customer have already performed a rudimentary cost/benefit analysis and have decided that your UAV must have a parachute recovery system for one or more of the usual reasons. We will discuss the factors affecting the recovery system with the ultimate goal of helping you to become a "smart buyer" able to make informed and intelligent decisions throughout the design and qualification process of the recovery system for *<u>your</u>* UAV.

[1] In this document "we" refers to the authors and/or Butler Unmanned Parachute Systems, LLC (**BUPS**); "you" refers to the reader, presumed to be in the role of the program manager or engineering staff of the UAV manufacturer whom we shall call Generic UAV Associates (**GENUAVASS**) when we need to have a name to put in the story; "customer" means the ultimate user of the UAV, whom we shall call the Big Secret Agency (**BSA**) when we need to have a name to put in the story; "recovery system" will encompass parachute recovery system and all the associated components thereto; and the term "UAV" will apply to any type of UAV or target.

Background

Since 1976 the Butler Parachute Systems Group, Inc.[2], its predecessor and its various subsidiaries have designed and manufactured a wide range of parachutes and recovery systems. In 1979, we received our first FAA Technical Standard Order Authorization (TSO) for the harness and container components used for a personnel emergency (bailout) backpack parachute; in 1991, we received a TSO[3] on a round canopy designed for use in our emergency parachute systems; in 1992, we began making spin and deep stall recovery systems for flight test aircraft starting with a system for the Swearingen SJ-30; and in 1994, we began making UAV parachute recovery systems beginning with a recovery system designed and built for the Predator SBIR first article (see details in the reference section).

We have worked with over a dozen companies in the past 13 years and have developed parachute recovery systems for UAVs for weights from less than 50 pounds to over 6,000 pounds and recovery speeds from under 30 knots to nearly 500 knots.

[2] In 2002, Butler Parachutes Systems, Inc. was restructured as Butler Parachute Systems Group, Inc. with subsidiaries divided by product area. Of specific interest here is the subsidiary Butler Unmanned Parachute Systems, LLC (BUPS).

[3] The process of designing, testing and qualifying a personnel parachute canopy with our own funds, made us intensely aware of the vagaries of parachute testing. These problems inspired a search for a way to eliminate the root cause of these failures and eventually lead to the invention of the BAT Sombrero Slider (patents worldwide). In the references you can find links to substantial information on this device – but here, suffice it to say that the BAT Sombrero Slider increases the reliability of conventional parachutes by several orders of magnitude.

We have learned something from each of these programs both in technical experience but particularly in the program management arena.

Therefore, we feel well-qualified to present this information; particularly in hope that it will allow someone out there to avoid some of the pitfalls we have encountered. [4]

Program Management

Everyone in the aviation industry knows that some components of any aircraft are more or less "standard". So, as the program manager, you might occasionally discover that you can buy something like an alternator "off the shelf" and just bolt it on and go. However, a parachute recovery system is very seldom in that category. Therefore, as the program manager, you must approach the process for the design, testing and qualification of a recovery system for a UAV as similar to that for any other complex aircraft sub-system; i.e., one must continuously consider the "6-pack" of form, fit, function, performance, schedule, and, as always, cost. Although this is a tongue-in-cheek reference to a 6-pack – this particular 6-pack can definitely cause headaches and a hangover if not managed appropriately; and it will certainly help to spread the workload around to those most qualified for each part of the project.

The Organization of GENUAVASS

The team leaders at ***GENUAVASS*** (presumed herein to be the engineering and program managers) must set the precedence of each factor in the 6-pack at the earliest possible point in the program. They will also assign work areas to, and determine the interaction of, the team members working under their supervision. The team leaders at ***BUPS*** will do the same.

And, of course, by setting *realistic* parameters for all of these factors you should be able to avoid the common penalties such as unnecessary weight, volume, and cost and/or schedule impact to the program.

Nearly any size organization can work well with the process outlined in this paper so of course we must start with a kickoff "Team Meeting" with all of the players present, whereupon everyone involved must acknowledge that:

- the goal of the team is to complete the recovery system on time, within budget and within the desired performance parameters;
- the team consists of you (the buyer, ***GENUAVASS***) and us (the seller, ***BUPS***) - and the customer (***BSA***), and all the employees thereof, working in a cooperative environment;
- no one can make any unilateral changes;
- form, fit, function and performance are inextricably linked with each other;
- schedule and cost are inextricably linked with each other;
- these two subgroups are also inextricably linked but in a somewhat different manner;
- all of these factors can be manipulated to some extent but only with the knowledge and concurrence of all the players;
- any changes in any of the factors will ripple through the process and must be approached with care.

Please note that even though we insist upon a "kickoff" meeting, as well as a "graduation" meeting when we're finished, we do strongly feel that meetings in general must be minimized or avoided if at all possible.

In fact, given that everyone on the team can be in more-or-less constant communication, by email, some sort of protocol (other than CC to the universe) should actually be established for email communications amongst the team members. The team members should decide who needs to see what – the point is not to hide anything, it is to avoid adding to the "junk" mail.

Remember that if a particular team member sees ten useless messages for every relevant one, they will soon begin to ignore all of them.

Cost & Schedule

This subject could take weeks all by itself but just briefly, keep in mind *the most important aspect* of achieving the program goal of finishing on time and within budget is:

Set Realistic Parameters in the Beginning!

For example, if you set total system weight as the primary factor within the performance parameters (while still holding firm on the rate of descent), you may inadvertently require the use of exotic materials; e.g., carbon fiber vs. ABS; or some sort of fancy Mylar film instead of Nylon parachute cloth, etc. You can break the bank (and the schedule) to reduce the weight of the recovery system by perhaps 10-15%. That could be a very expensive diet just to save one or two pounds that will more than likely be easier to save elsewhere.

And, of course,

Cost is Inversely Proportional to Time!

In this sense, the development of a recovery system for your UAV is no different than any other part of the UAV program. And the farther ahead of the due date you give the necessary information to your recovery system builder, the less the overall cost of that part of the project.

One particularly important issue for all parties to keep in mind is that the team must avoid the tendency to "gold plate" the program via "requirement creep" once the contract is signed and underway.

[4] At this point, it is only fair to note that there are other companies that manufacture parachute recovery systems for UAVs; the most prominent are Irvin Aerospace and Pioneer Parachute Company.

The Design Process

A few of the common design issues include: routine or emergency use; gross weight range (specifically anticipated weight growth); flight envelope; opening load limits; required rate-of-descent; stowage shape and volume; deployment initiation and means; ground release; and safety issues.

But before delving into the details of a recovery system design project, let's start with a review of the variables used to determine the canopy size and the related factors that flow from that. After that, we'll do a design exercise so we can illustrate the entire process from beginning to end.

Basic Equations

The definitions of the components of the basic performance equations used in parachute design are:

- The *canopy surface area* (S) expressed in $ft.^2$ or SF.
- The *coefficient of drag* (C_d) is an empirically derived, dimensionless number used to quantify the performance of the parachute canopy. For the type of canopies we are considering here C_d can range from about 0.7 to 1.3. For our case study, we will use $C_d = 1.0$ to simplify the math.
- The *drag area* which is the surface area of the canopy (S) times (C_d) and is expressed in square feet ($C_dS \sim ft.^2$) or SF;
- The *air density* (ρ) "rho"; ρ at sea level is the usual reference value ($\rho_{sl} \sim 0.002378$ lb/ft^3);
- V_t is the terminal velocity ($V_t \sim$ ft/sec.) of any device in freefall; e.g., a 200 pound cylindrical test vehicle (CTV) made from 14"-diameter steel pipe (14" dia = 1 $ft.^2$ & use $C_d = 1.0$) left to accelerate in freefall will reach a terminal velocity of approximately 410 ft/sec or about 240 KIAS.
- $V_{T\text{-}ROD}$ is the steady-state, terminal rate-of-descent (ROD) desired ($V_{T\text{-}ROD} \sim$ ft/sec.) at ground impact
- V_i is the initial velocity when the parachute is opened ($V_i \sim$ ft/sec.)
- Drag (D ~ pounds) is the force generated by airflow at a particular velocity
- The gross weight (W) of the vehicle. Note that W = D at any steady-state condition; which, in our discussions will most often be $V_{T\text{-}ROD}$.
- The weight of the parachute, W_p refers to the canopy by itself.
- The opening force reduction factor (X_1) [5]is an empirically derived, dimensionless factor that quantifies the effects of the deceleration of the payload during the opening process. This reflects that the maximum drag area (and thus maximum force) of the canopy occurs at a significantly lower velocity than initial. The X_1 factor ranges from about 0.05 at very low canopy loading (<0.5 PSF) to its maximum value of 1.0 at canopy loading of higher than 80 PSF; which for practical purposes correspond to a velocity > 250 ft/s. In this design exercise we will use 0.05 and 0.10, corresponding to the loads of 200 and 400 pounds.
- The opening force coefficient at infinite mass conditions (C_x) is an empirically derived, dimensionless factor that quantifies the effects of opening a parachute in a wind tunnel (in effect, an infinite mass) whereupon the payload does not decelerate during the opening and the parachute will over-inflate momentarily, thus causing an overshoot in the load – the ratio of the overshoot to the steady state load is C_x. For parachutes such as those under discussion here (i.e., final descent with ROD under 30 FPS) the infinite mass condition is, in effect, nearly the opposite of the real world condition reflected by the X_1 factor described above. We will use 1.8 in the design exercise.
- The reefed percentage (R ~ %) indicates how much (if any) the parachute has been reefed by traditional pyrotechnic means or some other device[6]. R is expressed as the remaining drag area; e.g., 25% in these equations means that the drag area is reduced by 75%.
- The maximum opening force (F) which is calculated based on the initial velocity, weight and design factors.
- The dynamic pressure $\boldsymbol{q}$ is derived from $\frac{1}{2} \boldsymbol{\rho} V^2$ and is embedded in all the following equations in one form or another. In fact, the term "$\boldsymbol{q}$" is used frequently in design discussions of parachutes (as well as all other airborne devices).

Keeping in mind that this not a tutorial on the design of parachutes, we will utilize the simplest form of all of the following calculations. Putting these components together in the usual forms, allows us to begin our design calculations as follows:

A - *Dynamic Pressure*

The dynamic pressure "$\boldsymbol{q}$" is derived from $\frac{1}{2} \boldsymbol{\rho} V^2$ and is expressed in lb./$ft.^2$ or PSF.

$$\boldsymbol{q} = \tfrac{1}{2} \boldsymbol{\rho} V^2$$

B - *Steady-State Drag*

The steady-state drag (equal to the weight) is derived from:

$$D = \tfrac{1}{2} \boldsymbol{\rho} V_t^2 C_dS$$

C - *Steady-State Rate-of-Descent*

The terminal ROD (V_t) is derived from the basic drag formula by substituting W for D

$$V_t = [(2\, W) / (\boldsymbol{\rho}\, C_dS)]^{\frac{1}{2}}$$

D - *Required Drag Area for Steady-State Velocity*

In order to find the drag area required to reach a desired steady-state velocity at a known weight, we use:

$$C_dS = (2\, W) / (\boldsymbol{\rho}\, V^2)$$

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[5] X_1 and C_x are taken from Knacke (see references)

[6] The BAT Sombrero Slider is one of these "reefing methods" as it allows almost total control over the opening process - specifically control of the maximum opening force. We can easily reef the parachute to as small as 10% but we will use 50% for our design review. See the references.

E - *Maximum Opening Force*

The opening force at the stated velocity (V_i) is calculated using

$$F = \frac{1}{2} \boldsymbol{\rho} V_i^2 C_dS X_1 C_x R$$

Derived Values: There are dozens of combinations of the input values (W, V, C_d, etc) and the results of the basic equations listed above. The most useful of these follow below.

F - *Canopy Loading*

One of the most useful reference numbers used by parachute designers is the so-called *canopy loading* (CL) expressed as pounds of gross weight (W) per square foot (PSF) of canopy drag area: CL= W/C_dS. This provides a quick glimpse at the situation without going back to the calculator or computer – one of the most useful tidbits to remember is that a canopy loading of 1.0 PSF results in a rate-of-descent (ROD) of 29 ft/sec at sea level. Note that the canopy loading corresponds to the dynamic pressure; i.e., ***q*** at 29 ft/sec is 1.0 PSF.

And since all of these relationships are related by V^2 then you can quickly estimate the ROD once you know the canopy loading; for example, if you reduce the canopy loading by half, the new rate of descent will be:

$$V_2 = V_1 * (\tfrac{1}{2})^{\frac{1}{2}} = V_1 * 0.707$$

Conversely, if you were to double the canopy loading, the ROD will be:

$$V_2 = V_1 * (2)^{\frac{1}{2}} = V_1 * 1.414$$

Easy rules to remember on canopy loading:

Table 1

Canopy Loading (PSF)	Multiply 29.0 Times	ROD (ft/sec)
0.25	0.50	14.5
0.50	0.71	20.5
1.00	1.00	29.0
2.00	1.41	41.0
4.00	2.00	58.0
8.00	2.83	82.0

G - *Canopy Drag Efficiency* [7]

Another handy number is the *drag efficiency* of the canopy itself expressed as square feet of drag area (C_dS) per pound of canopy (W_p): $C_{eff} = C_dS/ W_p$ expressed in ft^2/lb. This reflects many of the factors that go into designing and building the canopy; i.e., the shape, materials, construction details and so forth. The value can range from the low 40's (for antique designs such as the USN/USAF 28' flat circular) to the low 80's for state-of-art parachutes for very specialized applications (also with very little structural reserve). In order to simplify the math we will use a value of C_{eff} = 50 ft^2/lb. in the following design exercise.

H - *Canopy Weight*

Once we know the drag area required and can estimate the drag efficiency (usually based on prior work with similar designs) we can determine the weight by simple multiplication. For example using a 600 ft canopy with a drag efficiency, we find:

C_dS / C_{eff} = 600 ft.^{2} / (60 ft.^{2}/lb) = 10 lb.

I - *Pack Density*

The so-called *pack density* expressed in pounds per cubic foot (lb/ft^3 or PCF) is used with the derived (or actual weight) of the canopy to determine the volume needed to stow the parachute (at least the canopy).

Packing methods include traditional hand pack with limit of about 25 PCF; vacuum "bag and bake" [8] to a limit of about 40 PCF; pressure packing[9] with a limit of about 50 PCF.

You should use these pack density values with caution because there are many variations in packing methods as well as many other factors such as the pack geometry which affect the actual density that can be achieved.

[7] Butler Parachutes offers a wide range of canopies with drag efficiency values from the low 50's (our SMARTChute cargo items) thru the high 60's to mid-70's for our HX-Series canopies. All of the HX-Series utilize the BAT Sombrero Slider and many are authorized under FAA TSO C23d.

[8] *Bag and bake* is a term we use to describe a packing method that is derived from the techniques used in the fabrication of composite components. See an example and a more detailed explanation at the end of the paper.

[9] *Pressure packing* encompasses a wide range of techniques including hydraulic presses, mechanical devices and so forth. See several examples at the end of the paper.

Design Decision Hierarchy

Now that we have the tools in hand to properly analyze the performance requirements we are almost ready to begin our design exercise. However, before we get started on any recovery system project, the following questions must be answered. Note that we have arranged these roughly in the order of importance and influence on the project.

1. Will this be used for routine recovery or for emergency only?
2. What are the *minimum and maximum allowable* rate-of-descent (ROD) for both maximum gross and empty conditions?
3. What is the *desired* ROD? (typically in the range of 17 to 24 ft/sec)
4. What is the aircraft weight at deployment - minimum and maximum expected - and specifically the allowance for weight growth?
5. What is the aircraft speed at deployment; both minimum and maximum expected?
6. What is your desired opening load limit; expressed in pounds force? Alternatively you may specify a maximum load factor typically in the range of 5-to 10-g's at maximum deployment speed.
7. What are the maximum structural interface limits?
8. What structural interface is required - typically 1 to 4 attachment points?
9. What is the desired landing attitude – i.e., right side up; upside down; nose up or nose down or __?
10. Where do you envision stowing the recovery system? For example, this could be internal below the mold line or external on the outer skin somewhere.
11. What volume is available in the stowage compartment as envisioned?
12. Will the parachute be reused? If so, which components will be recycled?
13. Will you land in the water (many targets) or on the dirt (most UAVs)?
14. Will the aircraft fly in the rain?
15. Do you wish us to provide the stowage container (we can provide vacuum molded or composite shells as needed)?
16. How much of the pre-deployment sequence do you wish us to handle?
17. Do you need a "smart" system with the deployment sensitive to altitude or speed?
18. Do you require a ground (or water) release system? If so, do you want us to supply it?
19. If it is to be reused will it be repacked in the field or sent back to manufacturer?
20. Is this aircraft "stow-able" as in the form of gliders - or is it fully permanently assembled – what influence, if any does this have on the recovery system?
21. Many UAVs have the sensor packages on the bottom side and therefore, the net cost (airframe damage vs. sensor damage) of a landing under the parachute can be significantly lower when landing upside down. Does that apply to your program?
22. Please provide 3-view drawing of the aircraft with the CG marked.
23. Please provide details on the aircraft layout & propulsion: i.e., pusher or tractor, jet, prop, ducted fan or ___?
24. Based on the aircraft configuration and the details of the stowage compartment, you must choose a deployment method. Can you accept an increase in the likelihood of entanglement or other failure in order to use a simpler deployment method?

Although this looks like a lot of information to provide to the recovery system designer, much of it should evolve with the aircraft design; i.e., the gross weight and desired rate of descent, the flight envelope and the permitted shock load, etc.

A SIMPLE EXERCISE IN THE PROGRAM MANAGEMENT AND DESIGN OF A RECOVERY SYSTEM FOR A UAV[10]

Note - this exercise is written as an historical narrative in order to make it easier to follow. By doing this, we are attempting to address as many of the issues as practical. All dates are relative and so designated as month "0","3", etc. With little intro out of the way, here we go:

Let's presume that Generic UAV Associates (***GENUAVASS)*** has been approached by a customer, the Big Secret Agency (***BSA***), to develop a new UAV. ***BSA*** and ***GENUAVASS*** have reached an agreement on the mission and performance requirements. You are now far enough into the design process that you are both fairly comfortable with the overall design and have jointly decided that you must have a recovery system.

Therefore, ***GENUAVASS*** has come to Butler Unmanned Parachute Systems (***BUPS***) for a recovery system for your new UAV which has a working name of ***6BY*** to indicate that it is designed to ship inside a 6 x 4 x 4-foot crate.

BUPS and ***GENUAVASS*** have negotiated a time and materials (T&M) contract for the development and qualification of the recovery system. The timeline for the project is 6 months ARO to completion of the qualification program with a budget not to exceed $(__) without further negotiations. BUPS will retain all data rights on any existing products incorporated in the recovery system; data rights for any items developed specifically for the 6BY will pass to ***GENUAVASS***

Based on the preliminary analysis, we agreed upon a Not-to-Exceed (NTE) price of $ (__) per unit (which everyone acknowledges is highly dependent on the production rate). The contract was signed and everyone was authorized to begin work on day 1 of Month "0".

The new ***GENUAVASS 6BY*** vehicle has the following characteristics:

- the recovery system will be for emergency use only;
- no recovery system components will be reused;
- the UAV will operate over land;
- the UAV will not fly in the rain;
- a maximum gross weight of 200 pounds
- a maximum expected growth to 400 pounds;
- desired ROD of about 20 ft/sec at 200 pounds; maximum is 24 ft/sec; minimum is 15 ft/sec at 150 lb (empty fuel weight) in order to minimize dragging after landing;
- a maximum speed of 150 knots; typical deployment will be at 70-90 KIAS;
- maximum opening load allowed is 4,000 pounds force;
- there will be one attachment point located on the centerline just forward of the CG to induce a slightly nose-up attitude upon touchdown;
- the UAV has a small gasoline engine with a tractor prop mounted to the front of the fuselage;
- the UAV has a conventional cruciform tail mounted on a tubular tail boom;
- the UAV is designed for easy disassembly for transport - and repair via modular airframe components;
- A stowage volume near the tail boom has been tentatively assigned for the recovery system.

In one form or another, the simple paragraph above has answered *at least* questions 1 through 14 raised in the design decision hierarchy.

Now you want us to provide an estimate of the canopy size, weight and bulk before you finalize your decision on where to stow the parachute and how to deploy it (if only we were so lucky with all of our customers). Thus, we now begin the process of sizing a parachute canopy for the ***GENUAVASS 6BY***

To find the drag area needed, we begin with the usual aerodynamic equations (outlined above) to determine the drag area. For this task, we use equation D:

$$C_dS = (2\ W) / (\boldsymbol{\rho}\ V^2)$$

A shortcut to find the drag area needed. Although the equation certainly works, we can use one of the shortcuts mentioned earlier by using 20.5 ft/sec which gives us a required canopy loading of 0.5 PSF (see Table 1). Note that 20.5 ft/sec is certainly within range of the desired rate of descent of approximately 20 ft/sec.

To stabilize 200 lb. at a terminal velocity of 20.5 ft/sec (per Table 1) [11] we simply divide the payload weight by the canopy loading, yielding a required drag area of 400 ft^{-2}.

$$200\ lb / (0.5\ lb / ft^{-2}) = 400\ ft^{-2}$$

To calculate the maximum opening force at the maximum predicted speed we use equation E. Note that we must also cross-check our opening loads at the maximum allowed weight growth:

$\boldsymbol{\rho} = 0.002378\ lb / ft^{-2}$
$V = 150\ KIAS \approx 250\ ft/sec$;
$C_dS = 400\ ft^{-2}$
$X_1 = 0.05, 0.10$
$Cx = 1.8$

[10] This "story" is relayed in a narrative style in hopes of making the process easier to follow.

[11] Note that when we check this for maximum anticipated weight growth, we have 400 lb. /400 ft^2 = 1.0 which gives a ROD of 29.0 ft/sec per Table 1.
We also check to see if the ROD for the minimum weight of 150 lb. is greater than 15 ft/sec. The calculated ROD at 150 lbs. is 17.75 ft/sec.

R = various

$F = \frac{1}{2} \rho V_i^2 C_d S X_1 C_x R$

Table 2

Wt.	X1	Reefed to %	Max. Force
200 lb.	0.05	100 %	2,677 lb.
400 lb.	0.10	100 %	5,355 lb.
400 lb.	0.10	50 %	2,675 lb.
200 lb.	0.05	50 %	1,338 lb.
400 lb.	0.10	75 %	4,000 lb.

Note that when we cross checked the opening load for the maximum allowed weight growth we found that it exceeded the maximum allowed (4,000 lb.) in the specification. We then changed the reefing from 100% to 50% effective area, thus bringing the predicted load back under 4,000 lb. – rechecking the load for 200 lb. shows that the load has dropped as well. Just for curiosity we iterated to 75% reefing to exactly match the 4,000 lb. maximum. However, we have decided to use 50% for the program.

To find the canopy weight, [12] we'll assume a canopy drag efficiency $C_{eff} = 50\ ft^{2}/lb$ and arrive at a canopy weight of 8.0 lb.

$400\ ft^{2} / (50\ ft^{2} / lb) = 8\ lb.$

To calculate pack volume required for various packing methods;

- A medium hand pack of 24 PCF yields a pack volume of:

  $8.0\ lb/ (24\ lb/ft^3) = 0.33\ ft^3$

- A medium hard bag and bake pack of 40 PCF yields a pack volume of:

  $8.0\ lb/ (40\ lb/ft^3) = 0.20\ ft^3$

- A hard pressure pack of 48 PCF yields a pack volume of:

  $8.0\ lb/ (48\ lb/ft^3) = 0.16\ ft^3$

Again, approach the pack density values with caution. Based on the space allowed in the fuselage, the maximum allowed dimensions for the bucket are: 8" wide, 12" long and 6" deep = 576 CI = 0.33 CF. If the maximum volume is used then the predicted pack density for the canopy alone is 24 PCF but the deployment bag, pilot chute and part of the riser must be installed as well. Still, based on our experience this should be a fairly comfortable pack.

To place the parachute within the fuselage: [13] Because of the configuration of the aircraft, you have planned for substantial volume within the fuselage just in front of the tail boom; therefore, you have decided to go with a ***simple hand pack***.[14] After further discussions, we have jointly decided to supply the parachute packed in a deployment bag which will, in turn be packed into a molded "bucket" with flaps to protect the d-bag. The bucket can be removed for routine service of the parachute itself or for access to any items within the fuselage in that area.

After discussions among all of the team members, in view of the condition that this is an emergency recovery system, you have decided to accept a small risk of entanglement (SWAG at 10-20%) in order to use the spring loaded pilot chute, the simplest of systems. Furthermore, you have decided to increase the leading edge sweep angle on the vertical and horizontal tail planes in order to reduce the frequency of entanglement.

Based on the discussion above, you have decided that the parachute will be deployed with a spring-loaded pilot chute held down and compressed by the "lid" which will release at its forward edge and blow aft and off of the vehicle; allowing the pilot chute a clear launch into the air stream.

We then jointly came to the conclusion that by making the lid part of the recovery system itself (rather than an aircraft part per se) it would be relatively easy to have the parachute packed into the bucket with the lid in place holding the pilot chute compressed. A quick discussion concluded that we should to place a small solenoid activated release on the inside of the front wall of the bucket.

Technical Review of the Recovery System

At this point we have

Tentatively
Finalized the design of the recovery system
and
The interface

to the aircraft as follows:

- The main canopy will be a LoPo-400, a derivative of our existing product line.
- The unit is designed as a self-contained field replaceable unit that must be returned to ***BUPS*** for inspection and repack every 12 months; [15]

[12] For comparison to a real world product, BUPS would probably offer an existing canopy model, the HX-300, with an actual weight of 5.8 lb.

[13] See additional discussion on deployment methods and placement of the recovery system at the end of the paper.

[14] Note that another advantage of the low pack density at this point is that you will be able to easily substitute a larger canopy (when the vehicle gains weight) by going to a bag and bake technique.

[15] If appropriate, based on the results of inspections upon repacking, ***BUPS*** will authorize a gradual extension inspection cycle in 6 month increments. The ultimate goal is to have a 3 year repack cycle.

- The approximate dimensions of the bucket are: 8” wide, 12” long and 6” deep. There may need to be a “step” in the bucket to clear the control linkage connector points.
- The bucket will be vacuum molded from 0.125” ABS plastic – the minimum acceptable thickness in any section after molding is 070”.
- A 1” wide by .090” thick “lip” will run around the entire perimeter of the bucket thus allowing it to support itself along the edges.
- The lid will be 0.125” thick molded ABS plastic with stainless half hinges to allow the lid to fall free after 90^o rotation.
- The lid will have an overlapping means of providing at least minimal water tightness.
- The lip will be seated on a ¼” joggle in the skin on the fuselage so that the lid will approximately flush with the fuselage.
- The lip will fasten to the fuselage skin with a total of 8 (2 on each side) Camloc 4002 Series quarter turn fasteners.
- The lid will have “half-moon” cutouts on top of the Camloc fasteners to allow the parachute to be installed and removed without opening the lid.
- A single riser will lead out of the front lip of the bucket and run forward 30” to a bracket attached to the main beam of the aircraft.
- The riser will be made of two layers of 1” wide Kevlar (6,000-lb. tensile) and will be completely covered with UV-resistant heat shrink tubing.
- The riser will be laid into a ⅜” deep by 1.25” wide joggle in the skin of the aircraft; the riser will be covered and held in place with ordnance tape.
- The riser will have a 1”x ¾” x ⅜” bushing to fit within the bracket and the riser will be “pinned” to the bracket with a ⅜” x 1.5” ball-lock pin.
- A 4-pin electrical interface cable with a 24” tail, for the solenoid; maximum load will be 5A @ 12V.
- The UAV manufacturer will supply all power, sensing, and circuitry necessary to initiate the recovery by sending a current to the solenoid.
- There will be no ground release at this point – perhaps it will be added later if needed.

Qualification - Test Plan

Any component destined for flight should be of the highest quality and must demonstrate its capabilities under the most realistic conditions feasible. In this case, we will be able to perform drop test using a mockup of the fuselage section where the parachute is stowed. It will be fairly straight forward to design a drop test vehicle with the section

BUPS will design and build one (or more) test vehicles as directed by ***GENUAVASS***; each will be equipped with at least two video cameras in order to be sure to capture as much detail as possible on every test. In addition, each test will be filmed from the aircraft tailgate and three positions on the ground. No other instrumentation is planned.

We are going to use a canopy (our LoPo-400) with a pedigree and we can provide prior test data on the canopy itself. Therefore this test program will need to concentrate on the deployment of the parachute rather than what happens after it opens. Accordingly, we at **BUPS** recommend the following test plan:

- Five (5) consecutive successful bench tests to prove the functionality of the solenoid release mechanism.
- Five (5) consecutive successful truck top tests at 75 mph on the runway to verify that the lid will release and begin to deploy the parachute (which not be hooked to the truck).
- Up to five air drop test with hopes of success on all drops. However, given the known vagaries of the deployment past the tail feathers (which you have accepted early on in the program) a ***failure on an airdrop does not constitute a program failure.***
- ***BUPS*** will provide a complete test report with documentation of all aspects of the test program. The report will include copies of all of the raw video as well as an edited version for show and tell.

All parties from ***BSA***, ***BUPS*** and ***GENUAVASS*** accepted the proposed test plan and the authorization to proceed were signed on day 1 of month “0”.

Program Conclusion & Review (Graduation)

All bench tests were completed by the end of month “3”; all truck top tests were completed by the end of month “4” and the final airdrop test was successfully completed by the end of month “5”.

The final program review (“graduation”) meeting was held at the end of month “6” with the entire team present including representatives from ***BSA***, ***BUPS*** and ***GENUAVASS***. All aspects of the program were reviewed and all parties declared their pleasure that the project has gone so well. The few minor missteps were attributed to minor communication problems in the email protocol and the cure for that noted for future reference.

Butler Unmanned Parachute Systems and ***GENUAVASS*** have co-authored a report covering all aspects of the program from start to finish. This report was completed and ready for distribution two weeks after the graduation meeting.

BUPS will be able to initiate series production beginning within 60 days ARO.

THIS ENDS OUR DESIGN EXERCISE

Review of the Design Exercise

As shown in this simple but realistic and relatively detailed exercise, there are no more secrets to this part of the process than in any other part of the project. However, we hope that you have developed an appropriate respect for the process of designing and qualifying a recovery system.

You should be aware of course that, although we have everything we need to build the recovery system, you are long way from having all the details you need to build it yourself.

Additional Notes on Parachute Recovery System Design

Now we can fill in a few of the gaps in our previous discussion and the design exercise.

Modular Design and Building Blocks

Even with our extensive experience, we do not offer a "generic" UAV recovery system. However, by using a modular approach, we can offer a wide range of existing main canopies that have already been developed and qualified at various speeds and weights[16] (see the table in the reference section). And because the canopy is typically the most expensive component in the recovery system we can offer significant savings in time (which is usually more important) and money. But even with that said, we must reiterate that we will not force a solution using existing products.

We utilize various deployment methods including pilot chutes, extraction rockets, and ejector airbags. Because we typically use a deployment bag, nearly all of our recovery systems are designed as a field replaceable unit; i.e. it is self-contained to the degree that it can be handled without the parachute spilling out.

BAT Sombrero Slider[17]

All solid cloth canopies developed by Butler Parachutes since 1998 have used the BAT Sombrero Slider which *literally eliminates inversion type malfunction and literally increases the reliability by several orders of magnitude*, when compared to identical canopies without the device installed. It also allows significant control over the inflation process and, in effect, provides continuous, speed-sensitive disreefing rather than fixed time-delayed incremental reefing as provided by pyrotechnic devices.

The BAT Sombrero Slider also greatly increases the maximum allowable deployment speed when compared to similar canopies without the Sombrero. You may find extensive information in the publications listed in the references.

Additional Notes on Parachute Deployment

When considering how to deploy the parachute, you must first consider the aircraft layout and then the stowage location of the parachute. In general, with many aircraft layouts and container arrangements, specifically including the one in our design exercise, it is feasible to use a spring loaded pilot chute for deployment. However, there is always a possibility that deployment using a pilot chute (either soft or spring-loaded) could occasionally hang-up on the tail feathers and not fully deploy - or occasionally deploy with the riser underneath the tail - thus causing a nose down or inverted deployment.

Each program must conduct its own cost/benefit analysis; however, the authors wish to point out that a recovery system designed purely for range safety (i.e., salvaging the vehicle is not a concern) is much more likely to be appropriate for this type deployment than the emergency recovery of a multi-million dollar vehicle with a delicate payload and a pusher prop.

Alternate Deployment Means

Even though an aerodynamic deployment using a pilot chute (soft or spring-loaded) is feasible in many instances (particularly when the recovery system team is an integral part of the entire UAV team from the very beginning), there are some instances where it is just not practical or advisable to use this method. Alternate deployment methods are commonly used because of aircraft configurations such as a pusher prop or just too much "stuff" in the deployment path.

For example, in many instances with a pusher prop, a rocket deployment can be used to ensure that the parachute (in a deployment bag) will be lifted up and over the prop.

In some instances where the parachute is stowed close by the prop or the aircraft is flying at higher speeds (say 100 KIAS for discussion), it might be possible for the riser to contact the propeller before the aircraft is decelerated and stalled to cause it to pitch up. For one customer where we had such concerns, we placed extreme reinforcements on the risers in the area that they might possibly contact the prop. This customer then dropped a weighted riser through the prop arc while running the engine on a test stand. The riser was manufactured from 6 layers of 1" x 6000# Kevlar webbing and it *shredded* the hollow carbon fiber prop with very little visible damage to the riser.

Of the common force-deployed means, only a rocket will continuously apply force to the parachute until it is fully deployed and during this time the separation velocity (from the vehicle) continually increases. The other methods, such as the drogue gun or an airbag ejection, impart all of their available energy to the parachute deployment bag during the first few milliseconds after initiation and after the launch the separation velocity will continually decrease as the kinetic

[16] In some cases, such as target recovery systems, a multiple canopy system is appropriate. We also have about a dozen ribbon parachute designs that have qualified for various higher speed applications up to 500 KIAS.

[17] BAT is Butler Aerospace Technologies, Inc. It is an affiliated company but is not part of the Butler Parachute Systems Group, Inc. The BAT Sombrero Slider is extensively reviewed in the publications listed in the references. We also have a derivative version that we call the BAT Flat slider; it is nearly as effective, but significantly easier to manufacture.

energy dissipates. Another significant disadvantage to the drogue gun is that it must be mounted to a structure that can withstand the reaction force (typically, a one-pound slug will accelerate to over 200 ft/sec in a space of 6” or so).

This brings up other issues such as personnel safety, service life and shelf life of the components, HAZMAT handling for the user of any explosive device. Be advised that since 9-11, the transportation of the rocket motors (which are Class 1.3 explosives under DOT regulations) has become a huge problem – when you get a quote to ship rocket motors it almost looks like you’re paying for an armed escort by Delta Force for the entire trip.

Furthermore, the electrical igniters used for the rocket motors and most drogue guns are Class 1.4 – they are fairly easy to ship in comparison, but it still a consideration.

CONCLUSIONS

We have presented the information required by the aircraft manufacturer and the end user to successfully specify, qualify, procure and integrate a parachute recovery system into an Unmanned Aerial Vehicle.

We have presented a detailed design exercise that illustrates the technical part of the process, while also emphasizing the importance of the appropriate involvement of the program management.

We have presented a program management approach that emphasizes the free flow of information without drowning everyone in paper; an approach which allows everyone involved in the process to stay informed and to contribute their best and most effective efforts thus ensuring the success of the project.

References

Butler, Manley C., Jr. and Crow, Michael D. *The Design, Development and Testing of Parachutes Using the BAT Sombrero Slider™*. June 1999, AIAA 99-1707

Butler, Manley C., Jr. *Additional Applications of BAT Sombrero Slider Technology.* May 2001, AIAA 01-2037

Butler, Manley C., Jr. and Loney, Troy *Design, Development and Testing of a Recovery System for the Predator™ UAV.* May 1995, AIAA 95-1573

Knacke, T. W. *Parachute Recovery Systems Design Manual*. 1992, Para-Publishing, Santa Barbara, CA,.

Manley C. Butler, Jr. is the **President and Chairman of the Board** of Butler Parachute Systems Group, Inc. Manley has a BS in Aerospace Engineering from the University of Texas at Austin; over thirty years of experience in parachute systems use, design, testing and manufacturing; three years as a combat aircrewman in the US Navy on the S3-A Viking; and an FAA Master Parachute Rigger license with all ratings. He also worked for four years as a Project Engineer/Program Manager in the Recovery Systems Design Branch at the Naval Weapons Center at China Lake, California, and worked for one year as Director of Engineering at ParaFlite, Inc. in Pennsauken, New Jersey. He is a licensed private pilot, an experienced parachutist with over 1,200 jumps and an avid sailor (see above for "happy sailor" mode ☺).

Roberto Montañez is the **Vice-President of Operations**. He is in charge of the day to day operations of the company. Roberto has a B.S. in Aerospace Engineering from Parks College of Saint Louis University. He has experience in the design and integration of parachute and electronic control systems, testing and instrumentation, and computer modeling and simulations. Roberto also wrote the code for our purchasing, inventory management and quality tracking systems. He also holds a private pilot license.

Appendix A – Examples of Packing Methods

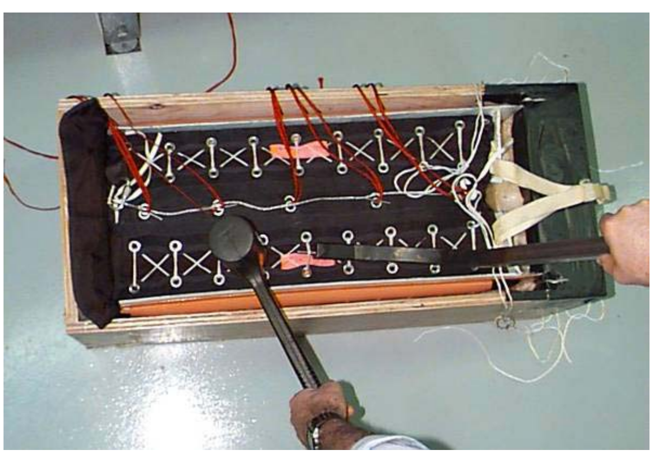
A1 - Hand Pack to High Density

This is a classic example of the results of setting unrealistic performance requirements – in this case the rate-of-descent was so low that we were forced to use a fairly large canopy even though it is a very efficient shape. And, in almost direct conflict with the ROD requirement, the customer demanded that the parachute be "hand packed".

This is the original configuration of a multi-stage recovery system for a target drone. The container shell is supplied by the target manufacturer and the side flaps are supplied by BUPS. The original method to close the pack used lacing to close the flaps while pounding on the bulk to make it settle into the pack. This process could easily take 3 to 4 man hours over the course of an entire day.

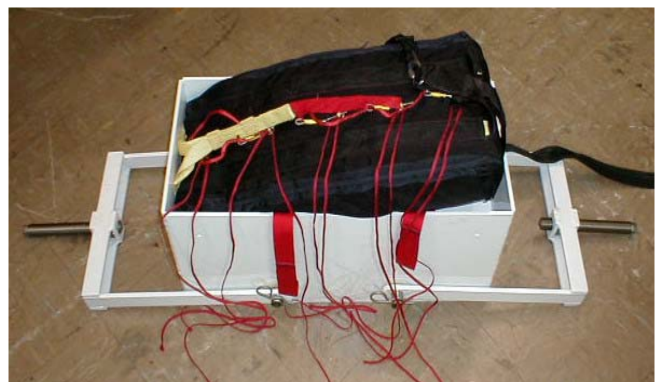
Over time, the field service personnel eventually decided that the hand pack was just a bit too difficult and we have since developed a mechanical pressure packing device.

A1-1) Original Container



A1-2) Packing Method

A1-3) Fabricated aluminum packing fixture (empty)



A1-4) Packing fixture with d-bag partially fitted.

A1-5) Packing fixture with parachute compressed to proper point to soak and relax.

A2 -Bag and Bake

In this case, the parachute (already packed in the deployment bag) is placed into a rigid fixture that will control the final shape.

The parachute and the fixture are enveloped in a special film and the edges are heat sealed. A vacuum pump draws the excess air out (usually to around 24 in Hg) and the atmospheric pressure squeezes the parachute down into its mold. The rigger can poke and prod the parachute to move (or remove) the lumps around until the shape suits him; then the entire assembly (fixture and parachute) are placed in an oven and baked at 160 to 180 degrees F for 15 to 30 hours. This process causes the parachute canopy to relax and form into the shape induced by the mold; with careful handling, it will retain its shape indefinitely.

A2-1) A fixture to duplicate the container shape required.

A2-2) The parachute which is hand packed into a shaped deployment bag is placed into the fixture.

A2-3) The fixture and parachute are "bagged".

A2-4) The vacuum port is placed in the film.

A2-5) The parachute is sucked down to the rigger's satisfaction and is ready to go into the oven to bake.

For larger production runs, a custom-made fixture is sometimes manufactured from steel and a rubber membrane is used to replace the film. These fixtures are expensive to make (even in-house as done at BUPS) but they quickly pay for themselves with reduced aggravation and a reduction in the cost of consumables.

A2-6) A parachute in a permanent fixture without the cover.

A2-7) A permanent fixture in the oven prior to pulling a vacuum.

A-3 Pressure packing in complex shapes

With some shapes it is necessary to construct elaborate forms to support the container while pressure packing. Here is an example of a complex container supplied by the customer – made of carbon fiber and presumably quite expensive. For this system we provide complete support throughout the bottom of the shell with a poured concrete base that we made with the actual container to be packed. Additional support is provided with ½" thick steel side and end plates. The side plates are lined with 1/8" high density closed-cell foam to prevent pressure damage to the shell.

A3-1) Customer supplied carbon fiber shell

A3-2) The concrete mold to support the shell evenly

A3-3) Steel plates support the walls of the container.

A3-4/5/6) The shell is placed into the fixture, the side and end plates are closed up, then tightened down with the cross bolts.

Even though this is a 50-ton press, this particular parachute requires only about 1.5 ton to complete the packing. This particular press has an "advance and hold" feature which allows one to set a given pressure and then leave for the night; each time the parachute compresses a bit, the pump starts and the ram repressurizes to the limit, then cuts off again.