Development of a Low Cost 10,000 lb Capacity Ram-Air Parachute, DRAGONFLY Program

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A 3,500 ft^2, 10,000 lb capacity, low cost cargo Ram-air is being designed and developed by Para-Flite, Inc. for the U.S. Army Natick Soldier Center (Natick) under the JPADS ACTD program. The airdrop system has been designed for deployment from 25Kft MSL at speeds of 150 KIAS. Test drops have been conducted with the system in order to finalize the deployment process and generate trajectory data suitable for the development of an autonomous guidance algorithm, of which C.S. Draper Laboratory is the designing authority. This paper presents the design philosophy and outlines the aerodynamic, structural and manufacturing considerations. Being driven by cost reduction, the design focused on using conventional materials and manufacturing techniques while trying to maximize gliding performance. The main canopy uses a cutterless slider reefing method which eliminates a dependency for complicated staged openings. Drop tests indicated that the parafoil was extremely stable in flight and generated a maximum glide ratio of 4:1. This level of glide efficiency matches or exceeds prior performance characteristics for similarly sized systems. Guided tests showed that the parafoil is also reasonably responsive for it size, with maximum steady state turn rates exceeding 9.0 deg/s.

Nomenclature

ACTD	Advance Technology Concept Demonstration
AGU	Airborne Guidance Unit
CEP	Circular Error Probable
DRAGONFLY	Deployable Ram-Air Glider with Optimum Navigation FLYing
FTS	Flight Termination System
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
JPADS	Joint Precision Aerial Delivery System
MC	Motor Controller
MSL	Mean Sea Level
PRO	Proper Ram-air Orientation
PSF	Pounds per Square Foot
RF	Radio Frequency
YPG	Yuma Proving Ground, Yuma, AZ

I. Introduction

Para-Flite has been developing a range of low-cost Ram-air precision cargo delivery systems since 2001. The 10,000 lb. capacity system is the largest of a family of systems capable of carrying 2,000 lb. 5,000 lb. and 10,000 lb. loads. The effort to mature the 2,000 lb and 5,000 lb products beyond their proof-of-concept stages has been continued privately, while the 10,000 lb system is currently under Natick contract jointly with Draper Laboratory (GN&C), Wamore Inc. (Air Guidance Unit), and Robotek Engineering (avionics). The 10,000 lb system, the DRAGONFLY, is part of the JPADS ACTD program, which serves as a technology demonstrator for concept feasibility. The DRAGONFLY demonstrates a high offset, high glide, low cost solution for cargo re-supply. The DRAGONFLY is being designed to meet with existing Air Force and Army airdrop infrastructure.

Figure 1: DRAGONFLY in Flight

II. DRAGONFLY System Description

A. Top-Level Design Requirements

The design requirements as outlined per the Army draft Capabilities Development Document for this JPADS exploratory program are:

- Maximum All-Up Weight: 10,000 lbs Target
- Reliability: 0.95, Target
0.95, Objective
- Accuracy: 100 meters CEP, 80% frequency rate, Target
50 meters CEP, 60% frequency rate, Objective
- Exit Altitude: 25,000 ft, Target
>25,000 ft, Objective
- Horizontal offset (from 25,000 ft): 3-5 km, Target
15-25 km, Objective
- Ground Wind Limitations: 17 knots, Target
25 knots, Objective

Design requirements derived specifically for the JPADS DRAGONFLY configuration from Program Management authorities, Natick, or the parafoil design authorities, Paraflite:

- DRAGONFLY System Cost per Pound Cargo: \$3-\$6/lb Target, Main Canopy Cost per Pound Cargo: \$3.5/lb, Target
- Exit Speed: 150 KIAS, Target
- All re-usable DRAGONFLY components retained after deployment , Target
- Designer Dynamic Pressure at Drogue Release: 10 psf, Target
- Minimization of Expendables; General Design Focus
- Simplification of Packing, Rigging, and Recovery; General Design Focus
- Compatible with a Variety of Payload Configurations and Aircraft Types; General Design Focus

B. System Design

The DRAGONFLY system includes two 28 ft flat-circular ring-slot drogues, a 3,500 ft^2 main canopy with multi-grommet slider reefing, and a suspended Airborne Guidance Unit. The DRAGONFLY system is gravity dropped and uses two static line anchor cables when dropped from C-130 aircraft. Consideration was given to the manufacturing engineering of the main canopy to better meet low cost goals.

C. Drogue Design

The drogues serve to lift the AGU from the payload, achieve a safe dynamic pressure with a near vertical trajectory for main canopy deployment, and then perform the extraction and deployment of the main canopy.

Two release-away static line Army 28’ ring-slot flat-circular drogues were originally selected for convenience and availability. The terminal dynamic pressure for this configuration is 13.6 psf, which is 36% higher than the design target, 10 psf. However, these drogues allowed for immediate testing of the main canopy at sub max weights and sub max exit speeds.

After a safe dynamic pressure has been reached, a drogue release mechanism is designed to cut a set of Kevlar drogue release straps. A lazy line from the drogue bridle then pulls a specially designed anti-line dump main canopy deployment bag from the AGU and permits line payout followed by canopy extraction. The deployment bag remains attached to the two drogues and becomes free.

The drogue release mechanism utilizes a pair of mechanical timed cutters to achieve 100% independent redundancy. When in drogue fall, the zero margin safety factor of the system, with respect to the vertical load bearing members, is just over 80,000 lbs. Should the opening shock of the drogue ever generate 8 g’s, the failure mode would be the structural failure of the Kevlar drogue release straps. These straps are normally cut by the drogue release according to the selected cutters’ time, and a failure of this part would simply result in a premature deployment. A premature deployment of the parafoil is considered preferable to alternative failure modes such as a separation of drogues from the system and a resultant ballistic descent of the AGU, canopy, and payload until ground impact or a payload separation from the system, in which the payload would be ballistic until impact and the AGU, main canopy and drogues would not be heavy enough by themselves to deploy the main canopy.

D. Main Canopy Design

The philosophy of the main canopy design derives from the ability to make a high performance wing theory scale up while maintaining an otherwise conservative empirical wing surface area to suspension line ratio under the restrictions of conventional manufacturing and low cost design principles.

The main canopy has the following specifications:

Span	100	ft
Chord	35	ft
Chord Reduction Factor	0.82	
Aspect Ratio	3.2:1	
Surface Area	3,470	ft^2
Leading Edge Cut	41	deg
Airfoil Thickness	17	% of chord
Cell Count	35	
Max Wing Loading	2.88	lb/ft^2
Glide, L/D	4:1	
Weight	350	lbs

Figure 2: DRAGONFLY Canopy Specifications

The performance characteristics sought from the wing shape are high glide and high speed. The canopy has a 3.2:1 aspect ratio and an elliptical planform to help achieve this. The rib spacing becomes progressively narrower at the wingtips to facilitate pressurization and to maintain a smoother leading edge shape. The canopy has a cell count of 35 with all ribs loaded. The center 15 ribs are spaced at the maximum allowable width per the bolt width availability of the 1.5 and 1.9 oz nylon fabrics used, while the wingtip rib spacing is less than half. The canopy has no stabilizers in an effort to reduce wingtip drag.

Figure 3: DRAGONFLY Main Canopy Model vs. In-Flight

The main canopy has 900 lb spanwise reinforcements and 500 lb chordwise reinforcements that coincide with each of the line attachment points. These reinforcements prevent excessive tearing should the canopy suffer damage during deployment. The sheer size of the canopy permits navigation even with severe damage to the canopy surface area. As long as one of the control lines remains intact, the canopy retains some degree of controllability.

The main canopy is reefed by a unique multi-grommet slider. No pyrotechnics are used to stage the reefing process. To control the effects of the main canopy / slider rebound after extraction from the deployment bag, and to prevent an otherwise premature disreefing, the slider is retained to the canopy for a period of time by a design that is currently patent pending by Para-Flite. The slider size, shape, and arrangement of grommets is designed to remove congestion of the leading edge cells outboard of the center cell, so the outboard cells don't compete for the same airstream to inflate. This promotes uniform inflation of the canopy with respect to the slider during and just after the snivel stage. Reinforcement tapes are sewn to the slider spanwise and chordwise and intersect at each of the grommets.

Figure 4: DRAGONFLY Slider

The line configuration of the canopy was modeled after smaller scale personnel canopies that have proven wing surface area to suspension line ratios at similar wing loadings. The DRAGONFLY canopy has line groups A through G, and control lines. The average surface area to suspension line is 12 ft^2 / line. The line material selected was Spectra throughout. This material is cheaper and more readily available than other dimensionally stable lines such as Kevlar^{TM} and Zylon^{TM} (relative to nylon and polyester lines). A pyramid cascading technique is generally employed to minimize line drag. Four 1,500 lb upper lines converge to a 3,000 lb lower line in a loop-to-loop arrangement, e.g. line attachment points A1, A2, B1, and B2. The brake lines, 3 per side, are slightly different in that the uppers are 3,000 lb and the lowers are 6,000 lb. These are also loop-to-loop junctions, but these are only spanwise cascaded. Two of the 3,000 lb lines lower lines converge to a single riser of 6,000 lb strength. There are a total of 8 riser groups and 5 risers per riser group, with the exception of the two rear riser groups, which have only 3 risers. There is only one 6,000 lb trailing edge line per rear riser. The risers are constructed from 6,000 lb nylon webbing for ease of material availability, sewing, repair, and cost.

The trailing edge lines are released by mechanical timed cutters. There are three cutters per side. Only the outermost trailing edge lines are used as the control lines. This corresponds to the outboard 1/3 of the trailing edge per side that effectively serves to steer and brake the canopy (i.e. flare for landing). This results in control line loads and AGU power requirements that are much lower than would be present in other conventional arrangements, while still achieving comparable turn rates and soft landing capability.

Several manufacturing design considerations have helped to reduce overall system costs. The cost-minded philosophy applied includes using lighter duty sewing machines, common and widely used stitch patterns, a strict adherence to cost friendly material selection, the reduction of cut parts in critical areas, and improvements to rigging, maintenance, and packing times. The entire canopy is constructed using E-Thread single needle, double needle, and bartack machines. Only the risers and deployment bag use the heavier 5-cord Thread and 7 Class sewing machine. Junctions and seams are fashioned to work with lighter duty sewing machines. The soft materials used for the DRAGONFLY system consists of, for the greater part, nylon and spectra, and, when absolutely necessary, Kevlar^{TM}. The Kevlar^{TM} components are the cords or webbings that get severed by the mechanical cutters. All canopy fabric, reinforcements, line attachment points, and thread are nylon. Since the canopy cell width is no larger than the width of a fabric bolt, there are fewer subassemblies to build, expediting the canopy production.

The cascading design of the DRAGONFLY lines is such that the longest lines do not require special-made extra long cutting tables. The rigging of the 3,470 ft^2 parafoil has been mainstreamed and can be performed in a single day. This is largely due to the conventional attachment methods drawn from smaller personnel canopies. One large convenience is the method of connecting the lower lines to the risers. What would normally be connector links, as used across in the industry, has been changed to soft links. This has proven to be a savings of time, space, cost, and weight. Another savings realized is the space or room required to pack the parachute. The DRAGONFLY canopy is pro-packed over a hook/roller and can be done in a space the length of the lines.

Figure 5: Pro-packing the DRAGONFLY

Figure 6: Main Canopy in Longfold, Ready for Folding into Deployment Bag

E. AGU Design

The DRAGONFLY Airborne Guidance Unit (AGU) is suspended between the payload and the canopy. This configuration greatly simplifies the interface between the AGU and the parafoil as well as the DRAGONFLY system to the airdrop payload.

The AGU weighs approximately 175-lb and has the same footprint as the deployment bag of the parafoil. In general, the AGU consists of a pair of actuators with gear reducers powered by a 24VDC battery, a dual channel motor controller, and a 12 VDC battery to power the avionics. The avionics are mounted in a forward facing which can be removed and reinstalled when the parachute is rigged on top of the AGU if necessary. The actuator assemblies and avionics are mounted in a structural aluminum enclosure.

The avionics suite for the DRAGONFLY is very simple and consists of a microprocessor, a commercial Dual GPS receiver, and a 900-Mhz spread spectrum RF modem. The dual GPS unit provides actual system heading and heading rate information in addition to the course and velocity vector over ground information provided by standard single antenna GPS receivers. The RF modem is used for monitoring the system's state and taking over remote control if necessary from a ground station during the flight test. There are also two auxiliary bays in the forward section of the AGU which can house additional sensors or instrumentation.

The AGU's control line reels are readily accessible from the exterior aft face of the unit and there are no control lines resident on the spools. Rather, the control lines from the parachute exit the parafoil deployment bag and connect directly to the AGU reels. While the parachute is rigged to the AGU, the rigger can use toggle switches to manually adjust the reel position as necessary to set the proper control line geometry without powering up the whole AGU or using a laptop computer.

F. Deployment Sequence

The following illustration depicts the different stages of the deployment process:

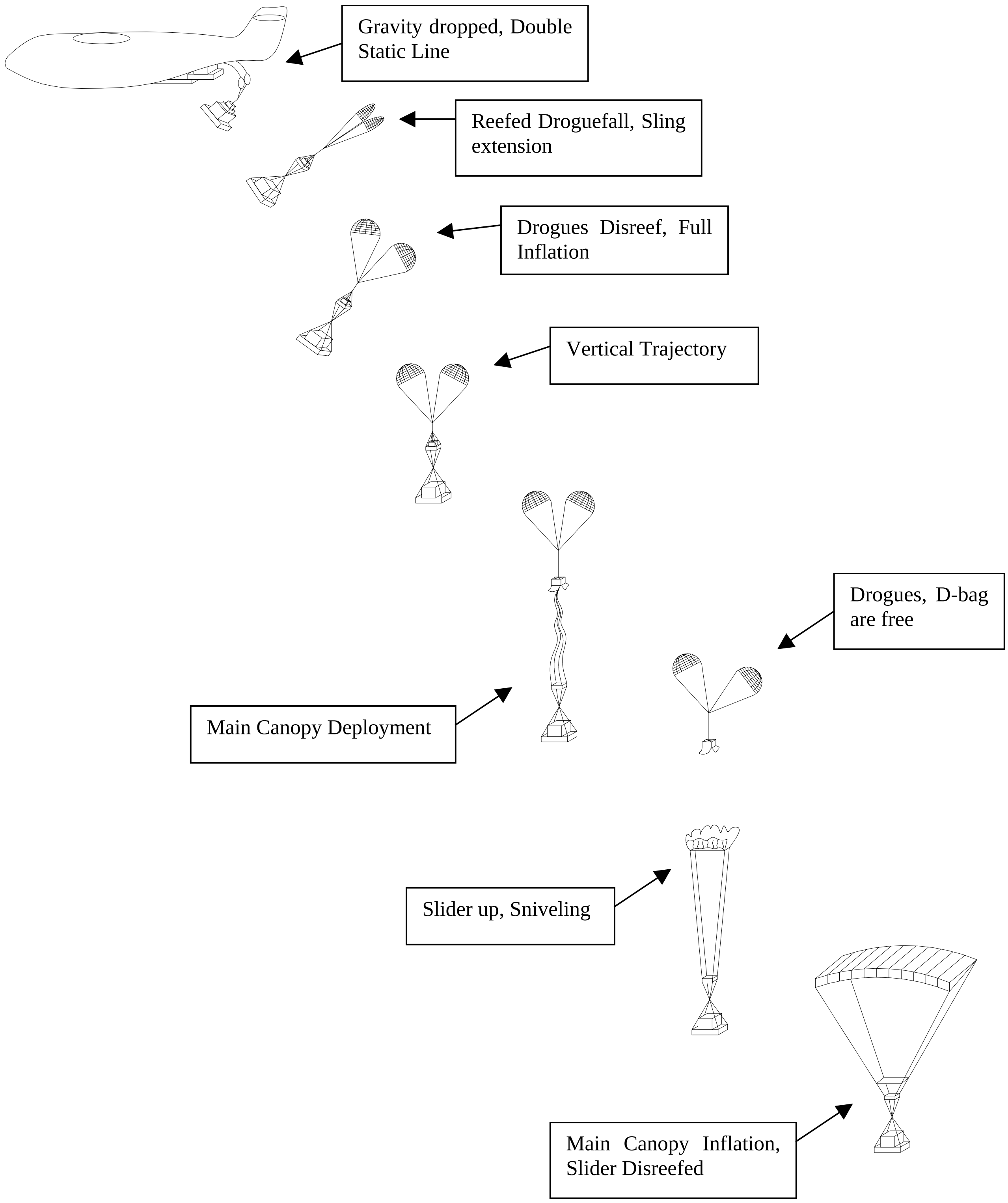

Figure 7: DRAGONFLY Deployment Sequence

III. Design Development

A. Drogue Development

In the past, a significant problem occurred when the AGU was lifted off the payload under the force of two deploying 28 ft. drogues. This event produces an extremely violent action of tug-of-war between the payload and drogues that occurs at payload sling stretch and causes the AGU to undergo multiple severe shocks. Accelerometer instrumentation onboard the AGU observed shocks up to ~45 g's in alternating positive and negative normal directions. Modifications were made to the 28' drogues, which consisted of installing reefing rings for a reefing line approximately 7% of the lower lateral. Cutters were then fitted to cut the reefing line on the drogues, which get pulled on canopy extraction from drogue bag. Staging the full inflation allows sufficient time for a gentle AGU lift-off. The full inflation stage of the drogues, however, needs to be monitored because high loads are encountered. A trajectory simulation of a payload with the reefed drogue configuration for a drop performed on 4-11-05 identified a maximum opening shock of 3.7 g's. Estimations of the inflation rate of the drogues during disreefing were identified by analyzing video time-clocks and the visual percentage of the canopies fully open.

Figure 8: Reefed Drogue-fall, Sling Extension

Following the implementation of the reefing modifications to the drogues, there was an instance where one of the two 28' drogues did not disreef as quickly as the other. There was a difference in time to disreef of approximately 2 seconds between the two drogues. The consequence of this scenario was a much higher than desired dynamic pressure at deployment, estimated from simulations to be 22.3 psf, in which the main canopy suffered catastrophic damage. The deviation in the time to disreef is not something believed to be correctable in the design of disreefing or in the method of packing. Instead this opening characteristic was accommodated in the deployment design by the selection of longer mechanical cutter times. The deployment design was adjusted to achieve a minimum of 4 seconds under fully inflated drogues, to include the 2 seconds of inflation variability observed.

A single 48' quarter-spherical ring-slot canopy has been designed that will achieve the target dynamic pressure of 10 psf at the maximum operating limits. This will be integrated in a test session in the near future.

B. Main Canopy Development

A particular challenge with respect to large Ram-air canopies and slider reefing has been the ability to control the lines and to avoid tension knots. The lessons learned over the course of testing has led to a fine tuned relationship between the slider grommets, number of grommets, size of grommets, location of grommets, line cascading design, and line grouping. The consequences of tension knots in a canopy of this size can be compromising to the mission. The lines involved in the tension knot are no longer loaded as designed, due to the effects of short-lining, whereby the line that makes the knot is effectively shorter since part of the line length is taken up by the knot. A line failure or canopy failure in the area of the knotted line attachment point is common. Depending on where the knot is located and the severity, the canopy may retain navigation ability.

Even though the max payload accelerations are only 4.5 g's, early testing proved some components would suffer a structural failure that was unexpected. The asymmetric opening load design factor for this style of canopy was re-evaluated completely. There is believed to be a wide range in loading rates and loading locations that change even from one drop to the next. As a result from this analysis along with the results from inspections on canopies having made repetitive drops and from drops where tension knots or excessive dynamic pressures at deployment cause damage, several structural areas of the canopy were redesign and / or reinforced.

Efforts were made to improve the line junction efficiency. Tests were conducted of the lower and upper line loops and fingertrap designs. The length of fingertrap and size and number of bartacks helped determine the optimum configurations for each of the line strengths used. The line attachment point design was strengthened and the holding stitches better distributed. Reinforcement patches were added at select locations around the canopy.

In order to facilitate testing at YPG, a Flight Termination System (FTS) was required to maintain a practical safety footprint of the system. Should the canopy become uncontrollable for any reason, a Glide Killer device, which consists of a specially constructed cruciform shaped canopy that is actuated by remote control when needed, was designed to reduce the effective glide of the canopy by causing significant drag to the payload. This technique has been used successfully and reduces the glide by approximately half.

The packing of the main parachute has been refined over time. During recent drops at Yuma Proving Ground (YPG) a hanging tower was used to aid in the packing process. The method of packing includes suspending the risers with canopy hanging below. The benefits of which are perfect uniform line tension and a minimal use of floor space. The canopy is then flaked, folded, and otherwise prepared, and then put inside the deployment bag using conventional Ram-air packing techniques. The risers are lowered as each line stow is made, maintaining uniform tension in the lines. As a result of this process, the main canopy can be packed by a single person in approximately 5 hrs with the assistance of a second person for 0.5 hrs to operate the winch and help fit the canopy into the deployment bag. The packed canopy is then given to another person who properly stows the risers, rigs the control lines to the AGU, rigs the deployment brake cutters, and then attaches the drogue parachute slings. At this point the canopy and AGU become a single assembly which is then rigged to the payload and drogue parachute system, which requires approximately 3 hrs. The system is then ready to be placed on the payload. Recovery and de-rigging procedures are very simple. Once disconnected from the payload, the canopy and AGU can be recovered by a team of 3 people in under 0.5 hrs, assuming no ground obstructions.

Figure 9: Main Canopy Hanging from Tower, Ready for Packing

Figure 10: DRAGONFLY Deployment Bag and AGU Rigged to Load

Observations of the canopy inflation process, even after the slider had come down, identified a struggling of the canopy to achieve full inflation across the whole canopy span. Several vents were then added at select locations on the bottom skin that would allow air in during the inflation process, but once inflated and rigid, would be sealed.

C. AGU Development

During the past year the AGU went through a significant design iteration to reduce its weight by application of a more efficient structural design and the redesign of the actuator assembly. The unit has proven itself quite robust in flight test.

Work will also continue to mitigate the severity of local accelerations experienced by the AGU during the series of deployment events. An AGU of the suspended type is subject to very large accelerations during exit from the aircraft, the drogue transfer event, and opening of the parafoil. Energy modulating tear strips have proven quite effective to maintain control over the AGU during select portions of the deployment. Further, this method is inexpensive and easily rigged into the system.

IV. Flight Test Summary

A. Flight Test Program

Flight testing of the DRAGONFLY system began in March, 2004 at Red Lake in Kingman, Arizona. Initial tests were conducted using remote controlled maneuvers in order to provide data for system identification purposes. Testing has continued over the last year in both Kingman and more recently in the Yuma Proving Ground in Arizona. Although initial tests were conducted using manual commands, subsequent flights testing the autonomous GN&C software occurred starting in May 2004. Major upgrades to the rigging, canopy, GN&C software, and avionics hardware have occurred during the testing period. Payload weights were gradually increased to 10,000 pounds following transfer of the testing to YPG using C-130 aircraft piloted by military personnel. Deployment altitudes were also increased from initial testing at 10K ft. MSL in Kingman to recent deployments at 14K ft. At the time of writing, there have been 38 drops of the DRAGONFLY system, testing all aspects of the canopy, AGU, and flight software design.

B. Steady-State Flight Characteristics

As mentioned above, initial flight tests were conducted to capture the steady-state velocity, glide-slope, and turn rate behavior of the DRAGONFLY system under varying levels of brake and differential toggles. Figures 11 and 12 show results from these tests, including a comparison with the current steady-state behavior of the parafoil simulation model. A reduction in glide-slope with increasing brake setting is clearly evident from the plots, however the loss in performance is very gradual until more than 50 inches of toggle. Tests have been planned to better capture the stall characteristics of the parafoil, but at the limits tested thus far no collapse of canopy cells is evident from video or flight data. Error bars on the L/D flight data are a result of noise on the GPS vertical velocity channel. Comparisons between test data and the simulation model are generally very favorable. Figure 12 shows the speed reduction of the system as the brake setting is increased. This behavior is consistent with the simulation prediction, and implies that within a 100-inch toggle range there exists nearly 20 ft/s variation in flight speed.

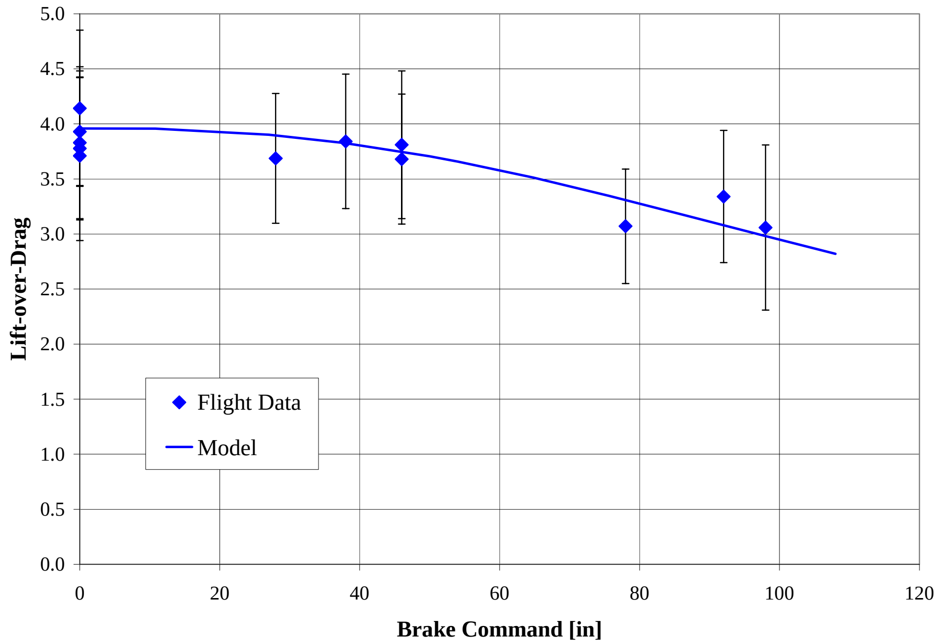

Figure 11. Lift-to-Drag Ratio vs. Brake Setting

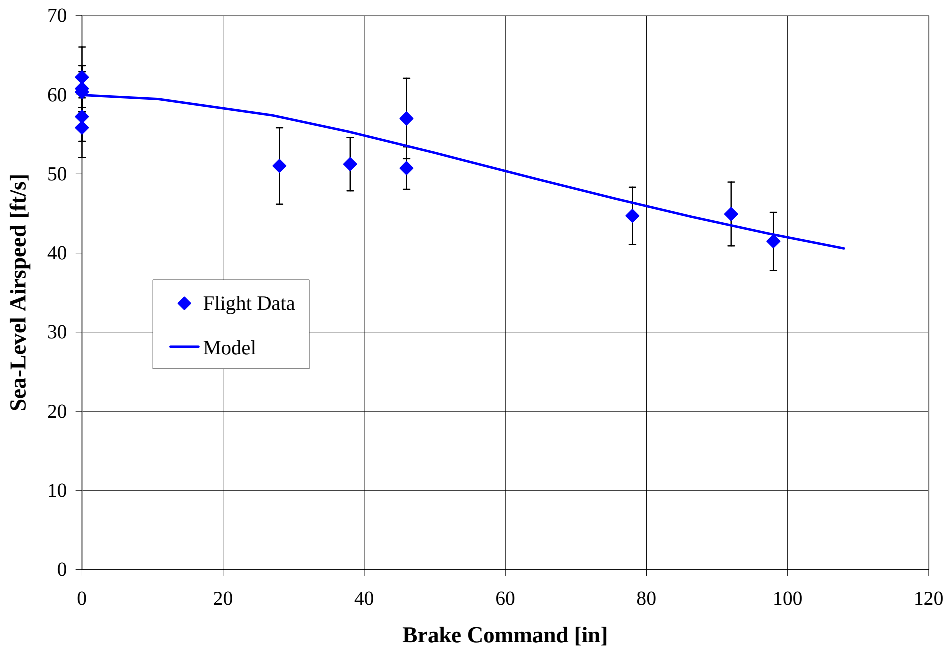

Figure 12. Sea-Level Airspeed vs. Brake Setting

Manual steady-state turn rate tests were also conducted on the DRAGONFLY system. Figure 13 shows the turn rate vs. differential toggle deflection. At the differential toggle limit of 100 inches, the maximum steady-state turn rate for the DRAGONFLY system exceeds 9 deg/s. This level of turn performance compares very favorably with other large scale parafoil systems, and shows that the system is capable of a turn radius of ~100 meters. The reason for the large error bars and non-zero turn rate at zero toggle differential is because of large noise in yaw channel as well as small turn asymmetries in some of the tests. The noise in the yaw channel appears to be a caused by some relative motion between parafoil and payload (with the AGU that holds the GPS navigation system located close to the payload), combined with wind perturbations. In general some small turn rate asymmetries were evident in the tests, likely a function of small differences in the rigging lines. These canopy/toggle asymmetries were relatively small, and are not seen as a problem for the closed loop system because of the heading rate feedback being applied in autonomous mode.

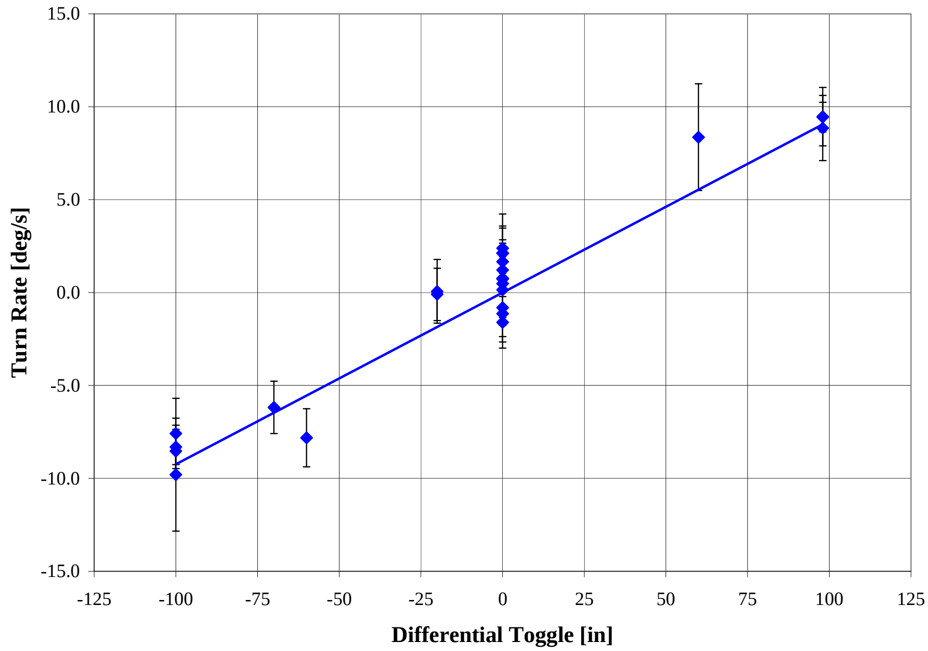

Figure 13. Turn-Rate vs. Differential Toggle Setting

C. Control Toggle Loads

The evolution of the avionics hardware onboard the DRAGONFLY system also included the capability of monitoring motor current and voltage during the flights. Static and dynamic laboratory tests of the motors provided a means to correlate the motor flight readings to specific line loads. Figure 14 shows the outcome of this analysis for a number of flight tests conducted on the system. As the line toggles reach a value of 100 inches, loads exceeding 600 lbs. are evident from the plots. This high level of loading was somewhat unexpected and is the cause for further development of the toggle actuator motors to enable robust and reliable actuation of the toggles to 100 inches of line travel.

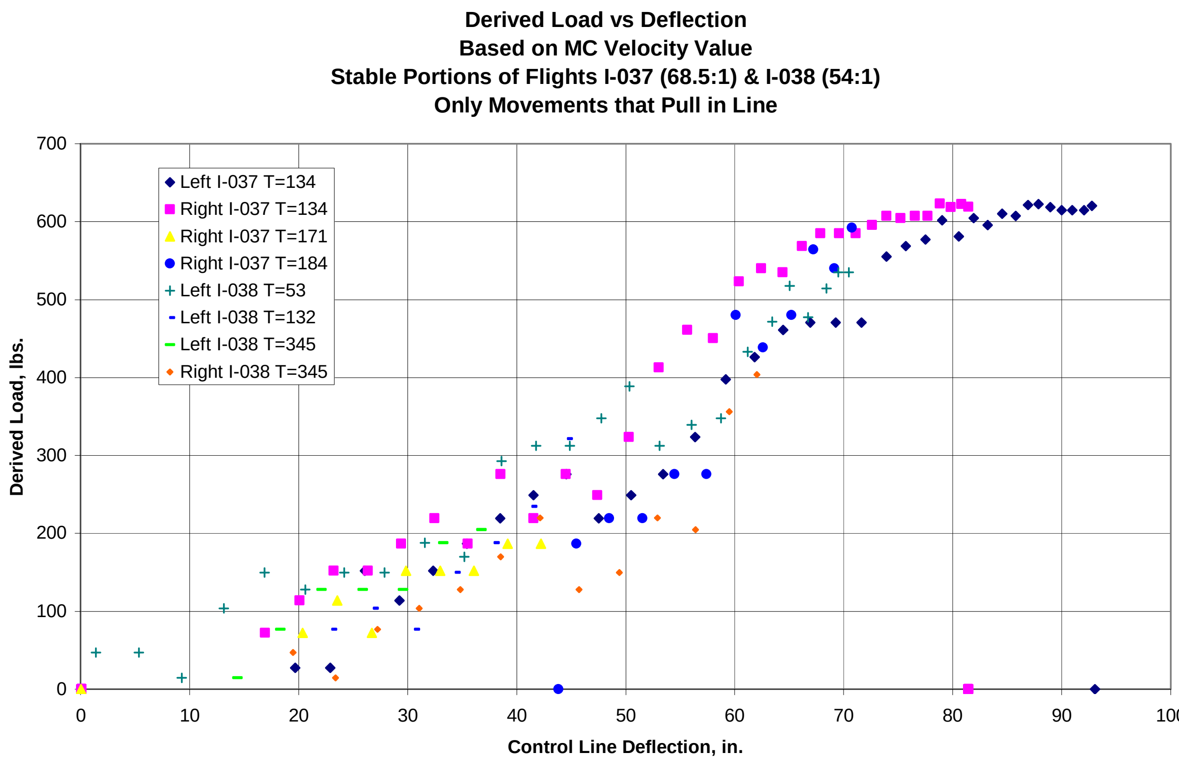

Figure 14: Toggle Line Loading

V. Conclusion and Future Development

There are several known areas of improvement that will be addressed in the near future. One of these improvements will be to incorporate a single drogue design. This will simplify the eventual move to retaining the drogue after deployment and remove a double static line dependency. Upon achieving this, the recoverability of all major components will have been accomplished.

As the program progresses, the primary thrust of continued AGU development will involve the integration of advanced sensors such as Military GPS, LIDAR real-time wind sensing technology, precision height sensors, and an 802.11 based wireless mission planning module.

An observation from recent test sessions shows that a yaw oscillatory motion exists in the payload. The cause is related to the payload angular momentum introduced from a turn in the main canopy and the geometry and coupling of the payload slings. This phenomenon has an affect on compass observations of the AGU. Investigations will be conducted in the future to identify means to lower the coupling forces that introduce this behavior and to increase the damping ability should yaw twisting be present. Future test sessions will study the flight performance of the main canopy in deeper brakes and larger differential toggle settings to expand the flight envelope of the system.

Based on the achievements of the DRAGONFLY system and in continuation of spiral development, Natick has recently begun a project to design and develop a low cost 30K canopy system. The test plan for this program includes a scale up from a modular 8K parachute to a 15K followed by the 30K. A Proof of Concept demonstration is currently scheduled for July of 2005.

Acknowledgments

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