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Autonomous Precision Delivery of 42,000 Pounds (19,000 kg) Under One Parachute

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This paper reviews the latest technological advancements and achievements in large ram-air parachute development with a focus on the advantages provided by modular design and large ram-air parachute fault tolerance. The State of the art of autonomously guided large ram-air parafoil technology has been rapidly advanced. With these advancements it is now feasible to recover "high end" cargo such as rocket boosters by a single ram-air parachute rather than a cluster of conventional ballistic parachutes. A systems engineering approach, integrating robustly designed airborne guidance hardware, flight software, and ram air parachute technology combined with a robust flight test program has resulted in the development of a precision guided ram-air parachute delivery system that is capable of delivering large payloads precisely, softly and safely.

30K MegaFly Drop Test with Deuce and a half truck

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I. Introduction

Airborne Systems North America of New Jersey (ASNJ) under contract with the U.S. Army Natick Soldier Research Development & Engineering Center (NSRDEC), and in collaboration with Wamore and Draper Laboratory for airborne guidance unit hardware and software, respectively, designed and developed an autonomously guided modular parafoil system for Joint Precision Aerial Delivery System (JPADS) 30K Army Technology Objective (ATO). The 9,000 square-foot, 63 cells, 3.25 aspect ratio, 30K parafoil weighs 960 pounds fully assembled. We divided the parafoil into five sections to keep the weight of each component less than 250 pounds so it could be handled by soldiers in the field without material handling equipment. NSRDEC's long term vision for large modular parafoils was to adapt a wider range of payload weights with a single parafoil design. The US Army currently uses round G-11 parachutes for cargo airdrop, and adds an additional G-11 parachute for each 5,000 pound increment of payload weight. It would be beneficial to the Army if additional sections could be added to a basic modular parafoil design as the payload weight increased or to remove sections as the payload weight decreased. This advanced modular concept was not part of the initial parafoil design plans; however it became evident during the program that the modular MegaFly design could be used to evaluate this concept of adding or removing sections based on the payload weight.

The airborne guidance unit is designed to be suspended between the payload and parafoil system. Airborne Systems considers the suspended AGU design to be preferable to the payload mounting approach for many reasons, including payload compatibility and issues related to AGU and payload relative yaw. Avionics in the 30K AGU is common to the platform used Airborne Systems family of JPADS systems (MicroFly, FireFly, and DragonFly) as well as the US Army's 2K and 10K JPADS systems. As such the avionics have been rigorously tested over more than 1,000 actual airdrop tests and has also been subjected to comprehensive environmental and EMI/EMC testing. The available navigation sensors include an IMU, magnetic compass, and commercial GPS. Two 15 Hp motors driven by a 36-VDC sealed lead acid battery system are used to deflect the parafoil's control surfaces.

Through the course of the MegaFly flight test program, a variety of canopy control techniques were explored within the operating specifications of the AGU. Initially the canopy was flown with control surfaces concentrated near the wingtips, and then inboard control was added as a 2nd stage. These "flaps" were eventually combined with the wingtip steering controls resulting in "flaperons" where the majority of the canopy trailing edge is under control for the duration of the flight. In addition, both the Draper Lab and Airborne Systems GN&C flight software implemented "braked control" where the system flew with trailing edge deflected during the terminal portion of the flight to reduce true airspeed and improve landing survivability. In this configuration, turns were made by extending the opposite toggle rather than retracting on the side of the turn.

The MegaFly is deployed directly outside the aircraft without a stabilizing drogue stage at altitudes from 15,500 feet MSL to 24,500 feet MSL and dynamic pressures up to 75 pounds per square foot. While this method of deployment has proven viable, three (3) of forty (40) test drops have resulted in significant damage to the parafoil structure, cloth, or suspension lines which negatively impacted flight performance, but did not result in a total malfunction. In these conditions we have demonstrated that the robust AGU and flight software, combined with effective mission communications and ground remote control intervention can be utilized to navigate the MegaFly to a safe and controlled landing, at the designated impact point, or a suitable alternate. As such, we believe that the reliability of these parafoils coupled with our sophisticated guidance system has expanded end use possibilities.

II. Modular Parafoil Design

There are several advantages to a modular canopy design for large parafoils. Sections of the parafoil can be quickly replaced instead of taking an entire parafoil out of commission for any period of time. The burdens of material handling during manufacturing and repair are substantially reduced. We confirmed through testing that sections from two different parafoils can be interchanged without impact to system performance The MegaFly was successfully flight tested with its center section removed, which reduced the canopy area, aspect ratio, and cell count to 6,500 square feet, 2.5, and 50 respectively and consequently reduced the minimum payload weight threshold to 15,000 pounds. Based on these preliminary achievements a more ambitious effort to expand the maximum payload weigh to 42,000 pounds was undertaken. Two modular approaches converting the 30K MegaFly to a 42K GigaFly were successfully demonstrated. First the center section of the 30K was increased to provide the additional canopy area to support the greater payload weight. Second the original 30K center section was used with higher aspect ratio left and right wingtip modules. The flexibility and robustness of both the Draper Lab and Airborne Systems GN&C software permitted these new canopy configurations to be integrated rapidly and resulted in autonomous navigation on the maiden flights. Our testing has proven that modular parafoils can be designed to operate for a wide range of payload weights, wing-loading, and deployment conditions.

A. 30K MegaFly

The original five (5) section, 63 cell, 3.25 aspect ratio 30K MegaFly parafoil was designed for payloads from 25 to 30 thousand pounds. Thirty-five (35) drop tests were performed between October 2006 and September 2008. Payloads, as low as 20,000 pounds, were successfully tested. These tests confirmed that the useful payload range for the 30K MegaFly is actually 20 to 30 thousand pounds. Figure 1 is the 30K MegaFly in flight.

Figure 1 – 30K MegaFly in flight

B. 15K Four Section MegaFly

The removal of a section from the MegaFly to create the 15K turned out to be a simple task. The resulting 6,500 square foot, 50 cells, 2.5 aspect ratio parafoil was successfully airdropped with 18,000 pounds. This four section parafoil should cover the weight range from 15 to 20 thousand pounds. Figure 2 is of the 15K Four Section MegaFly in flight.

Figure 2 - 15K Four Section MegaFly

C. 42K GigaFly

The next challenge was to increase the payload capacity of the parafoil. A capacity of 42,000 pounds was chosen since this covers the majority of payloads dropped for the US Army. The MegaFly would have to be made larger. We determined that adding cells amounting to 1,400 square feet would achieve the performance goal. A conservative approach was used for the first 10,400 square foot GigaFly. The 1,400 square feet was added to a MegaFly center section resulting in the Square Center GigaFly. This increased the center section by eight (8) cells for a canopy total of 71 cells and an aspect ratio of 3.7. Compatibility issues of section design, line geometry, slider design, and ease of manufacturing were all important factors requiring consideration. The 42,000 pound payload also added to the complexity of this design. Three successful drop tests have been completed on the Square Center GigaFly. The highest and heaviest flight was at 23,500 feet MSL with a 40,000 pound payload. Figure 3 is of the Square Center 42K GigaFly in flight.

Further refinement of the 42K Square Center GigaFly rendered a second generation 42K parafoil. We chose to redesign the tip sections for this version. Approximately 700 square feet in six (6) cells were added to each tip section increasing the planform ellipse to an aspect ratio of 4.0 and the number of cells to 75. The goal was to increase the system glide ratio. We believe that the resulting 10,400 square foot High Aspect Ratio 42K GigaFly is the largest high aspect ratio parafoil ever successfully deployed and flown. Figure 4 is of the High Aspect Ratio 42K GigaFly in flight.

Figure 3 - Square Center 42K GigaFly

Figure 4 – High Aspect Ratio 42K GigaFly

III. Fault Tolerance and System Reliability

Over the past 5 years Airborne Systems has been engaged in intense development of JPADS technology on a number of different platforms, both independently and in collaboration with other companies and with the support of the US Army and other customers. As a prime contractor and lead systems integrator, Airborne Systems has pursued a “family of systems” approach and employed a systems’ engineering strategy which takes maximum advantage of lessons learned and matured technology on one platform to exploit them on another. As such, overall system reliability and fault tolerance of JPADS systems has improved dramatically over the past few years. Proven structural integrity of the parachute and AGU hardware, refinements to the flight software logic, and the ability for intervention by ground personnel using remote control have combined to yield a delivery platform that is both highly reliable and also tolerant of failures to portions of the system. While remote control intervention may not be a viable solution to the US Army’s fully autonomous resupply requirement for JPADS, it does have direct applicability to recovery of other vehicles and payloads where a ground recovery crew is already required to support the mission.

A. Deployment System

Building from experience with the 1,025 and 3,500 square feet FireFly and DragonFly parafoils, these modular 6,500 to 10,400 square foot canopies are the largest ram-air systems to be successfully deployed without pyrotechnics. Airborne Systems' patented multiple grommet retained slider allows these large parafoils to act as their own drogue. While some were skeptical that this simple and elegant technique was scalable to MegaFly and GigaFly, the viability of the multiple grommet retained slider was proven early in the test program. On three (3) occasions we experienced deployment issues that resulted in significant damage to the parafoil where the AGU was used successfully to compensate for that damage.

The parachute system has been proven structurally sound up to the worst case drop conditions of maximum weight, altitude, and speed. Therefore, canopy damage can be best attributed to packing techniques which evolved through the duration of the test program. Airborne Systems was fortunate to have a large fleet of test assets, a well planned flight test program, and the freedom to explore improvements to the packing procedure with the confidence and support of our US Army customer. New techniques emerged from traditional methods which both dramatically improved the consistency of the parafoil inflation sequence and reduced packing and rigging time. A byproduct of this experience was the realization that the AGU and software were capable of compensating for significant damage to the parafoil when it occurred.

B. Ram-Air Canopy

Before this program our ram-air technology was at the level where we knew this would be successful but we did not know how much more performance and flexibility we could achieve with this canopy. It was not until we studied the structural issues caused by problems found in testing that we realized the full extent of both the parafoil and AGU capabilities.

Figure 5 shows a 20 foot tear in the bottom skin of one section along with a blown top skin in the same section and a 30 foot long top skin tear in the center section. Figure 6 shows three blown top skins on the center section. Both parafoils pictured were flown under control to safe landings. Though the damage is significant with respect to the total area of fabric involved and required repair, the canopy overall remains structurally sound, controllable, and flying at near nominal performance.

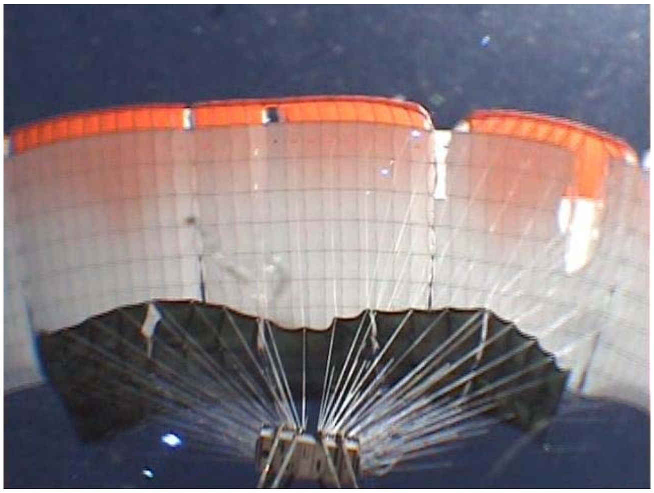


Figure 5 – 30K with significant damage

Figure 6 – 30K with damage

Depending on the 30K or 42K configuration, each parafoil has 4 to 6 miles of suspension line. The complex line system required for load management and directional control of each modular parafoil section provides structure redundancy. The loss of a few lines is inconsequential.

The High Aspect Ratio 42K parafoil has eight (8) lower control lines. In Figure 7 note that two (2) of the lower control lines are broken. Our AGU was able to bring this load to a safe controlled landing.

Figure 7 – High Aspect Ratio 42K GigaFly with two broken control lines

We have eliminated the problems that have caused this kind of damage while gaining a new appreciation for the design margins of the parafoil and the means by which the AGU and flight software can be used to effectively handle fault conditions regardless of the source of parafoil damage i.e. care and maintenance, enemy intrusions, improper rigging, we know that we have a significant margin to overcome and compensate to ensure mission success.

C. Airborne Guidance Unit and Flight Software

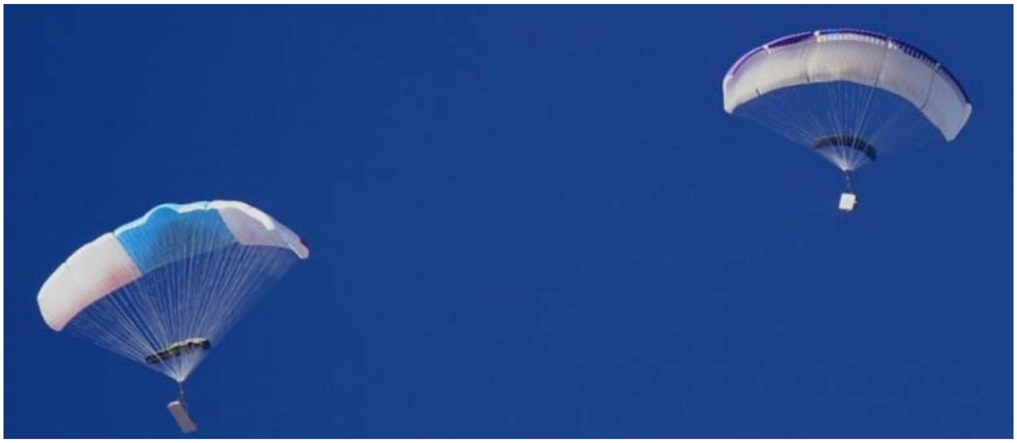
The flight software and airborne guidance unit are the brains and brawn of every JPADS system. Designed and manufactured by Wamore, the 30K/42K AGU also broke new ground and advanced the state of the art to provide a light weight but powerful control system that was suitable for the suspended configuration. The AGU performed nearly flawless throughout the test program. A single total malfunction was experienced when an out of sequence release of the AGU from the payload early in the deployment caused the AGU to strike the payload/platform with excessive force, inducing a power interrupt which reset the flight computer. This failure mode was addressed for subsequent drops with minor changes to the parachute restraint and flight software.

Both the Draper Lab and Airborne Systems flight software was effective in compensating for the parafoil damage described above. While some canopy damage scenarios were handled autonomously by the software, the ability to intervene from a ground control station has proved critical. A telemetry and health status downlink combined with an intuitive graphic display has empowered ground support and mission controllers to make real-time decisions to ensure the success of the mission and the safety of the range in the event of a problem. Remote control intervention was used on 6 flights during the test program.

IV. Conclusion

The forty (40) drop tests performed under this NSRDEC 30K ATO program have proven that autonomous precision delivery of 15 to 40 thousand pound payloads under a single modular parafoil is a viable cargo delivery system with applicability beyond US Army resupply. Results on the 30K program are further reinforced by the successful application of the technology at 10K, 2K and 500-lb scale where successful test drops now number well over 1,000 and hard, statistically significant data exists to accurately quantify reliability and fault tolerance. JPADS utilizing a single large ram air parafoil as the primary decelerator is mature, operationally suitable, and effective. We believe it should be considered as an alternative to conventional ballistic recovery for high value payloads (such as military or space vehicles) where high altitude or offset release conditions, and precision soft landing are mission requirements.

Square Center 42K GigaFly and a 30K MegaFly sequential drop



Square Center 42K GigaFly and a 30K MegaFly sequential drop

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