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The Dragonfly 4,500 kg Class Guided Airdrop System

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The *Dragonfly* is a 3500 ft^2 ram-air, precision airdrop system being developed under the Army JPADS ACTD program. The system; which includes an innovative main canopy, hardened airborne guidance unit (AGU), and autonomous GN&C algorithms; has been developed under a multi-contractor effort and managed by the Natick Soldier Center. *Dragonfly*'s canopy was designed to give maximum gliding performance while minimizing system cost. Using standard manufacturing techniques and low-cost materials, a glide-ratio of nearly 4:1 was achieved. The system's AGU consists of two small, high-powered motors that operate the parafoil control lines, as well as an avionics suite to generate trajectory information for the flight software. The on-board GN&C algorithms have been developed to accommodate a low-cost processor by utilizing very simple command logic and a table driven trajectory profile for final-descent maneuvers. The flight software on-board the *Dragonfly* has also been tightly integrated with previously developed PADS mission planning software. Test drops of the Dragonfly have been conducted over the last year to evolve key components of the system and to evaluate the autonomous flight performance. The *Dragonfly* system had routinely demonstrated landing accuracies of 200 meters in flight tests, with a recent best of 23 meters.

Nomenclature

ACTD	Advance Concept Technology Demonstration
AGU	Airborne Guidance Unit
CEP	Circular Error Probable
DZ	Drop Zone
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
JPADS	Joint Precision Airdrop System
KIAS	Knots Indicated Air Speed
LIDAR	Light Detection and Ranging
MSL	Mean Sea Level
NSC	Natick Soldier Center
PADS	Precision Airdrop System
PGAS	Precision Guided Airdrop System
PID	Proportional, Integral, Derivative
R/C	Remote Control
SBIR	Small Business Innovative Research
YPG	US Army Yuma Proving Ground

I. Introduction

A key element of the U.S. Army's Joint Precision Aerial Delivery System Advanced Technology Concept Demonstration (JPADS ACTD) is the development of airdrop system capable of accurately delivering 10,000 lb. loads from a deployment altitude of 25,000 ft. The *Dragonfly* system is one candidate for the ACTD that was designed by a multi-contractor team that includes Para-Flite, Inc. (canopy, rigging, extraction system), WAMORE Inc. (airborne guidance unit), RoboTek Engineering (avionics), and Charles S. Draper Laboratory (GN&C algorithms and software). The *Dragonfly* system's main goal was to demonstrate a low cost solution to cargo re-supply that offers high precision and large offset capability. Evolution of the many components of the system has been on-going over more than the last year with drop tests conducted at facilities at Kingman Red Lake Drop Zone and the Yuma Proving Ground (YPG). The *Dragonfly* system is being designed to comply with Air Force and Army airdrop infrastructure, including tight integration with the existing Army Precision Airdrop System (PADS) mission planner software.

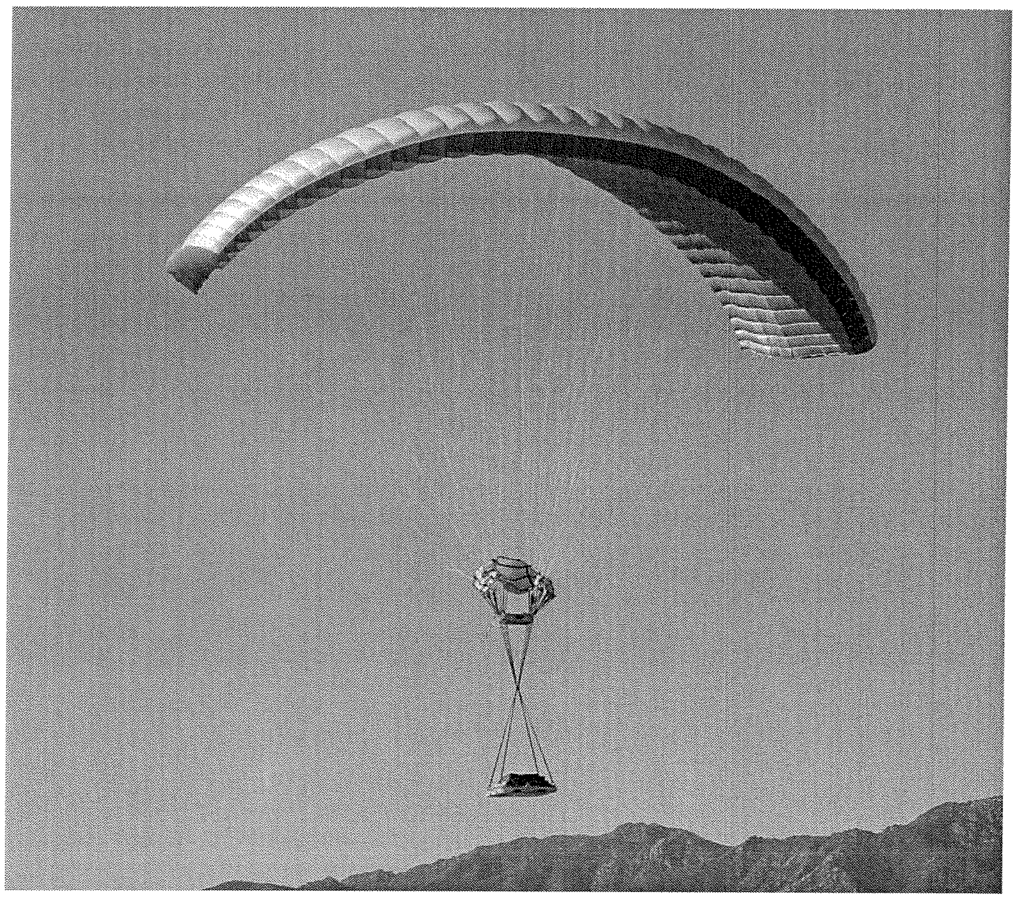

Figure 1 – *Dragonfly* in Flight at Kingman, Arizona

II. Design Requirements

The JPADS ACTD has many stringent requirements for the 10K airdrop system that have been outlined in an Army draft Capabilities Development Document. Chief among these is the capability to reliably land to within a 100 meter CEP of a designated target from an initial horizontal offset of at least 3-5 km at 25,000 ft; a goal is to achieve this performance from offsets greater than 15 km. The system must be capable of being deployed at exit speeds up to 150 KIAS to ensure compatibility with most cargo aircraft types. The system must be usable with ground winds as high as 17 knots; 25 knots is a goal. The *Dragonfly* design is also constrained by significant cost and re-usability goals: total system cost should not exceed $6 per pound of payload cargo, the number of expendables should be minimized, and all re-usable components should be retained after deployment. The rigging system was also designed to be compatible with a variety of payload configurations and airdrop platforms.

III. Main Parafoil Canopy

The *Dragonfly* main canopy is designed for high glide ratio performance, but uses conventional manufacturing techniques to maintain low-cost production. The canopy has a 3.2:1 aspect ratio and an elliptical planform to help achieve the desired glide characteristics. Tests indicate that the system is capable of a glide ratio of nearly 4:1. The main canopy has a span of 100 ft and a chord of 35 ft. The system was designed for a maximum wing loading of 2.88 lb/ft^2, which corresponds to its design all-up weight of 10,000 lbs (4500 kg). The main canopy itself weighs only 350 lbs, and is composed primarily of 1.5 and 1.9 oz. nylon fabric with reinforcements at each line attachment point to prevent tearing. The canopy is actually composed of 35 separate cells, with rib spacing varied from the center-line to the wing-tips to ensure full pressurization. Figure 2 shows two views of the system in flight, and gives a good perspective on both the canopy ribs and the rigging geometry.

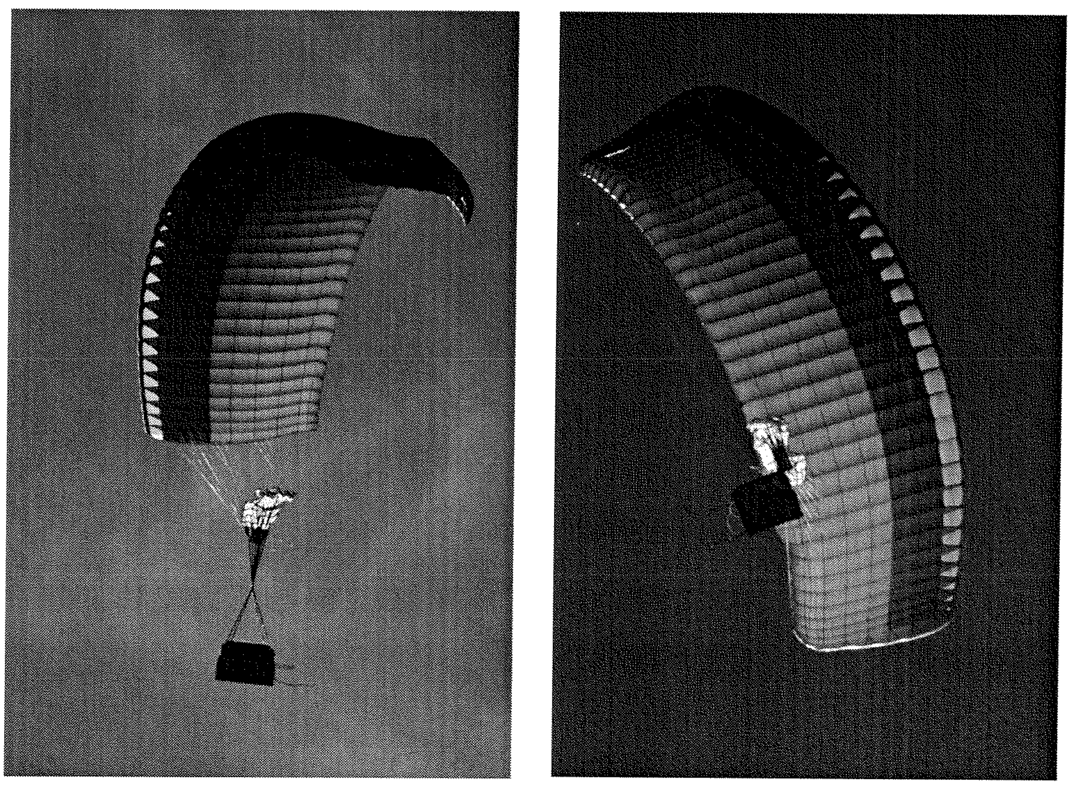

Figure 2 – *Dragonfly* in Flight at the Yuma Proving Ground

The *Dragonfly* canopy has a cascading line configuration (and resulting wing surface to suspension line area ratio) modeled after successful, smaller personnel canopies; with line material composed entirely of Spectra for cost savings purposes. Control of the parafoil is directed by two toggle lines that run from the trailing edge of the canopy down to the motors in the AGU. *Dragonfly* is capable of turn rates exceeding 9.0 deg/s by differentially pulling and releasing the control lines – thereby distorting the surface of the canopy in a similar fashion to flaps on an aircraft. Unlike an aircraft, turn control is dictated by the drag differential between the two slides of the canopy, and the resulting skid generated by the yaw torque. The skidding, or side-slip, causes the canopy to bank, generating a steady-state heading rate change. Control toggles, when pulled in tandem, can be used as brakes for the system with a resulting loss in flight speed.

The main canopy exits the aircraft in a fully packed configuration and then is inflated for forward flight (the details of which will be described in the Extraction section). The main canopy reefing and inflation process is controlled via a unique multi-grommet slider design (Figure 3). No pyrotechnic cutters are used to control the deployment of the parafoil; however, timed pyrotechnic cutters are used to release the trailing edge lines once the parafoil is fully inflated. The trailing edge is retracted during the parafoil opening to reduce the tendency of the parafoil to "surge" during the early stages of inflation as well as to isolate the AGU actuator assembly from the opening shock loads. The control toggle lines are actually only connected to the outboard 1/3 of the canopy's trailing edge lines to minimize motor torque loads and power requirements.

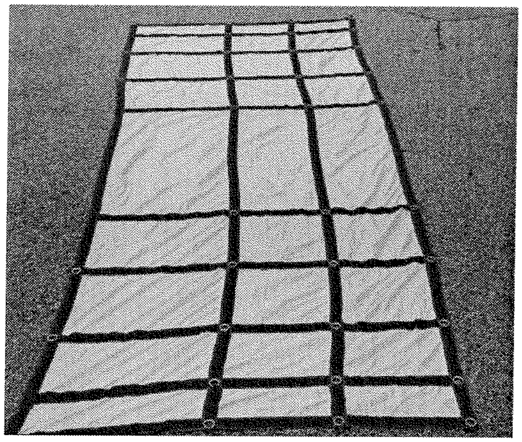

Figure 3 – *Dragonfly* Slider

A host of cost-saving measures, retained from years of experience with personnel canopies, have been taken with the *Dragonfly* parafoil to reduce the construction, sewing, and rigging time of the canopy. The *Dragonfly* canopy can be pro-packed over a hook/roller (see Figure 4) and completely rigged in a single day, within a space no larger than the rigging lines. Rigging the canopy for flight is a staged procedure. Initially the canopy is suspended by its risers to allow for uniform line tension during packing. While suspended, the parafoil is flaked, folded and prepared for insertion into the deployment bag. Figure 5 shows the canopy before and after being packed into the deployment bag and rigged to the AGU. The completely stowed canopy, firmly attached to the AGU, makes for an extremely tight package with easy integration to a variety of payload platforms.

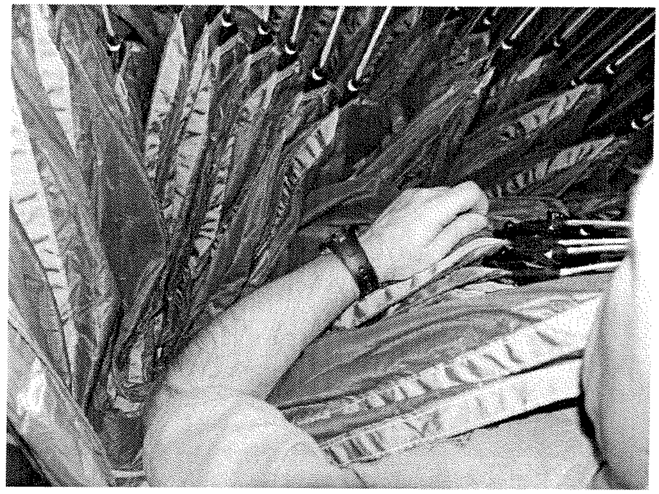

Figure 4 – Pro-packing the Canopy – Flaking

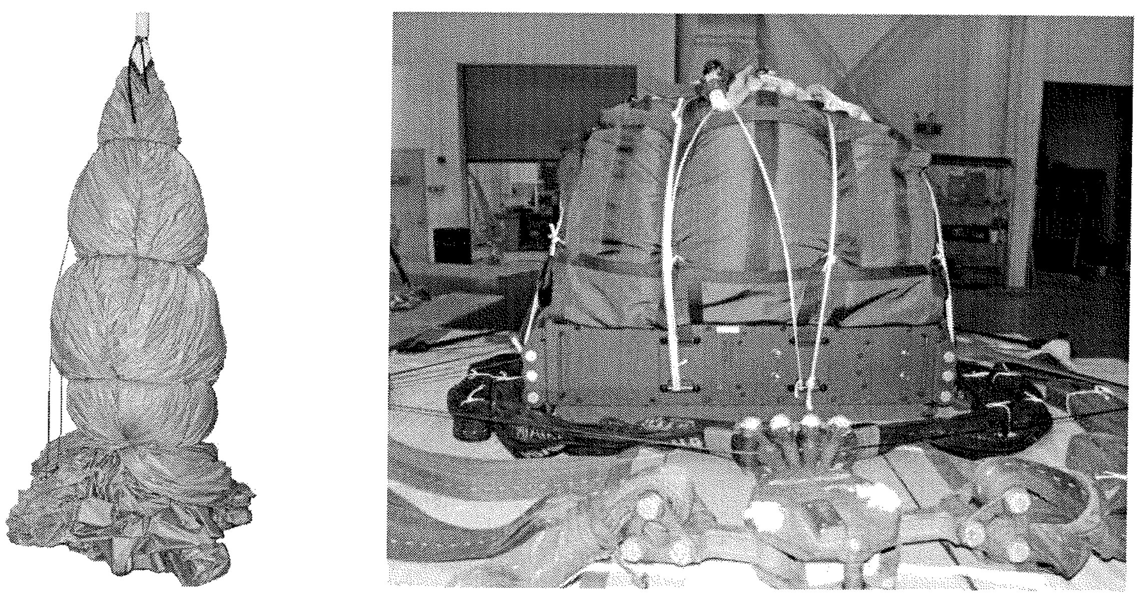

Figure 5 – Canopy Pre and Post Deployment Bag Packing

IV. Extraction System

The *Dragonfly's* complete deployment sequence is shown in Figure 6, with the various stages from aircraft exit to main canopy inflation. The system is extracted from the carrier aircraft using two release-away static lines attached to a pair of Army 28 ft. ring-slot drogue parachutes. The drogues are reefed to attenuate the opening shock and limit the pitch oscillatory motion of the system. Once the drogue parachutes fully inflate, the load is allowed to decelerate for approximately 10 seconds, allowing the payload to achieve a nearly vertical orientation at a dynamic pressure safe for main canopy deployment. A timed drogue release mechanism is used to cut a set of Kevlar release straps, allowing the deployment bag to be pulled from the AGU and the main canopy to be freed from the bag. The deployment bag is retained with the drogues and descends harmlessly to the ground where it is recovered for re-use.

The full inflation of the main canopy is held in check for a short time, by the slider described above, in order to ensure sufficient airflow into the cell inlets for more uniform pressurization. The span-wise inflation of the canopy forces the slider down the rigging lines, where it collects above the AGU. Once the canopy fully inflates, the cutters are fired, releasing the trailing edge lines, and the canopy reaches its steady-state flight condition.

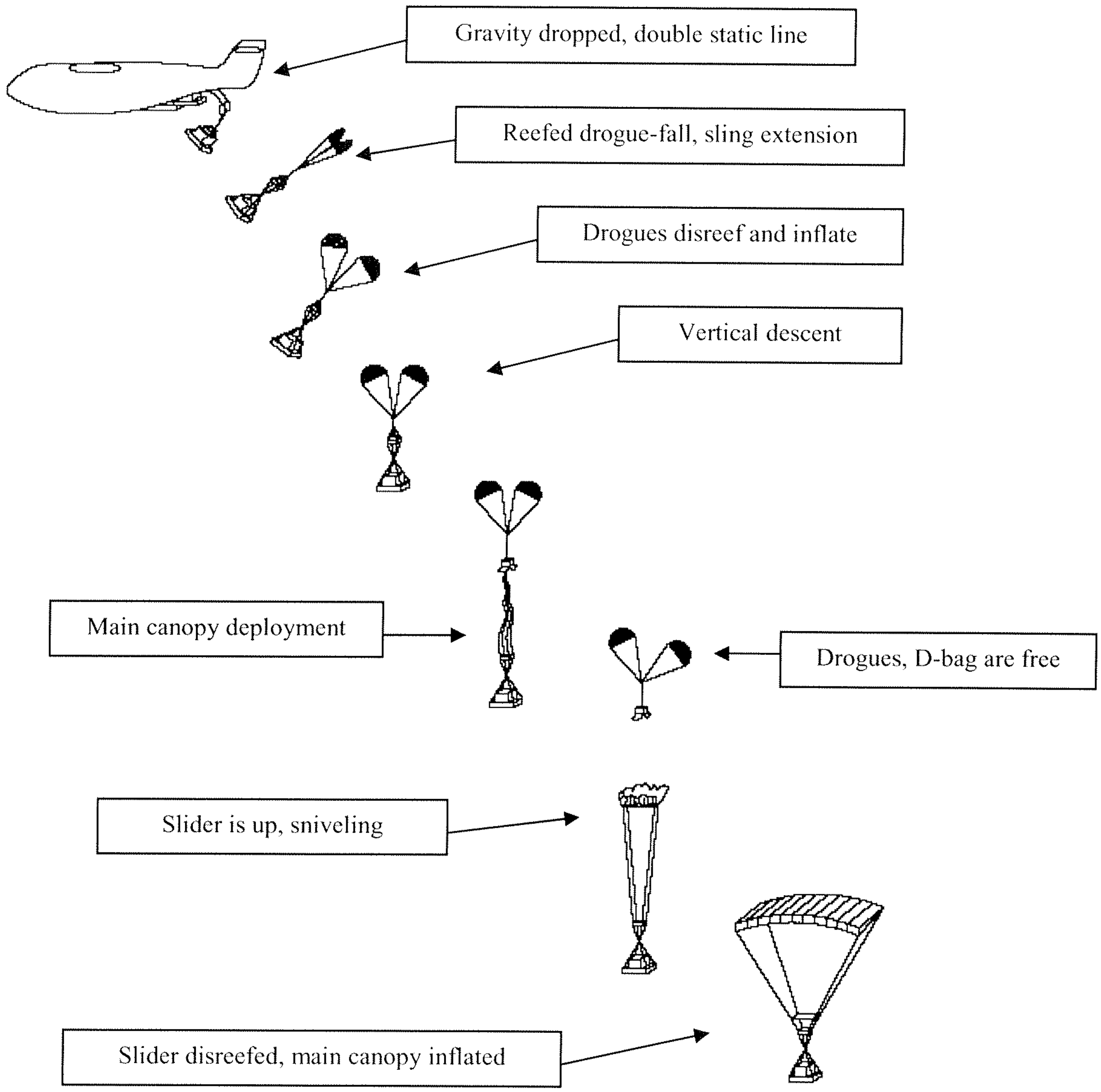

Figure 6 – *Dragonfly* Deployment Sequence

The dual 28-ft drogue extraction chutes were originally selected based on availability and cost, however they were never intended as the final design but merely as a means to allow convenient testing of the system. The terminal descent of the system under the drogue pair is 13.6 psf, 36% higher than the main canopy's target deployment dynamic pressure of 10 psf. The use of the drogue pair limited the maximum deployment altitude and speed, and required significant effort to engineer the reefing stage of the drogues to attenuate the inflation loads. Work has already progressed on the development of a single, 48-ft drogue to deploy the main canopy. The new drogue parachute will permit use of a single release away static line, be compatible with the C-17 and C-130 cargo aircraft, simplify the *Dragonfly* rigging, and improve the dynamics of the exit and deployment sequences. Ballistic tests confirming the deployment and steady-descent characteristics of the 48-ft drogue have already been accomplished (see Figure 7 for fully inflated chute picture). In addition, the single drogue has been successfully used to deploy a 3000 ft^2 parafoil canopy under similar loading conditions as the *Dragonfly* system. Future efforts will be focused on a drogue retention rigging scheme that reduces the overall operational cost by enabling the system to preserve the deployment chute for re-use.

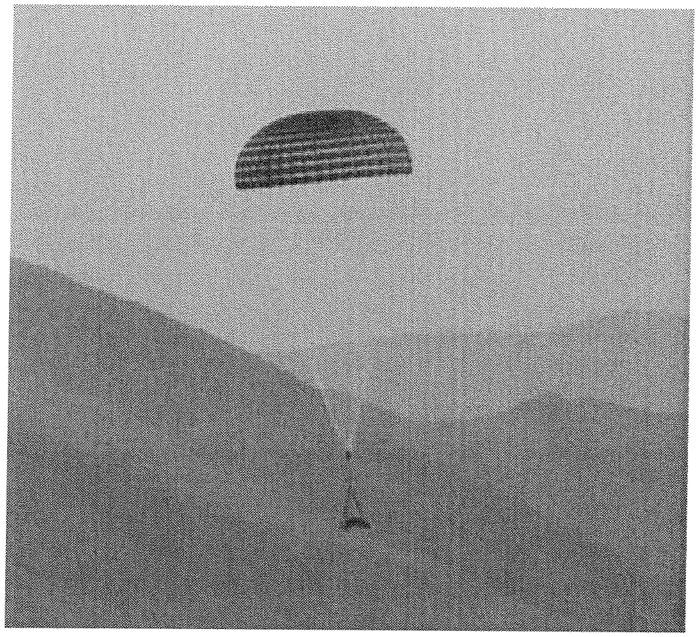

Figure 7 – *Dragonfly* 48-ft Single Drogue

V. Airborne Guidance Unit and Avionics

Dragonfly's airborne guidance unit (AGU) is suspended at the confluence point between the payload and the canopy (see Figure 1 for best view). This configuration simplifies the interface between AGU and canopy, as well as providing a very flexible attachment point for a variety of payload sizes and shapes. The AGU (shown in Figure 8) is constructed of heavy gauge aluminum to ensure survivability during landings, but weighs only 175 pounds and has the same area footprint as the main canopy deployment bag. Handles on the side of the case make the system easily transported by two individuals. The AGU contains a pair of servo motors with worm gear reducers powered by a 24 VDC battery, a dual channel motor controller, and a 12 VDC battery to power the avionics. The control line interface with the canopy trailing edge rigging lines is designed to make detaching the AGU from the canopy simple and quick, even in severe landing conditions. The AGU's control line reels are readily accessible from the exterior aft face of the unit. When the system is completely packed, the control lines exit the parafoil deployment bag and connect directly to the AGU reels. The rigger can use toggle switches on the AGU to adjust the motor reel position as necessary for the proper control line geometry; and it is not necessary to power up the whole AGU to do this, nor is special equipment necessary.

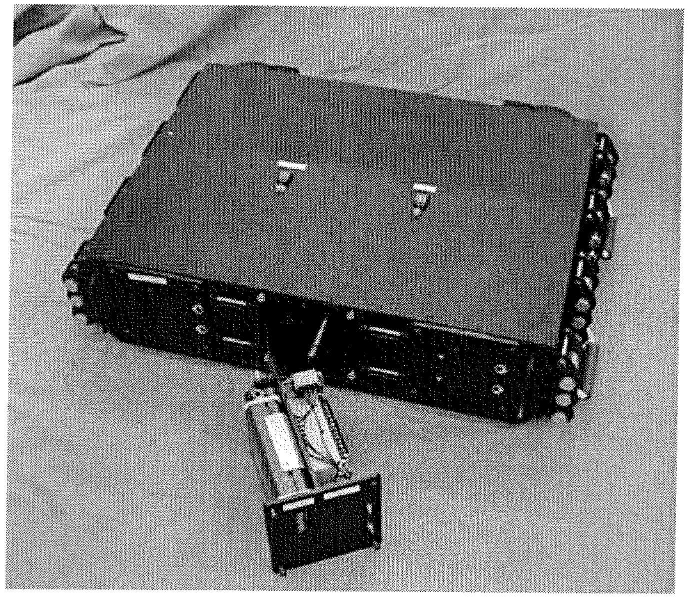

Figure 8 – *Dragonfly* AGU with Avionics Tray

The avionics are mounted in a forward-facing tray which can be removed and reinstalled even when the parafoil is rigged on top of the AGU. Figure 8 shows the AGU with the avionics tray in the foreground, removed. The avionics for *Dragonfly* consists of a 44.2 MHz 8-bit microprocessor with 1024 KB static RAM and 8 MB serial flash memory, a commercial dual-antenna GPS receiver, and a 900 MHz spread spectrum RF modem. The dual antenna GPS provides heading and heading rate information, in addition to position and the velocity vector with respect to the ground provided by standard single antenna GPS receivers. The RF modem is used for transmitting system state data during flight tests, and it also permits manual remote control during test, should this be necessary. Figure 9 shows a close-up of the avionics tray. The front panel connector is used to load flight software, to load mission information prior to flight, and to download telemetry data which has been logged to flash memory during a flight test.

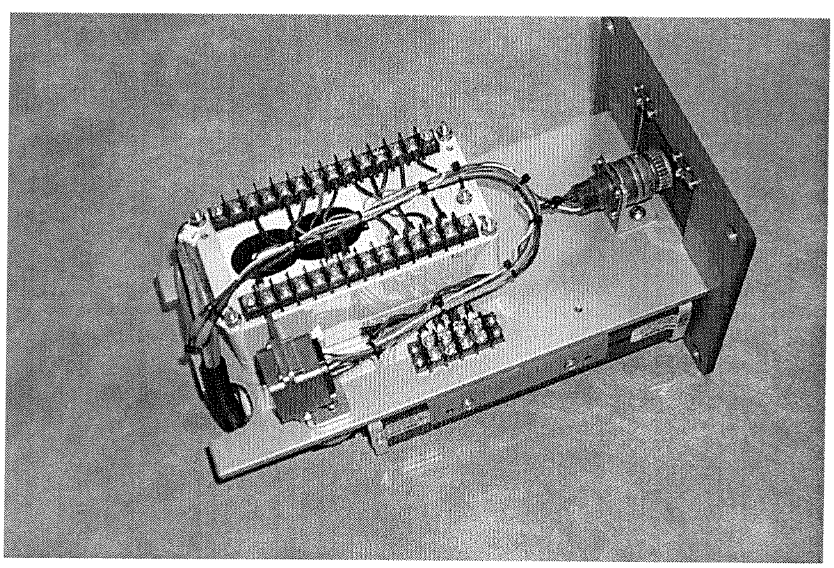

Figure 9 – *Dragonfly* Avionics

VI. Navigation, Guidance and Control Strategy

The complete guidance, navigation, and control flight software operates on the *Dragonfly*'s small 8-bit processor. A broad outline of the GN&C processes can be illustrated in Figure 10, which is a top-level overview of the software interfaces. The mode controller dictates some of the higher-level functions of the software by specifying discrete modes (and transitions). The modes currently being used by the GN&C software are ***Initialize***, ***Preflight***, ***Trimflight***, ***Autoflight***, ***Manual***, and ***Terminal***. These modes are used to sequence the activities of a normal autonomous flight and direct changes to guidance.

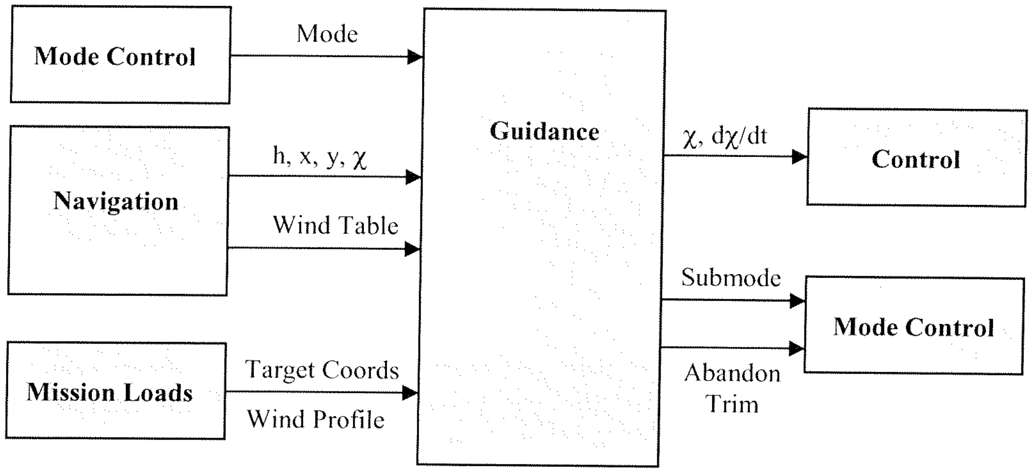

Figure 10 – Flight Software Top-Level Block Diagram

The ***Initialize*** mode happens prior to flight and is used to specify the mission-based input conditions to the system. This procedure is handled by an operator creating a mission file for the drop using the GUI interface developed for the PADS mission planning software. The main information contained in the mission file is the target coordinates and a set of wind velocities specified at discrete altitude layers (nominal wind table), which are both passed to guidance in order to create a "wind-relative" target position. There are a number of additional GN&C software parameters controlled using the system mission file, all of which can be adjusted using the PADS software. The high fidelity wind forecasting capability offered by PADS can vastly improve system performance because it provides the nominal wind table used by the system, and it affects the initial target offset position estimated by the GN&C software to compensate for wind.

The system is in ***Preflight*** mode from aircraft exit (when the AGU is powered up) until the main canopy reaches complete inflation and is ready for flight. The end of this mode is sensed by monitoring sink rate, since there is a pronounced reduction in vertical velocity following the canopy's disreefing. The mode controller then transfers to ***Trimflight***, and the system operates to null out any initial turn rate bias caused by rigging asymmetries. Actual autonomous flight begins following the trimming mode and is called ***Autoflight***. There are actually several sub-modes within Guidance during ***Autoflight*** that will be discussed later. After the system has proceeded toward the target and has reached a user specified altitude, ***Terminal*** mode is set and the canopy is commanded to flare for landing. ***Manual*** mode is not used in general autonomous operation, but is available in case of problems with the canopy or the flight.

The Navigation for *Dragonfly* is accomplished using the 2-antenna GPS receiver that generates position, velocity, and heading data with respect to the ground. The GPS receiver sends standard National Marine Electronics Association (NMEA) data packets containing this data to the *Dragonfly* navigation software. Navigation provides Guidance and Control with the north and east coordinates of the vehicle with respect to the target, altitude relative to the ground, heading, and heading rate. Using the GPS estimated ground speed, together with a relatively simple analytic model for the parafoil airspeed, the navigation algorithm also estimates wind velocity at the current altitude.

Navigation uses the estimated wind velocity to update the nominal wind table during the flight. The corrected table differs from the nominal table in two ways. First, the Navigation software inserts the estimated wind velocity into the corrected wind table at the current altitude. In addition, the wind velocities in the entire wind table below the current altitude are re-calculated as weighted averages of the velocities in the nominal table and the current wind estimate. The weighting is based on a decaying exponential with altitude separation, which adequately represents the statistical correlation between the wind velocity estimate at one altitude layer with another different layer. Estimates of the characteristic correlation length scale used for the exponential weighting have been gleaned from PADS related wind profile forecasting.

To estimate wind velocity using the GPS data, Navigation makes the assumption that sideslip is generally small, so that velocity of the parafoil with respect to the air mass is generally in the direction of GPS-indicated heading. By differencing GPS-indicated altitude and lowpass filtering, Navigation obtains a measurement of vertical velocity. The vertical velocity is converted to an estimate of vehicle airspeed using trim L/D characteristics measured in tests; of course this approximation neglects vertical winds. Combining the airspeed estimate, the heading information, and the assumed L/D; Navigation obtains an estimate of the velocity with respect to the air mass. The wind velocity estimate is obtained by subtracting the vehicle's estimated air velocity from the GPS-indicated ground velocity.

Guidance accepts north and east coordinates of vehicle position with respect to the target, altitude relative to the ground, heading and heading rate, and the corrected wind table from Navigation. Using this information, it generates a heading rate command for Control. Guidance does its calculations in a wind-fixed frame; a portion of the anticipated displacement due to wind, computed using the wind table, is added to the navigated position so that steering calculations can be done as if winds were zero. Reduction of the precision flight problem to a wind-relative frame accomplishes a number of important objectives. First, calculations in this frame automatically adjust the parafoil's planned trajectory with the best estimate of prevailing winds, causing the system to drift toward the target rather than fight the winds to generate a fixed ground-relative track. Second, calculations in the wind-frame enable a single reference look-up table to be used for terminal approach to the target, since the wind drift offsets are automatically compensated for by biasing the target position. Provided the wind profile estimation is reasonably good, even very strong wind fields can be compensated for using this method.

A nominal trajectory in this wind-fixed frame is shown in Figure 11. The complete Guidance strategy is best understood by considering this trajectory, which is colored and labeled to show the different flight phases (sub-modes). The trajectory begins with ***Preflight*** (blue X) and ***Trimflight*** (black O) described previously. ***Autoflight*** begins with a ***Homing*** sub-mode (blue +), in which guidance simply instructs the system to turn and fly toward the target. This sub-mode continues until the parafoil is sufficiently close to the target, where Guidance transitions into an ***Energy Management*** sub-mode (red *). This sub-mode is used only if the system needs to burn off altitude, and involves the parafoil completing up-wind "figure-eights" until the altitude is low enough to initiate the final approach maneuver. The final approach sub-mode is coined ***Table Lookup*** (blue squares), because it involves the Guidance algorithm making successive calls to a pre-computed table of optimal trajectory paths that are referenced according to the system's position and heading. The trajectories are designed to minimize landing distance at a specific impact heading, all within the constraints imposed by the maximum turn rate of the system. Finally when the altitude above the ground reaches a threshold value, the Guidance transitions to ***Terminal*** mode and a flare is initiated (red diamonds). The software executes the flare maneuver by commanding the motors to pull the toggles to a pre-defined maximum brake position, then the parafoil slows down and the system impacts the ground at nearly the minimum flight speed.

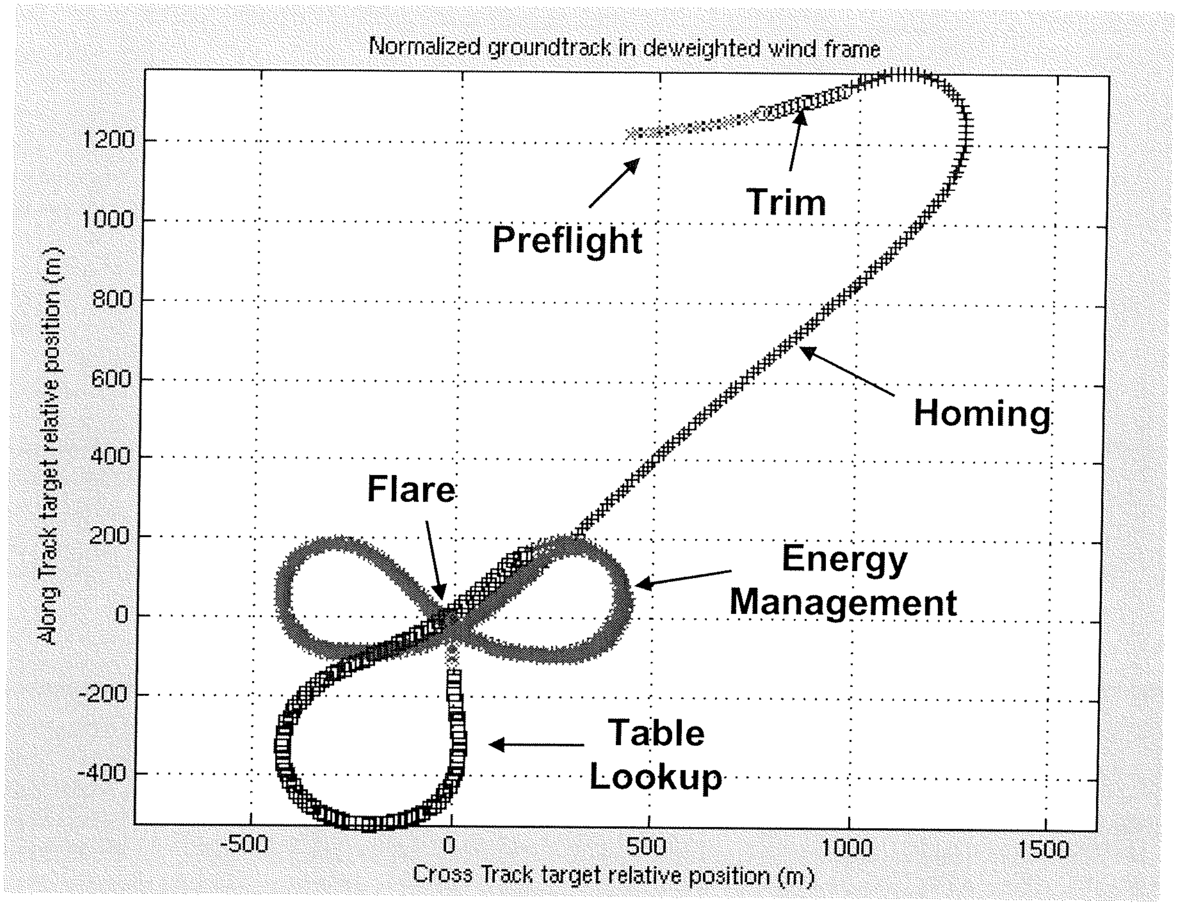

Figure 11 – Trajectory in the Wind-Fixed Frame, Showing Guidance Submodes

VII. Flight Test Summary

Flight testing of the *Dragonfly* system began in March, 2004 at Red Lake in Kingman, Arizona. These initial tests were conducted entirely using remote controlled maneuvers, and were focused on providing basic deployment and flight performance data. Data on the steady-state velocity, glide-slope, and turn rate as a function of brake and differential toggles was collected and used to develop a parafoil simulation model. Tests have confirmed that the *Dragonfly* system is capable of flying at a lift-to-drag (glide-slope) of nearly 4:1 at speeds exceeding 15 m/s. Turn rates exceeding 9.0 deg/s have been achieved at a differential toggle stroke of 100 inches, resulting in a turn radius of ~100 meters. This same 100-inch toggle stroke length, when applied in tandem as a brake command, is capable of generating a ~6 m/s reduction in flight speed without substantial degradation in the glide characteristics of the system. The decrease in flight speed from extended brakes allows a substantial reduction in impact speed during flared landings. Even at the 100-inch toggle setting, no collapse of the canopy cells or other signs of stall onset have been observed, therefore with further testing the complete speed and turn rate flight envelope could be expanded.

Drop testing has continued over the last year in both Kingman and more recently at the Yuma Proving Ground using C-130 aircraft to achieve higher payload weights and drop altitudes. Autonomous tests first began in May 2004 and have proceeded through many iterations. A continuous evolution of the GN&C software, the canopy, and the avionics hardware has paralleled the testing cycles; leading to a much more capable and reliable system. One of the largest changes was a completely re-designed set of motors for the AGU, including revised interface software and the capability for substantial motor diagnostic data to be captured during flights. This change has facilitated the ability to collect on-board motor current and voltage data, which have been correlated with motor torque loads in laboratory tests. At the maximum design all-up weight of 10,000-lbs and a toggle retraction of 100 inches, line loads exceeding 600 lbs. have been observed. The collection of this data has allowed improvements in the motor design and gearing, as well as increasing confidence in our overall understanding of the system.

The most recent flight tests occurred in late June 2005 at Yuma Proving Ground. Figure 12 shows a wind-track plot of the parafoil trajectory as it approached the target during the final drop test. This plot provides a useful comparison with the idealized guidance-derived trajectory from Figure 11. The parafoil has already completed its homing mode, steering toward the target, when it enters the energy-management mode (depicted in red *). The ideal "figure-eights" generated by the guidance algorithm are reasonably followed, however it is evident that wind, sensor errors, and control lags degrade perfect compliance with the ideal trajectory geometry. Despite the errors, the GN&C algorithms guide the parafoil into its final approach where the table-lookup mode is initiated (blue square). Again the completely smooth trajectory profile generated by an ideal guidance sequence is not evident; however the updates by the guidance serve to correct errors as the system proceeds to the target. The final "S-turn" correction, in which the system un-intuitively proceeds away from the target location, is actually a perfect example of the Guidance algorithm automatically compensating for anticipated flight-track landing errors. The parafoil lands only 23 meters from the target and is able to align its final impact direction within several degrees of the heading directed in the mission file. The final flight test exhibited the corrective action and optimal trajectory forecasting intended by the guidance algorithm design.

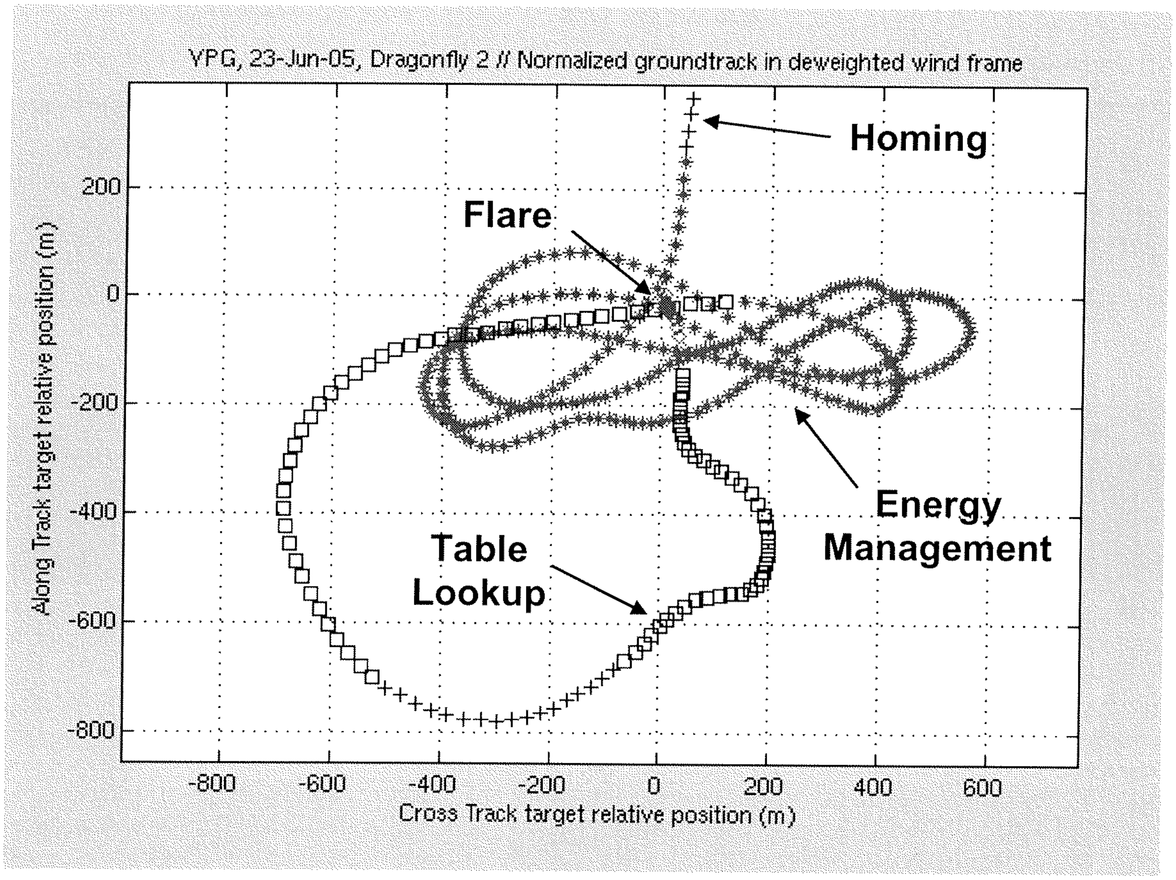

Figure 12 – Cross-Track of June 05 Drop

VIII. Conclusions and Future Development

The *Dragonfly* program has required the effective synthesis of a number of innovative system components developed by the project team. The evolution of the design has encompassed important changes to the canopy, airborne guidance unit, and GN&C software; resulting in a substantially better performing and more reliable system. Autonomous flights over the last several test series have averaged landing accuracies of approximately 200 meters. In a recent test the *Dragonfly* system has achieved a landing error of 23 meters. With additional flight experience, we expect the system to be capable of satisfying the Army's 100-meter CEP requirement. This level of precision, coupled with the extremely high offset capability offered by the canopy's 4:1 glide characteristics, provide a unique capability for the airdrop community.

Future development is planned in a number of important areas. Significant progress has already been demonstrated with the design and testing of a single drogue deployment chute that will improve the canopy extraction and substantially reduce cost. Future effort will be focused on simplifying the canopy's rigging system, including minimizing the number of pyrotechnic cutters currently being used in an effort to reduce cost. GN&C software development is focused on refining the table look-up Guidance algorithm currently being used for final approach. Current on-board memory constraints have limited the capability of the algorithm, however effort will be applied to up-grading this capability to provide higher landing accuracy. There are also some sensor development paths currently being explored. Progress is being made on two separate US Army funded Small Business Innovative Research (SBIR) projects to develop additional sensor capability. Work is underway to develop a low-cost ground proximity sensor that could be incorporated into precision airdrop systems for more accurate flare maneuvers. In addition, research is also being directed toward the development of a low-cost LIDAR wind sensor that could be carried on-board *Dragonfly*. Reducing these two primary errors sources, using higher accuracy altitude and wind estimation, should provide a significant improvement in autonomous flight operation.

Acknowledgments

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