Autonomous Guidance, Navigation, and Control of Large Parafoils

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Under the Joint Precision Airdrop System program, a Draper Laboratory autonomous Guidance, Navigation, and Control (GN&C) software package that enables precision payload airdrop delivery using large parafoils has been developed in prototype form and successfully flight tested. The modular software design is structured to accommodate parafoil airdrop systems for payloads ranging from under 2,000 lb to over 30,000 lb. The initial GN&C software implementation has been demonstrated on the Para-Flite *Dragonfly* 10,000 lb-class parafoil using an Airborne Guidance Unit (AGU) provided by Wamore, Inc. and an avionics package provided by RoboTek. Among the primary avionics selection criteria was low component cost, resulting in use of a processor with very limited data throughput capability. To accommodate the processor limits, the Guidance algorithm includes table driven trajectory data that guides the parafoil through precision final-descent maneuvers while imposing very limited processor throughput burden. The GN&C algorithms and associated mission planning software have also been incorporated into the Precision Airdrop System laptop personal computer. This accommodates easy, in the field, ground loading of the GN&C software onto the AGU and enables PADS updates of the airdrop system mission files during flight of the carrier aircraft to the airdrop release point. The details of the GN&C design and flight test results to date are discussed.

Nomenclature

ACTD	Advance Concept Technology Demonstration
AGU	Airborne Guidance Unit
CEP	Circular Error Probable
D	Drag
DZ	Drop Zone
CARP	Computed Air Release Point
DOF	Degrees of Freedom
FY	Fiscal Year
GMI	Graphical Map Interface
GN&C	Guidance, Navigation, and Control
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision

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HWIL	Hardware-in-the-Loop
JPADS	Joint Precision Airdrop System
KIAS	Knots Indicated Air Speed
L	Lift
LIDAR	Light Detection and Ranging
MSL	Mean Sea Level
NMEA	National Marine Electronics Association
NSC	Natick Soldier Center
PADS	Precision Airdrop System
PC	Personal Computer
PGAS	Precision Guided Airdrop System
PID	Proportional, Integral, Derivative
R/C	Remote Control
RT	Remote Terminal
SBIR	Small Business Innovative Research
SODAR	Sound Detection and Ranging
UTC	Coordinated Universal Time
YPG	US Army Yuma Proving Ground

I. Introduction

A key element of the Joint Precision Airdrop System (JPADS) Advanced Concept Technology Demonstration (ACTD) is the development of Guidance, Navigation and Control (GN&C) software to autonomously fly the *Dragonfly* 10,000-pound capable parafoil. This software must guide the parafoil from deployment altitudes up to 25,000 feet above Mean Sea Level (MSL) to landings within a 100-meter Circular Error Probable (CEP) of the target. Other key goals include robustness to a variety of failure modes, algorithms that are sufficiently generic to facilitate adaptation to both smaller and larger decelerators, efficient enough to perform well on a very modest microprocessor, and capable of meeting system performance requirements with a navigation sensor suite limited by recurring system costs. Also important are Government ownership of the resulting code, the ability to handle user-supplied waypoints, plus efficient and cost-effective integration with the previously developed Air Force and Army Precision Airdrop System (PADS) mission planner. Draper Laboratory, one of the developers of the PADS planner, is implementing the autonomous GN&C.

II. The Flight Hardware Configuration

As noted, an important goal of this program is to keep recurring system costs at a minimum. Hence, the avionics selected are the ultimate in simplicity. The sole navigation sensor is the CSI Wireless *Vector* dual-Global Positioning System (GPS) receiver, which provides not only system position and velocity, but also heading and heading rate. The *Vector* unit provides this by using two tightly coupled high performance GPS receivers and two antennae, separated by 10-inches, providing a good balance between heading accuracy and GPS acquisition time. This approach avoids including a magnetic compass for the heading reference, with their attendant difficulties due to local changes in the magnetic field and field perturbations from the various metal masses in the Airborne Guidance Unit (AGU). Other means of determining heading without additional heading sensors were examined and determined to be operationally unattractive. The flight processor selected is the *Rabbit* RCM3400 microcontroller, augmented by 8 MB of flash memory to hold Guidance data tables and record GN&C parameters during flight for later analysis. A Freewave 902-928 MHz spread spectrum modem is also utilized to receive remote control commands from the ground and to downlink mission data for post-flight analysis. This modem can be used for downloading mission files prior to airdrop system release, though 802.11g wireless network components are being integrated as a replacement for operational use.

III. Basis for the Initial Airdrop System Dynamics Models

Draper Laboratory has a long history of research in guided ram-air parafoils beginning with work on the Precision Guided Airdrop System (PGAS) [Refs. 1-2]. As part of this program an engineering simulation was implemented based on numerous technical references detailing the appropriate structure for a 6 Degree of Freedom (DOF) parafoil dynamics model complete with high fidelity environment models. The initial *Dragonfly* dynamics models were derived from this simulation framework and then substantially updated using the best available experimental and theoretical analyses of large-scale parafoil systems. In particular, a wealth of incredibly detailed

flight performance data has been generated by the NASA X-38 program on two parafoil systems in the same size category as the *Dragonfly* system [Refs 3-4]. In addition, an updated theoretical treatment of apparent mass effects was undertaken in Reference 5, the results of which were rolled into the initial *Dragonfly* simulation. It was understood from the start of the program that there would be opportunities for conducting performance estimation tests on the new canopy, therefore most of the initial work focused on developing tools that could be used to quickly update the original models as performance data was collected. It should be understood, however, that due to the lack of inertial instrumentation on board the *Dragonfly* system as well as a program focus on cost effectiveness, no attempt has been made to complete a detailed system identification of all parameters in the *Dragonfly* parafoil model. Rather, the focus of the modeling effort has been on matching 1) steady-state velocity and turn rate, 2) toggle line actuator dynamics, and 3) the basic turn rate time constant. Given the uncertainty in measurement data as well as wind conditions during flight testing, it is believed that engineering models suitable for GN&C development have been generated.

Analysis tools have been developed that attempt to fit longitudinal lift-to-drag and velocity flight data to relatively simple mathematical expressions for the lift, drag, and pitch moment characteristics of the parafoil. The parafoil aerodynamics model is used to generate tabular force and moment coefficient data as a function of brake setting and angle of attack as inputs into the simulation. Values for various aerodynamic parameters were originally set using past historical data collected on PGAS as well as general trends seen in the X-38 program. The process to ascertain whether the parametric aerodynamics model had sufficient complexity was to attempt to match X-38 L/D and velocity performance. The aerodynamics model was able to reasonably produce the steady-state response for this large parafoil airdrop system; therefore there was confidence that subsequent test data on the *Dragonfly* could be used to give a good engineering model of the flight performance. The main uncertainty in "fitting" aerodynamic parameters against the flight data was that, unlike X-38 flights, angle-of-attack was not explicitly measured by the *Dragonfly* AGU. Instead, trends from the X-38 program, coupled with ensuring physically reasonable constraints on aerodynamic parameters, were used to help produce a longitudinal model for the Dragonfly. Detailed analysis of flight data is shown in Section V.B, with comparisons from the parafoil model updated to match the steady-state response of the system.

The lateral model parameters for the *Dragonfly* were based on both theoretical calculations as well as appropriately scaled historic data from the PGAS and X-38 programs. Originally a very complicated yaw rate response model was used that tried to match the non-linear steady-state turn characteristics seen with the X-38 at low brake settings. Subsequent flight tests did not show this type of behavior, therefore the turn rate response was augmented to a more linear relationship with differential toggle (see section V.B). The turn rate dynamics are generally dominated by two factors; the inertial (both "real" and apparent) properties of the system, and the toggle actuator response. Effort was given to an appropriate dynamics model for the toggle motors. Generally, the *Dragonfly* motors are capable of ~2 ft/s of maximum line pull rate and have relatively high acceleration characteristics. Full-scale toggle changes from 0 to 100 inches generally take ~5 seconds. In addition, yaw inertial and damping characteristics were originally chosen to give the parafoil turn rate response a 5 second time constant. The overall sluggish turn behavior of the parafoil was well modeled by the original model parameters used, and generally corresponded to a fairly highly damped large inertia system. Subsequent flight tests were used to slightly modify the parameters, but in general the original lateral model was sufficient to give the gross dynamic behavior of the *Dragonfly* system.

IV. The GN&C Design

A. Top-Level Overview

The GN&C flight software resides in the AGU. While the airdrop system is in flight, the software receives information from a navigation package about system position, velocity, and heading. Based on these inputs, it computes a trajectory toward the programmed target landing point. It then flies the system toward that point via a series of extensions and/or retractions of the parafoil's two control lines.

After a stable canopy opening, the GN&C software optionally enters a control line trim mode in which it adjusts the control line lengths for straight flight. After completing (or skipping) the trim mode, state estimates derived by filtering the position, velocity, and heading inputs from the Navigation package are utilized by Guidance to begin directing the control algorithms to home the airdrop system toward the target. When the airdrop system comes within about 200 meters horizontal distance from the target, it enters an energy management mode, flying figure-eight patterns in the vicinity of the target until ground-relative altitude drops below 500 meters, at which point it steers toward the target to establish the final approach. From this point until landing, the Guidance software utilizes pre-computed steering commands from a look-up table with a large family of trajectories that minimize final

position and heading error. This table-driven approach minimizes the trajectory determination processing burden on the available, small, low-throughput flight processor.

The navigation instrument is a CSI Wireless, dual-GPS receiver-based Navigation package that generates position, velocity, and heading data. The processed GPS data from the Navigation package is filtered by an algorithm in the GN&C software, with the resulting state estimates sent to the Guidance software in the form of airdrop system altitude, heading, and estimated wind velocity. The wind estimates are derived by comparing the GPS velocity data with a model of the expected parafoil air-speed.

Using gain scheduling, the Control software attempts to maintain the heading rate commanded by the Guidance software, by extending or retracting the left and right parafoil control lines. The Control software also attempts to maintain symmetric operation of the control lines about a base retraction length when determining the line positions that will achieve the desired heading rate. Also, a parafoil flare capability, achieved by fully retracting both control lines, achieves a stall condition that is used just before touchdown to reduce the parafoil's ground impact velocity.

Development of the GN&C software began in government FY 2004. Draper Laboratory developed, integrated, and validated the autonomous GN&C flight software for initial use on the Para-Flite 10,000-pound capable parafoil equipped with the Wamore, Inc. AGU and RoboTek-supplied avionics. All aspects of the GN&C design are modularized to readily accommodate eventual adaptation to other smaller and larger guided parafoil airdrop systems. Also, both the GN&C software and mission planning algorithms associated with the use of guided airdrop systems that apply the GN&C algorithms have been hosted onto the PADS mission planner laptop PC. This will facilitate the use of the PADS PC as a common platform for download of the GN&C software and data files to the AGU on the ground as well as for generation of airdrop load-specific mission files shortly before release on–board the carrier aircraft.

B. GN&C Development, Integration, and Test Methodology

The development, integration, and test methodology applied by Draper staff has followed a rigorous process tailored to the flight prototype demonstration objectives applicable to the current program. The key process steps are summarized below:

- Algorithm Conceptualization, Preliminary Design, and Evaluation. This development phase involved preliminary algorithm design and off-line evaluation of the algorithms by the individual developers. This process included internal and external (customer) reviews of the proposed algorithms before their integration into a complete GN&C implementation.
- GN&C Integration and Software Simulation Assessment. A 6 DOF model of the parafoil dynamics was formulated and validated against available parafoil test data. A software simulation was developed, using the 6 DOF parafoil model that provided data interfaces for GN&C software equivalent to those on the AGU. The GN&C algorithms were then integrated together and into the simulation. Closed-loop GN&C assessments were then performed using this simulation, the results of which were subjected to internal and customer review. This simulation tool has subsequently supported evaluation of flight test results.
- HWIL Simulation Assessment: A HWIL simulation was assembled at Draper, using actual AGU processors and memory as well as a set of control line actuation motors. This HWIL facility was used to evaluate proper code function with the real timing, space, and word-length limitations of the target processor and memory, and was used to demonstrate proper message handling by the control actuation motors. Subsequently, the CSI navigation package was added. The navigation package provided means to evaluate proper message interfacing, though the static nature of the HWIL simulation assembly prevents use of the actual Navigation package during flight dynamics simulations.
- Pre-Flight Code Validation and Freeze. Prior to each flight test cycle, the intended GN&C implementation was integrated and validation tested, first on the software simulation, and then on the HWIL simulation. When the intended performance was realized, the GN&C software was frozen as a defined code release under a configuration control process, and it was then delivered for field test use. A final integration test was performed at the AGU vendor's facility prior to first flight of each new software release.

C. Guidance Implementation Details

The primary function of Guidance is to compute steering commands for use by Control, given position, heading, and estimated wind profile from Navigation. As a part of the steering calculation, Guidance is responsible for timing the flare (deep brakes) maneuver prior to landing, signaling Mode Control to transition to flare; Mode Control then commands the other parts of the system accordingly.

Throughout flight, Guidance accepts the system mode from Mode Control. The mode can be any of the following: Initialize, Preflight, Trimflight, Autoflight, Manual, or Terminal. Steering calculations, including timing

of the flare maneuver, are performed only when system mode is Autoflight. When the mode is Trimflight, Guidance monitors altitude and distance to the first waypoint (which could be the target); if the ratio of distance to altitude becomes sufficiently small, Guidance requests that trim be abandoned, causing transition to Autoflight mode. In the modes Initialize, Preflight, Manual, and Terminal, Guidance monitors system position but is otherwise inactive.

Guidance obtains MSL altitude, the north and east position coordinates with respect to the target, flight path azimuth (the direction of the air velocity vector), as well as a table of wind velocity vs. altitude from Navigation. It also accepts a list of waypoints, given as north and east offsets from the target, from the Mission Loads file. During Autoflight mode, Guidance computes the commanded rate of change of the flight path azimuth, which is referred to as "turning rate," and sends this to Control. Guidance interfaces are shown in Figure 1.

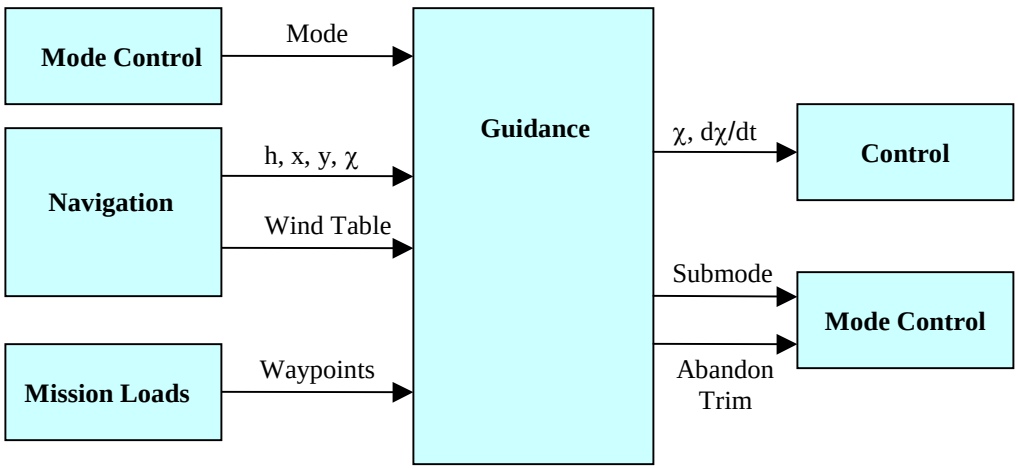

Figure 1. *Dragonfly* Guidance Interfaces.

Guidance does its calculations in a de-weighted wind-fixed frame; a portion of the anticipated displacement due to wind is added to navigated position with respect to the next waypoint (or the target), so that steering calculations can be done as if winds were zero. A nominal, single waypoint trajectory in this wind-fixed frame is shown in Figure 2. The guidance strategy is best understood by considering this trajectory, which is marked to show the different flight phases (modes and submodes).

The system mode is Preflight (located at top center) when the system exits from the carrier aircraft, and remains in Preflight through the stages of canopy deployment. When deployment is complete, which is sensed by monitoring sink rate, the system transitions to the Trimflight mode, and Control adjusts the toggles to null any initial turning rate. When turning rate has been nulled, or on request from Guidance (if the turning rate cannot be nulled quickly), the system transitions to the Autoflight mode; initially using the Guidance Homing submode. In this submode Guidance commands the system to turn and fly toward the target (the origin, in Figure 2).

When the system is sufficiently close to the target, and if altitude is sufficiently high, the Guidance submode changes to Energy Management, and the system flies in figure eights which are transverse to the desired heading at landing until altitude is low enough that the final approach maneuver can be executed. Final approach is done in Lookup submode. Turning commands in this critical submode are obtained from a pre-computed lookup table stored in the system flash memory. The lookup table turning commands are indexed by altitude, north and east position, and heading. The table essentially gives directions for computing a family of trajectories; one for each choice of initial position and heading. Each of these trajectories either hits the target, or if that is not possible from the given initial position and heading, minimizes a function of position and heading error at impact. Finally, when altitude above the ground reaches a threshold value, the Guidance submode becomes Flare, and the system mode changes to Terminal. The flare maneuver is executed, forward velocity slows, and the system lands.

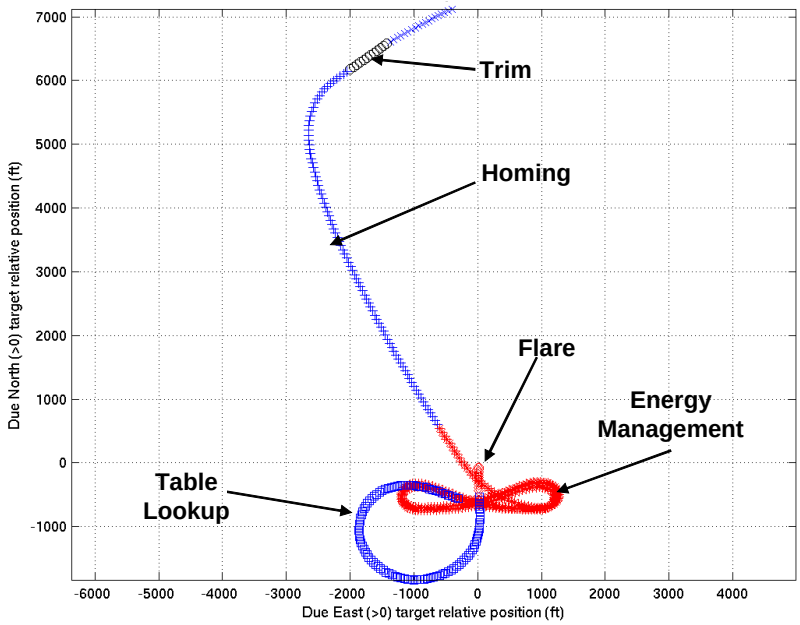

Figure 2. Trajectory in the De-weighted Wind-Fixed Frame, Showing Submodes.

D. Navigation Implementation Details

Navigation uses data from a dual-antenna GPS navigation package to compute position and flight path azimuth for use by Guidance, and flight path azimuth and flight path azimuth rate (turning rate) for use by Control. Using GPS-measured velocity with respect to the ground, together with a simple analytic model of system airspeed and GPS-measured heading, Navigation estimates wind velocity. The wind velocity estimate is used to correct an *a priori* table of wind vs. altitude; the correction is largest for altitudes close to the altitude at which Navigation's wind estimate is valid. Navigation sends the corrected wind table to Guidance. Early in the flight, Navigation monitors sink rate in order to detect canopy inflation; this information is important for system moding. Navigation interfaces are shown in Figure 3.

Navigation receives standard National Marine Electronics Association (NMEA) data messages from the dual-antenna GPS navigation system. Coordinated Universal Time (UTC) time, latitude, longitude, and altitude MSL are obtained from the "GGA" data message. The GGA message also contains a quality indicator, the number of satellites used in the position calculation, and an estimate of Horizontal Dilution of Precision (HDOP). Navigation considers the GPS position data to be valid provided the time has been updated from its previous value, the quality indicator takes values of 1 or 2, the number of satellites used in the position fix is at least 4, and HDOP does not exceed a configurable threshold whose current value is 10.

Navigation receives ground velocity (speed and course) from the "VTG" data message. This message is considered to be valid whenever its numeric fields are fully populated. Navigation receives true heading from the "HDT" data message, and heading rate (rate of turn) from the "ROT" message. These messages are considered valid when their numeric fields are populated; this happens only when the receiver has lock on both channels.

When the HDT message is valid, Navigation sets the flight path azimuth equal to HDT heading. This amounts to asserting that sideslip is zero, an approximation which seems to work well for low bandwidth GN&C of large parafoil systems. Likewise, Navigation identifies flight path azimuth rate with heading rate from the ROT message, when this message is valid. Wind estimates are made only when valid GGA, VTG, and HDT data is available. Horizontal velocity with respect to the ground is obtained from the VTG message. Altitude is obtained from GGA, and used together with data provided in the Mission Loads file to compute atmospheric density and nominal airspeed (which depends on atmospheric density). Air velocity is estimated using computed nominal airspeed, nominal flight path angle, and measured heading from HDT; the calculation assumes that sideslip is negligible. The air velocity estimate is low-pass filtered and subtracted from ground velocity to obtain the wind estimate.

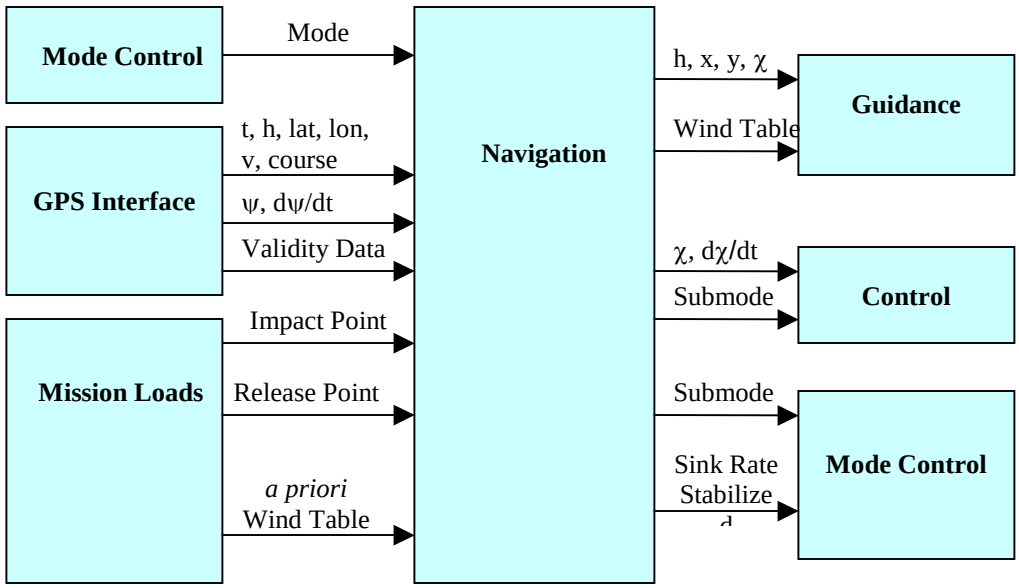

Figure 3. *Dragonfly* Navigation Interfaces.

E. Control Implementation Details

When formulating the control algorithm for *Dragonfly*, we stipulated the following control objectives: (1) the closed-loop system must track wind-relative lateral rate commands issued from Guidance, and (2) the control algorithm must reject external disturbances, in particular, the frequency of the payload oscillation relative to the canopy. In this phase of the program, control only regulates lateral directional heading rate errors based on commands produced by Guidance; flight speed is treated as a system parameter governed by the base (nominal brake setting) deflection during the flight. From initial, manually-controlled, system-identification parafoil flight drops, we identified the heading and side-slip rate dynamics in response to the lateral controls or differential toggle commands (Right Toggle – Left Toggle). We operate the vehicle at a 25% base deflection of 50 in. since this allows the parafoil turning dynamics to be nearly linear and ensures that flight operations do not show the reflexive behavior that was observed in the small toggle deflection dynamics of the X-38 parafoil canopy. Around this base deflection, we collectively represented the heading and slide-slip lateral dynamics mode shapes in terms of flight-path azimuth ($\chi=\Psi-\beta$); experimental results showed that heading rate and slide-slip had nearly identical natural modes so we were able to collect the terms. We identified a second order heading rate model shown in Eq. 1 using parameter identification techniques:

$$\dot{\chi} = \frac{a \cdot k}{1 + bs + as^2}\Delta = G \cdot U \qquad \text{(Eq. 1)}$$

where Δ is the control deflection difference between the left and right toggles and serves as the lateral control input. G represents the open-loop plant heading rate transfer function. Because we operate around a 25% base deflection, we achieve the desired deflection difference by symmetrically operating the line deflections about the base setting; similarly, we identified the plant model parameters for symmetric toggle commands produced about a 25% base deflection. The lateral control toggle commands, Δ, are issued by symmetrically deflecting the left and right toggles around the base deflection, b: $\delta_L = b - \Delta/2$; $\delta_R = b + \Delta/2$

Figure 4 shows the measured values of *Dragonfly* heading rate ($d\Psi/dt$) and its side-slip rate in response to a 100 inch differential control toggle step from which the plotted flight path azimuth rate quantity was also derived. Based on simulations, it was determined that the natural open-loop bandwidth was 12.5 seconds with a damping coefficient of about 0.6. Figure 5 shows the derived azimuth rates obtained from the parafoil at two different toggle deflections as well as the corresponding response of the simulated second order plant model that has the input gain, bandwidth,

and damping characteristics determined from system identification. The second order model can not capture very precisely the small overshoot combined with large settling times seen in the high deflection regimes. Nevertheless, the rise time, overshoot, and time constant are matched quite well.

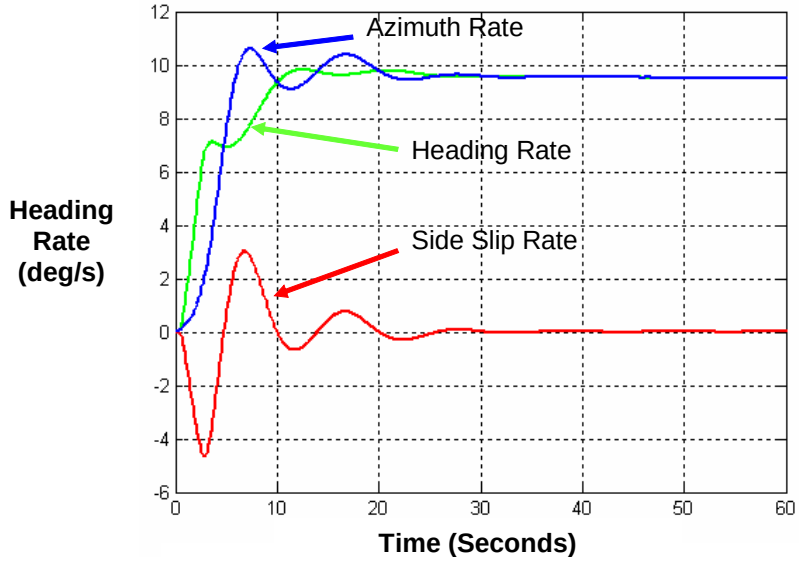

Figure 4. Measured *Dragonfly* rate response for a 100 inch differential control toggle step

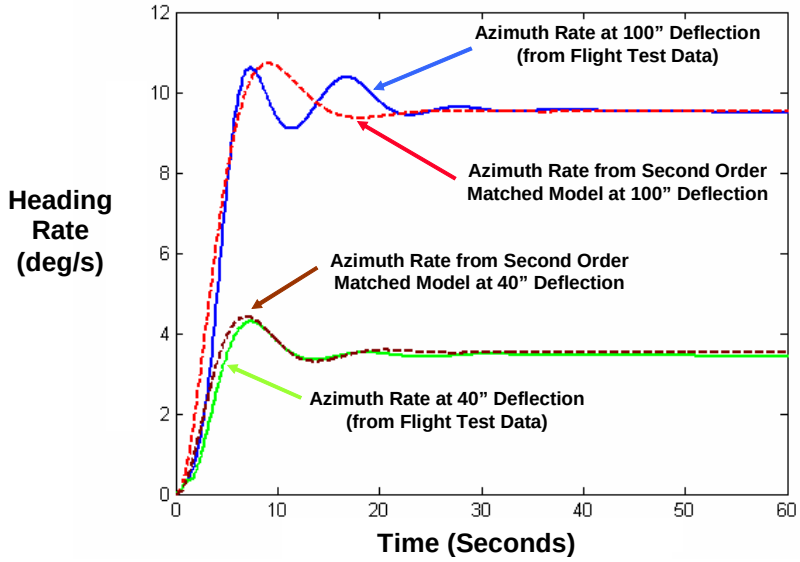

Figure 5. Comparison of predicted and flight-measured *Dragonfly* rate response at two differential control toggle settings

Figure 6 shows the feedback control block interconnections. The controller rate errors are based upon commands from Guidance; it forms the left and right toggle commands to the motor controllers. Plant response is measured relative to the wind-frame. Disturbances result from unexpected wind gusts, unknown and un-modeled plant dynamics, and payload oscillation frequencies that appear in the feedback signal. Based on this plant model, we identified control gains for a Proportional, Integral, Derivative (PID) control structure that maximized the closed-loop bandwidth, provided at least 60 degrees of phase margin, and minimized the gain of the auxiliary output-input loop to limit the impact of the payload oscillation frequency on the control applied. Since the payload oscillates with pendular motion beneath the AGU, these oscillations are picked up by navigation sensors and appear in the feedback signal even though the canopy itself does not exhibit significant oscillations. Therefore, one control objective was to synthesize the control gains so that the control line deflection command sent to the motors was

desensitized to this disturbance signal and did not attempt to correct for this spurious measurement. Thus we designed the control gains to manage gain and phase margins of three significant transfer functions shown in Eq. 2. The transfer function P measures the gain between the commanded line deflection and the heading rate command error. S is the sensitivity function and T the closed-loop plant transfer function.

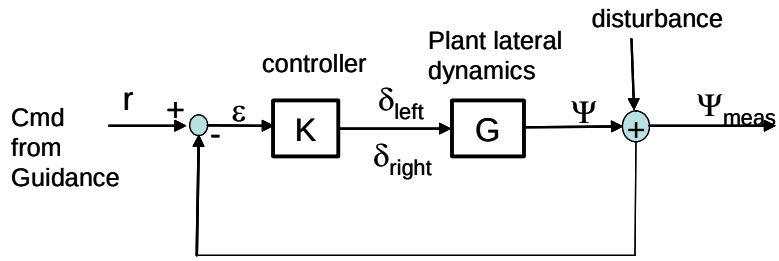

Figure 6. *Dragonfly* Feedback Control Block Interconnections

$$T = \frac{KG}{1+KG}, P = \frac{K}{1+KG}, S = \frac{G}{1+KG} \qquad \text{(Eq. 2)}$$

We posed a multi-objective optimization problem and solved for the control gains that maximize three gain and phase quantities at suitable frequencies. This produced a control structure: $K = (k_1 + k_2 s + k_3 \cdot \frac{1}{s})$, where ($k_1$, k_2, k_3) are the outputs of the robust optimization problem. We used the following control gains in the controller: (k_1=1.65, k_2=3.0, k_3=1.07). The controlled-system transfer function characteristics are shown in Figures 7-8 below. We designed the control gains to maximize the bandwidth and phase margin of the controlled-system transfer function (T), minimized the gain of the input transfer function (D) at the payload natural frequency; and maintained low sensitivity at all frequencies.

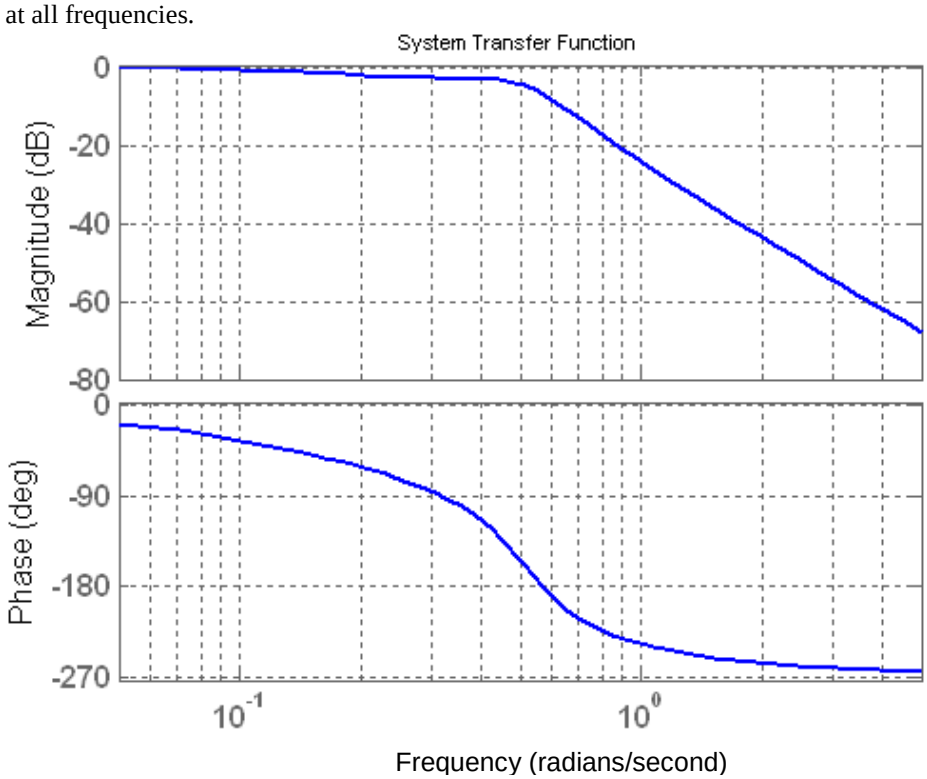

Figure 7. *Dragonfly* Controlled System Open-Loop Bode Plot

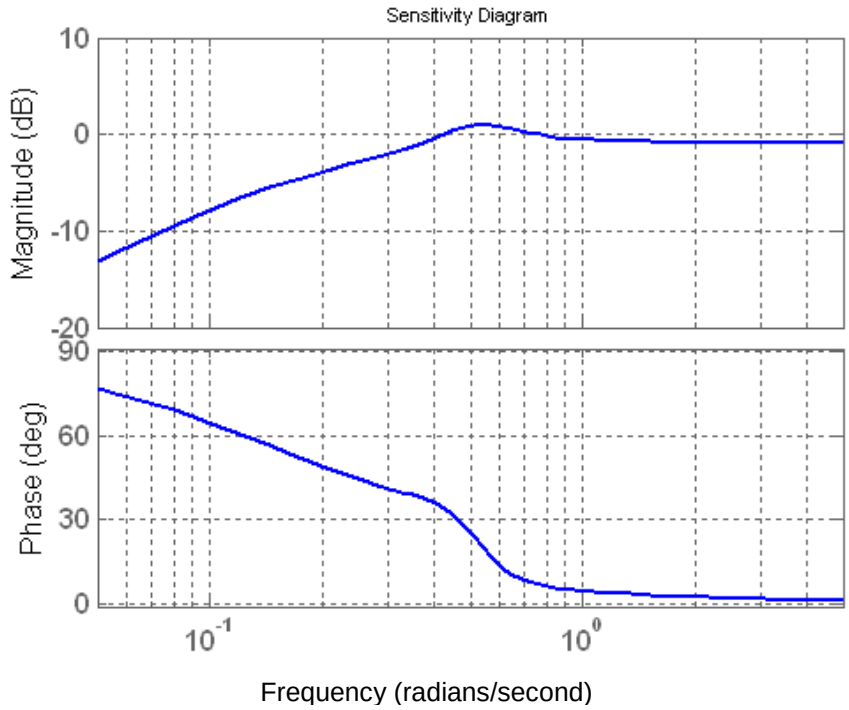

Figure 8. *Dragonfly* Controlled System Transfer Function (GK) Sensitivity Features

F. Supporting PADS Mission Planning and File Download Capability

The PADS program has developed a laptop PC-based airdrop mission planning capability to support determination of proper airdrop release points and to enable updates to guided airdrop system mission files while aboard the carrier aircraft in transit to the drop zone. The PADS implementation architecture is shown in Figure 9. The PADS PC includes means to access current meteorological information, and uses the altitude-dependent wind and density data, combined with models of the release and flight dynamics of airdrop systems to derive optimized Computed Air Release Points (CARPs) for unguided airdrop systems, and allowable release envelopes for guided airdrop systems. Also, for the guided airdrop systems, nominal CARPs are designated within the derived release envelope. Meteorological data can be collected by PADS from any combination of the following sources: Forecasts loaded before takeoff; data received through an encrypted satellite link during transit flight to the drop zone; sondes released from or near the carrier aircraft, with the data retrieved by PADS through the carrier aircraft UHF antenna, and processed into suitable form by software within PADS. All the available meteorological data is assimilated within PADS into a best estimate of current conditions near the drop zone.

PADS has an interface to connect to an RT on the carrier aircraft 1553 data bus to acquire the current vehicle navigation state, to obtain the current aircraft at-altitude wind measurement, and to monitor various airdrop-related mission parameters. The vehicle navigation state is used to enable PADS to display the aircraft position relative to the CARP and/or release envelope on a FalconView GMI. The at-altitude wind measurement serves as an additional source of meteorological data that is assimilated with the other available data. The airdrop-related mission parameters are recorded during release operations to enable post-release assessment of the release condition accuracy.

PADS also includes a wireless link to enable loading mission file updates generated by PADS to guided airdrop systems while on-board the carrier aircraft. These mission file updates reflect the PADS-computed meteorological state in a format uniquely designed to be compatible with each airdrop system class.

More details about the PADS design, current features, and flight test experience are provided in References 6-9. Limited quantities of the PADS units are in field use supporting mission planning with unguided airdrop systems. Updates to PADS to support field use for mission planning and mission file updates for several classes of guided airdrop systems are now in work. In-country operational demonstrations of these systems are expected presently.

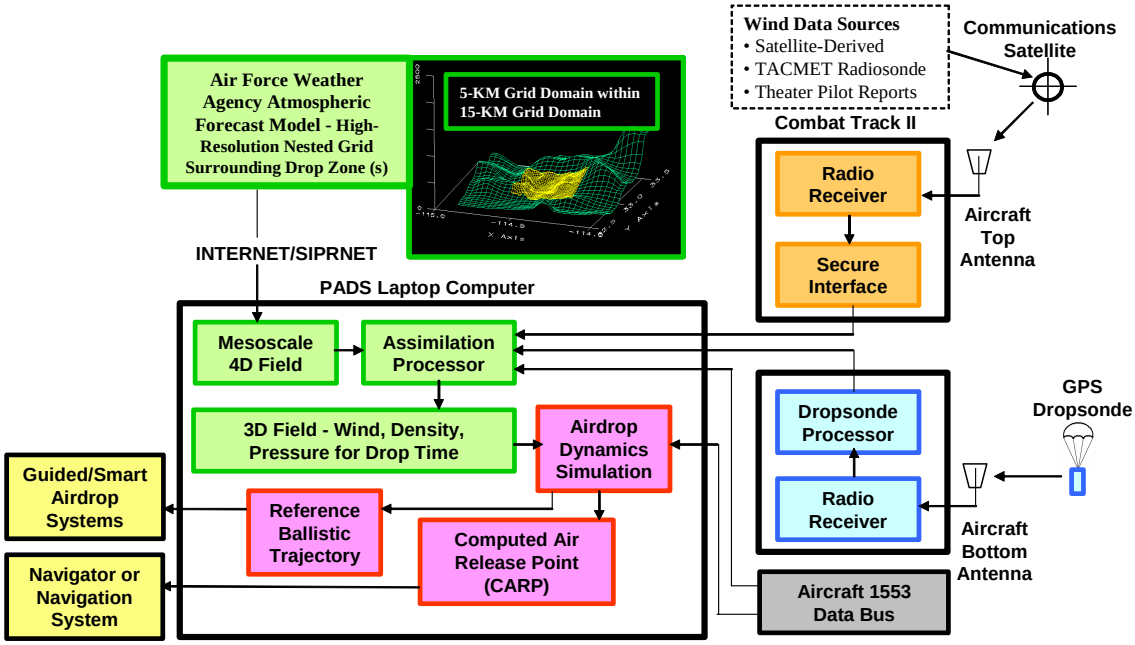

Figure 9. The PADS Planning System Architecture

A version of PADS has been updated to include models of the Para-Flite *Dragonfly* 10,000 lb-class parafoil. This enables the PADS computer to provide mission file updates to the AGU prior to flight test release of the parafoil in tests of the autonomous GN&C system. This version of the PADS PC also includes a load of the GN&C software to enable use of the same PC in the field to load that software onto the AGU via the wireless link or a temporary cable connection. This added PADS capability demonstrates the intended use of PADS as a common platform for pre-flight and in-flight support of all future airdrop operations from Air Force carrier aircraft (e.g., C-17s and C-130s).

V. Flight Test Program

A. Flight Test Program Overview

Flight testing relevant to the development of the autonomous GN&C software commenced in March, 2004 at Red Lake in Kingman, Arizona. Initial flights were remote controlled, executing planned maneuvers to establish the flight characteristics of the *Dragonfly* system; these occurred in March and April. Draper Laboratory used the results of these flights to conduct system identification and establish GN&C parameters as described elsewhere in this paper. First flight of the autonomous flight software occurred in May 2004. Testing has continued since then at approximately six-week intervals, with flights starting in October occurring at the Corral Drop Zone (DZ) at Yuma Proving Ground (YPG), Yuma, Arizona. During this time, the GN&C software was matured in parallel with evolution of the canopy, rigging, and airborne hardware, including a major upgrade to the AGU involving new actuation motors, necessitating revised flight software motor interfacing. The move to YPG was a milestone as this was the first time the system flew from a C-130 airplane, deploying at 130 Knots Indicated Air Speed (KIAS), considerably faster than the C-123 used in Kingman. Flights from military aircraft commenced in February 2005. As the flight test program proceeded, system weights were gradually increased up to the *Dragonfly* maximum of 10,000 pounds, as were drop altitudes, heading toward a goal of flights from 18,000 feet Mean Sea Level (MSL) by spring 2005. Initial autonomous flights were deployed directly over the targeted impact point, and then gradually more offset from the target was introduced. GN&C software was initialized in early tests assuming no winds, then forecast winds were used, and eventually flight tests will include updates of the GN&C mission file while enroute to the DZ with current winds estimates based on an assimilation of forecast and dropsonde wind and density data.

B. System Identification from Flight Test Data

As mentioned in Section III, flight tests were used to update the original models of the *Dragonfly*. A sequence of manual input tests were conducted to capture isolated flight conditions under varying brake and differential

toggles. Longitudinal tests using nominally zero turn maneuvers under varying brakes were used to generate a map of the glide-slope (lift-to-drag; L/D) and speed characteristics of the parafoil over a prescribed flight envelope. Figures 10-11 show some results from these tests, including a comparison with the current parafoil model. Figure 10 demonstrates a clear reduction in glide-slope with increasing brake setting; however the loss in performance is very gradual up until more than 50 inches of toggle. Tests have been planned to examine performance at toggles exceeding 100 inches, to 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 particularly large because of the large noise generated by the GPS navigation package in the vertical channel. The model comparisons show that a relatively simple aerodynamics model can be used to capture most of the steady-state performance of the system. Figure 11 shows the speed envelope of the parafoil over the range of tested brake settings. The original toggle limit of 100 inches (it is now 200 inches) resulted in nearly 20 ft/s variation in flight speed.

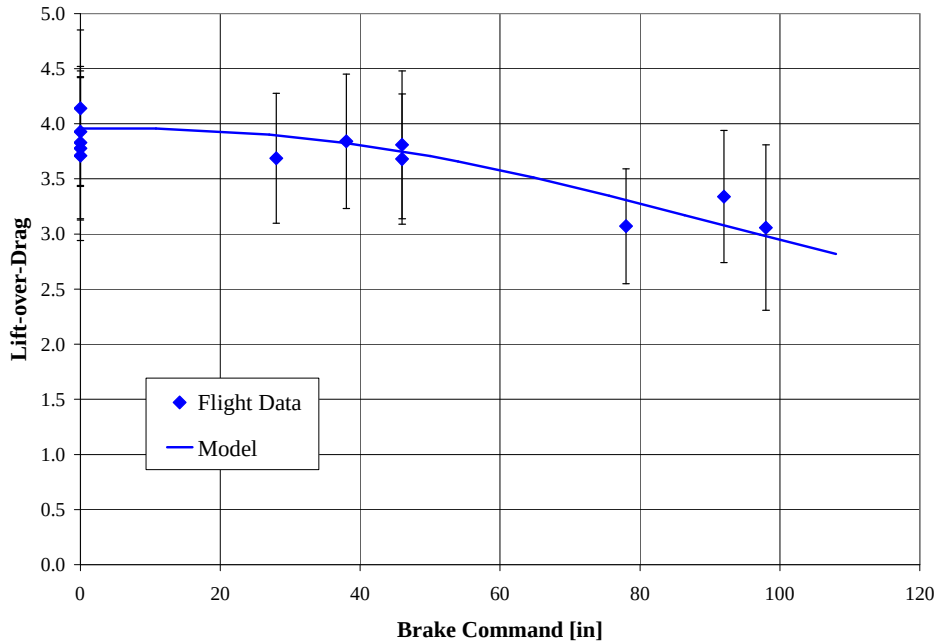

Figure 10. Lift-to-Drag Ratio vs. Brake Setting

Manual steady-state turn rate tests were also conducted on the *Dragonfly* system. Figure 12 shows the turn rate vs. differential toggle deflection. Several conclusions can be drawn from this plot: 1) Maximum steady-state turn rate is ~9 deg/s at a toggle of 100 inches, 2) There is a considerable amount of yaw oscillatory noise that permeates the heading data channel causing significant variance in the data, 3) The data collected shows a near linear relation between differential toggle and turn rate. The noise in the yaw channel appears to be 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. Small yaw oscillations persisted throughout most flight tests and did not appear to correspond to changes in the commanded turn rate of the parafoil. These oscillations were not indicative of the highly damped dynamics of the parafoil's general turn rate response. Earlier X-38 studies showed a non-linearity in turn rate performance at low brake settings that resulted in nearly zero response up to almost 35-40% of the stall differential toggle limits. There is insufficient data at this time to ascertain the exact low-brake response characteristics of the *Dragonfly* system since we have conducted the majority of our autonomous flights near 50 inches of brake to reduce risk and complexity. Future plans call for additional low-brake setting turns that should help document if a turn rate dead-band exists. Thus far we have seen no evidence that the *Dragonfly* exhibits this non-linear turn-rate behavior.

The variability in the observed *Dragonfly* turn rate at zero toggle deflection (seen in Figure 12) results from a combination of some of the effects just noted (rotation of the payload relative to the canopy and wind-driven canopy rotation) as well as some asymmetric control response. The asymmetric control effect varied from flight to flight, possibly indicating some flight-specific rigging effects and/or individual control motor response variations.

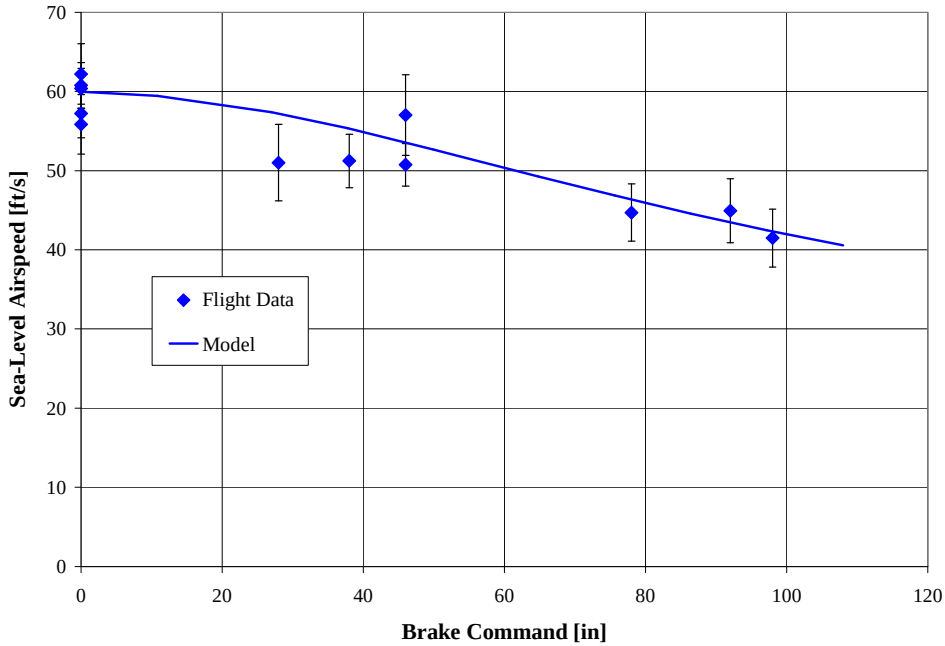

Figure 11. Sea-Level Airspeed vs. Brake Setting

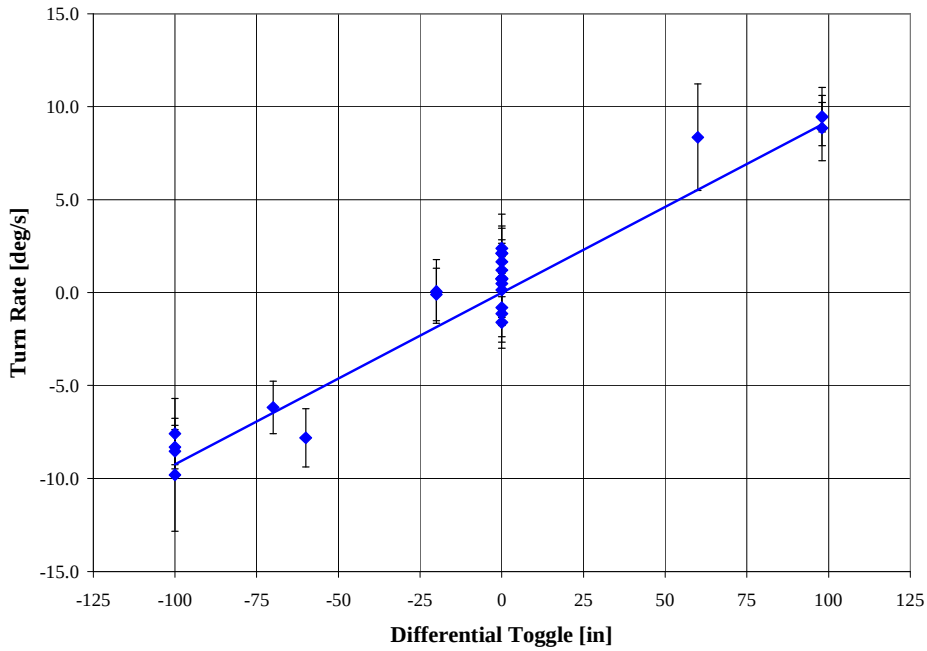

Figure 12. Turn-Rate vs. Differential Toggle Setting

Flight data analysis also resulted in some changes to the toggle actuator model that included the effects of aero-loading. Data collected on commanded line toggle position vs. actual position indicated some response degradation at higher brake settings, indicative of a fall-off in motor response. Revised torque limits and a more elaborate line acceleration sensitivity to load were added to the general actuator model to represent this behavior. The response characteristics of the first-generation-AGU motor also resulted in a re-design of the toggle actuator models to increase torque limits on the lines. Insufficient data was collected on these motors from flight tests, however updates to the simulated actuator models has already been completed based on manufacturer specifications. In

general, the torque limits of the motors did not impact system response except during flare maneuvers. Some small modifications to the lateral model parameters were undertaken following test flights. In general, the focus was on insuring proper steady-state response characteristics, but in addition some small changes were made to ensure that the turn rate characteristics matched flight data which showed a time of ~10-12 seconds from commanded differential toggle until steady-state turn rate was reached (with the indicated time including actuator response).

C. GN&C Flight Test Performance and Associated Design Evolution

Table 1 gives a summary of the *Dragonfly* flight tests to date that have provided canopy dynamics data in response to scripted manual Remote Control (R/C) inputs or that enabled autonomous GN&C flight with on-board logging of system performance data. Other flight tests that experienced prototype avionics or canopy-related hardware failures that precluded GN&C-related testing or that inhibited essential data logging have not been included in the table. The five listed flight tests in March-April 2004 were performed under R/C to support system identification objectives. The first tests of the autonomous GN&C occurred in May 2004. Post-flight analysis revealed that large misses in these initial autonomous GN&C tests were due, at least in part, to unintended limiting of toggle commands by the flight software. This software error was corrected before the next test cycle, in August of 2004.

Some of the initial flights in August experienced read/write failure of the flash memory chip used for in-flight data logging, and for storage of the large data table applied by the look-up terminal guidance algorithm. Consequently, to avoid additional flash memory problems during that flight test cycle, the look-up algorithm was disabled for flight on August 12, and the system was allowed to fly to the ground using the energy management technique (circles with adjustable radius, which was the baseline at the time, rather than figure eights). This was moderately successful.

Despite a series of deployment and avionics malfunctions in October and December 2004, two drops on December 8 and 10 enabled reasonably successful GN&C tests; the system deployed well and flew autonomously to within 140 meters and 170 meters respectively of the target.

The February 2005 test series was the first to use Wamore's second generation AGU. Of the two drops performed in this series, on February 2, enabled autonomous GN&C usage. While the apparent GN&C performance on this flight was somewhat poorer than anticipated, that deficiency was later traced to a communication glitch with the servo motors in the new AGU which has since been rectified.

Table 1. Initial GN&C-Related *Dragonfly* Flight Test Results

Date	Control State	Drop Aircraft	Drop Speed (KIAS)	Release Altitude (ft MSL)	GRW (lbs)	Miss Dist (m)	Comments
3/1/04	R/C	C-123K	110	9K	8K	n/a	Good flight characterization data
3/2/04	R/C	C-123K	110	9K	8K	n/a	Good flight characterization data
3/4/04	R/C	C-123K	110	9K	8K	n/a	Good flight characterization data
3/5/04	R/C	C-123K	110	9K	8K	n/a	Good flight characterization data; hard landing but no damage
4/21/04	R/C	C-123K	110	12K	8K	n/a	Good flight characterization data
5/20/04	Auto	C-123K	110	12K	8K	~400	Excellent deployment and auto flight; very good landing
5/21/04	Auto	C-123K	110	12K	8K	~1000	Excellent deployment and auto flight; very good landing
8/12/04	Auto	C-123K	110	12K	8K	183	Guidance table mode disabled; very soft landing
12/8/04	Auto	C-130A	130	10K	8K	142	Extended drogue descent; good canopy opening; good energy management and final approach/flare
12/10/04	Auto	C-130A	130	10K	10K	170	Extended drogue; good canopy opening; auto, high offset, navigation to target; good final approach/flare
2/2/05	R/C, Auto	C-130H	130	14K	8K	256	Extended drogue phase; good canopy opening; auto, high offset, navigation to target; good final approach/flare

VI. Next Design and Development Steps

Given the generic, modular architecture of the autonomous GN&C software, its adaptation to fly other parafoils will be straightforward. This year, flight characterization of two sub-scale models of 30,000-pound (30K lb) capable parafoils are planned, followed by adaptation of the existing GN&C software and then autonomous flight tests of

these canopies. Following this, it is expected that the software will be adapted to fly the full-size 30K lb systems when they are developed.

The Natick Soldier Center (NSC) is developing, through the Small Business Innovative Research (SBIR) program, two navigation sensors to enhance the landing precision of guided airdrop systems. The *Dragonfly* parafoil, with the GN&C flight software described herein, will be the initial flight test vehicle for these sensors. The most mature of these sensors, in the middle of Phase II at this time, is a precision ground-relative altitude sensor under development by Creare, Inc. of Hanover, NH. Utilizing primarily SODAR to detect the ground over varied terrain, including through foliage, this sensor will provide height precision of +/- 1 foot during the terminal phase of the flight, allowing GN&C to precisely time the final braking maneuver, thereby increasing landing accuracy. This sensor will be small, lightweight (less than 5 pounds), with a recurring cost of less than $500 per unit, cheap enough to be installed in just about any airdrop system from the 2000 lb class and up. Testing of this sensor will take place this calendar year.

Wind uncertainty remains a significant error source for airdrop systems despite improvements provided by the PADS mission planner discussed above. For guided systems, which have varying degrees of wind penetration capability, the wind uncertainty at lower altitudes, when there is less time for correction, is a significant problem. Also under development, nearing completion of Phase I SBIR trade studies, are several competing LIDAR wind sensors, which will provide real-time wind speed and direction to the GN&C software along the sensor line of sight ahead of the vehicle. This will allow GN&C to refine its onboard wind estimate during final maneuvers, further improving overall system landing performance. Initial tests of one of these units should take place in about one year.

VII. Conclusions

A Guidance, Navigation, and Control (GN&C) system that enables autonomous precision payload delivery using the *Dragonfly* 10,000 pound-payload-class parafoil has completed prototype development and has undergone initial flight testing. The guidance algorithm uses a proportional scheme for initial homing to the target, S-turns for energy management near the target, and a table-look-up implementation of optimal terminal control for final approach. A terminal flare maneuver capability is provided for landing. The control algorithm is a proportional, integral, derivative design with account for control actuator deflection constraints. Navigation relies on a coupled pair of Global Positioning System receivers with two antennas to determine position velocity, and heading. Wind velocity is also estimated in flight from the navigation data for use by the guidance algorithm. A *Dragonfly* mission planning capability has been integrated into the laptop-computer-based Precision Airdrop System (PADS) that is used on-board the *Dragonfly's* carrier aircraft to determine the desired aerial release point as well as to wirelessly transmit the mission plan file to the *Dragonfly*, including the best current estimate of the expected winds near the drop zone during descent. Flight testing of the *Dragonfly* has included system identification tests, the results of which have been analyzed and factored into the dynamics models used in the GN&C algorithm design. Autonomous GN&C flight tests have already demonstrated a delivery accuracy capability of about 200 meters despite a variety of developmental problems with the prototype canopy, avionics, and actuation systems that have been experienced to date. Assessment of the simulation and flight test results suggest significant improvement in the payload delivery accuracy will be realized once the canopy and actuator dynamics are more fully characterized, and the avionics/actuator developmental problems experienced to date are overcome by design refinements and/or component upgrades.

Acknowledgments

The autonomous GN&C software described in this paper is one part of the *Dragonfly* program, developed through a team effort of many individuals. The tireless efforts of the rest of the contractor team, ParaFlite, Wamore, and RoboTek, provided the vehicle to be flown. Test support by C-123 pilot Jim Blumenthal of Kingman, Arizona, and his ground support team, got us through the early months of the program. We would also like to thank the large team of professional system testers at the US Army Yuma Proving Grounds who helped bring the system so much closer to military utility.

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