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Parafoil Glide Slope Control Using Canopy Spoilers

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Current autonomous parafoil and payload aircraft are controlled by deflection of left and right brakes, leading to lateral-directional control. While left and right brakes can be deployed symmetrically, the main effect is to alter speed and not glide slope of the vehicle. Thus the use of left and right brakes produces lateral control but not longitudinal control of the vehicle. As a consequence, landing accuracy is reduced, especially when difficult terrain or significant atmospheric gusts are present near the landing area. Previous research has shown that improved landing accuracy can be achieved using glide slope control generated by dynamic modification of the canopy incidence angle. The work reported here considers generation of glide slope control authority for parafoil and payload aircraft using a novel approach of integrating aerodynamic spoilers into the canopy. Both an upper surface slit-spoiler and a lower surface flap-spoiler are investigated. It is shown that significant glide slope control can be achieved with either device.

I. Introduction

Airdrop systems offer the unique capability of delivering large payloads to undeveloped and inaccessible locations. Traditionally, these systems have been unguided and, consequently, either a large landing zone is required or a high probability of losing individual payloads must be accepted. Autonomous guided airdrop systems based on steerable, ram-air parafoils were developed with the goal of improving the precision and accuracy of air-dropped payload delivery.

These systems use trailing edge brake deflection for control. Differential brake deflection produces lateral control. Symmetric brake deflection predominantly causes a change in the flight speed with small changes in glide slope until stall. The extent to which symmetric brake deflection yields glide slope change varies from canopy to canopy with some systems generating more glide slope change than others, but the major trend is that symmetric brake deflection yields relatively minor glide slope changes. Typical flight control laws for guided parafoil systems posses direct lateral control and achieve a limited degree glide slope control using an altitude-dump maneuver in the form of a series of S-turns [1]. A flare is often performed immediately before touchdown to minimize impact velocities and forces. This method of terminal guidance is susceptible to atmospheric gusts and surface conditions at the target area and can induce significant errors in final landing position. Numerous researchers have developed parafoil control schemes using rights and left brakes as the control mechanism. The algorithms have become steadily more sophisticated and have achieved better and better accuracy. However, with the current left and right parafoil brake control mechanism it appears that a limit is being reached in terms of accuracy. The addition of glide slope control has been shown to be a powerful means to increase impact point accuracy. Slegers, Beyer, and Costello [9] demonstrated effective glide slope control by dynamically varying the canopy incidence angle and estimated a factor of three improvement in landing accuracy in simulation. This was accomplished by varying the length of the leading edge (LE) risers in concert with the trailing edge (TE) brakes, thereby rotating the canopy longitudinally and controlling the trim angle of attack directly in flight. Another means for achieving glide slope control is activation of spoilers on the upper surface of a wing. Sailplanes have traditionally used this control mechanism for altering speed and glide slope [14**]**. In the 1960's, spoiler devices were incorporated on powered aircraft for direct lift control (DLC). Kohlman and Brainerd [10] demonstrated the benefits of using upper wing surface aerodynamic spoilers for glide path control on light aircraft. Yet another method for glide slope control is through the use of auxiliary flaps mounted on the bottom surface of a wing. Ellis [11] showed that when a bottom surface auxiliary flap is deflected in

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conjunction with a traditional trailing edge flap, the performance of the combined actuation exceeds the sum of the individual effects of both flaps due to the positive interaction between their flow fields.

The research reported here explores control mechanisms for the generation of glide slope control on parafoil and payload aircraft with a focus on mechanisms that generate substantial glide slope perturbations in an efficient manner. Two devices are considered, controllable slits in the upper surface of the canopy and a deployable fabric flap on the lower surface of the canopy. The ability of these mechanisms to provide glide slope control is examined via a flight test program using a small powered parafoil and payload system. The paper begins with a detailed description of each control mechanism which is followed by a description of flight hardware and flight operation. Next data processing of flight measurements is discussed. Flight test results for each glide slope control mechanism are presented, including parametric trades varying mechanism characteristics.

II. Glide Slope Control Concepts

A schematic of the upper surface slit concept is shown in Figure 1. On the top surface of the canopy, a spanwise slit is introduced across a number of cells near the center of the wing. The slit location was determined using computational fluid dynamics simulations as a guide and corresponds to the minimum pressure point on the upper surface. All the cells that contain a slit have a control line attached to the leading edge side of the slit. These lines pass through the bottom surface before joining and connecting to a single winch servo. When the winch servo actuates the control line, the material ahead of the slit is deflected downward. The remainder of the cell on the trailing edge side of the slit remains unperturbed, due to the internal pressure of the canopy. This causes an airflow bubble on the upper surface which distorts the airflow, much like conventional aircraft spoilers. The opening also allows some internal pressure to be released, increasing the effective size of the spoiler. This slit spoiler configuration uses mostly ram air as a spoiler rather than a mechanical flap. When the slit is not actuated, the spanwise tension in the canopy is sufficient to keep the slit closed. Figure 2 shows the slit control mechanism as implemented on a small 2.4 m^2 (projected) canopy. The slit connections are attached to a single winch servo using a cascaded control line. The location of the spoiler array is near the quarter chord on the top surface across 6 cells near the centerline. Actuation of the spoiler produces the openings and the final spoiler shape shown in the second part of Fig. 2.

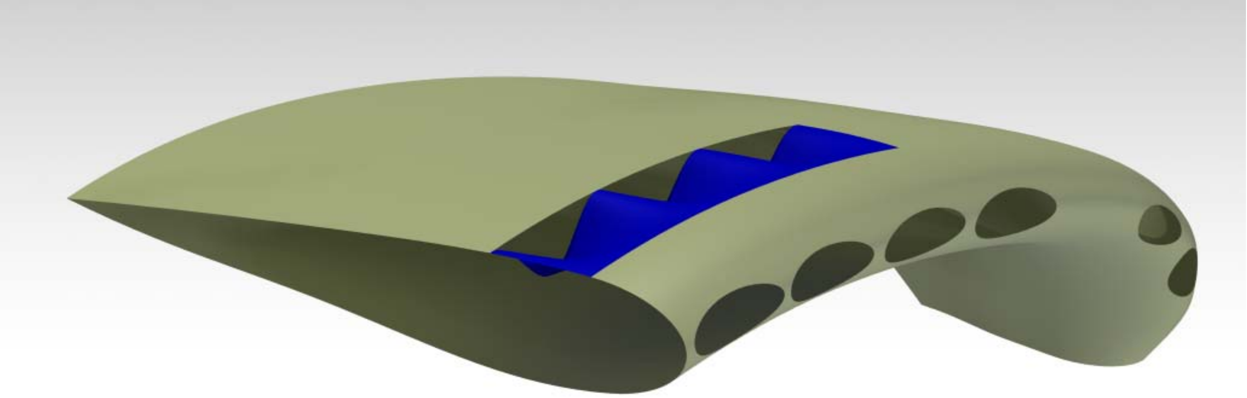

Figure 1. Upper Surface Slit Spoiler Concept

a) slit spoiler at rest *b) actuated slit spoiler detail*

Figure 2. Upper Surface Slit Spoiler on Test Flight Canopy

A schematic of the lower surface flap concept is shown in Figure 3. The lower surface spoiler is simple in construction, and similar in concept to a split flap or airbrake. It consists of a trapezoidal piece of ripstop fabric, attached to the bottom surface just behind the A-lines. The leading edge of the flap spoiler is attached using adhesive tape, allowing for simple adjustments to the chordwise location. The trailing edge of the flap spoiler is attached to a single winch servo using a cascaded control line. In the retracted position, the flap spoiler sits completely flush with the bottom surface. When the winch servo actuates the control line, the flap spoiler is extended into the airflow, thus “spoiling” the smooth airflow over the lower surface of the canopy. Figure 4 depicts the lower surface spoiler concept as implemented on a test canopy.

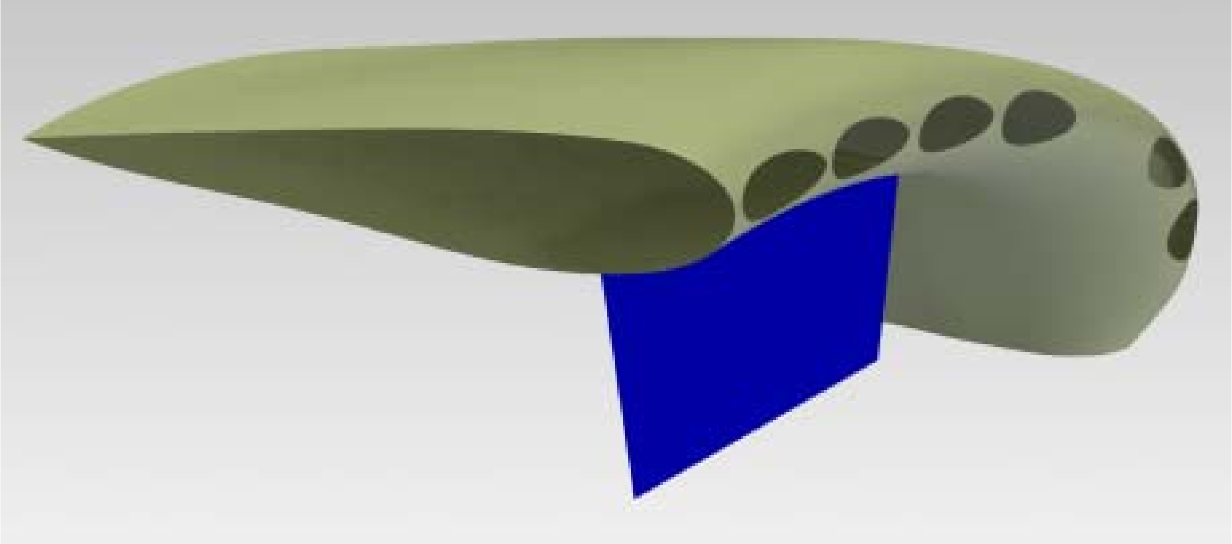

Figure 3. Lower Surface Flap Spoiler Concept

Figure 4. Lower Surface Flap Spoiler on Test Flight Canopy

III. Flight Test Description

The ability of the slit spoiler and flap spoiler concepts to create significant in flight glide slope changes was evaluated experimentally. The flying test system is shown in Figure 5. The payload consists of a wooden frame to which the flight components are attached. Wheeled landing gear and a .60 in^3 model airplane engine allow for self-powered flight and rolling take-offs. Three main servos are used to achieve basic control of the system. Two servos attach to different halves of the trailing edge and are used for steering and braking.

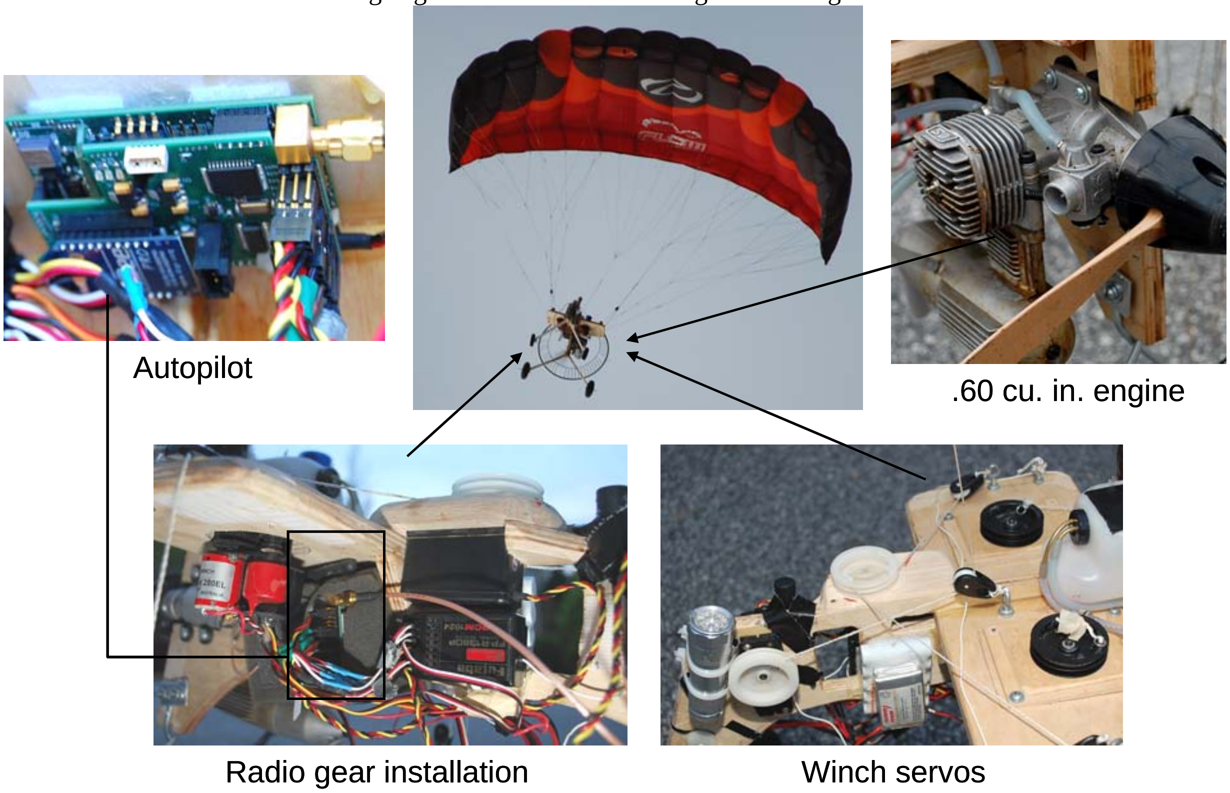

Figure 5. Powered Parafoil in Flight

The leading edge lines are attached to a single servo and are used for incidence angle control in conjunction with symmetric brake deflection. Additional control mechanisms can be actuated through a fourth servo which is not necessary for basic flight and is available for spoiler control or other tasks. The instrument package includes a GPS sensor, barometric altimeter, accelerometers, and compass. During data acquisition the payload is controlled through the instrument package. Both payload position and control actuation are recorded in the output data. A set of LED lights provide illumination for night flying. The fuel tank can hold a maximum of half a pound of fuel which is rarely used up completely. Thus the weight change during flight remains low compared to the total aircraft weight to avoid affecting the parafoil's glide performance. A typical flight test profile is illustrated in Figure 6.

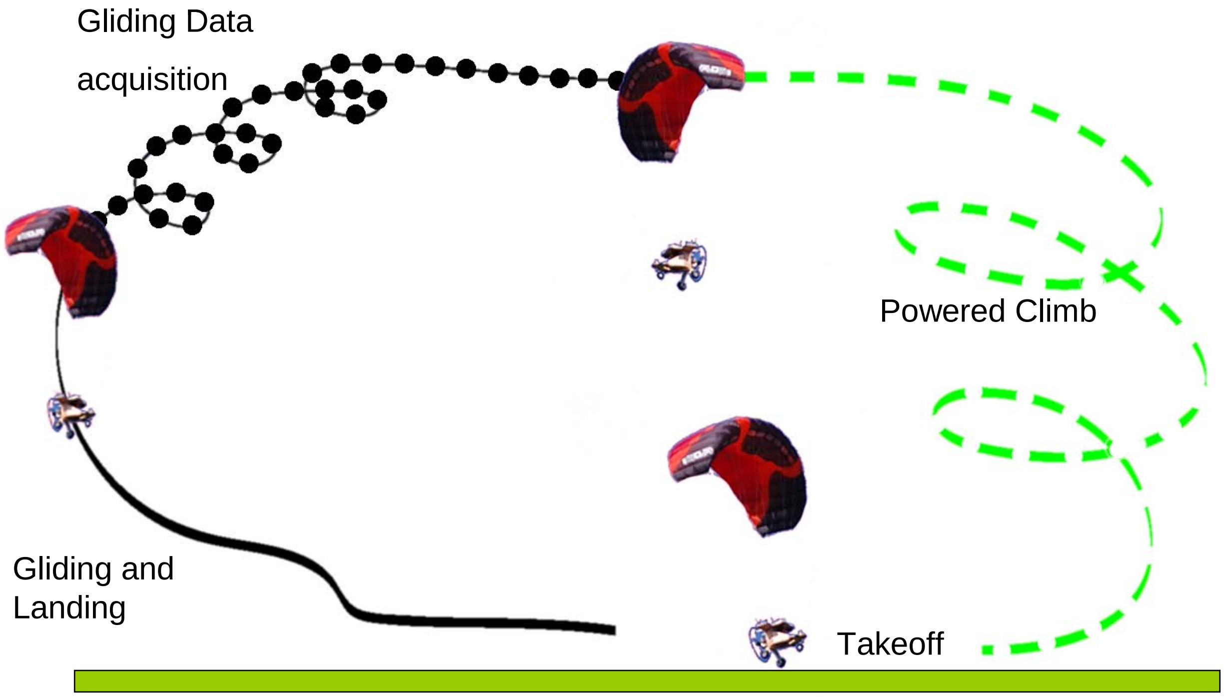

Figure 6. Typical Flight Test Profile

Takeoff is followed by a powered climb to a safe altitude, during which the payload is configured for optimal climb performance (dashed line). After reaching altitude, the payload is set in the test configuration and the engine speed is reduced to idle. Data acquisition is initiated while the system is in gliding flight (dotted line in figure). When sufficient data is collected, or the payload descends to a low altitude, data acquisition is terminated and another climb to altitude is performed.

Flights typically end with a dead-stick landing to minimize the possibility of line tangles and propeller strikes. This flight test setup eliminates the issues of canopy deployment from free-fall, reduces overall cost, and reduces the time between test runs.

Figure 7. shows typical position data obtained during a single flight using GPS. In order to separate the wind speed from the flight airspeed, a circular pattern is flown during data acquisition. The drift in the ground tracks in Fig. 7 indicate the wind vector. Vertical position data was obtained with a barometric altimeter. The altimeter output for the same flight with three data acquisition sequences is shown in Figure 8. Barometric altimeter data is useful since it is available at a higher frequency than the GPS measurement and is more precise than GPS in the vertical direction. This particular flight includes three data acquisition sequences.

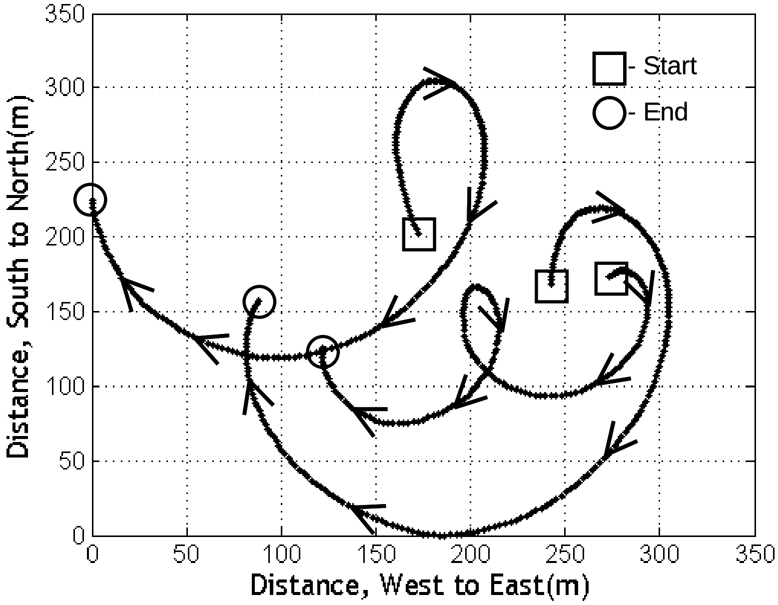

Figure 7. Example Ground Tracks generated during one flight (3 virtual drops)

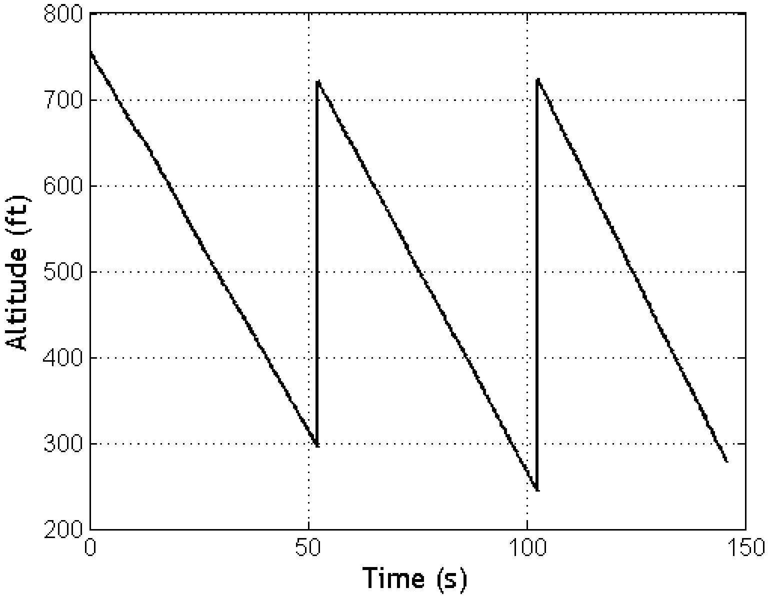

Figure 8. Altitude measured during one flight

For the purpose of glide slope estimation the ratio of forward velocity to vertical velocity is needed. Computation of the forward velocity of the vehicle relative to the air mass requires knowledge of the atmospheric wind conditions. To achieve this, test flights are conducted with the vehicle flying at a constant and small turn rate. The total vehicle velocity then contains sinusoidal variations due to the wind, allowing simple estimation of the horizontal airspeed, shown in Figure 9.

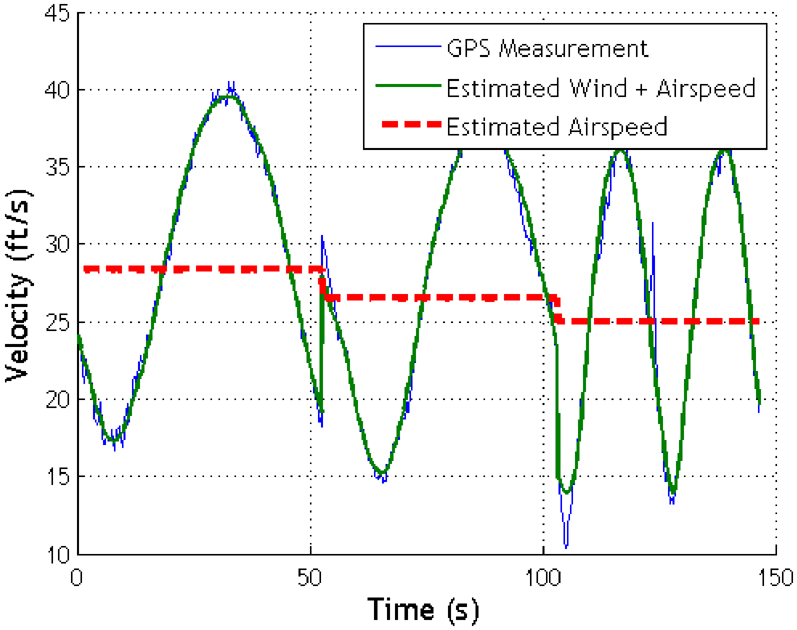

Figure 9. Extracting Horizontal Airspeed from Velocity Data

The vertical airspeed is obtained by differentiating the altitude data. This yields sufficient information to estimate the glide slope of the vehicle. In addition, the control inputs are recorded and a relationship between GS and control input can be established. The output data also contains heading information that can be used to estimate the turn rates attainable for different control deflections.

IV. Results

Data for the results presented below was gathered during approximately 12 flights performed at a sport flying field near Atlanta, GA. To obtain high quality data, test flying was conducted only in very calm atmospheric conditions (normally just after sunrise, just before sunset, or at night),

A. Lower Surface Spoiler

The lower surface spoiler was placed just behind the A-lines, 15% of the canopy chord from the leading edge. The spoiler span is 40% of the canopy span, and the spoiler chord was 20% of the canopy chord. Flight test results varying the deflection of this spoiler are shown in Figure 10 and Figure 11.

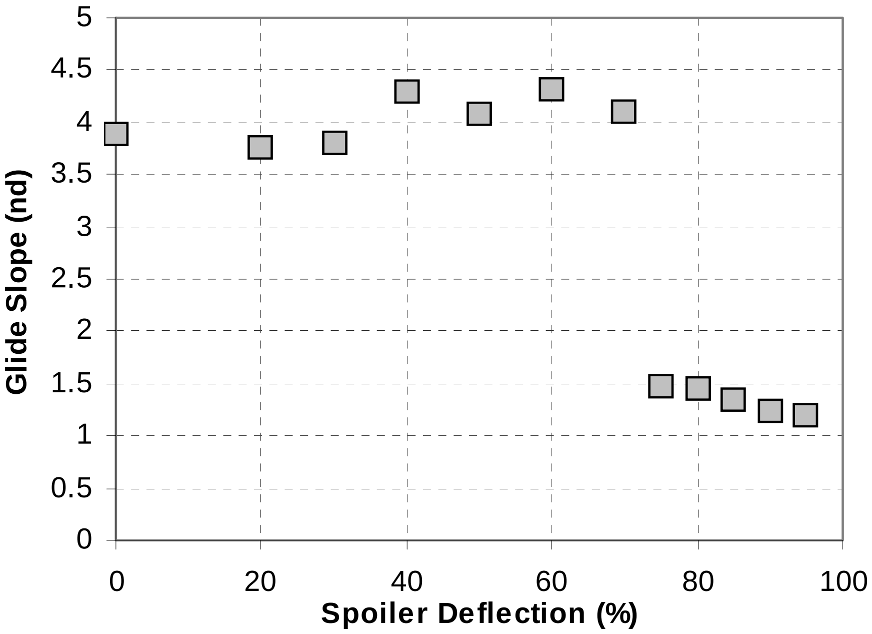

Figure 10. Lower Surface Flap Spoiler: Flap Deflection versus Glide Slope

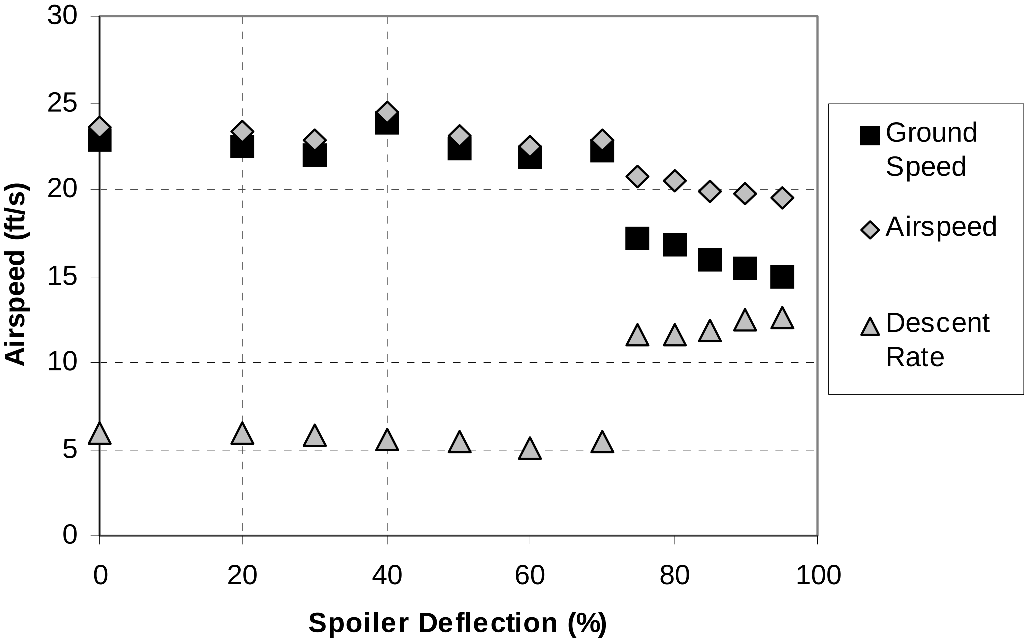

Figure 11. Lower Surface Flap Spoiler: Flap Deflection versus Airspeed

The bottom surface spoiler is capable of producing significant changes in glide slope. Deflections up to 70% of the control travel produce a slight increase in glide slope and a slight reduction in airspeed. In particular, descent rate is reduced. In this respect, the flap spoiler functions initially like conventional trailing edge brakes . A maximal increase in glide slope of 0.5 points was observed at 70% spoiler deflection.

Beyond 70% of the control travel, the glide slope is reduced drastically. Forward speed is reduced and descent rate is increased, resulting in higher overall airspeed. This effect is similar to stalling the canopy with large symmetric brake deflection, but none of the instability and control difficulty associated with stall was present when using the spoiler. At the maximal spoiler deflection, glide slope is reduced to values around 1.2. It should be noted that the addition of the spoiler to the lower surface did not degrade the nominal glide slope value of 3.8.

B. Upper Surface Spoiler

A total of three upper surface slit spoiler configurations were evaluated. Each has the slit located at the quarter chord on the top surface, and has a different number of cells connected to the control servo. With 2 cells connected to the control servo, the 2 cells on each side of the centerline deflect when the servo is actuated. A small opening is created in this fashion, with a small effect on canopy performance and glide slope. The slit cells that are not actuated remain in the closed position due to the canopy's tension. Increasing the size of the uppers spoiler is accomplished by adding slit cells on either side of the centerline symmetrically. A maximum of 6 slit cells, 3 on either side of the centerline, was tested. A summary of the configurations tested is given in Table 2.

Table 2. Parametric Studies Summary

Spoiler Type	Chordwise Location	Span
Upper Surface	0.25	**42%**
Upper Surface	0.25	**28%**
Upper Surface	0.25	**14%**
Asymmetric Slit	0.25	21%

The addition of a slit across the top surface of the canopy seems to have produced a small degradation of the nominal glide slope, from around 3.8 to 3.2. This was expected since little effort was made to completely seal the slits when they are not deflected. Deflection of the slit spoiler produces a reduction in both glide slope and flight speed. The mechanism of glide speed control if fundamentally different from that of lower surface spoiler. An immediate reduction in lift due to spoiler deflection is observed, resulting in a lower glide slope value (Figure 12). The descent rate is increased and the forward velocity is decreased, producing an overall decrease in flight speed (Figure 13).

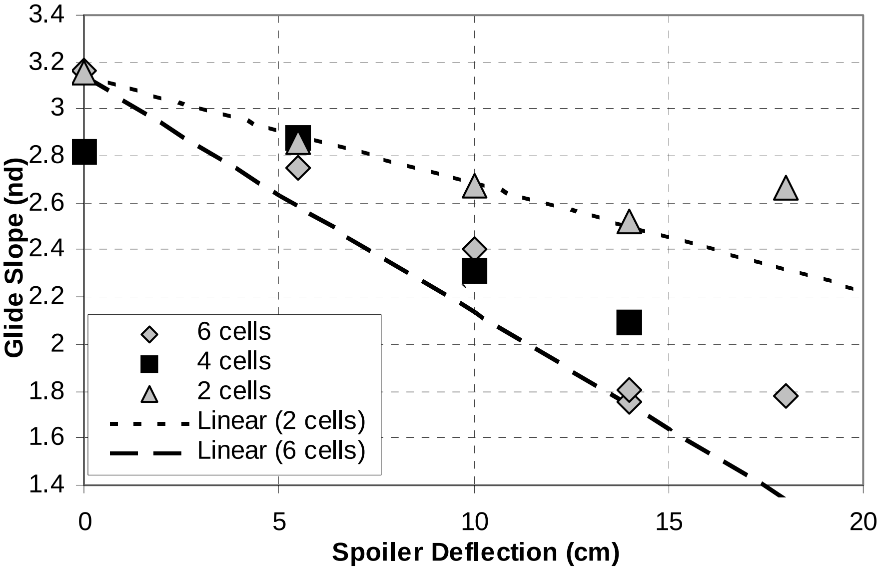

Figure 12. Upper Surface Slit Spoiler: Slit Deflection versus Glide Slope

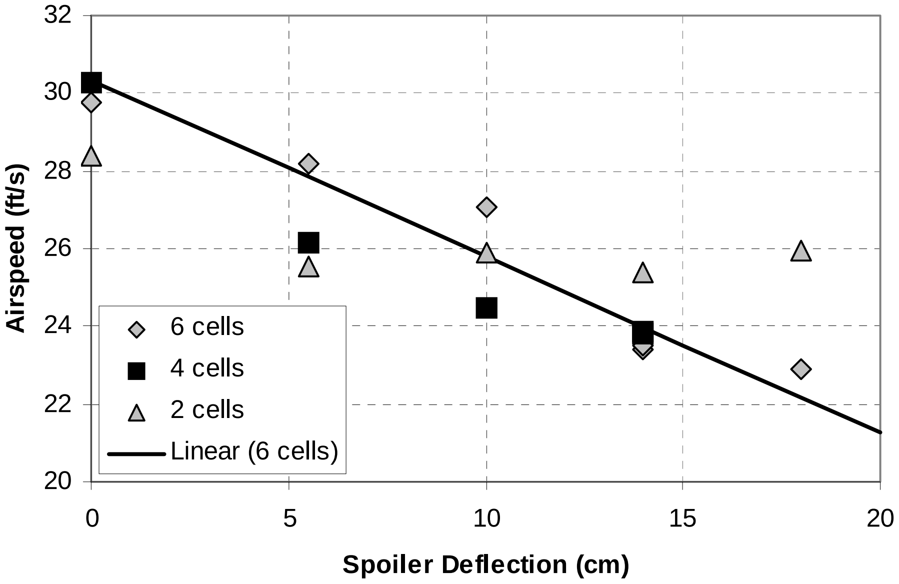

Figure 13. Upper Surface Slit Spoiler: Slit Deflection versus Airspeed

The slit spoiler effect on glide slope and airspeed is largely linear for slit deflections below 18 cm. The canopy itself is roughly 20 cm thick and further actuation causes the top and bottom surfaces of the canopy to come in contact with each other. Actuation past the point of surface contact produces an unfavorable canopy shape and stall. In Figures 12 and 13, this final point is seen to depart from the otherwise linear response trend. At the maximum practical deflection setting, glide slope is reduced from 3.2 to 1.8.

The effect of increasing slit size was examined by comparing the maximum glide slope changes of the different configurations. Figure 14 depicts the growth in spoiler effectiveness by increasing the number of cells containing actuated slits. This linear trend is expected to reach a plateau as the overall size of the slit cells begins to approach the span of the canopy. This increase in slit size is relatively simple to implement, as the control servo deflects a limited part of the top surface by a limited amount.

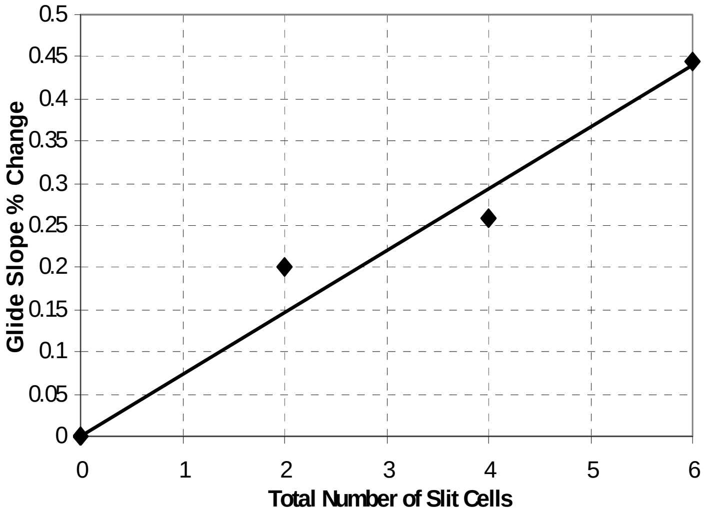

Figure 14. Upper Surface Slit Spoiler: Number of Slit Cells vs. Glide Slope

V. Conclusion

Current guided airdrop systems employ right and left brakes that yield lateral control with very limited longitudinal control. The addition of control channels, particularly ones that enable longitudinal control of autonomous airdrop systems, promises to enable substantial improvements in impact point accuracy. This paper explores generation of glide slope control of parafoils with two different canopy spoiler configurations. The flap spoiler uses a fabric flap on the lower surface of the canopy and acts like a forward mounted airfoil flap. This concept generates large glide slope change of 2.4 but in a very nonlinear and abrupt manner. The slit spoiler concept opens an array of slits on the upper surface of the canopy and creates a virtual spoiler. This concept generates large glide slope change of 1.5 in a linear manner. These glide slope control mechanisms are relatively simple and straightforward to implement on future autonomous airdrop systems.

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