A Precision Autonomous Parachute Delivery System

by

Olaf Bleck

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Massachusetts Institute of Technology

Submitted to the Department of Mechanical Engineering
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Signature of Author..
Department of Mechanical Engineering

Certified by..
Brent Appleby
Charles Stark Draper Laboratories
Thesis Supervisor

Certified by..
Ernesto Blanco
Adjunct Professor of Mechanical Engineering
Thesis Advisor

Accepted by..
Ain A. Sonin
Chairman, Department Committee on Graduate Students

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ABSTRACT

Based on previous projects within the author's engineering group and his own experience as a sport parachute jumper, a robotic parachute system was designed and flight tests were conducted to evaluate flight performance in deep brakes, for eventual use in autonomous accuracy landing approaches for targets two meters in size or smaller. Numerous design improvements were evaluated and/or implemented, and additional improvements are suggested.

Using the implemented system, flight tests gathered GPS data used to evaluate canopy glide ratio changes, stall characteristics, and in-flight rotational oscillations in deep brakes flight, a region of the flight envelope not used in previous work. Results show that the low-porosity canopy used exhibits adequate glide ratio changes for closed loop glide path control, but has poor stability in deep brakes flight. The investigation suggests that canopies with higher porosity fabrics would perform superbly.

Technical Supervisor: Brent Appleby
Title: Member of Technical Staff, Charles Stark Draper Laboratories

Thesis Advisor: Ernesto Blanco
Title: Adjunct Professor of Mechanical Engineering

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Olaf Bleck

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Terminology

The following terms are referred to in this paper:

Angle of attack	In aerodynamics, the angle an airfoil makes with the mean direction of airflow.
Brakes	Two fabric flaps, one on either side of the trailing edge of a ram air parachute, which depending on deployment cause the parachute to brake or turn.
Braking	A maneuver executed by deploying in tandem some level of left and right brakes to slow down a ram-air parachute, usually increasing the angle of attack.
Control Lines/ Brake Lines/ Steering Lines	Two lines that can be actuated by a parachute pilot or piloting system that control the amount of left and right brake deployment.
Deep Brakes Flight	A region of flight of a ram air parachute in which both brakes are nearly fully deployed.
F-111	An industry standard rip-stop nylon fabric, commonly used in parachute construction.
Glide Ratio	In aerodynamics, the ratio of horizontal distance traveled to altitude lost.
GPS	Global Positioning System, a satellite/radio-based infrastructure which can be used to determine the receiver's location in three dimensions and time anywhere on earth.
Lift to Drag Ratio (L/D)	Another term for Glide Ratio.
Ram Air Parachute	A modern parachute design that consists of a self-inflating fabric airfoil.
Riser	A portion of a parachute system which connects the load to the parachute suspension lines.
Slider	Small rectangular fabric panel with grommets on each corner which aids in canopy deployment by slowing down the opening speed and preventing line entanglement.
Stall	In aerodynamics, the condition where the flow over an airfoil for various reasons no longer suffices to generate lift.

Static Line	A line attached to a packed parachute which aids in deployment as the system is launched from an aircraft.
Suspension Lines	Lines that transmit a parachute's lifting force to the load.
Zero porosity fabric (Z-Po)	Nylon fabric which is treated with a coating or otherwise designed to have very low porosity. Examples: "ZP3", "Soarcoat", and "Exacta-chute"

Chapter 1: Introduction

Delivery of cargo via unmanned parachute system is commonly used for a variety or reasons including lack of adequate landing facilities, aircraft time and cost savings, and endangerment of the aircraft due to hostility. Traditionally, cargo is dropped out of a tailgate cargo aircraft under round canopies at fairly low altitudes. The cargo drifts uncontrolled with the wind until it lands, and thus low altitude deployment increases landing accuracy.

However, under many circumstances, high altitude deployment is desirable and the necessary degree of landing precision may be as small as a meter. The autonomous technology required to achieve this goal is currently under development. Such systems are based on modern *ram-air* canopies, which are self inflating fabric airfoils with steering capability. However, unlike an aircraft wing, ram-air canopies tend to have fairly constant glide ratios throughout the nominal flight envelope [5], [6], [9]. Operating in this envelope makes glide path control difficult since there is no way to vary the glide slope in order to stay on a desired glide path with closed loop control.

This project examines ram-air canopy operation on the edge of the normal flight envelope, in the region where the canopy begins to stall, or in other words where the canopy crosses over and begins to assume properties of a round parachute. This is the region of operation which sport parachute jumpers (including the author) use to achieve precise landings, particularly in the final 1000 ft. of a mission where atmospheric conditions become more variable due to heating and turbulence caused by objects on the ground. This effect is also noticeable in the research presented [4] [5], [6], [8], [9], but the primary focus in these studies is on full-flight, optimized glide ratios.

Additionally, this project examines and suggests improvements to various aspects of the hardware used in previous experiments by the engineering group of which the author is a member.

Canopy Technology

Round or conical parachutes (see Figure 1) have been in use since ca. WWI to drop cargo and humans. These canopies are circular in plan-view and have an opening in the center which permits the air which is compressed by the canopy to escape through the center, instead of escaping over the canopy edge. The latter causes an undesirable pancaking instability. Some models of these canopies utilize additional *vents* sewn into the trailing sides of the canopy, allowing air to escape through the rear. By opening and closing these vents, the canopy can be turned and also achieves a small amount of forward flight. Typical glide ratios are 0.5:1 with loading of 0.5 lbs/sq. ft.

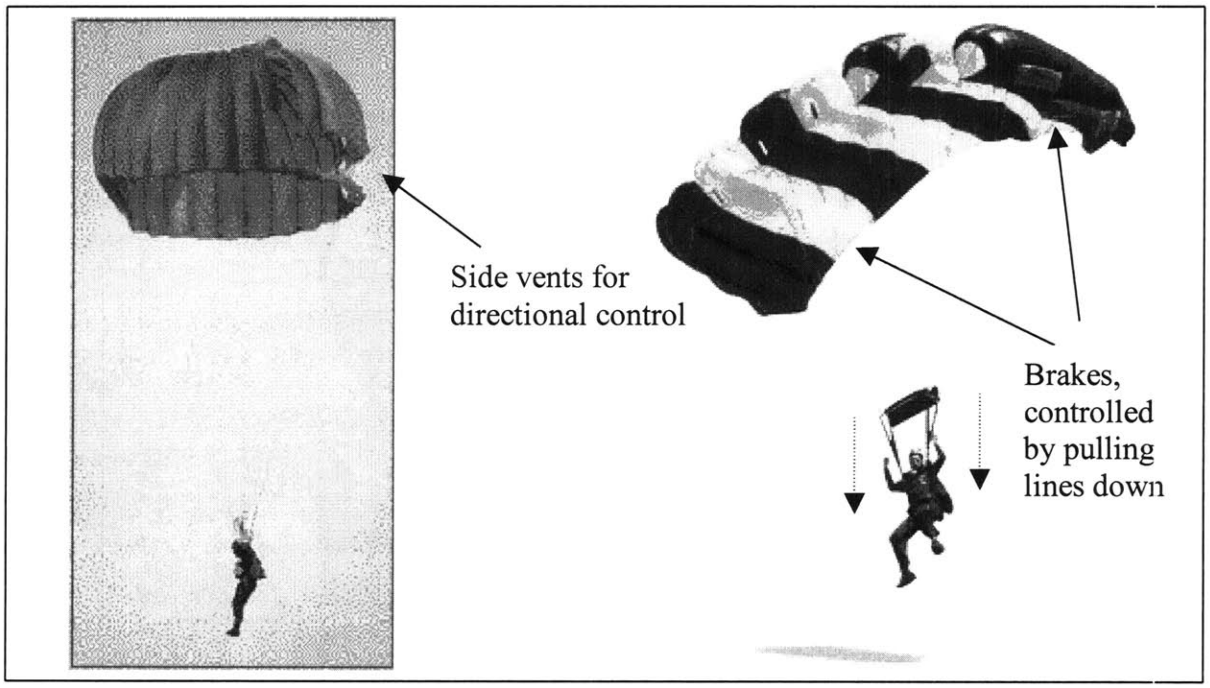

Figure 1: Round and ram-air parachutes

Ram-air canopies (see Figure 1) were invented in the 1960s and have been significantly advanced since then, even to this day. These canopies are rectangular in shape and consist of seven or more inflatable *cells* which, when inflated, have an airfoil-like cross section. The leading edge of each cell is cut open, allowing the incoming air to inflate the cell, and then the entire inflated assembly behaves much as an aircraft wing. Glide ratios are typically 2:1 – 4:1 with loading of 1-2 lbs/sq.ft. Additionally, ram air canopies are directionally controlled by pulling on one or both *brakes*, fabric flaps at the trailing edge of the canopy, much like ailerons.

Ram air canopies are manufactured typically out of fine nylon fabric. Older fabrics such as F-111 are moderately porous, while modern zero-porosity ("z-po") fabrics are coated with Teflon and other materials and make them virtually airtight. This makes the canopies fly faster with higher glide ratios, increased lift, and smaller size.

However, unlike aircraft wings which can affect the glide ratio by adjusting angle of attack and by deploying flaps and air brakes, ram-air canopies are remarkably consistent in their glide ratios under forward flight. The exceptions to this are when turning, and also in a *flare*, a landing maneuver in which both flaps are pulled down and the canopy's momentum is briefly converted into a near-horizontal glide, much like that of an aircraft just before touchdown. The less porosity a canopy has, the more it exhibits these constant glide ratio characteristics [10].

Mission Profile

A typical high altitude precision cargo drop can be broken into several phases, consistent with what is regularly done in sport parachuting.

<u>Freefall:</u> consisting of launch from an aircraft at altitudes exceeding 3000ft AGL (above ground level). Terminal freefall velocity typically is 120mph, and rarely exceeds 150mph due to extreme stress on the parachute hardware on deployment. For heavy loads with little drag, surface area, or a naturally stable freefall attitude, a drogue parachute is often used to stabilize the freefall and to limit the maximum fall rate. Altitude is measured with a barometric altimeter and horizontal translation is dictated by the winds aloft, which commonly exceed 30mph, and can be at greatly differing directions at various altitudes. For cargo, wind drift is another key reason that freefall is desirable, since cargo can then be dropped from high altitude and reliably fall into the

desired target area. Launch is done over a *spot* which takes freefall drift into account, in addition to drift due to the ground winds during the parachute descent phase.

Parachute Deployment: deployment may be done through one of several methods. In cases where no freefall is required, a *static line* is most often used, a line that attaches to the aircraft which pulls out the parachute's suspension lines and inflates the parachute as the cargo falls away. Pilot chute deployment is used in the case of freefall. A small round parachute is deployed, sometimes spring loaded or through pyrotechnic means, which generates enough drag to cause line stretch and canopy inflation. Proper parachute packing usually results in an on-heading opening, but this is not guaranteed.

Flight Phase: during this phase the pilot or piloting device flies the canopy in the nominal full-flight envelope. Steering is accomplished by pulling on either of two brake lines (see Figure 1). Turns can be extremely fast and violent, particularly if a spiral turn is induced, and the load can swing out from the canopy to near horizontal. Spiral turns can be used to rapidly descend in flight mode, but the precision is limited. In full flight the canopies tend to exhibit a constant glide slope, regardless of combined brake actuation or flare. Thus, in order to guide the parachute to a particular location, a series of previously "rehearsed" maneuvers is usually employed that have a predetermined effect. The flight phase can be used to guide the parachute to the ground, but landing precision is limited, and control is difficult.

Accuracy Approach and Landing: more typically, if a parachute pilot is attempting a precision landing, at approximately 1000ft AGL the flight phase is terminated and a series of gentle maneuvers are executed in order to determine the effective winds with respect to the ground (see Figure 2). Then, given some knowledge of the wind vector, the pilot estimates a final glide slope, sloping skyward in the downwind direction from the desired target (under low to moderate wind conditions, that is. See **Figure 3**). The pilot steers the canopy to intersect this final glide slope at between 300 and 600 ft, at which point the canopy is turned into the wind. The canopy is usually piloted in *deep brakes*, in which the nearly flared brake setting is held continuously. In order to servo around the desired final glide slope, the brakes are released slightly if the canopy is going to undershoot (i.e. the glide ratio is increased), and the brakes are increased in order to reduce the glide ratio for overshoot (see Figure 4). There is typically no flare on a precision landing, which increases the force of impact somewhat. For this reason most sport drop zones have special gravel *pea pits* set up to soften the landing. An experienced jumper can land within 2 meters of a target 95% of the time and a skilled accuracy jumper can touch down on a 5cm target 5 of 5 times in competition.

The accuracy approach has not been used in previous autonomous experiments and very little performance data has been published on canopies in this region of the flight envelope.

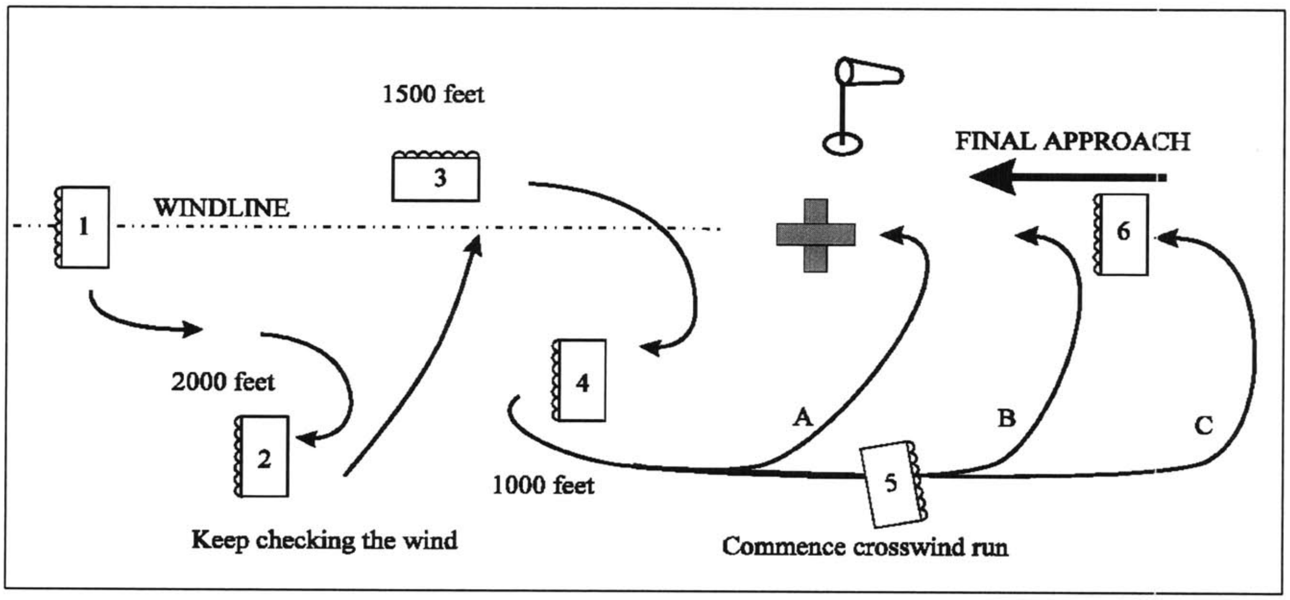

Figure 2: Typical accuracy landing approach pattern

(courtesy Australian Parachute Federation [1])

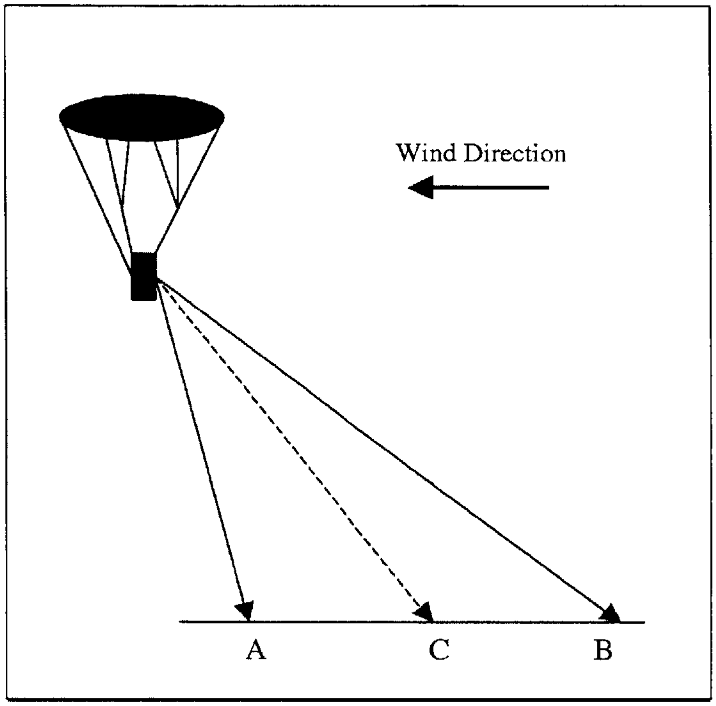

Figure 3: Range of achievable glide paths.
Parachute can land between points A and B based on minimum and maximum controllable glide paths, with C being nominal and desired.

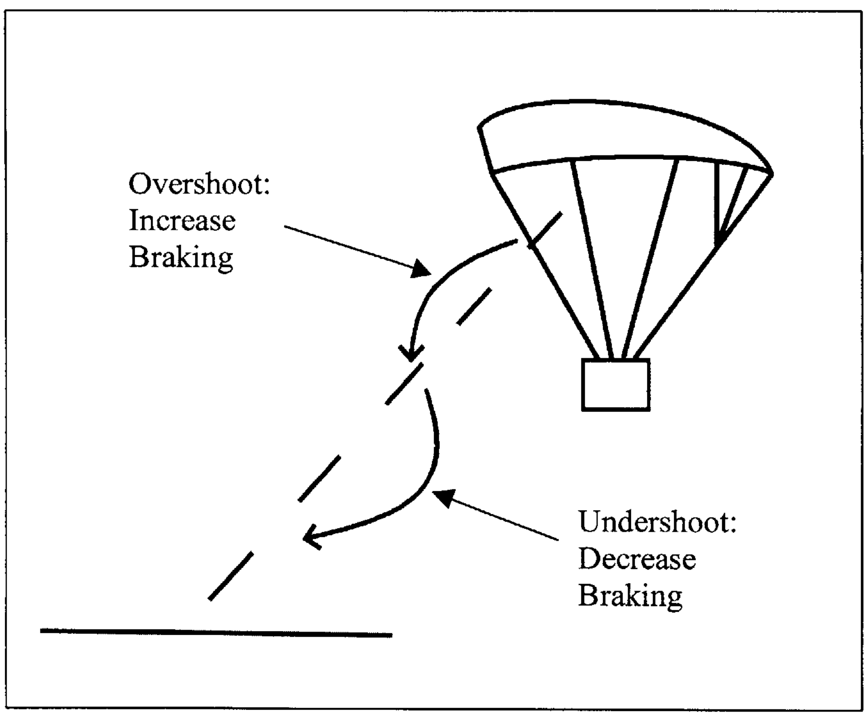

Figure 4: Typical glide slope modulated canopy control

Research Objectives

A three-tiered approach was chosen to investigate and implement a low cost robotic system capable of shooting an accuracy approach based on the methods used by sport jumpers.

The first area of research and development incorporated evaluation of previous robotic parachute systems. Chapter 2 presents design considerations and implementation of a low cost, simple system capable of quick turn around for extensive experimentation.

The second phase of the project is presented in Chapter 3, with the results of multiple flight tests and subsequent conclusions about deep brakes canopy performance, glide ratio behavior, and load oscillation. Recommendations for future work and expected results are also given.

The third and final phase of the project, autonomous final approach and landing, had not been completed at the time this paper was written.

Chapter 2: Design Considerations

A practical, commercially or militarily viable autonomous parachute delivery system consists of the canopy and the robotic unit. The payload is additionally strapped to it. Such a system should be designed with the following criteria:

- Inexpensive: the unit must be disposable since it may not be recoverable.
- Robust: must be able to operate reliably in a moderate range of weather conditions (wind, clouds, temperature, humidity) and light levels (day or night).
- Simple: the unit must be operable by non-expert personnel with minimal training.

Care was taken to design this project with these requirements in mind.

In addition, this project addressed design issues involved with field development, since a great deal of trial and error is required given the limited published data on the subject. Previous trials have exhibited the following bottlenecks and problems.

- Slow turnaround time. Factors: tedious canopy packing, access to system components for preflight checks and data recovery difficult.
- Load oscillation in flight.
- Limited and sluggish response to control inputs.
- Complex components and software.
- Electronic noise.

Methods used to address these issues are described in this chapter, followed by recommendations.

System Design:

The basic system was built out of inherited components, which was to a great degree desirable because it necessitated the need to "make due", keeping the system simple and functional without the very latest technology.

The system consisted of a plywood box 16"x8"x8".

The canopy itself was also inherited from a previous experiment. It was a 50 sq. ft. low porosity ram-air canopy custom built by Strong Enterprises for the author's engineering group. The canopy was scaled down from standard sport parachute designs, which typically measure 135-240 sq ft. depending on the weight of the jumper. The canopy was constructed out of a low porosity fabric and had a transverse panel of moderately porous F-111 fabric sewn across the top, part of a previous experiment to affect glide ratio though venting[1].

The canopy packed into a small deployment bag held to the top of the box by a series of rubber bands which release during deployment, a commonly used method in sport jumping.

The two rear brake panels were attached to brake lines which run into a pair of servo-driven spools. The remaining parachute lines were attached to a standard harness configuration which connected to four eye bolts, one on each corner of the box.

Internally, the system had a main system integration board, onto which were mounted a GPS card, a microprocessor board custom designed to connect directly to a commercial hobby-grade 7 channel radio control receiver, integration electronics (A/D, serial communication ports), power management, and user interface. Additionally, a GPS antenna was mounted flush on the top face of the box.

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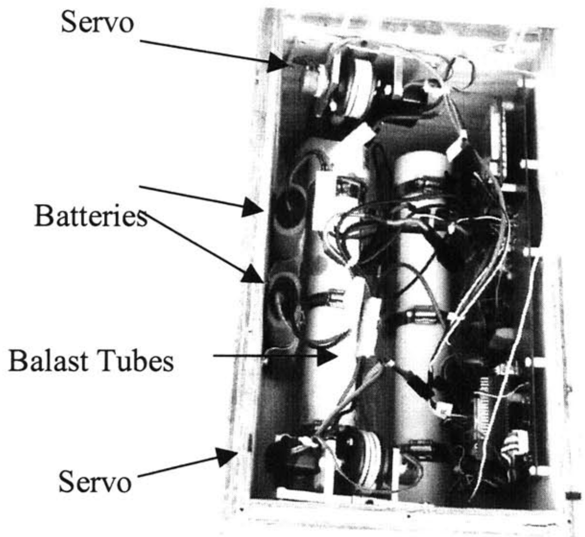
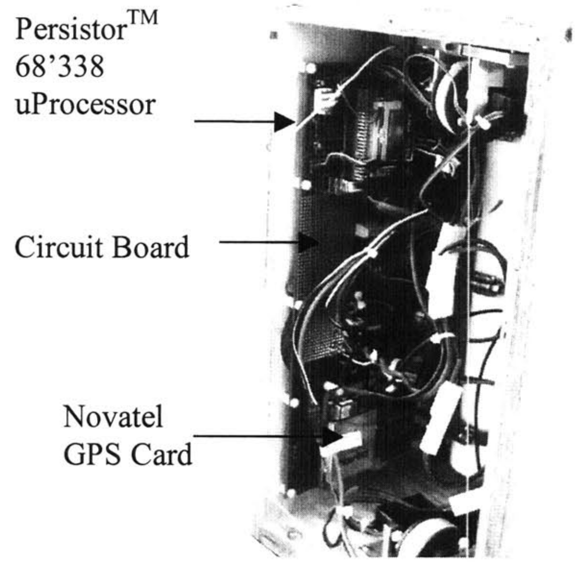
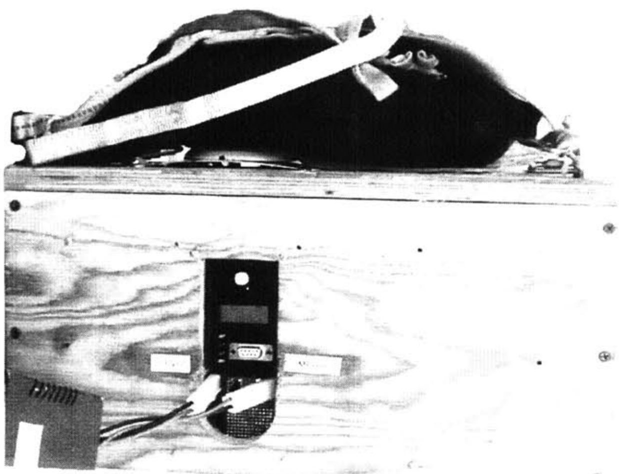
[1] Experiments showed that this particular level of venting had no noticeable effect on canopy performance

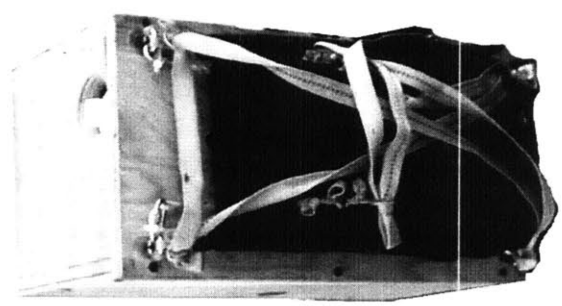




Bottom Views, showing internal components.



Front View, including user interface panel and packed parachute on top of GPS antenna.



Top View, showing static deployment line and ballast tube access and mounting eye hooks. Direction of flight is toward top of page.

Figure 5: Various photographs of completed system

Design Improvements

Design improvements were implemented in an attempt to accomplish four goals:

1. Expedite turnaround time such that testing could proceed at a quick rate.
2. Simplify and modularize hardware and software, particularly for maintainability and expansion.
3. Low cost.
4. Deep brakes canopy control.

• Servos

Deep brakes flight required servos with extended travel and quick spooling response time. New servos were developed.

Specifications:

Base servo unit: Airtronics high performance servos with heat sinked motors and amplifiers, modified for unlimited travel (i.e. limit stops removed), independent motor power supply for noise isolation, and external position feedback.
Spool: simple spooling mechanism with 10-turn position feedback potentiometer and line retention clip.
Effective spooling capability: 24 inches of 1/8" nylon parachute cord
Speed: 12in/sec @ 9V
Torque: 200oz-in with 9V source (exceeding 5lbs of spooling tension and 20lbs stalled)

Additionally, the brake lines were routed through the surface of the box to the internally mounted servo spools via polyethylene tubing. Previous designs utilized pulleys and external spool mechanisms which were prone to potential damage in landing, handling, or fouling the parachute deployment.

Problems:

- the servos experienced motor burnout in several off field landings. The cause of this was extended stalled operation after landing while the system was being recovered. Software was written to prevent the servos from stalling after landing, detected by watching for constant GPS altitude for 20 seconds.

- line jamming: in this and older servo designs, line tension was required in order for the spools to properly wind out the brake line without it jumping off the spool or otherwise jamming. The problem was solved in the interim through specific procedures in powering up the unit and software state control.

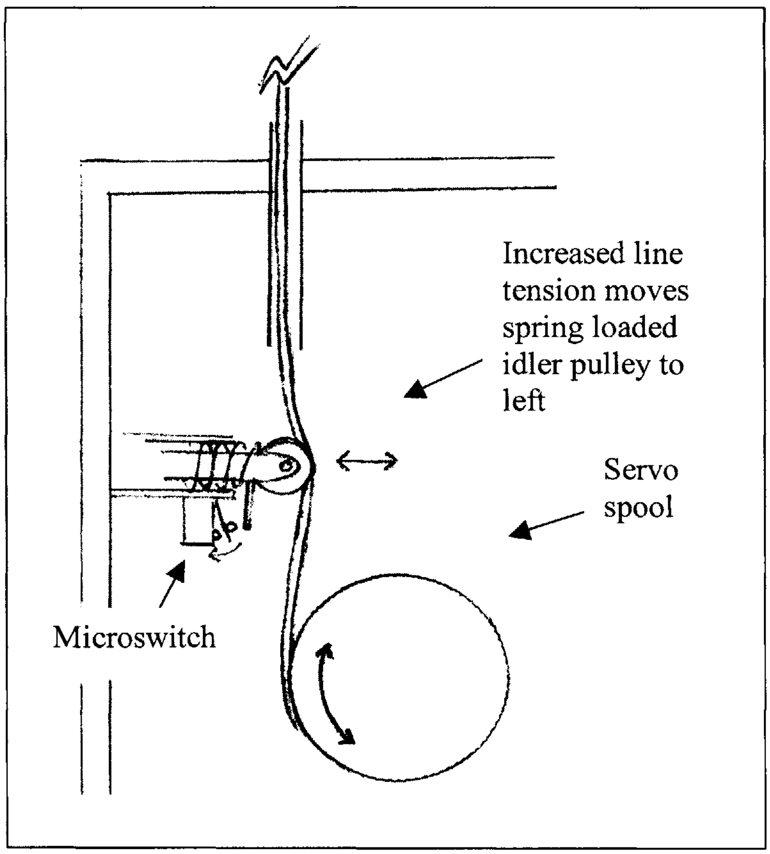


Figure 6: Schematic of proposed tension sensing idler pulley for servo activation

Recommendations: future servo implementations can utilize RC electronics, but are far better implemented with industrial servo motors and gear sets. Additionally, the tension problem can be resolved with a spring-loaded idler pulley which would sense the line tension and disable the motor when the lines are slack (Figure 6).

• Electronics

Older implementations of similar systems utilized a host of electronic hardware, including a DSP, inertial navigation unit, GPS, interface microprocessors, and a complex web of power conditioning modules.

The primary concern for this project was to minimize the electronics and to integrate them onto a single printed circuit board, while at the same time maintaining modularity and providing for expansion.

Evaluation of previous experiments and comparison to the author's own personal experience in accuracy landing approaches, suggested that GPS alone was adequate for the project, even with the error and low bandwidth (2-4hz effectively) GPS provides. The inherent nature of an accuracy approach and the relatively slow response but high airspeed of a parachute system in general is consistent with these GPS specifications, and the signal to noise ratio was deemed adequate.

Given the low bandwidth requirement, a 2hz control frequency was chosen and the electronics stripped down to a minimum system with the following specifications:

- Microprocessor: Persistor™ Motorola 68x338 board running at 20Mhz, running a C based real time operating system and handling all system I/O including SPI (serial peripheral interface) fetches of GPS data and analog voltage measurements, data storage on a flash memory card, and running the real time control loop. In actuality this system is probably capable of 10-20hz operation, far in excess of the requirements of a parachute system.
- GPS Unit: Novatel OEM4 card (obsolete) with a high grade dome antenna.
- A/D: 8 channels of 12 bit acquisition
- 64Meg of flash data storage

- All components mounted on a single circuit board with externally accessible built in volt-meter, status indicator LEDs, battery charge ports, and serial port.
- Two 8.4V nominal NiCd batteries, 2000mAhrs each, one for electronics and one for driving the high-noise servo amplifiers.
- Simple power distribution scheme with one single 6V regulator powering the RC receiver (both the Persistor™ and GPS card have on board power regulation).
- Extensive use of ground planes and careful physical layout of components to increase electronic noise rejection.
- Generous use of screw terminal connectors for easy interface.
- Prototyping space for expansion and quick addition of additional circuitry.

Problems: the electronics as implemented performed splendidly. No additional shielding was needed whereas older designs had significant problems with GPS and RC receiver operation. A simple revision of the circuit board would make incremental improvements, particularly to incorporate the latest changes made in the field during testing.

• Software

Significant effort went into redeveloping C-based software for the Persistor™ board, based on code used in previous projects. The new software was designed so as to handle not only the real time control and collection of data, but also to allow for simple user interface via a since RS232 serial port to monitor all system functions.

A modem-like "+++" escape sequence followed by one of many commands caused the system to display in real time on a terminal any of several system functions, such as servo control outputs and response, A/D measurements, GPS data and bi-directional communications, and system status. Thus, by plugging in a serial port one could monitor and/or reprogram the entire system.

Problems: methods of downloading data via the same serial interface directly to a MS Windows file system were not investigated. Data recovery involved removing the flash card and plugging it into a commercial USB downloading device, though any of several serial-port based data transfer schemes could be implemented.

• Other Hardware:

Other hardware improvements included the following:

- Ballast tubes: 2" PVC pipes with screw-on end caps for easily adding lead ballast.
- Audible Beacon: a high pitched buzzer which could be activated remotely in the case of off field landings to aid in recovery.

• Parachute Rigging:

The canopy itself was designed in such a way that full deployment of the brakes, as limited by riser hardware, barely flared the canopy during landing and extended deployment would slowly cause the parachute to become unstable as it came close to stalling. However, most canopies are designed such that they will fairly quickly stall if kept in full brakes for more than a few seconds, which is useful in landing since the parachute's speed can be quickly converted into a level glide for landing until the airspeed diminishes and the canopy stalls, setting the jumper on the ground. In other words, over-control is possible and sometimes desirable.

To achieve over-control capability, the attachment point for the servo spools on the canopy's brake lines were modified so that brakes could be deployed further (see Figure 7).

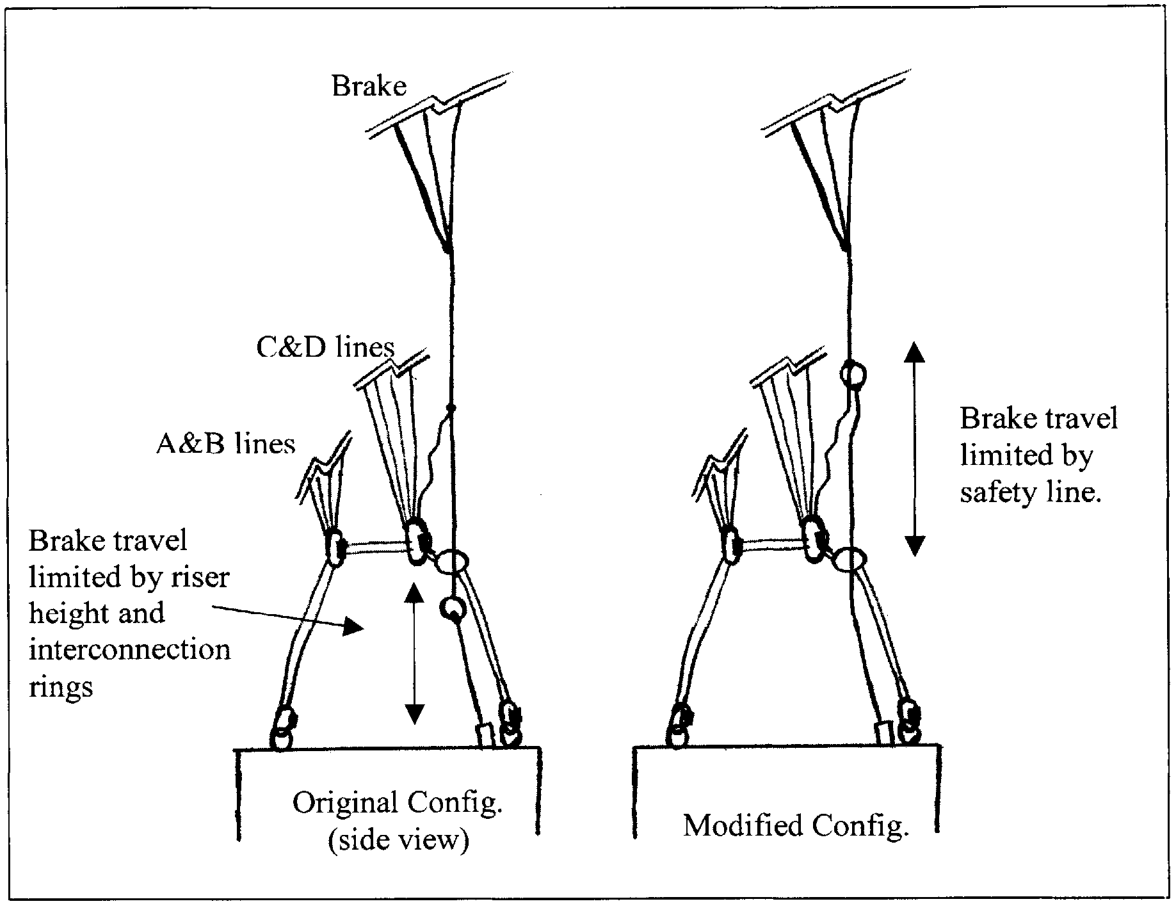


Figure 7: Brake line modification

Additionally, the *slider*, a small rectangular fabric panel with grommets on each corner through which the canopy's lines pass, was removed. The slider is used to slow down the canopy opening and to aid in keeping the lines from becoming entangled with the canopy as it deploys.

Removing the slider was necessary in order to implement the brake over-control, but also to help address the box oscillation issue, described below.

Problems: on two occasions after the modifications, non-terminal deployment failures occurred which forced those drops to be aborted. One of these failures was due to improper re-rigging, but the other was due to the removed slider. As the canopy deployed, part of the canopy blew through some of the lines as they extended, which kept the canopy from fully inflating, a condition known as a "line-over" malfunction. This problem was ultimately solved by adding a rubber band and an extra line stow to the trailing edge of the canopy, which during packing is wrapped around the rest of the parachute material to aid in avoiding tangling. This line stow released only after enough tension was imparted on the lines by the partially inflated canopy to release the lines out of the rubber band. Subsequent tests with this packing modification deployed properly.

• Load Oscillation:

Previous tests showed substantial aerodynamically induced rotational oscillation by the box during steady flight, to the degree that aerodynamic stabilizers were being considered as a solution. In these cases, the box was mounted in what was believed to be the aerodynamically obvious (most stable) way, with the narrow cross section facing the direction of flight. The system acted as a rotational pendulum. However, an energetics-based analysis of the rigging suggested that mounting the box transversely would improve the natural stability of the box.

The analysis goes as follows: as the box begins to rotate and thus initiate slight line twists due to some disturbance, the box is elevated by a trigonometric function of the line length and spread, which then results in a rotational pendulum effect as the box unwinds and then winds up again in the other direction in a cyclic process. For fixed length lines, the energy required to induce a line twist of a given angle σ is thus only related to the distance between the lines' narrowest points, which ultimately go to zero as the lines wrap completely around each other. In this limit case, the object can wind up quite freely. Conversely, the potential energy gained by the box as it winds up σ degrees increases as the spread between the lines increases, and thus more energy is required for the same rotation.

With the slider removed, the spread between the suspension lines increases such that the narrowest point of line spread is at the harness attachment. Additionally, the transverse mounting increases the aerodynamic drag in flight, pitching the canopy slightly forward and increasing the tension on the forward suspension lines. This further aids in the energetics argument.

In summary, increasing the line spread effectively increases the amount of rotational and potential energy needed for steady state oscillation. As a result the natural oscillation frequency is increased and the oscillations theoretically dampen out. In all likelihood the aerodynamic response to a disturbance by transverse mounting also changes.

Telephoto ground video of a flight shows deployment and oscillation for a few seconds after entering stable flight, but the oscillation quickly dampens out and the box appears stable for the remainder of the flight.

Chapter 3: Canopy Performance Testing

A series of test drops was conducted with the system as implemented in the previous chapter. Unfortunately, an in-flight system failure on the seventh drop resulted in a river landing and system repair had not yet been achieved at the time of writing.

The test program was organized into two phases:

- Canopy performance analysis in a deep brakes final approach.
- Closed loop final approach.

The first phase was largely completed and the results are presented below. The second phase was not carried out and remains the subject of future testing.

Mission profile

The system was dropped repeatedly from a small high-winged aircraft (Cessna 185 and 206) by a jumpmaster at 1500ft AGL upwind of the landing site. The freefall, deployment, and flight phase of a complete mission have been successfully demonstrated in prior projects.

The system was remote piloted, though on the final test where the system was lost it had been programmed to execute similar maneuvers autonomously.

The principal objective was to measure flight in stable, straight flight with increasing levels of brake deployment, to the point of stall. Of particular interest was the glide ratio and/or rate of descent, which necessarily must be variable in order to implement an on-heading closed loop accuracy approach. From the author's experience such performance has been observed in larger canopies.

Glide Ratio vs. Braking

Reference to the effect of deep braking on glide ratio *L/D* in published studies are limited. A number of studies [4] [5], [6], [8], [9], present limited glide ratio data and mention that there is a decrease as the angle of attack is increased, the angle of attack obviously being affected by the level of braking. [4] and [8], provide enough data to suggest that that there is a maximum glide ratio at some intermediate level of braking, as shown in Figure 8. Of particular interest are predictions for aspect ratios of 1.5-2, typical of modern ram-air canopies.

However, all of these studies use only a single canopy design and fabric type, so substantial characterization of porosity, canopy loading, airfoil design, and braking on glide ratio remains to be done.

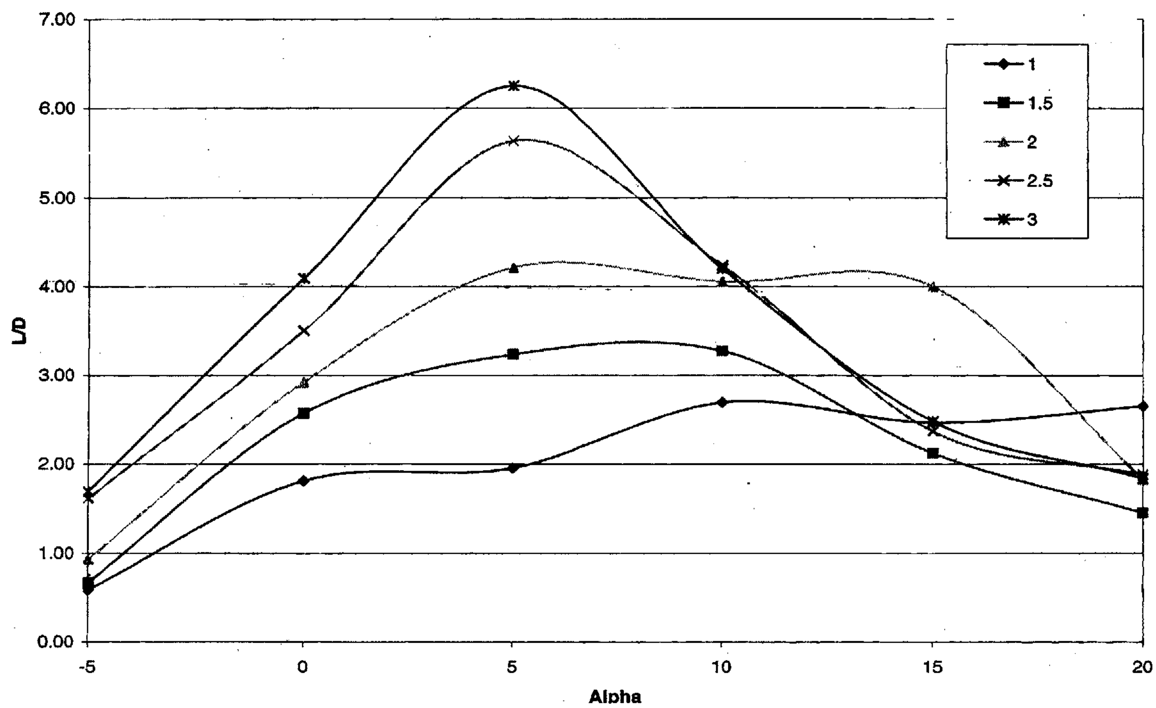


Figure 8: Ram-air canopy glide ratios vs. angle of attack with varying aspect ratios

Using data extracted from [4]

Data and Analysis

Two drops successfully logged deep brakes, on-heading glide slope data, with ramping increases in brake deployment. The first drop recorded one sequence (Sequence A), and the second drop recorded two sequences (Sequences B and C).

All data collected were solely from the GPS return, which has inherent noise and error, but the intent of the project in part was to demonstrate ultimately that GPS is adequate for the task.

Sequence A (Figure 9) spans a twenty second interval with step increases in brake deployment approximately every five seconds until the canopy stalls. A ground relative glide ratio of nearly 3:1 decays to approximately 1.5:1. This test was conducted in relatively calm conditions, and the ground relative numbers fairly closely represent the expected air-mass relative performance[2].

As the canopy approaches maximum brake deployment, it becomes unstable, as observed through increasingly noisy heading and glide ratio data. As this particular canopy approaches stall, it begins to surge and parts of it begin to collapse momentarily. Given the pendulum effect of the suspended mass, the system becomes very unstable. As mentioned, this effect is not typical in sport jumping when using canopies with higher porosity.

A pilot induced control disturbance at the 92 second mark as the canopy nears stall, in an attempt to correct a heading change by the surging canopy, sheds uncertainty on what actually happens as the test sequence completes, since the box is now swinging laterally and is no longer in controlled on-heading flight.

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[2] The system has no way to measure winds, so air-mass relative glide ratio cannot be determined. In sport jumping this is done by executing certain "S" patterns which by comparison yield the effective ground wind speed and direction. This comparison is done by observation of ground features, but GPS could equally well be used to implement such measurement by an autonomous system.

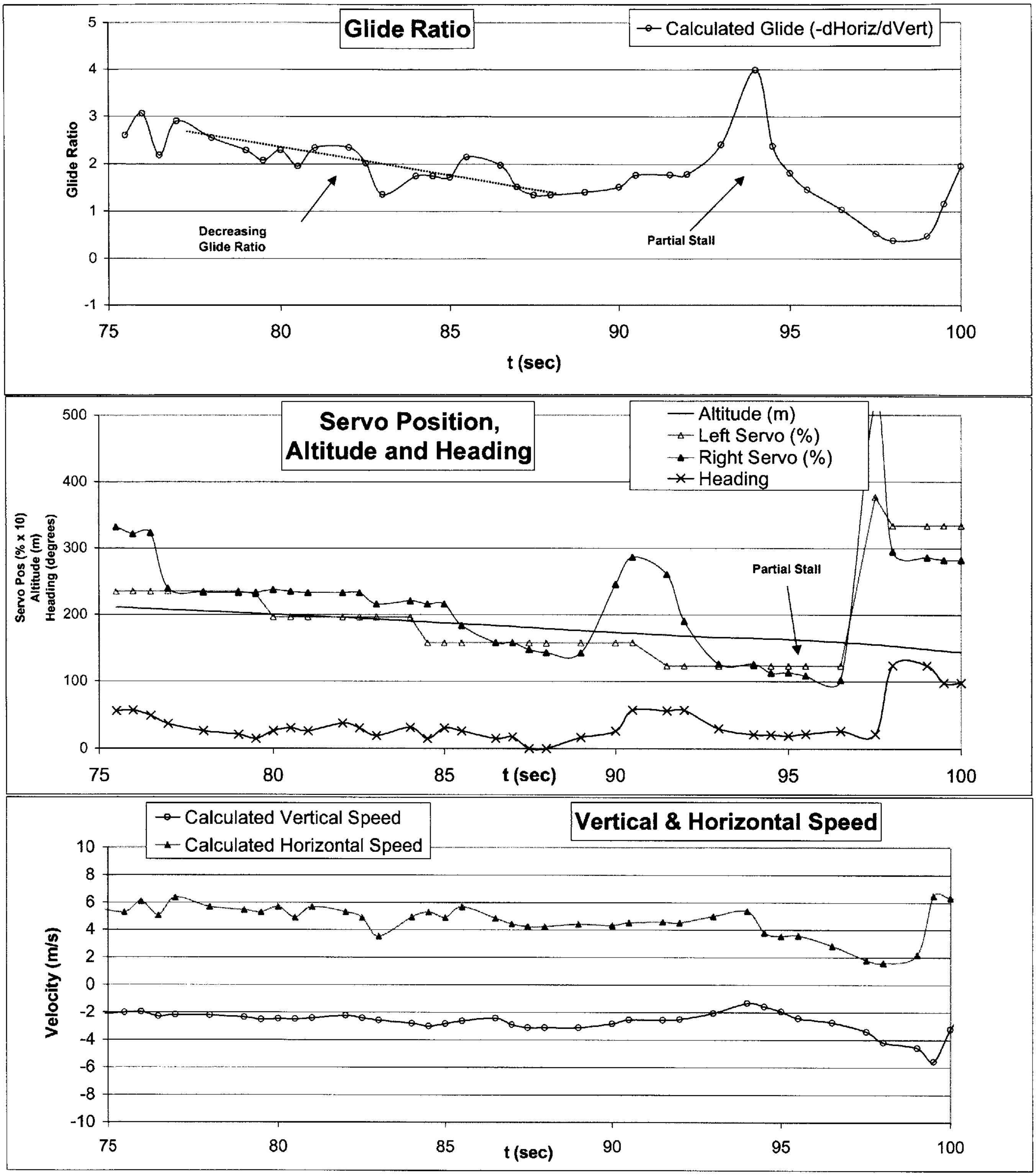

Figure 9: Test Sequence A

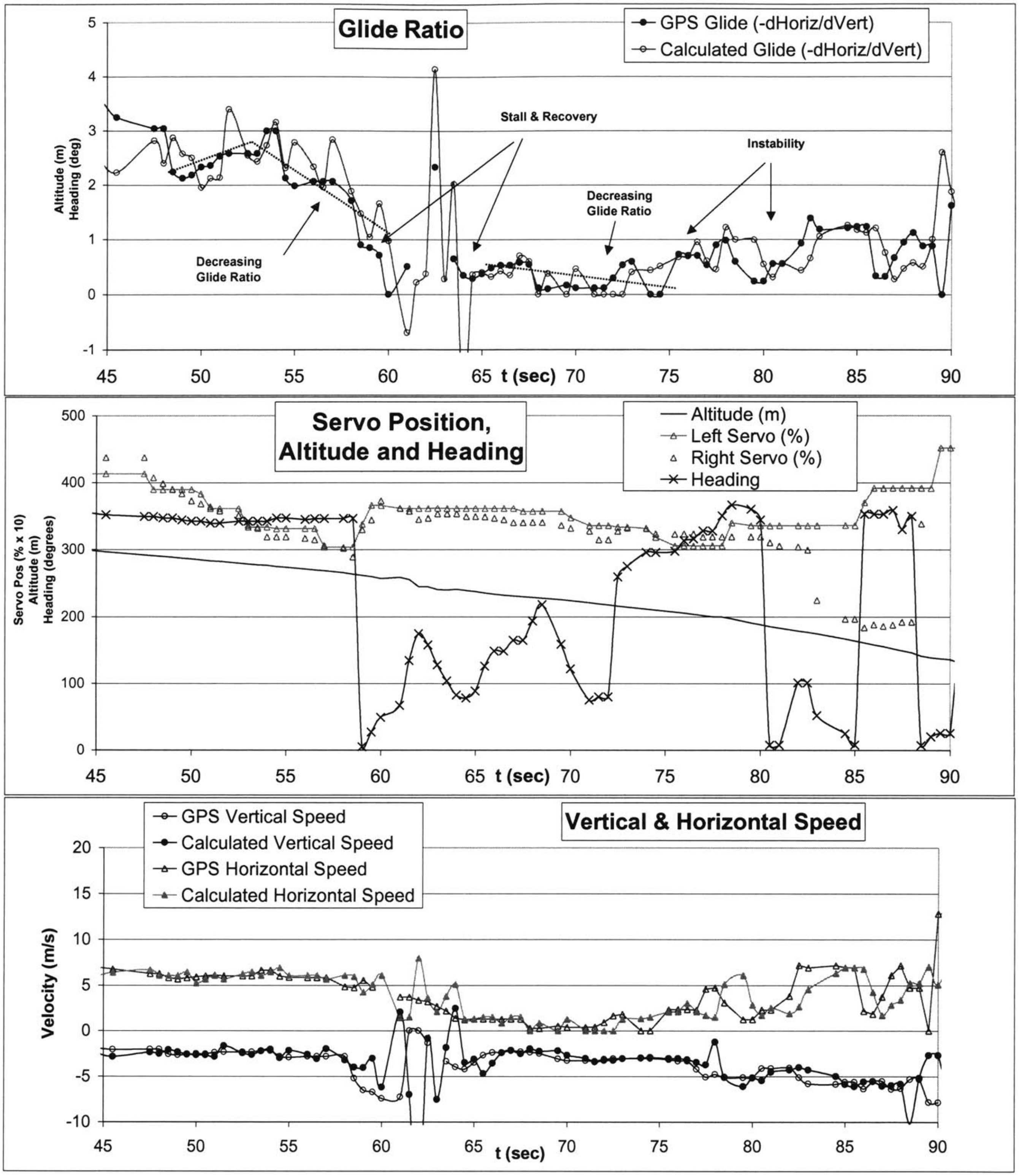

Figure 10: Test Sequences B and C

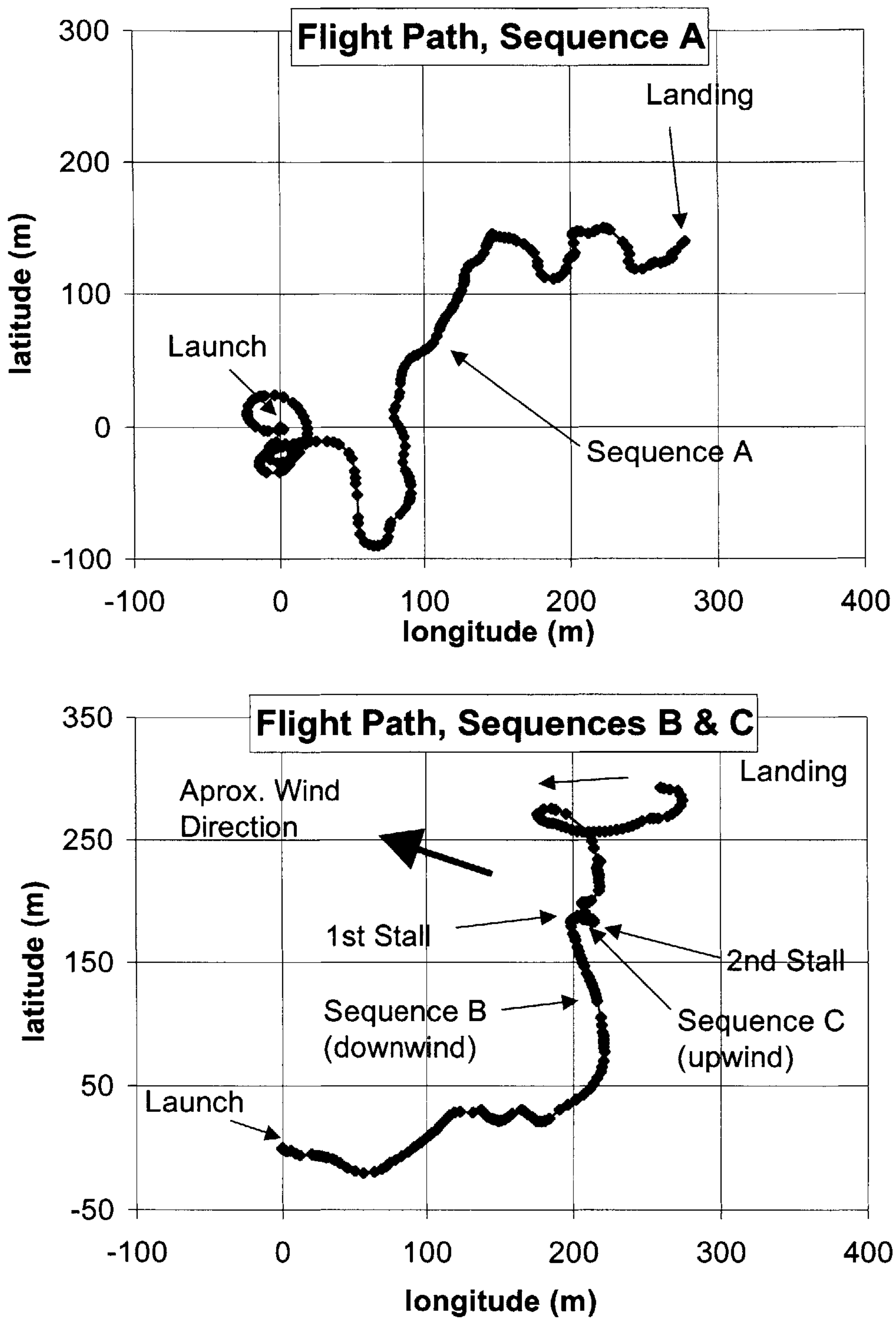

Figure 11: Trajectory Maps, Sequences A, B, & C

Sequence B spans the 45-60 second interval in Figure 10. This test occurred under windier conditions and is in the down-wind direction. Seven pounds of lead ballast were also added, which increased the descent rate.

Again the canopy shows a moderately stable decrease in glide ratio from 3:1 to 1.5:1 as the braking is increased, with a decreasing level of stability. Note that the true air mass-relative glide ratio is slightly lower in this case after subtracting out the ground winds. At 58 seconds the canopy stalls completely, as indicated by the sudden change in heading, the ripples in altitude, and the violent oscillation in measured glide ratio as the canopy collapses and re-inflates several times. The brakes are subsequently released slightly so as to return the canopy to deep brakes flight.

Also of interest in Sequence B is that the glide ratio appears to show an increase with moderate braking levels between 45-55 seconds, which is consistent with the limited published data. However, the data collected is too noisy to determine whether the glide ratio increases and then falls off linearly, or if there is some repeatable curve to the function.

At 65 seconds, the canopy recovers though it has turned nearly 180 degrees in the process. In Sequence C (Figure 10) the system is flying at its nominal airspeed into the wind which results in much lower ground relative horizontal speed. In fact, at times the horizontal speed and thus the resulting glide ratio reaches zero. In this case the canopy is effectively sinking vertically straight down to the ground.

Again the canopy exhibits a decreasing glide ratio with decreasing stability, resulting in further changes in heading and glide ratio oscillation. As the canopy changes heading, the apparent glide ratio increases again, since the ground wind now provides a cross-wind component to the measured horizontal velocity. At 86 seconds the canopy again stalls out completely and the brakes are released for recovery.

Conclusion:

The system clearly exhibits some level of decreasing glide ratio in deep-brakes flight, verifying what was loosely presented in prior published work. However, the non-porous fabric of which the canopy is constructed contributes to high levels of instability, particularly as the air-mass relative glide ratio reaches approximately 2:1 and below. Oscillations in heading and glide ratio dominate as the stall point is reached, due to partial deflation and re-inflation of canopy sections.

Recommended Experimentation:

The tests conducted in this project suggest several areas of further research.

The first is to conduct similar tests with F-111 constructed high porosity canopies, particularly those designed for sport parachute accuracy landing. These canopies are very large and while they do not have very good full flight performance, they are very stable where other canopies tend to stall. Older sport canopies, particularly those that were state of the art in terms of performance in the 1970s and 1980s combine properties of both, sacrificing some stability for performance. The author has logged over 250 jumps with such a canopy. Tests of this nature can be expected to have results that show considerably more stable deep-brakes flight and greater glide ratio response, though the full flight characteristics will be diminished.

Secondly, sport jumpers shoot accuracy approaches directly into the wind, since this is simplest to control, has the lowest ground speed, and provides the most docile landing given that there is no flaring maneuver possible in a deep brakes landing. However, with GPS and some ability of the payload to land much harder than a human would want to recreationally endure, there is no reason that an accuracy approach cannot be executed in some direction that is not directly upwind. The advantage of this capability is that multiple possible glide paths exist for the final approach once the wind vector is known. For example, as is apparent in Sequences B and C where the speed of the moving air-mass approximates the system's deep brakes airspeed, one possible approach is downwind with a high ground relative glide slope, whereas another may be upwind with a near-vertical descent to the target. Cross wind approaches are also possible by this same reasoning which results in a whole host of possible control strategies for landing in variable conditions.

At the time the system was lost, it had been programmed to execute maneuvers similar to those presented herein. Computer generated control in many regards may actually be better than what a human can do, since a human pilot is dependent purely on observing the ground and the pilot's own sense of inertia. A computer with GPS, on the other hand, has ironically (in robotics) much more precise data available to it, and can determine various flight conditions with superior accuracy. Thus, autonomously running tests similar to those that were conducted with a human pilot are expected to result in significantly smoother and clearer results.

Additional research with varying payloads is of interest. As the system scales up in mass (i.e. with increasing canopy loading [lbs/sf]), the stability potentially increases since the moments of inertia increase and particularly since the aerodynamic pressures encountered by the canopy are higher. This is effectively equivalent to increasing the porosity. Experiments with increased payload are thus expected to yield greater stability and response, similar to experiments proposed with higher porosity fabrics.

Once a canopy reliably exhibits a suitable controllable glide ratio, a final approach based on a pre-selected coordinate and an approach vector calculated by the system in real time as it nears the landing vicinity would be possible with standard PID control based on GPS data.

Lastly, while GPS units are becoming less and less expensive, high quality units are still in many respects beyond "low cost". Similar data may be generated by very low cost pressure-based altimeters and consumer-variety video equipment, utilizing basic image slip methods to determine movement [2.]. While the algorithms required to do this are complex, once developed the total hardware cost may be significantly lower than a GPS based unit given present day hardware costs.

Credits

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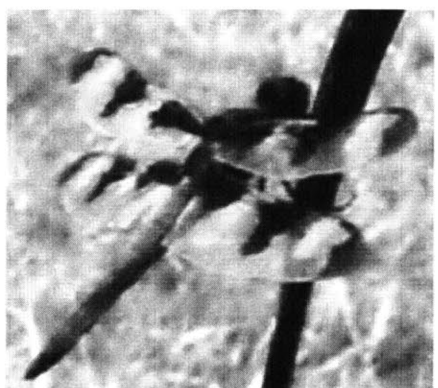
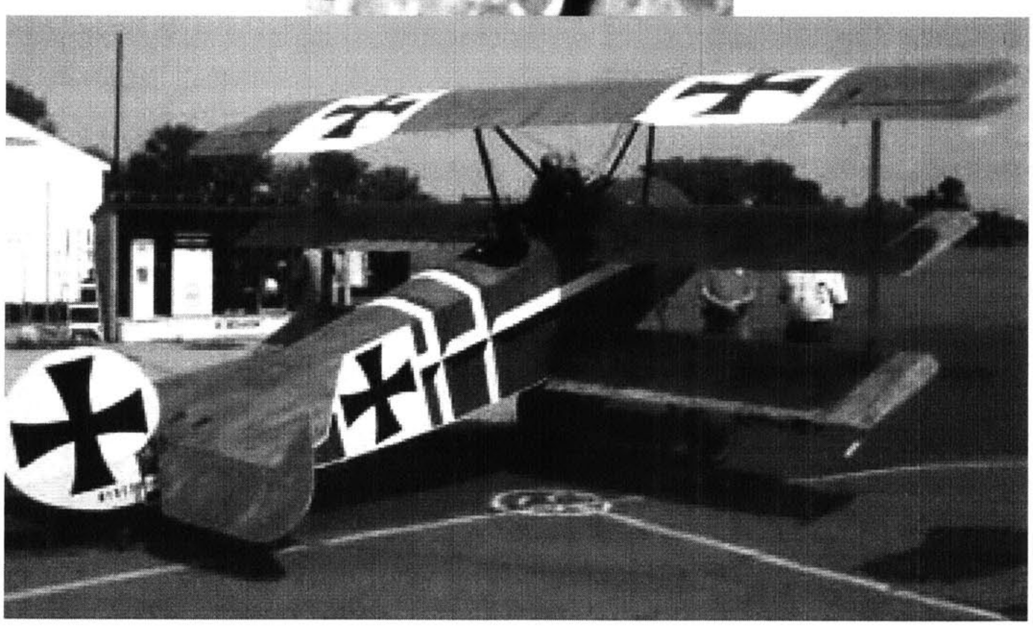
- Teresa Castano, my good friend in Northampton.
- The tiger-striped dragon fly that kept me company one day, and the tri-plane
- My parents for nagging me.





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