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Steering a Flat Circular Parachute – They Said It Couldn't Be Done

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How can the military services accurately deliver critical cargo to its soldiers and to those needing humanitarian relief? This is the question that the Precision Airdrop team, led by Natick Soldier Center, is aggressively addressing. The United States Army and Air Force have stepped up initiatives for improving the accuracy of cargo aerial delivery with the execution of the New World Vista – Precision Air Delivery program. The three major components of these efforts include improved real-time wind estimation, enhanced on-board Computed Air Release Point (CARP) calculations, and the development of autonomously guided parachute systems. This paper focuses on the technology efforts associated with one variant of autonomously guided parachute systems; the Affordable Guided Airdrop System (AGAS). The focus of the AGAS program was to develop the technologies required for steering flat circular parachutes such that existing inventory parachutes and containers could be utilized. A Guidance, Navigation, and Control kit is installed on top of an A-22 container with connections of pneumatic actuators to each of four risers on a G-12 parachute. A prototype system was developed and flight-tested by the team of Natick Soldier Center, Yuma Proving Ground, Cibola Information Systems, Vertigo, Incorporated, and the Naval Postgraduate School. Twenty-six airdrops were conducted using two prototype systems. Numerous challenges were overcome during flight-testing including pneumatic valve problems, system communication issues, and rigging problems. The latest series of drops developed and validated new rigging procedures for the AGAS. Flight test data indicate that autonomous flight of a flat circular parachute is very feasible. Accuracies of 70 meters Circular Error Probable (CEP) were demonstrated with fifteen successful fully autonomous airdrops. Data analysis indicates that further improvements can be made to reduce the number of actuations and, perhaps, increase the end-game accuracy. These improvements have been demonstrated in simulation but have not yet been flight-tested. These results clearly demonstrate the feasibility of steering a flat-circular parachute providing one variant

Introduction

The United States Army and Air Force have joined forces with industry to improve the accuracy of airdrop. Throughout the history of airdrop, our soldiers have been plagued with the inability to get materiel where it needs to be. From humanitarian relief to critical re-supply for our soldiers, the inaccuracies inherent in airdrop continue to be a major hindrance to our forces. The Natick Soldier Center is tackling this problem on many fronts. Significant efforts are underway to improve the ability to reduce the uncertainty in winds used to determine the Computed Air Release Point (CARP), improve the ability to rapidly and accurately determine the CARP for multiple parachute systems using these improved wind estimates, and develop multiple variants of autonomously guided decelerator systems. One significant goal of these efforts is to provide the services multiple AFFORDABLE options for precision re-supply.

One of the variants of decelerator systems that has been studied is the development of a kit that can be put in line with existing payloads and currently fielded parachute systems, specifically, flat-circular parachutes. A technology development program was successfully executed to demonstrate the ability to autonomously steer a G-12 (64 foot flat-circular cargo parachute) with a 2,200-pound payload in an A-22 container. This concept and prototype system has become known as AGAS (Affordable Guided Airdrop System).

AGAS Concept

The design goal of the AGAS development is to provide a Guidance, Navigation, and Control (GNC) system that can be placed in-line with existing fielded cargo parachute systems (G-12) and standard delivery containers (A-22). The system is required to provide an accuracy of 328 feet (100 meters), Circular Error Probable (CEP), with a design goal of 164 feet (50 meters) CEP. The system should not require any changes to the parachute or cargo system. The current design concept includes implementation of a commercial Global Positioning System (GPS) receiver and a magnetic compass as the navigation sensors, a guidance computer to determine and activate the desired control input, and the application of Pneumatic Muscle Actuators (PMAs)[1] to affect the control. The GNC system will be rigged with the payload and the PMAs will go in-line with each of four risers.

Pneumatic Muscle Actuators

Vertigo, Incorporated developed Pneumatic Muscle Actuators (PMAs) to effect the control inputs for this system. A PMA is a braided fiber tube that contracts in length and expands in diameter when pressurized. The contraction is quite forceful when compared to a piston-in-cylinder of the same diameter and a contraction stroke of up to 40% of the original length is obtainable. Upon pressurization, the PMAs contract in length and expand in diameter. For this demonstration, a displacement of approximately 6.4 feet (10% of D_o of the G-12 parachute) was selected. When depressurized, the PMAs are completely flexible allowing for efficient packing of the actuators with the parachute. A reservoir of pressurized nitrogen is stored within the payload as the fuel source. Figure one illustrates the AGAS GNC Kit integrated with the A-22 container and G-12 parachute system.

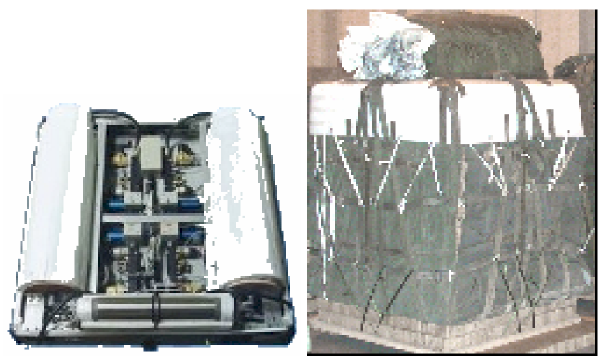

Figure 1. AGAS GNC 'Kit'

Initially, all actuators will be pressurized upon successful deployment of the parachute. To affect control of the system, one or two actuators are depressurized thereby lengthening one or two system risers. This action "deforms" the parachute (Figure 2) creating drive in the opposite direction of the control action.

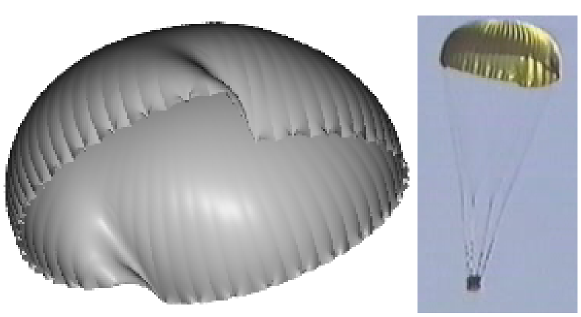

Figure 2. Parachute with Control Activation

Control System

The accuracy of uncontrolled airdrop systems relies on precise knowledge of the winds at the time of the drop and precise guidance of the aircraft to the predicted release point. However, wind estimation is far from a precise science. The calculation of the Computed Air Release Point (CARP) relies on less than perfect estimates of parachute aerodynamics and the aircraft crews cannot fly exactly to the predicted release point for each airdrop mission. Therefore, the AGAS control system design must help overcome these potential errors. Cibola Information Systems developed the flight computer, integrated the sensor suite, and hosted the Yuma Proving Ground/Naval Postgraduate School guidance algorithms.

The parachutes to be utilized for this effort were not designed for glide or to be controlled. Therefore, limited control authority was expected. The G-12 parachute system is a flat-circular parachute (one when lying flat on the ground, forms a circle) without any glide or control capabilities. Considering the relatively low glide ratio and a descent rate of approximately 25 feet per second, it is estimated the AGAS can overcome only a twelve foot per second (approximately 7 knots) horizontal wind. It is therefore imperative to implement the system to overcome poor estimates in the wind and not try to steer the system against the entire wind. In other words, the drive of the system is insufficient to attempt to fly straight to the target but is likely sufficient to overcome errors in the wind estimate. For this reason, a trajectory tracking techniques were selected. A pre-planned trajectory, based on the best wind estimate available, must be determined and provided to the guidance computer. The GPS navigation system will provide continuous position of the system. The guidance computer will compare the actual horizontal position, at the system's current altitude, to the planned trajectory. This represents the position error (P_e) at the current time. A tolerance cone is established about the planned trajectory starting at 600 feet at the beginning of the trajectory and gradually decreasing to 100 feet at ground level. Should the position error be outside this tolerance, a control is activated to steer the system back to the planned trajectory. When the system is within 30 feet of the planned trajectory the control is disabled and the parachute drifts with the wind. Thirty feet was selected to encompass approximately 1-sigma of the GPS errors (each axis, no Selective Availability GPS errors).

As outlined above, the control system relies on the current horizontal position error to determine if control input is required. This position error (P_e) is determined in inertial space and is then rotated to the body axis using an Euler angle rotation with heading only (equation 1).

$$P_b = {}_u^bR \cdot P_e;$$

where ${}_u^bR$ is the euler rotation matrix

The resultant body-axis error (P_b) is then used to identify which control input must be activated as shown below:

$$input = sign\left(\frac{P_b}{\|P_b\|}\right)$$

Two components are returned, a + or - for the x-axis and a + or - for the y-axis. It was assumed for this simulation that +x would activate control A, -x activates control C, +y activates control B, while -y activates control D (Figure 3). The actual rigging of the operational system must align these control actuators to the compass reference line to ensure proper control. We assume that Control A is aligned with the compass zero reference line.

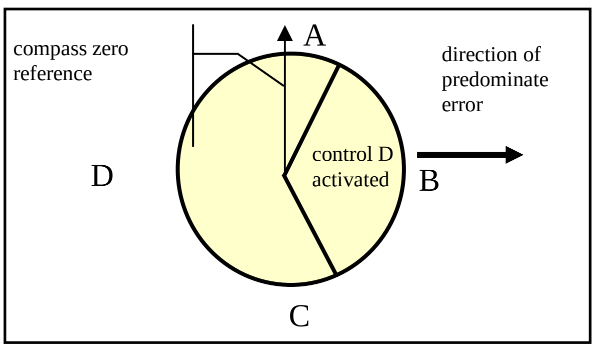

Figure 3. Control Activation

The magnitude of the individual x and y components of the normalized body-axis position error vector is used to determine if the selected control will be activated. If the magnitude is greater than 0.3, then that control is activated. This concept will allow the activation of a single control input or two simultaneous control inputs.

Flight Testing

The flight test effort focused on the collection of flight dynamic data to support the evaluation of autonomous system performance. The flight test effort was conducted with four actuators in-line with a G-12 parachute and an A-22 container. Vertigo, Incorporated and Cibola Information Systems fabricated two prototype systems. Flight dynamic data were obtained including the position, velocity, acceleration, attitude, and attitude rates of the system. It was necessary to correlate these data with control inputs. Therefore, the state of control activation was monitored. Parachute performance is significantly influenced by the winds. It was critical to this effort to measure the winds as precisely as possible.

Throughout the test effort, many considerations and trade-offs were made. For example, trade-offs between fuel (or energy) consumptions and accuracy were made. The responsiveness of the actuator system was a consideration and the amount of wind variation from the planned winds was evaluated. Trade-offs between sensor performance and cost were also a critical factor in this effort. Once we were able to autonomously steer a 2,200 pound payload to overcome wind estimation errors, we modified the control strategies to help us deal with sensor errors, specifically, compass errors induced by the low-grade compass used and the oscillatory nature of the flat-circular parachute. Additional control algorithm changes were made in an attempt to improve the end-game performance. Flight test clearly demonstrated that the increased uncertainty of wind estimates within the final 2,000 feet of flight presented challenges to the system. The control algorithm was modified to incorporate the use of system velocity in an attempt to predict the need for control activation. The modified algorithm will be flight tested in November 2002 and January 2003.

Test Results

The following information was gathered throughout the duration of the AGAS test program. Data plots from varying flight tests are presented that best exemplify the overall results achieved. A compilation of end accuracy information is also presented.

Aerodynamic Performance

The G-12 parachute, like most flat circular parachutes, exhibits significant oscillatory motion. During some of the flight-testing, the AGAS system was instrumented with an Attitude Heading and Reference System (AHRS) which provided attitude and attitude rate data along with heading information. Figures 4 and 5 displays the roll and pitch data for one airdrop. The parachute release is evident at approximately 180-seconds. After the inflation process, the parachute begins oscillating (approximately 200-seconds). Oscillations of ± 30 degrees are apparent in either pitch or roll. In some cases, the motion is apparent in both pitch and roll simultaneously (coning motion). At approximately 490-seconds, a control actuator was activated. At this time, nearly all the oscillatory motion was reduced indicating a significant damping effect of the oscillatory motion.

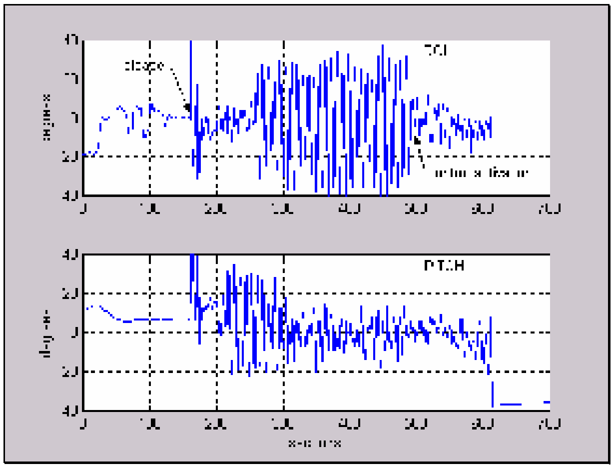

Figure 4. Oscillatory Motion

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Figure 5 illustrates the portion of the airdrop discussed above from 450-seconds to 540-seconds. During the interval from 450 to 490 seconds, the data shows approximately 4.5 cycles showing a period of approximately 8.5 seconds. Again at 490-seconds, a control actuator was activated and the oscillatory motion dampens significantly.

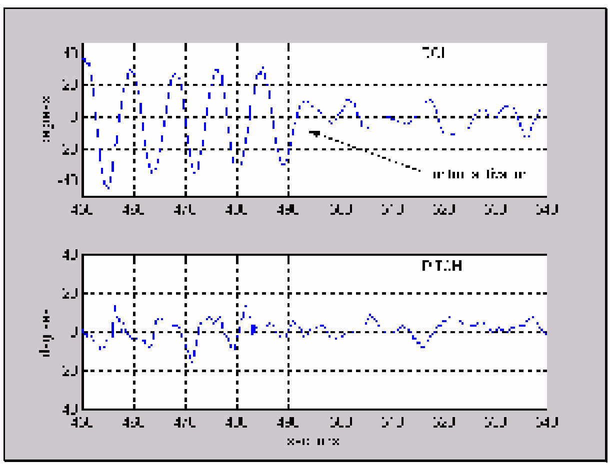

Figure 5. Oscillatory Motion, Expanded Time Segment

Figure 6 presents the same data for another time segment of the drop. In these data, oscillations are apparent in both roll and pitch, again, with a period of oscillations of about 8.5 seconds. The heading information collected presents some interesting insight to system and sensor performance.

After characterizing the oscillatory motion early in the program, the AHRS was not used in remaining testing due to damage suffered on a different test program. The following data presents the results obtained in the most recent testing of the AGAS system (January 2003).

The heading sensor utilized in the AGAS system is a digital compass with tilt compensation. It is important to note that the oscillatory behavior of the parachute system can influence the quality of the compass data. This is evident by the lower amplitude, higher frequency variations in the Figure 7 (note: these data were obtained in a different airdrop from the roll and pitch data presented above). Figure 8 shows the frequency of these variations to be very close to the frequency of the roll/pitch oscillations.

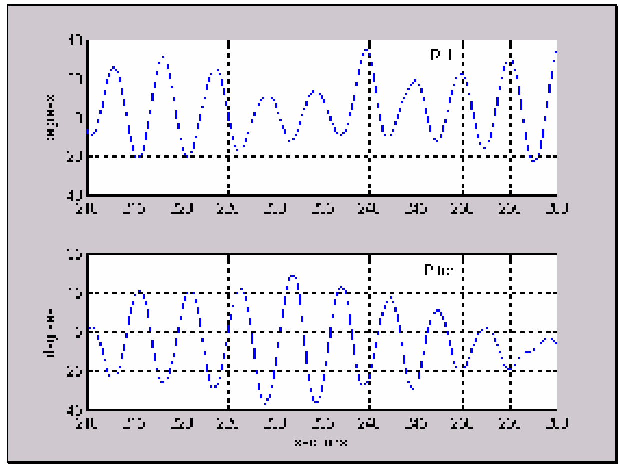

Figure 6. Oscillatory Motion, Expanded Time Segment

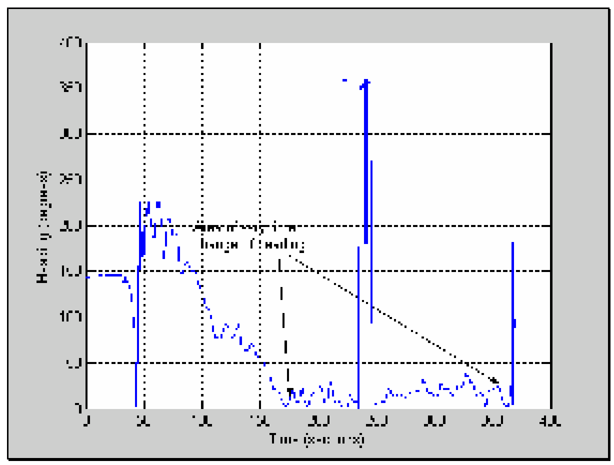

Figure 7. Heading Data (8 Jan 03)

The heading data is critical to the AGAS control algorithm. As described in the system description, above, the Position Error from the AGAS to the predicted trajectory is rotated into the parachute body reference frame using an Euler Angle rotation with heading only. This allows for efficient determination of which control actuator must be activated to allow the parachute to be driven back to the reference (predicted) trajectory. Certainly, the quality of the heading information impacts the effectiveness of the control algorithm. Figures 8 and 9 show the heading and time correlated changes in control activations. Clearly, the variations in heading cause unneeded control changes.

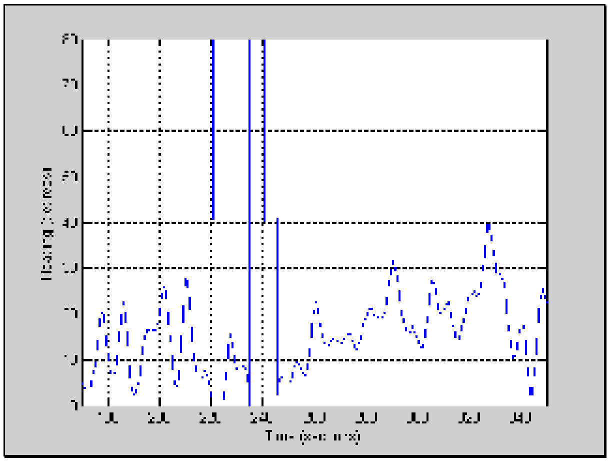

Figure 8. Heading Variations (8 Jan 03)

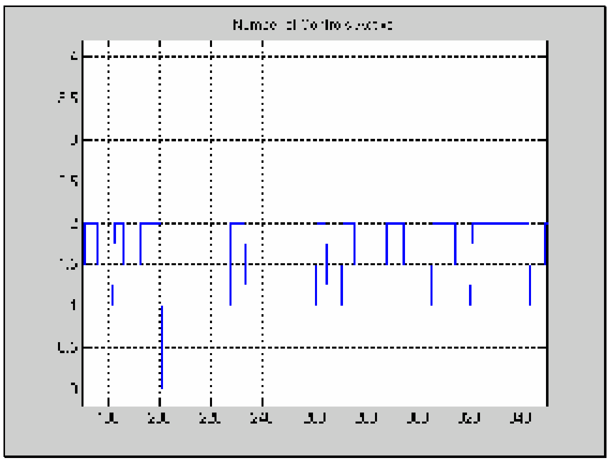

Figure 9. Control State for Four Actuators (8 Jan 03)

Estimation of Glide Capabilities

The effectiveness of the AGAS concept is directly related to the glide performance of the system when actuators are activated. To estimate glide performance, a glide ratio was calculated using the wind-corrected velocities (airspeed). The systems ground speed was measured using the GPS navigation sensor contained in the AGAS flight computer. The wind speed was measured using the tri-lobe wind measuring system known as the WindPak[2]. Both data sets were converted from the geodetic reference frame to a local tangent plane, centered at the projected impact point on the drop zone. The wind data was correlated with the AGAS data using the systems altitude and then differenced from the AGAS ground speed. The horizontal airspeed divided by the vertical airspeed represents an estimate of the glide ratio. Figure 10 presents the glide ratio obtained during AGAS Flight 20 in July 2001. It was one of the few airdrops where one single control input was used for a considerable period of time allowing for analysis of glide ratio with one control activation.

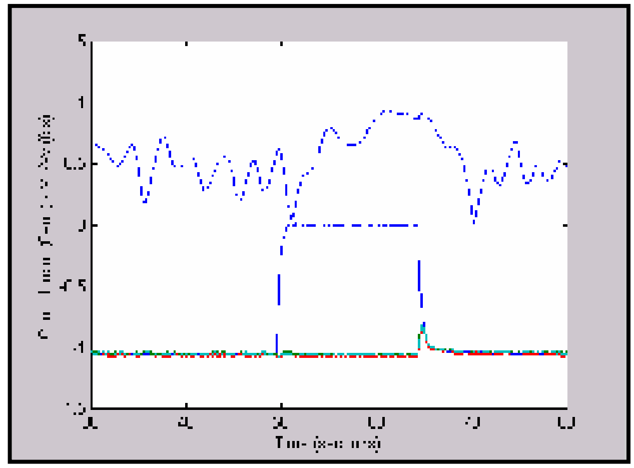

Figure 10. Glide Ratio, Single Activation, Jul 01

After activation of the control (approximately 50 seconds), the parachute begins to glide and achieves a glide ratio of approximately 0.8. The parachute has a response time of approximately 5-seconds to achieve steady state upon activation or deactivation of a control actuator. It is interesting to note that the data showed an apparent glide ratio of 0.5 with no control input. Wade Porter[3], US Army Yuma Proving Ground, is investigating this apparent glide ratio and has determined that it is an artifact of the calculation of horizontal velocity. Each velocity component oscillated about zero but was significantly out of phase. The calculation of horizontal velocity resulted in the apparent glide that is not in the system. Porter is presenting appropriate methods for effectively determining glide of a decelerator system. One method considered is to filter out the oscillations in each velocity component prior to calculating the horizontal velocity. This method was used for data obtained during the 10 Jan 03 flight test and is presented in Figure 11 and Figure 12 presents the number of controls active. These data present the glide ratio for a two-control activation on 10 Jan 03.

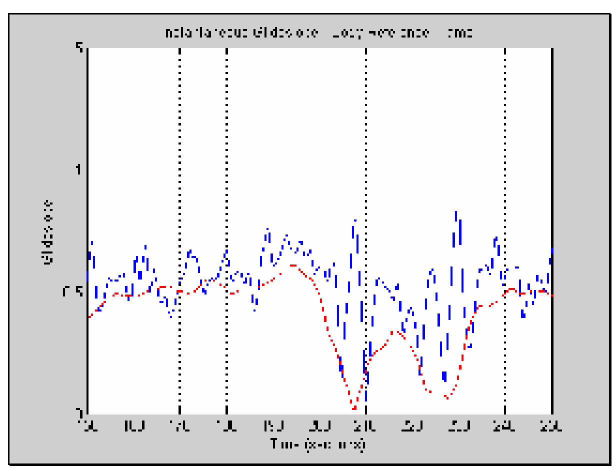

Figure 11. Glide Ratio, 2 Control Activations, Jan 03

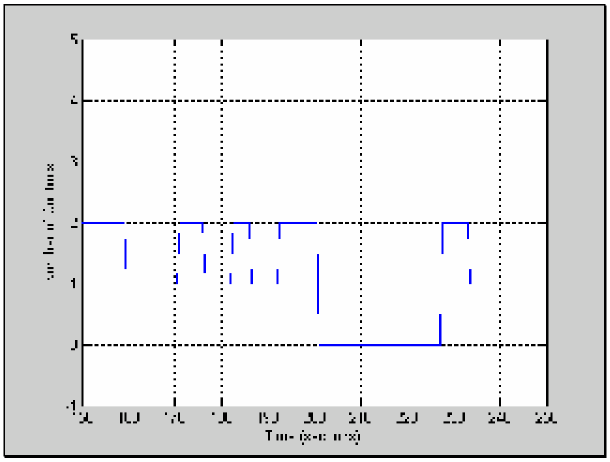

Figure 12. Number of Controls Active

Throughout the initial interval presented, the control state toggled between two- and one- control being active. Throughout this time, the glide ratio obtained was approximately 0.5. This was observed to be the typical glide ratio for the AGAS system when two controls were activated. For the time interval from 200 to 228 seconds, no controls were active for this airdrop. The glide ratio data (Figure 11) shows an apparent glide ratio of about 0.4. However, using Porter's alternate method (shown with the smoothed line), the glide ratio for this time frame was near zero as expected for a flat circular parachute.

In summary, flight test data indicates that glide ratios of approximately 0.8 are achievable with a G-12 parachute and a single-control activation (lengthening of one riser 6.4 feet) while glide ratios of 0.5 are achievable with a two-control activation. The response time of the system is on the order of 5-seconds. These data were utilized to update the AGAS model and run numerous simulations. Yakimenko, et al, concluded that the simulations showed sufficient performance for the AGAS to meet its design objectives[4].

<u>Trajectory Analysis</u>

As stated earlier, the guidance algorithm is a trajectory-control algorithm. That is, controls are activated as needed to 'drive' the parachute system back to a predicted or reference trajectory. Figure 13 shows the reference trajectory and actual AGAS trajectory in a 3-dimensional view. The plot illustrates how the two trajectories start apart from each other and the AGAS drives to the reference trajectory. To further illustrate this drive, the horizontal distance from the AGAS to the reference trajectory was calculated (Figure 14). As the plot illustrates, the AGAS was deployed more than 800 meters (shown at 25-seconds [after GPS reacquisition]) from the planned trajectory. After parachute deployment and initialization of GPS, the AGAS system activated the proper controls (Figure 15) steering the AGAS to the reference trajectory (trajectory error goes to zero). Figure 16 presents an expanded view of the trajectory error for this airdrop. As can be seen, the trajectory error reduces as the parachute drives to the trajectory. When the system is within 30 meters of the reference trajectory, the controls are deactivated and the parachute "floats" with the wind. Once outside the programmed threshold, controls are activated and again the trajectory error reduces.

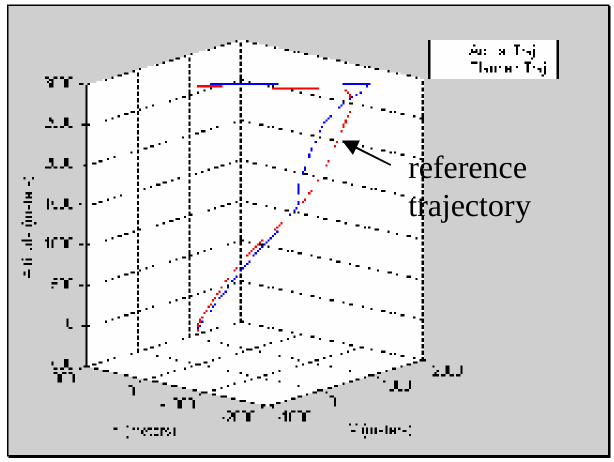

Figure 13. Actual and Reference Trajectories

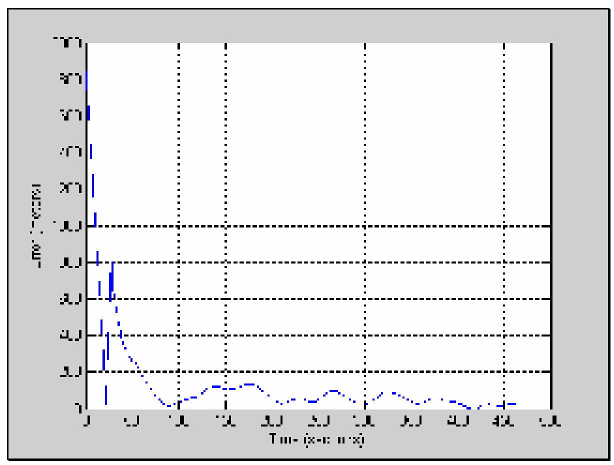

Figure 14. Horizontal Trajectory Error (10 Jan 03)

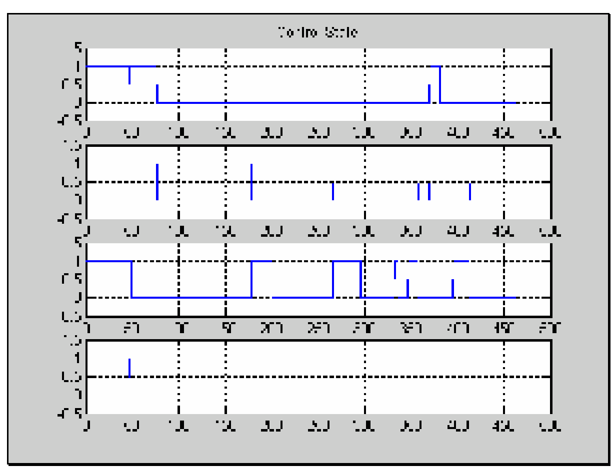

Figure 15. Control State (10 Jan 03)

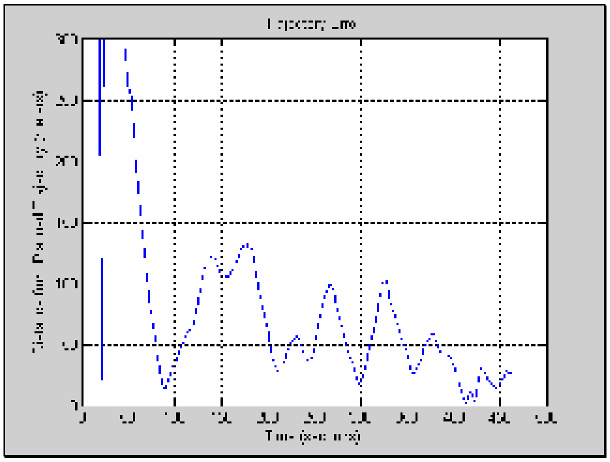

Figure 16. Horizontal Trajectory Error

Figures 17 and 18 show the trajectory error for the airdrop conducted on 09 Jan 03. The AGAS was deployed close to the reference trajectory (less than 100 meters). Again, with no controls active, the parachute floats with the wind and once outside the programmed tolerance, controls are activated and the system drives to the trajectory. In this case, the system was within 10 meters of the reference trajectory within 30 seconds from ground impact. However, since no controls were active, the system drifted away from the reference trajectory and impacted the ground at approximately 43 meters from the desired impact point. Additional considerations can be made in the control strategy to further reduce the impact error under these conditions.

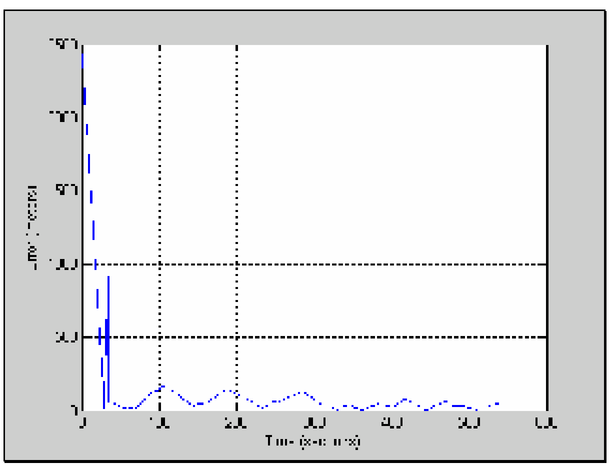

Figure 17. Trajectory Error (09 Jan 03)

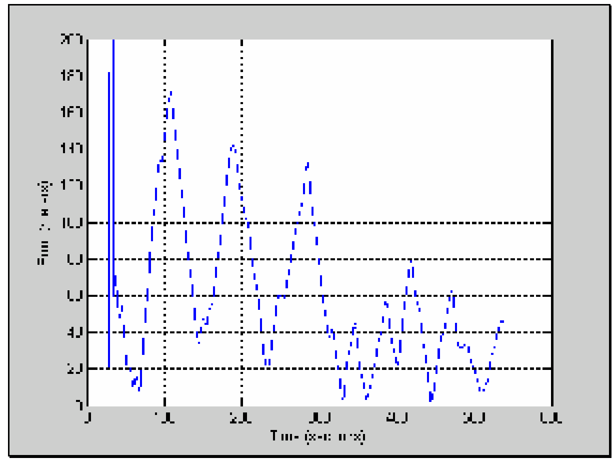

Figure18. Trajectory Error (09 Jan 03)

Impact Accuracy

Fifteen successful fully autonomous airdrops were conducted. Other testing was conducted but data-link problems, twisted risers, and control valve problems inhibited the use of this information. Table one presents the impact points referenced to the predicted impact point (zero, zero).

Table One. Impact Results

	X-Error (meters)	Y-Error (meters)	Radial Error (meters)
1	-152	-61	164
2	-72	74	103
3	-39	153	158
4	-25	8	26
5	-24	-50	55
6	-21	-10	23
7	16	19	25
8	25	-39	47
9	30	-18	35
10	31	54	62
11	61	100	117
12	69	-25	73
13	69	-8	69
14	76	0	76
15	78	-1	78

Table two presents the statistical results for the radial error.

Table Two. Summary Results

Mean	74.1
Median	69.5
Standard Deviation	44.7
Minimum	23.1
Maximum	163.8
Count	15.0

These data show that a Circular Error Probable (CEP) of 69.5 meters was achieved with fifteen fully autonomous airdrops. These results are illustrated in Figure 19. The individual impact points are plotted along with the circle containing 50% of the results (CEP).

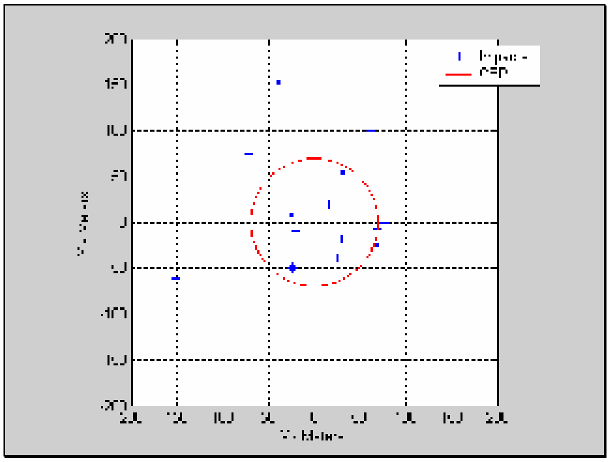

Figure 19. Impact Results and CEP

Conclusions

The initial feasibility of the AGAS system was demonstrated through modeling and simulation[5]. The flight test program of the fully autonomous system, discussed here, clearly demonstrated the reality of the AGAS concept. The goal of steering a flat circular parachute to within 100 meters (CEP) of the intended target, with 70 meters CEP actually achieved, is a reality – even though ***THEY SAID IT COULDN'T BE DONE!***

Acknowledgements

Special thanks to Jim Bybee, Cibola Information Systems, for the tremendous efforts to develop the flight computer and data acquisition system for this effort. Additional thanks go to the entire Precision Airdrop team for their continued efforts to improve the airdrop capabilities for our soldiers.

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