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Preliminary Design and Control Strategy Analysis of the Affordable Guided Airdrop System

Oleg Yakimenko[#], Isaac Kaminer[#], and Scott Dellicker[&]

This paper addresses the development of an autonomous guidance, navigation and control system for a flat solid circular parachute. This effort is a part of the Affordable Guided Airdrop System (AGAS) that integrates a low-cost guidance and control system into fielded cargo air delivery systems. The paper describes the AGAS concept, its architecture and components. The synthesis of the optimal control strategy based on Pontryagin's principle of optimality is also presented. The paper is intended to be a summary of the current state of AGAS development. The paper ends with the summary of the future plans in this area.

Index terms -- autonomous cargo delivery systems, Pontryagin's maximum principle

I. INTRODUCTION

The first attempts to develop autonomous payload delivery systems are as old as the introduction of gliding, maneuverable parachutes.¹ However, practical systems had to wait for the development of hi-glide parachutes, especially the ram-air inflated parafoil. In 1969 the U.S. Army defined requirements for and discussed such a cargo point delivery system.² None of attempts in the 70's and 80's to develop such a system were operationally acceptable, however nowadays such systems have been developed (see for example Ref.3).

These large-scale parafoil systems use a marker or beacon on the ground and ensure 99% landing accuracy in a hundred-yard circle around the beacon. Therefore, they provide the accuracy required with delivery from high altitude and large offset distances. The drawback is prohibitive cost for each pound of payload delivered. Alternate approaches were required to reduce system cost. Improved Affordable Airdrop Technologies are being evaluated by the team of the US Army and Air Force, the Naval Postgraduate School, The Boeing Company, and Vertigo, Incorporated. These efforts include the design and development of the AGAS, which incorporates a low-cost guidance, navigation, and control system into fielded cargo air delivery systems. This study focuses on evaluating the feasibility of the AGAS concept and encompasses the design and execution of a flight test program to assess dynamic response of a flat circular parachute, the design of initial guidance and control techniques, and to evaluate the feasibility of the AGAS concept.

II. AGAS CONCEPT, ARCHITECTURE AND COMPONENTS

AGAS is being evaluated as a low-cost alternative for meeting the military's requirements for precision airdrop.^{4,5} Designed to bridge the gap between expensive high glide parafoil systems and uncontrolled (ballistic) round parachutes, the AGAS concept offers the benefits of high altitude parachute releases but cannot provide the same level of offset from the desired impact point as high-glide systems. The design goal of the AGAS development is to provide a guidance, navigation, and control system that can be placed in-line with existing fielded cargo parachute systems (G-12 and G-11) and standard delivery containers (A-22). The system is required to provide an accuracy of 100m, Circular Error Probable (CEP), with a desired goal of 50m CEP. No changes to the parachute or cargo system are allowed.

The current design concept includes implementation of commercial Global Positioning System receiver and a heading reference as the navigation sensors, a guidance computer to determine and activate the desired control input, and the application of Pneumatic Muscle Actuators (PMAs) to effect the control. The navigation system and guidance computer will be secured to existing container delivery system while the PMAs would be attached to each of four parachute risers and to the container (Figure 1). Control is affected by lengthening a single or two adjacent actuators. The parachute deforms creating an unsymmetrical shape, essentially shifting the center of pressure, and providing a drive or slip condition. Upon deployment of the system from the aircraft, the guidance computer would steer the system along a pre-planned trajectory. This concept relies on the sufficient control authority to be produced to overcome errors in wind estimation and the point of release of the system from the aircraft. Following subsections discuss main AGAS components.

For an airdrop mission, the aircrew will determine the Computed Air Release Point (CARP) based on the best wind estimate available at that time. The aircraft will then be navigated to that point for air delivery of the materiel. Should the wind estimate and calculation of the predicted release point be perfect and the aircrew gets the aircraft to the precise release point, then the parachute would fly precisely to the target without control inputs. However, wind estimation is far from a precise science. The calculation of the CARP relies on less than perfect estimates of parachute aerodynamics and the flight crews cannot possibly precisely hit the predicted release point for each airdrop mission.

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Therefore, the AGAS control system design must help overcome these potential errors.



Figure 1. Affordable Guided Airdrop System¹

A. Parachute

Until now two solid flat circular parachutes C-9 and G-12 were modeled to demonstrate a feasibility of AGAS concept. (A flat circular parachute is one that when laid out on the ground forms a circle.¹) Figure 2 shows a deployed configuration of C-9. Although the C-9 was initially designed as an ejection seat parachute, it is a standard flat circular parachute as are the larger G-11 and G-12 cargo parachutes on which AGAS will ultimately be used. Some data on these parachutes can be found in the Table 1.

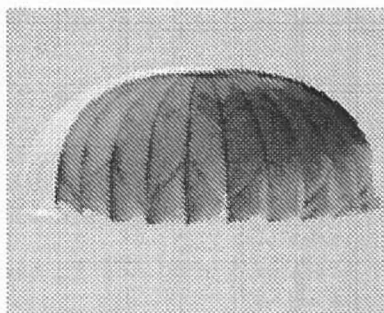


Figure 2. C-9 Parachute with 28 gores

Table 1. Parachutes data²

Parameter	C-9	G-12	G11-A
d_0 (ft)	28	64	100
d_p / d_0	0.67	0.67	0.67
Number of suspension lines	28	64	120
l_0 / d_0	0.82	0.80	0.90
C_{D0}	0.68	0.73	0.68
Parachute weight (lbs.)	11.3	130	215
Payload weight (lbs.)	200	2,200	3,500
Rate of descent (fps)	20	28	22

¹ Courtesy of Vertigo, Inc., Lake Elsinore, CA.

In this table d_0 denotes the nominal diameter of the parachute, d_p - inflated canopy diameter, C_{D0} - a drag coefficient, and l_0 - a suspension line length.

A cargo box is suspended from the system and houses the remote control system, control actuators, and instrumentation system.

B. Actuators

Vertigo, Incorporated developed PMAs⁶ to effect the control inputs for this system. The PMAs are braided fiber tubes with neoprene inner sleeves that can be pressurized. Uninflated PMAs as installed on a scaled system are shown in Figure 3. Upon pressurization, the PMAs contract in length and expand in diameter.

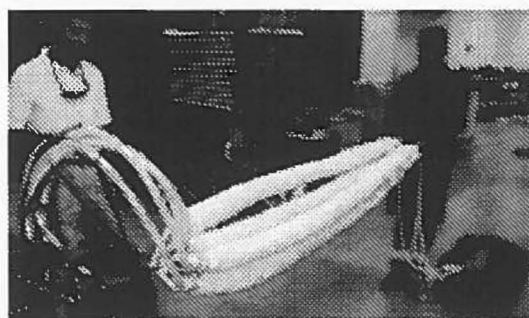


Figure 3. Pneumatic muscle actuators

With four independently controlled actuators, two of which can be activated simultaneously, eight different control inputs can be affected. The concept employed for the AGAS is to fully pressurize all actuators upon successful deployment of the parachute. To affect control of the system, one or two actuators are depressurized. This action "deforms" the parachute creating drive in the opposite direction of the control action.

Figure 4 shows a diagram of the actuator setup in the parachute payload provided by Vertigo, Incorporated, the makers of the PMAs. The gas for filling the actuators comes from 4500psi reservoirs (the diagram shows two, but in the simulation for this study, only a single 4500psi reservoir is used). Each of the four actuators are then connected to this same reservoir of nitrogen gas through some piping or tubing leading to a fill valve. The fill valve is opened to allow gas to fill the actuators when a command to take an actuation off is received. When the pressure inside the PMA reaches a certain value, a pressure switch signals the fill valve to close.

Since the fill valve works with high-pressure gas it has a small orifice and therefore opens and closes rather quickly upon receiving the correct electrical signal. The time to open and close the valve is roughly 100ms. However, the decrease in pressure of the gas tank as more and more fills are completed slows down the actual filling process. Some of this data is plotted in Figure 5, showing increasing fill time as a function of decreasing tank pressure for actuators being filled to three different pressures.

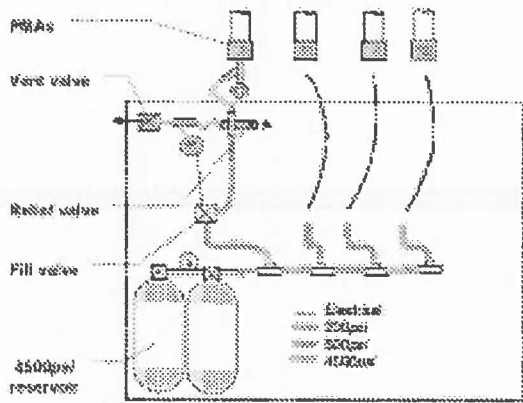


Figure 4. Vertigo, Inc. actuator system concept

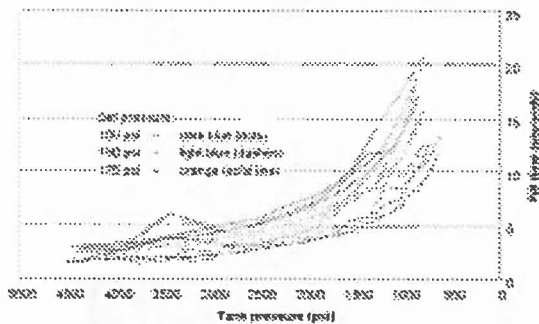


Figure 5. Fill time versus tank pressure

The vent valve opens to empty the actuator when a command to actuate is received. The vent valve has a large orifice and can open quickly to vent the PMA, but requires a certain time to vent the gas and close the orifice. The opening of the vent valve requires approximately 100ms, but the venting process and closing of the valve depends on the maximum pressure of the actuator fill. This process also takes a constant amount of time (approximately) because the pressure in the actuators is the same upon each vent. Figure 6 includes a diagram of the computer-modeling concept for the actuators.

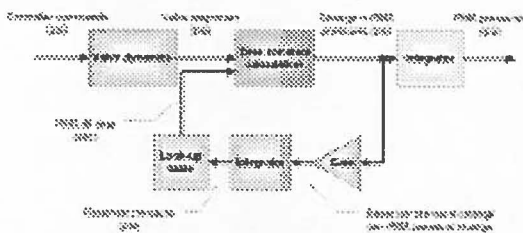


Figure 6. Actuator model

Controller commands are input to the system for each of the four PMAs. The controller commands are the pressure signals for each PMA; with ψ being a vent of the actuator and 175psi (or the maximum pressure of the actuator) being a fill of the PMA. These commands are then passed through code that models the dynamics of the valves. This code is just a first order lag with a rise time of approximately 100ms to model the opening and closing of the valves. The valve responses are then passed to a code that models the

actual venting and filling of the actuators, keeping in mind that the venting process takes a constant amount of time and the filling process increases with decreasing tank pressure. Once again this behavior is modeled as a first order lag. This code outputs the derivative with respect to time of the PMA pressures. This is integrated to give the current state of each of the PMAs at a given time. PMA fill time is calculated by passing the change in PMA pressures through a gain that reflects data taken on the reservoir pressure changes per PMA pressure changes or the amount of reservoir pressure depleted for every actuator fill. This negative gain is integrated from an initial reservoir pressure to give current reservoir pressure. A look-up table is used to provide a value for the fill time of the actuators based on the remaining reservoir pressure from experimental data.

III. DERIVATION OF THE OPTIMAL CONTROL STRATEGY

A. General statement of optimization problem

Based on the AGAS concept introduced above, the optimal control problem for determination of parachute trajectories from a release point to the target point can be formulated as follows: among all admissible trajectories that satisfy the system of differential equations, given initial and final conditions and constraints on control inputs determine the optimal trajectory that minimizes a cost function of state variables \bar{z} and control inputs \bar{u}

$$J = \int_0^T f_0(t, \bar{z}, \bar{u}) dt \quad (1)$$

and compute the corresponding optimal control.

For the AGAS, the most suitable cost function J is the number of actuator activations. Unfortunately this cost function cannot be formulated analytically in the form given by expression (1). Therefore, we investigated other well-known integrable cost functions and used the results obtained to determine the most suitable cost function for the problem at hand.

B. Application of Pontryagin's maximum principle of optimality

To determine the optimal control strategy we applied Pontryagin's principle⁷ to a simplified model of parachute dynamics. This model essentially represents parachute kinematics in the horizontal plane (Figure 7):

$$\begin{aligned} \dot{x} &= u \cos \psi - v \sin \psi \\ \dot{y} &= u \sin \psi + v \cos \psi \\ \dot{\psi} &= C = \text{const} \end{aligned} \quad (2)$$

Each of four actuators in two control channels can be activated in the manner allowing the following discrete speed components in the axis of the parachute frame: $u, v \in [-V; 0; V]$. We considered these speed components as controls for the task at hand.

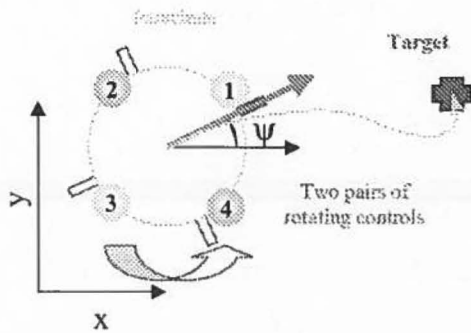


Figure 7. Projection of the optimization task onto the horizontal plane

The Hamiltonian⁷ for the system (2) can be written in the following form:

$$H = (u, v) \begin{pmatrix} p_x \cos \psi + p_y \sin \psi \\ -p_x \sin \psi + p_y \cos \psi \end{pmatrix} + p_v C - f_0$$

where equations for ajoin variables p_x , p_y , and p_v are given by

$$\begin{aligned} \dot{p}_x &= 0 & \dot{p}_y &= 0 \\ \dot{p}_v &= (p_x, p_y) \begin{pmatrix} u \sin \psi + v \cos \psi \\ -u \cos \psi + v \sin \psi \end{pmatrix} \end{aligned}$$

We consider two cost functions

$$\begin{aligned} f_0 &\equiv 1 && \text{- minimum time} \\ f_0 &\equiv |u| + |v| && \text{- minimum 'fuel'} \end{aligned}$$

According to Ref.7, the optimal control is determined as $\bar{u}_{opt} = \text{argmax} H(\bar{p}, \bar{z}, \bar{u})$. Therefore, for the time-minimum problem the optimal control is given by

$$u = V \text{sign} \left((p_x, p_y) \begin{pmatrix} \cos \psi \\ \sin \psi \end{pmatrix} \right), \quad v = V \text{sign} \left((p_x, p_y) \begin{pmatrix} -\sin \psi \\ \cos \psi \end{pmatrix} \right)$$

Figure 8 shows the graphical interpretation of these expressions. In general, the vector (p_x, p_y) defines a direction towards the target and establishes a semi-plane perpendicular to itself that defines the nature of control actions. Specifically, if an actuator happens to lie within a certain operating angle Δ with respect to the vector (p_x, p_y) it should be activated. For a time-optimum problem since $\Delta = \pi$ two actuators will always be active. Parachute rotation determines which two. (We do not address the case of singular control, which in general is possible if the parachute is required to satisfy a final condition for heading). Figure 9 shows an example of time-optimal trajectory. It consists of several arcs and a sequence of actuations (for this example $\dot{\psi} = 0.175s^{-1}$ and $V = 5m/s$).

For the 'fuel'-minimum problem we obtain analogous expression for optimal control inputs:

$$\begin{aligned} p_x \cos \psi + p_y \sin \psi > V &\Rightarrow u = V \\ p_x \cos \psi + p_y \sin \psi < V &\Rightarrow u = -V \\ p_x \cos \psi + p_y \sin \psi \equiv V &\Rightarrow u = u_{s.c.} \end{aligned}$$

$$\begin{aligned} -p_x \sin \psi + p_y \cos \psi > V &\Rightarrow v = V \\ -p_x \sin \psi + p_y \cos \psi < V &\Rightarrow v = -V \\ -p_x \sin \psi + p_y \cos \psi \equiv V &\Rightarrow v = v_{s.c.} \end{aligned}$$

In this case actuators will be employed when appropriate dot products will be greater than some positive value. Obviously, this narrows the value of the angle Δ . In fact, for this particular cost function $\Delta \rightarrow 0$. In general any cost function other than minimum-time will require an operating angle $\Delta \leq \pi$ (Figure 10).

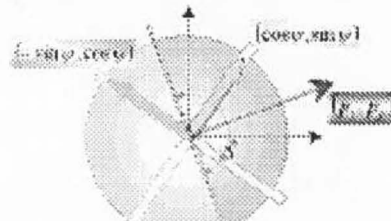


Figure 8. Time-optimal control

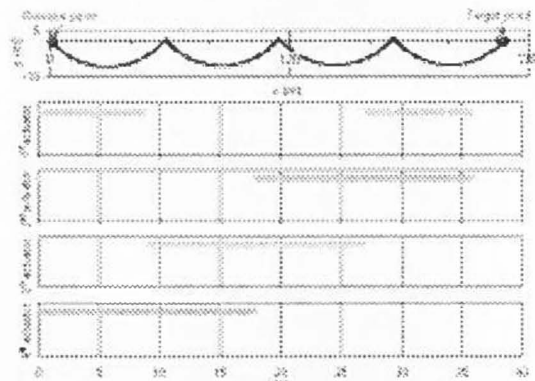


Figure 9. Example of the time-optimal trajectory and time-optimal controls

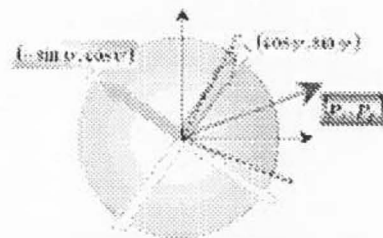


Figure 10. Generalized case of optimal control

Figure 11 shows the effect of operating angle on the flight time, 'fuel' and number of actuator activations. It is clearly seen that the nature of the dependence of the number of actuations on the operating angle is the same as that of the time of flight. This implies that by solving the time minimum problem we automatically ensure a minimum number of actuations. Moreover, it is also seen that the slope of these two curves in the interval $\Delta \in [0.5\pi; \pi]$ is flat. This implies that small changes of an operation angle from its optimal value will result in negligible impact on the number of actuations. Therefore, changing the operating angle to

account for the realistic actuator model will not change the number of actuations significantly.

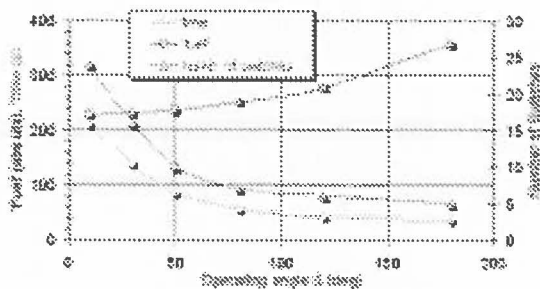


Figure 11. Influence of operating angle

IV. CONCLUSIONS

Preceding analysis suggested that the shape of optimal control is bang-bang. The work on implementation and flight testing of this control strategy is currently being conducted.

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