EVOLVED ACCELERATION GUIDANCE FOR PLANETARY ENTRY

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ABSTRACT

The U.S. Apollo and Shuttle programs have proven the viability and effectiveness of acceleration guidance. New capabilities have been developed to augment this basic concept. Algorithms have been designed for low lift to drag ratio vehicles and for mid to high lift to drag ratio vehicles. These algorithms have been tested for Mars landing and for earth entry of reusable launch vehicles and have performed well in both cases. Also the trajectory planner has been incorporated into a landing footprint generator that is designed for on-board use.

1. INTRODUCTION

Next generation reusable launch vehicles (RLVs) and future Mars landers can benefit from advances in entry guidance. Entry guidance is needed for low, medium and high lift-to-drag ratio (L/D) vehicles. Some vehicles maneuver by bank angle control alone, while others maneuver by a combination of angle of attack and bank angle control. The potential benefits include landing precisely and reaching more of the landing footprint of which the vehicle is capable. In some cases, high degrees of autonomy and adaptability are required, including for example onboard trajectory planning to accommodate a change in mission objectives or failure scenarios.

In this paper an overview of a new entry guidance is given and results from simulation testing are presented.

2. ENTRY GUIDANCE METHOD

An entry guidance approach, which includes onboard trajectory planning, has been developed for mid to high L/D entry vehicles with angle of attack and bank angle control [1-4]. The approach is a direct extension of the longitudinal acceleration guidance used for the U.S. space shuttle orbiters [5] to include the lateral dimension. Whereas the shuttle drag planning is based on the assumption that the entry trajectory is a great circle arc, the trajectory planning in the new approach accounts for trajectory curvature in the horizontal direction. With this extension the new approach can guide large cross range entries as well as the descent portion of aborts that require significant cross range. Like the shuttle entry guidance, the new approach delivers a lifting entry vehicle to a target point at which terminal area energy management (TAEM) phase guidance takes over. Because the guidance approach is based on planning and tracking aerodynamic accelerations, it is robust to errors in the aerodynamic and atmospheric models on which it is based. Because the approach is a natural evolution of the shuttle entry guidance approach, we refer to it as the evolved acceleration guidance logic for entry (EAGLE).

EAGLE is composed of a planning function [1] that generates a reference trajectory and a tracking function [4] that issues bank angle and angle of attack commands to follow the reference trajectory. In addition there is higher level logic [4] to adjust the reference angle of attack profile, the TAEM target point, and the tracking strategy. The planner uses a successive approximation approach to design reference drag and heading angle profiles. The tracking law builds on a previously developed feedback linearization based drag tracking law [6]. The bank angle command meets a weighted combination of demands for drag and heading angle tracking. Much the same as in the shuttle entry guidance, the angle of attack is also commanded as a secondary means of trajectory control, based on a washout filter that reduces high frequency drag errors.

Figures 1 and 2 show the results of a closed-loop simulation. Because we are showing the results just to illustrate the general features of EAGLE, the specific conditions for the simulation are not given; see [2-4] for detailed presentations of simulation results. Figure 1 shows the planned drag profile (dashed curve) as a function of normalized energy. By design, the drag profile lies within the minimum and maximum drag boundaries. The maximum drag boundary is determined by the heat rate, acceleration, and dynamic pressure limits. The minimum drag boundary is an equilibrium glide limit [5]. Figure 2 shows the corresponding planned bank and attack angles. Although not very apparent, the reference profiles are updated several times during entry. Figure 1 also shows the drag profile (solid curve) that is actually flown under the closed-loop guidance, according to the simulation, and Fig. 2 shows the required angles of bank and attack (solid curves).

A modification of this guidance approach suitable for low L/D capsules with only bank angle control has been developed as well [7] and is discussed in the next section.

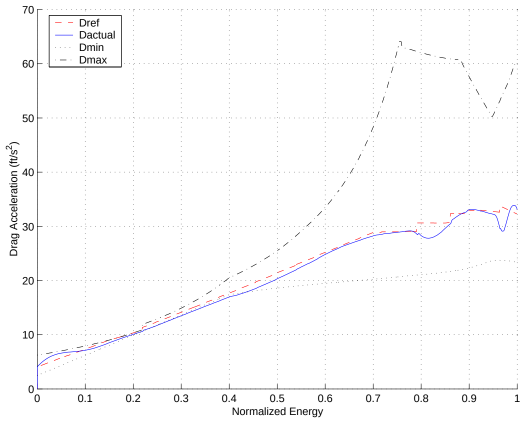

Fig. 1. Planned reference and simulated (actual) drag profiles within maximum and minimum drag boundaries

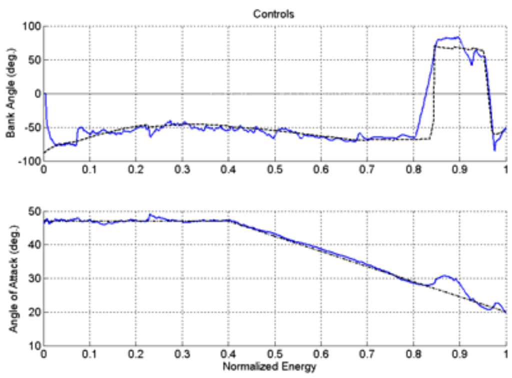

Fig. 2. Planned (dashed) and simulated (solid) bank and attack angle profiles

3. MARS LANDING

A low L/D version of EAGLE [7] was tested in the Mars Surveyor Program 2001 (MSP 01) study [8]. MSP 01 was intended to demonstrate precision landing (error < 10 km) although this demonstration was later cancelled. Two lander configurations with *L/D*'s of 0.06 and 0.12, respectively, were considered. After evaluating the test results for this as well as 4 other algorithms, the down-selection board concluded that any of the 5 algorithms would work in flight and perform well. An algorithm [9] adapted from the Apollo program was selected as best and is now the baseline algorithm for the Mars Science Laboratory (MSL) 2009 mission. Pinpoint landing (< 100 m) is scheduled to be demonstrated in a 2011 Mars mission; no entry guidance algorithm has been selected as yet.

4. REUSABLE LAUNCH VEHICLE ENTRY

The mid-high L/D version of EAGLE [2-4] was tested for an X-33 type reusable launch vehicle in the Advanced Guidance and Control Study led by the NASA Marshall Space Flight Center [10]. The test results show excellent performance and significant improvement over the current state of the art. Figure 3 shows 6 of the nominal entry cases. EG 16-18 are early entries from an International Space Station orbit. EG 19-21 are entries from a U.S. shuttle orbit. For each of the nominal cases and for many variations from these nominal cases [4,10], the entry guidance should deliver the vehicle to within 3 nmi of a 30 nmi circle centered at the heading alignment circle (HAC) point, heading toward the HAC point to within 5 deg. The TAEM geometry is shown in Fig. 4. Figure 5 illustrates the guidance algorithm's ability to achieve the required horizontal position accuracy. Though not shown, the algorithm also achieved the required accuracy at the TAEM interface for heading, altitude, and flight path angle and kept the vehicle within the acceptable limits for heating, acceleration and dynamic pressure [2-4]. The overall scores for all the test cases – which included suborbital (abort) cases, return form orbit cases, failure cases, cases with significant modelling errors, and may dispersions – are shown in Fig. 6. The scores are on a scale from 0 to 1. A score of 1 means that all guidance requirements were met. A guidance algorithm with scores greater than 0.9 is considered viable.

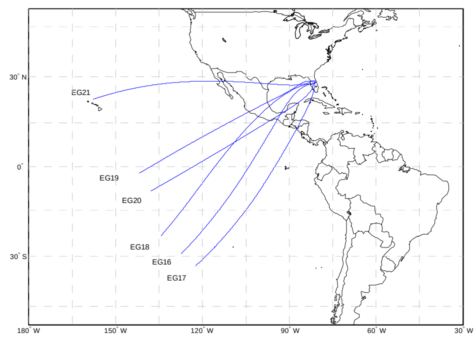

Fig. 3. Ground tracks for nominal entry cases

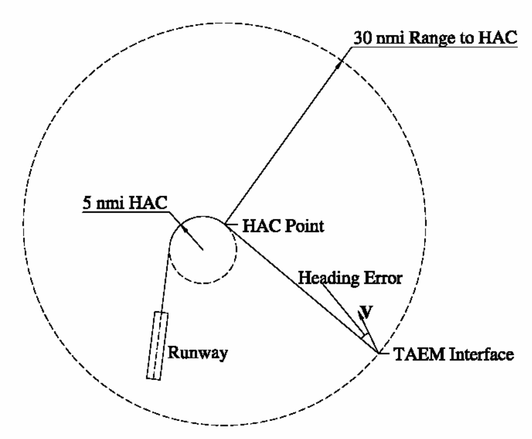

Fig. 4. TAEM geometry

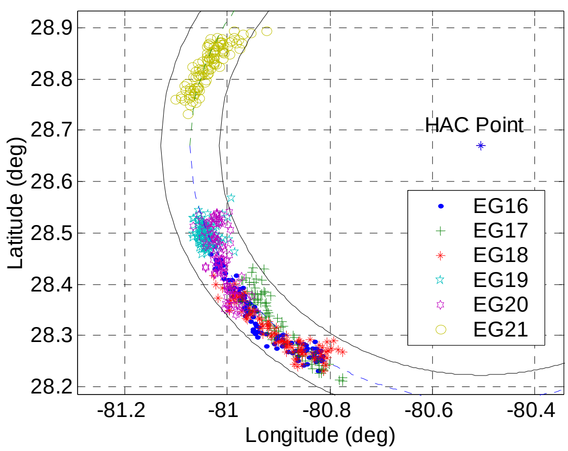

Fig. 5. TAEM point control for dispersed cases

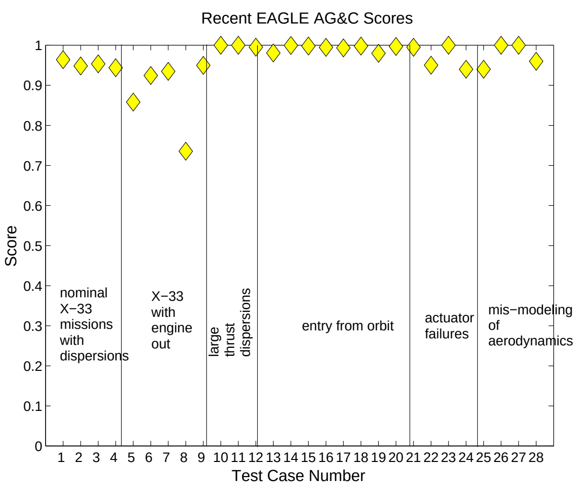

Fig. 6. Test results for dispersion and failure cases

5. LANDING FOOTPRINT

A landing footprint generator [11] has been developed, based on the trajectory planning function in EAGLE. Figure 7 shows the landing footprints for three different shuttle entry conditions. Each footprint can be computed in less that 1 sec on an Intel Pentium 4, 2.66 GHz, personal computer, so it is expected that the footprint generator can be used in an on-board flight management system for landing site selection. The footprint generator automatically determines the drag and angle of attack profiles to compute the boundary of the footprint.

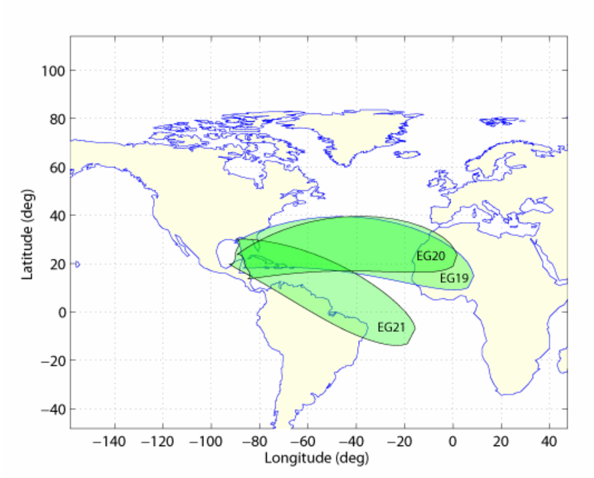

Fig. 7. Landing footprints for 3 initial entry states

6. SUMMARY

The U.S. Apollo and Shuttle programs have proven the viability and effectiveness of acceleration guidance. New capabilities have been developed to augment this basic concept. Algorithms have been designed for low lift to drag ratio vehicles and for mid to high lift to drag ratio vehicles. These algorithms have been tested for Mars landing and for earth entry of reusable launch vehicles and have performed well in both cases. Also the trajectory planner has been incorporated into a landing footprint generator that is designed for on-board use.

7. REFERENCES

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