Aerocapture Guidance Algorithm Development and Testing

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***Abstract* – An analytic predictor corrector guidance algorithm has been developed and tested for aerocapture at several destinations in our solar system, and proposed for demonstration through an Earth based flight test. This paper gives an overview of the guidance algorithm and results of simulation tests at Earth, Mars, Titan, Neptune, and Venus.**

INTRODUCTION

Aerocapture is a flight maneuver performed by a spacecraft upon arrival at a planet in which atmospheric drag is used to decelerate the spacecraft into orbit during one atmospheric pass. This is in contrast to using an all-propulsive system to place the spacecraft into orbit. By using aerocapture, propellant mass is significantly reduced, which allows more scientific payload to be delivered to the planet, or smaller launch vehicles to be used to launch the spacecraft from Earth. This in turn, enables more extensive and cost effective space science missions.

An aerocapture trajectory consists of the following main events (as illustrated in Fig. 1):

- Entry Targeting – The vehicle approaches the target planet and the trajectory is adjusted such that the atmospheric entry angle is within acceptable bounds.
- Energy Dissipation – The vehicle flies through the atmosphere at nearly constant altitude to dissipate excess energy.
- Exit Atmosphere – The vehicle flies out of the atmosphere, controlling the altitude rate and velocity at atmospheric exit so as to achieve the target orbit apoapsis.
- Periapsis Raise – After achieving apoapsis altitude, a small propulsive maneuver is used to raise periapsis to the desired altitude so that the vehicle does not reenter the atmosphere.

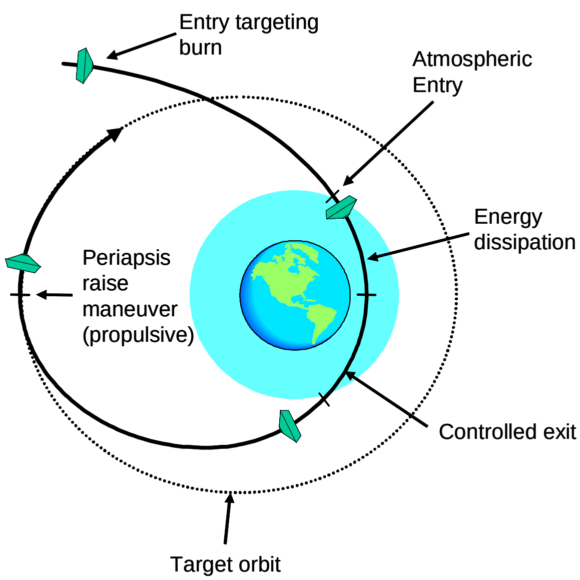

Fig. 1. Aerocapture trajectory consists of several key events.

A key component required to perform aerocapture is the guidance algorithm, which generates commands to steer the vehicle through the atmosphere to the desired final orbit altitude and inclination. During atmospheric flight, the vehicle's aerodynamic drag provides the change in velocity needed to capture into orbit, while aerodynamic lift provides the capability to control the trajectory under dispersions. The guidance algorithm continuously computes bank angle (rotation about the velocity vector) commands to point the lift vector in the desired direction and control the trajectory under dispersions. The vehicle's attitude control thrusters are then used to rotate the vehicle to achieve the commanded bank angle.

An analytic predictor-corrector (APC) guidance algorithm for aerocapture has been developed. The algorithm is derived from that developed for the Aeroassist Flight Experiment (AFE) program circa 1989 [1] and has been refined through several aerocapture systems analysis studies for aerocapture at Mars, Titan, Neptune, Venus, and Earth. These efforts have resulted in a mature, flexible, and robust algorithm that is independent of vehicle and mission design parameters, tolerates dispersions and uncertainties in atmosphere density, vehicle mass, aerodynamics, and delivery and knowledge errors. This paper provides a summary of the development, analysis, and testing efforts. Details of the guidance development and testing efforts can be found in a series of previously published papers [2], [3], [4], [5], [6], [7]. [8], [9], [10], [11].

GUIDANCE ALGORITHM DESCRIPTION

The aerocapture guidance algorithm targets a lifting vehicle through the atmosphere to a desired exit orbit apoapsis and inclination (or plane) by commanding rotation about the vehicle's velocity vector (bank angle). The bank angle is continuously commanded so that the vertical component of the

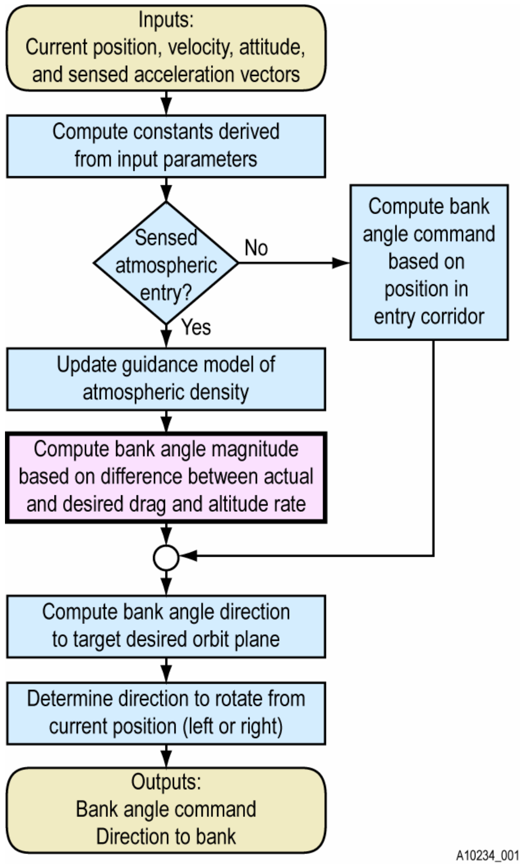

Fig. 2. The APC algorithm consists of a sequential, non-recursive sequence of operations to compute the bank angle command.

vehicle's lift vector controls altitude rate to target the desired apoapsis, and the lateral component of the lift vector controls the orbit plane. Periodic bank reversals keep the orbit inclination (or wedge angle) error within desired limits.

The top-level logic flow of the guidance algorithm is shown in Fig. 2. The algorithm by design uses a sequence of non-iterative, non-recursive calculations, resulting in a very efficient, predictable, and consistent execution time. Inputs to the guidance algorithm are the current vehicle position vector, velocity vector, sensed acceleration vector, and vehicle attitude obtained from the on-board navigation system. When the vehicle is outside of the atmosphere, it commands the bank angle based on its estimated position in the entry corridor. Once inside the atmosphere, the algorithm uses the sensed acceleration to estimate the atmospheric density, then updates its internal model of the atmosphere density, allowing the algorithm to automatically adjust to the measured atmospheric conditions. The algorithm then uses drag and altitude rate error feedback to compute the bank angle magnitude that will guide the vehicle to the desired apoapsis altitude. Bank angle direction is simply selected to steer toward the desired orbit plane. The algorithm outputs a desired bank angle and direction to rotate (clockwise or counter clockwise) toward the desired bank angle, which is then executed by the vehicle's attitude control system.

The guidance algorithm is adaptable to a wide range of initial state vectors, vehicle lift-to-drag (L/D) ratios and ballistic coefficients, planetary atmospheres, and target orbits by only changing a small set of initialization constants. Through analysis of performance under a wide variety of situations, refinements have been made to result in a robust algorithm with the ability to handle all of the following dispersions simultaneously:

- Variation in atmosphere density
- Random atmosphere density perturbations
- Entry targeting errors
- Navigation system errors
- Uncertainties and variability in vehicle aerodynamics
- Uncertainties and variability in vehicle mass properties

Demonstration of this capability for several destinations is discussed in the following section.

GUIDANCE ALGORITHM PERFORMANCE RESULTS FOR MULTIPLE DESTINATIONS

The performance and robustness of the APC algorithm have been demonstrated using validated trajectory simulation tools for a variety of aerocapture mission concepts at Mars, Titan, Neptune, Venus, and Earth. Two different trajectory simulation tools were used: SORT [12] and POST [13]. The tools were used in their 4-degree-of-freedom mode, where the Cartesian equations of motion about a central rotating body are integrated, and rotation about the velocity vector is simulated with kinematics. Both programs are general purpose trajectory simulation tools designed to accommodate various types of models for gravity, atmosphere, aerodynamics, propulsion, and vehicle mass. In the aerocapture systems analysis studies, the central body was modeled as an ellipsoid with central gravity field, and in some cases had J1, and J2 harmonics. For aerodynamics, the simulations used tables of lift and drag vs. Knudsen number, Mach number, and angle of attack. The vehicle mass is fixed throughout flight, and the trim angle of attack is dependent upon the location of the center of gravity.

In all cases, the trajectory simulations made use of Global Reference Atmosphere Models (GRAM) [14]. These are engineering models that provide atmosphere parameters (density, pressure, temperature) vs. altitude, latitude, longitude, season, and time of day. The models not only provide nominal atmospheric values, but also simulate variability and random perturbations for Monte Carlo trajectory analysis. This includes uncertainties in current estimates derived from scientific measurements, as well as perturbations based on models of dynamic processes. Models developed for Earth, Mars, Titan, Neptune, and Venus were used in the aerocapture systems analysis studies.

In order to demonstrate guidance algorithm performance, 4-DOF Monte Carlo trajectory simulations were completed for the following mission concepts utilizing aerocapture:

- Mars Sample Return Orbiter
- Titan Explorer
- Neptune and Triton Orbiter
- Venus Explorer
- New Millennium Program, ST9 Aerocapture Demonstration at Earth

The Monte Carlo simulations included variation in the atmosphere density profile, random density perturbations, variations in entry conditions, variations in aerodynamic parameters, and navigation errors. Specific values of the dispersions were selected for the particular mission and vehicle design, which were developed through systems level concept studies. A summary of the results of Monte Carlo simulations for each mission is given in the following sections. The reader is referred to the references on the specific mission studies for details on the results.

Mars Sample Return Orbiter Aerocapture

The Mars Sample Return Orbiter [15] aerocapture study was performed during the years of 1999 to 2000. The vehicle L/D was 0.23, and ballistic coefficient was 148 kg/m^2. The atmospheric entry velocity was 5.8 km/s. The target orbit altitude was 1400 by 165 km, at 45 deg inclination. The detailed results of the Monte Carlo simulations for this mission are shown in [4]. The results show 100 percent successful capture rate, with a 3-sigma post-aerocapture propulsive delta-V requirement of 54 m/s, resulting in 97.4 percent of the total orbit insertion delta-V provided by aerocapture.

Titan Explorer

A Titan Aerocapture Systems Analysis Study [16] was performed during the year 2002. The vehicle L/D was 0.25, and ballistic coefficient was 90 kg/m^2. The atmospheric entry velocity was 6.5 km/s. The target orbit altitude was 1700 by 1700 km, at 101.6 deg inclination. The detailed results of the Monte Carlo simulations for this mission are shown in [6] and [7]. The results show 100 percent successful capture rate, with a 3-sigma post-aerocapture propulsive delta-V requirement of 209 m/s, resulting in 95.8 percent of the total orbit insertion delta-V provided by aerocapture.

Neptune and Triton Orbiter

A Neptune Aerocapture Systems Analysis Study [17] was performed during the year 2003. The vehicle L/D was 0.82, and ballistic coefficient was 258 kg/m^2. The atmospheric entry velocity was 28 km/s. The target orbit altitude was 430,000 by 3,896 km, at 157.3 deg inclination. The results of the Monte Carlo simulations for this mission are shown in [9] and [10]. The results show 100 percent successful capture rate, with a 3-sigma post-aerocapture propulsive delta-V requirement of 177 m/s, resulting in 96.9 percent of the total orbit insertion delta-V provided by aerocapture.

Venus Explorer

A Venus Aerocapture Systems Analysis Study [18] was performed during the year 2004. The vehicle L/D was 0.25, and ballistic coefficient was 114 kg/m^2. The atmospheric entry velocity was 11.25 km/s. The target orbit altitude was 300 by 300 km, at 90 deg inclination. The results of the Monte

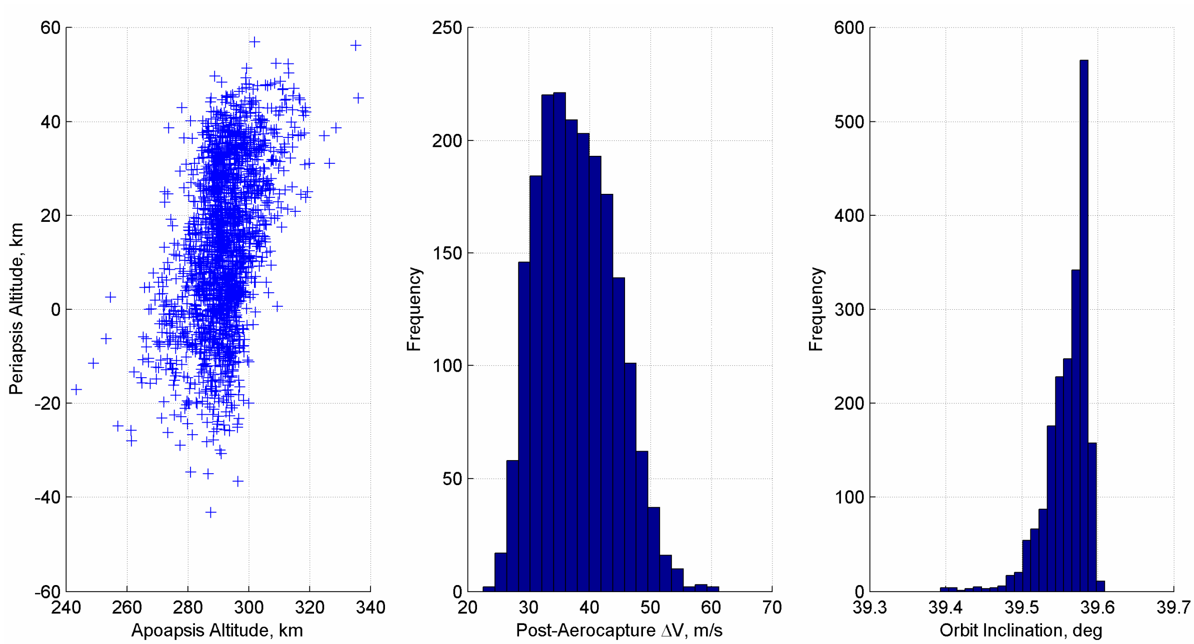

Fig. 3. Monte Carlo results for the proposed ST9 Aerocapture Demonstration Mission.

TABLE I

THE APC ALGORITHM DEMONSTRATES EXCELLENT PERFORMANCE WITH ROBUSTNESS TO DISPERSIONS IN ENTRY CONDITIONS, ATMOSPHERIC DENSITY, AND VEHICLE AERODYNAMIC PARAMETERS, REGARDLESS OF THE DESTINATION.

Destination	Entry Velocity (km/s)	L/D	Ballistic Coefficient (kg/m^2)	Target Orbit Altitude, km	Aerocapture Success Rate	Orbit Insertion Delta-V Provided by Aerocapture (3-sigma)	Orbit Plane Wedge Angle Error (deg, 3-sigma)
Mars	5.8	0.23	148	1400 x 165	100%	97.4%	0.48
Titan	6.5	0.25	90	1700 x 1700	100%	95.8%	0.35
Neptune	28.0	0.82	258	430,000 x 3896	100%	96.9%	0.43
Venus	11.25	0.25	114	300 x 300	100%	97.7%	0.10
Earth	10.0	0.20	209	300 x 130	100%	97.3%	0.11

Carlo simulations for this mission are shown in [11]. The results show 100 percent successful capture rate, with a 3-sigma post-aerocapture propulsive delta-V requirement of 90 m/s, resulting in 97.7 percent of the total orbit insertion delta-V provided by aerocapture.

Aerocapture Demonstration at Earth

The New Millennium Program ST9 Aerocapture Concept Definition Study was performed during the year 2006. The vehicle L/D was 0.20, and ballistic coefficient was 209 kg/m^2. The target orbit altitude was 300 by 130 km, at 39.5 deg inclination. The approach trajectory in this case was from a highly elliptical orbit, providing an atmospheric entry velocity of 10 km/s. The results of the Monte Carlo simulations for this mission are shown in Fig. 3. The results show 100 percent successful aerocapture, with a 3-sigma post-aerocapture propulsive delta-V requirement of 57 m/s, resulting in 97.3 percent of the total orbit insertion delta-V provided by aerocapture.

Summary of Monte Carlo Simulation Results

A summary of the Monte Carlo trajectory simulation results (2000 cases for each destination) is shown in Table I. A variety of destinations, target orbits, entry speeds and vehicle parameters have been investigated. As can be seen, the APC algorithm provides 100 percent aerocapture success rates, greater than 95 percent of the required delta-V for orbit insertion, and orbit plane wedge angle errors of less than 0.5 deg.

SUMMARY AND CONCLUSIONS

An analytic predictor-corrector algorithm has been developed and tested in exhaustive trajectory simulations for missions to Venus, Mars, Titan, Neptune, and Earth. This analysis, consisting of thousands of trajectory runs for each destination, has led to a mature, robust, and flexible algorithm, with excellent performance regardless of the mission and destination.

Using standard definitions for Technology Readiness Level (TRL) [19], [20], the APC algorithm has achieved at least TRL 4. Future work would include testing to assess performance using higher fidelity 6-degree-of-freedom, non-real-time trajectory simulations to increase the TRL to 5. The next step in development would be to perform real-time testing on a flight-like processor with simulated and flight-like hardware in the loop. Once hardware in the loop testing is completed, the algorithm will have achieved TRL 6, and can readily be implemented on flight hardware. TRL 7 or higher would be achieved through actual demonstration on a space flight mission.

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