Advanced Hypersonic Entry Guidance for Mars Pinpoint Landing

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***Abstract*— Hypersonic entry guidance technology is being developed to support a broad range of future Mars missions. The goal is to develop guidance technology that, in conjunction with other entry, descent, and landing (EDL) technologies, will allow greater landing accuracy, as well as access to higher elevation landing sites, than currently achievable. The guidance technology should be applicable to capsule-type landers, but also higher lift-to-drag (L/D) and ballistic coefficient configurations that will be required for landing higher mass and volume payloads. Our guidance algorithm is based on the concept of planning and tracking drag, and extends the state of the art represented by the entry guidance algorithm of the Space Shuttle Orbiter. Modifications to the planner have been introduced to extend its applicability to low L/D capsules. Final phase position guidance logic has been developed to improve the parachute deployment state control. The algorithm has been tested in simulated flight for a low L/D capsule and a mid L/D ellipsled. The results demonstrate the effectiveness and versatility of the guidance algorithm. The guidance technology is also applicable for landing missions to other atmosphere-bearing planets and satellites.**

I. Introduction

Plans for large payload robotic missions to the ancient highlands of Mars and for human Mars missions are driving the development of entry, descent, and landing (EDL) technology [1]. The five successful U.S. robotic landers to date have had masses below 0.6 metric tons (t), guaranteed landing accuracies on the order of 100 kilometers, and landing elevations below -1.4 km Mars orbiter laser altimeter (MOLA). For the next generation of robotic missions, it is desired to land 0.8 - 2.0 t payloads within 10 km or less of the specified landing site at an elevation of +2 km MOLA or more. The Mars Science Laboratory (MSL) mission, intended to land a 0.8 t payload within 20 km of a +2 km MOLA site using atmospheric guidance, will be the first step in this direction. Human missions require landing 40-80 t within 100 meters. To accommodate the large masses it is likely that higher ballistic coefficient landers will be used and require higher lift to achieve the higher elevation landing sites [1]. With higher ballistic coefficient comes the potential for higher heat flux and the need to fly the lander in a such a way that the heat flux does not exceed the vehicle limits.

In this paper, we describe our efforts to develop hypersonic entry guidance to meet the needs of future robotic and human missions to Mars. The responsibility of hypersonic entry guidance is to command the control variables – bank angle and possibly the angle of attack – during the atmospheric flight that deliver the vehicle to a desired state for deploying the supersonic decelerator (e.g., parachute) and keep the vehicle and payload within heating and acceleration limits along the way.

This work was supported by NASA.

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II. Objectives

The goal is to develop hypersonic guidance technology that, in conjunction with other entry, descent, and landing (EDL) technologies, will enable greater landing accuracy as well as access to higher elevation landing sites than currently achievable. The guidance technology should be applicable to capsule-type landers, but also higher ballistic coefficient and higher lift-to-drag ratio (L/D) configurations that will be required for landing higher mass payloads. And the guidance must avoid flight paths that would produce excessive heating, acceleration, or dynamic pressure.

III. Approach

A. Guidance Algorithm

The state-of-the-art in flight-proven entry guidance is represented by the Apollo and Shuttle guidance algorithms [2], [3]. A modified version of the Apollo (2nd entry) guidance [4] will be used on the MSL mission for the first guided Mars entry. The MSL baseline entry guidance uses the entry terminal point controller [4] to guide the vehicle until the velocity has decreased to about Mach 5, then to meet the challenging requirements for supersonic parachute deployment position control, the guidance switches to heading control logic. The MSL baseline guidance has shown very good performance in simulation testing and meets the requirements for the MSL mission.

Looking ahead to future missions, the entry terminal point controller has inherent features that may limit its applicability for higher L/D landers. It is based on linearizing the equations of motion about a pre-planned reference trajectory and thus lacks flexibility for enroute entry condition or landing site changes. The guidance parameters are pre-calculated for the reference trajectory, also limiting flexibility. The longitudinal guidance and lateral guidance are decoupled which introduces the need for conservatism and reduces the landing footprint relative to that for which the vehicle is capable. The entry guidance [3] for the U.S. Space Shuttle is on the other hand designed for a high L/D vehicle. The Shuttle entry guidance consists of a trajectory planner and a trajectory tracker. With the planner, the entry trajectory can be re-planned during flight, accounting for heating, acceleration and dynamic pressure constraints. However the planning approach is geared toward higher L/D vehicles and may not produce trajectories that are feasible for lower L/D vehicles. As with the entry terminal point controller, the longitudinal and lateral guidance logics are uncoupled. In the longitudinal plane there is onboard trajectory planning based on the assumption of a great circle flight path; as a result of this assumption and the conservativeness that must be exercised due to the decoupling of the longitudinal and lateral guidance, the landing footprint is compromised. The decoupling of the longitudinal and lateral guidance also limits the achievable accuracy.

Our hypersonic entry guidance development builds on previous entry guidance research for Mars landing [5] as well as for Earth entry [6], [7]. Our starting point in the current effort was the Evolved Acceleration Guidance Logic for Entry (EAGLE) [7] developed for future space transportation vehicles, such as the next generation reusable launch vehicles NASA is currently considering. Prior to the current effort, EAGLE was applicable to mid and high L/D vehicles. Test results for an X-33 type vehicle are reported in [8] and show excellent performance for a broad range of off-nominal conditions.

EAGLE is composed of a trajectory planner and a trajectory tracker; the tracker issues attitude commands to the autopilot that will size (angle of attack control) and direct (bank angle control) the aerodynamic lift force such that the planned trajectory will be flown. For a vehicle whose trim angle of attack is dictated by a fixed center of gravity offset or a fixed flap, EAGLE commands only bank angle. For a vehicle whose angle of attack can be controlled, EAGLE commands angle of attack and bank angle. The concept on which EAGLE is based has its heritage in the Apollo and Shuttle programs. It is to plan and track aerodynamic accelerations. Aerodynamic acceleration (or deceleration, such as drag) is related accurately to position via kinematic equations. Aerodynamic acceleration is measured directly by accelerometers and is thus well-suited for accurate tracking. Simply put, the vehicle feels its way through the atmosphere to the desired parachute deployment point; if the atmospheric density is higher or lower than expected, the vehicle adjusts its altitude until the desired drag is felt. Thus the guidance approach is robust to modeling errors. To accommodate a wider range of off nominal conditions, the planner can update the reference trajectory several times during the hypersonic entry phase. By accounting for the coupled longitudinal and lateral motion, the planner can generate a reference trajectory to practically any point in the feasible landing footprint, shaping the trajectory such that all the vehicle constraints are respected.

To adapt EAGLE to meet the needs of future Mars landing missions, the required developments are to improve the targetting accuracy for supersonic parachute deployment and to extend the algorithm's applicability to low L/D capsules.

B. Guidance Testing

The guidance algorithm is evaluated and further developed through extensive computer-based simulation testing. The medium-fidelity simulation testing is done in a Matlab-based 3 degree of freedom (DOF) Mars atmospheric flight simulation. High-fidelity Monte Carlo simulation testing is done in the Dynamics Simulator for Entry, Descent and Surface landing (DSENDS). DSENDS is a high-fidelity, 6 DOF, real-time spacecraft simulator for Entry, Descent and Landing (EDL) on planetary and small bodies. DSENDS was developed as a multi-mission tool and is designed to meet a wide variety of needs during the lifecycle of a mission - from simple workstation based simulations to integrated simulations involving flight software running under a real-time operating system such as VxWorks. DSENDS is being used for MSL [9]. DSENDS provides an interface to Mathworks's Matlab/Simulink environment for rapid prototyping and testing of user developed algorithms. DSENDS employs high-fidelity models as well as providing for easy interface to externally developed algorithms and models. Atmospheric models are based on the Mars Global Reference Atmospheric Model. DSENDS also includes a variety of spacecraft actuator and sensor models. These models include thrusters (both fixed and throttled), star trackers, gyros and accelerometers. DSENDS includes terminal guidance and control algorithms.

IV. Results

The trajectory planner in EAGLE has been re-designed to better accommodate low L/D vehicles. The construction of the drag profile in the Shuttle entry planning and in the previous EAGLE entry planning does not take into account the control capability. As a result, a drag profile can be constructed that is difficult to track and the guidance accuracy will suffer. The entry guidance of low L/D capsules presents a challenge for drag planning, because of the very limited control authority. Numerical integration with a constant intermediate bank angle has been used to generate an initial drag profile [2], [5]. In [4], two constant intermediate bank angle segments connected by a linear (with respect to velocity) transition segment are used to provide some additional shaping. A different approach to constructing a more easily tracked drag profile is presented in [10]. Interpolation and pre-tracking are used to reduce the complexity of the drag planning, yet produce a flyable drag profile. Pre-tracking begins with a trajectory generated by some means that neglects certain constraints or uses approximations to the equations of motion to simplify the trajectory computation. A simulation is then run in which the initial trajectory is tracked, using some control law, with some or all of the previously neglected constraints and modeling details included. The new planner matches the vehicle's initial flight path angle and bank angle and enforces the full three-degree-of-freedom (3-DOF) equations of motion with control derivative limits. These improvements increase the likelihood that the planned trajectory can be accurately tracked. Guidance simulation results using EAGLE with the new planner demonstrate the performance improvements. Insights from computing maximum crossrange trajectories were factored into the design of the planner. Comparisons of trajectories created by the planner and optimal trajectories demonstrated that the planner can generate trajectories to most of the landing footprint. This result is especially significant considering the planner's fast computation time.

To deliver the lander for the Mars Science Laboratory (MSL) mission to the parachute deployment point, the baseline guidance scheme uses the entry terminal point controller down to about Mach 5 and then switches to heading alignment logic for the supersonic phase to reduce the heading error and thus reduce the crossrange error. Smart chute logic may also be used to achieve the specified downrange accurately, though this is not currently baselined for MSL. The focus on downrange and crossrange errors can, however, result in the parachute deployment altitude being a couple kilometers off nominal. More recently, the MSL strategy has been to accept larger horizontal errors in order to better control deployment altitude.

We are developing final phase position guidance logic that reduces the altitude guidance error, without significantly compromising the horizontal accuracy. EAGLE is based on planning and tracking aerodynamic drag, and, as mentioned, it adapts to an off-nominal atmosphere by flying higher or lower as appropriate; however, for parachute deployment targetting, position is important. Thus the approach is to have EAGLE guide the flight in the first half of entry; then there is a switch to guidance logic that drives the heading error to zero while shaping the heading transient to control the parachute deployment altitude. Simulation results indicate that the entry guidance approach can deliver a lander to parachute deployment with less altitude error and similar horizontal error relative to using heading alignment only in the final phase.

The new hypersonic guidance algorithm has been tested in a medium-fidelity simulation for a low L/D capsule and a mid L/D ellipsled. This testing has led to further algorithm improvements and is continuing. Testing in the high-fidelity DSENDS simulation is beginning. Monte-Carlo simulations will provide more rigorous evaluation and are expected to lead to further algorithm improvements.

V. Summary

Hypersonic entry guidance is being developed to meet the needs of future robotic and human Mars landing missions. An algorithm suited for low, mid, and high lift-to-drag ratio Hypersonic entry guidance technology is being developed to support a broad range of future Mars missions. The goal is to develop guidance technology that, in conjunction with other entry, descent, and landing (EDL) technologies, will allow greater landing accuracy as well as access to higher elevation landing sites than currently achievable.

Our entry guidance algorithm is based on the concept of planning and tracking drag, and extends the state of the art represented by the entry guidance algorithm of the Space Shuttle Orbiter. Modifications to the planner have been introduced to extend its applicability to low L/D capsules. Final phase position guidance logic has been developed to improve the parachute deployment state control. The algorithm has been tested in simulated flight for a low L/D capsule and a mid L/D ellipsled. The results demonstrate the effectiveness and versatility of the guidance algorithm. The guidance technology is also applicable for landing missions to other atmosphere-bearing planets and satellites.

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